DEVELOPMENT OF A TUNABLE DIODE LASER PROBE FOR MEASUREMENTS IN HYPERVELOCITY FLOWS

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Abstract

Since the advent of hypersonic flow in the 1950s, scientists and engineers have been continually challenged to design and build aircraft and propulsion systems capable of sustained hypersonic flight. Unfortunately, flight testing of new systems is associated with high risks and costs, thereby requiring ground-based testing in artificially generated flows. In ground-based facilities an array of diagnostics are deployed to measure the pertinent performance parameters and to evaluate a design’s worthiness. Furthermore, an accurate assessment of facility performance and flow thermodynamic state is critical for worthwhile interpretation of test data and CFD model validation. Due to the harsh nature of the testing environment, developing instrumentation that is capable of making accurate and reliable measurements has proven to be difficult.

This thesis describes the development and demonstration of tunable-diode laser absorption spectroscopy (TDLAS) probes installed directly into high-velocity flowfields. The probes are fiber-coupled to laser sources which are repetitively tuned at kilohertz rates over spectroscopic tracer absorption transitions. The hardened probes contain the required electro-optical components to pitch and catch laser beams that non-intrusively interrogate the flowfield. By recording the transmitted radiation intensities, time resolved measurements of temperature, concentration, and velocity are obtained from water vapor absorption ($\nu_1 + \nu_2$ near 1.4 $\mu$m) while velocity measurements were obtained from potassium atom absorption ($D_1$ near 0.77 $\mu$m).

During the operational cycle of a gas-driven reflected shock tunnel, driver gas is known to permeate the test gas. When testing in air and using hydrogen as the driver gas, the resultant water vapor can be exploited as a spectroscopic target species. The water vapor measurements agree well with the computationally predicted values of velocity and temperature (4500 m/s and 600 K), implying that the calculated conditions exist early in the test time. However, later in the test an increase in water vapor concentration correlates with an increase in the velocity and changes in temperature. Additionally, traditional heat-flux and pitot measurements incorrectly indicated steady performance.

In a separate study, a miniaturized version of the water based probe was developed based on the presence of chemically frozen atomic potassium in the freestream. The reduced probe size
is a direct result of potassium’s large absorption coefficient. Velocity measurements consistent with both CFD models and simultaneous water-vapor measurements are reported. Additionally, an analysis of the radiative absorption in the boundary layer is presented.

A modified miniature probe was developed for expansion tube testing of radiative absorption of potassium atoms in the boundary layer. The presence of potassium in the Stanford shock/expansion tube was linked to the existence of a partially reflected shock from a facility diaphragm. Additionally, a simple exchange of probe optics and test-gas seeding enabled water vapor measurements with the same probe. The time average of temporally discrete velocity measurements using water agreed well with classical time-of-flight velocity measurements. However, the diode-laser measurements indicated an initial unsteadiness that may be caused by the boundary layer growth along the wall and/or the presence of a reflected shock.

This work successfully demonstrates that rugged probes based on relatively inexpensive tunable diode lasers are capable of making accurate and high-repetition rate measurements in hypervelocity flowfields and highlights their potential as permanent fixtures in large scale facilities and for performance surveys of smaller scale facilities.
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Chapter 1

Introduction

Reflected shock tunnels and shock/expansion tubes have been providing high-enthalpy flowfields for ground-testing applications for over forty years (Hertzberg 1951; Resler and Bloxsom 1952). Implicit in the operation of these facilities is the assumption that a steady-flow time interval – the test time – exists. Internal flowfields with combustion and external flows have been studied during this interval leading to advances in missile defense, atmospheric re-entry, and supersonic combustion ram (SCRAM) engine development. Both to advance the state of the art and meet future challenges in defense and space commercialization, more accurate determination of the flow test condition is required. Specifically, it is important to ascertain the duration and thermodynamic state of the test time to validate analytical and computational models. The significance of validation is two-fold: (1) researchers have essentially depended on non-equilibrium n-dimensional nozzle models to calculate the free stream conditions with input from facility instrumentation,\(^1\) and (2) the calculated freestream conditions are in turn used as inputs to computational models of the flowfield within or about test articles.

1.1 Motivation and Objectives

Typically, impulse facility measurements are averaged over a steady-flow interval. During this interval, radial surveys of stagnation pressure and heat-flux gauges are used to determine flow parameters like Mach number and velocity (Park 1997). Unfortunately, some of the commonly accepted techniques for determining uniform flow conditions (e.g., radiation intensity measurements, Langmuir probes, microwave interferometer measurements) have suggested steady-state test times that are significantly less than those inferred from the pitot and heat flux measurements. In addition stagnation-point heat-flux measurements have been found to be

\(^1\) Holder and Schultz 1962; Lordi, Mates, and Moelle 1979; Korte and Hodge 1994; Chadwick, Holden, Korte, and Anderson 1996.
of little value in determining the duration of uniform flow (Dunn 1969). With few exceptions, traditional instrumentation in hypersonic facilities is limited to these electromechanical devices for measuring pressure and temperature indirectly (Tishkoff et al. 1997). A shortcoming of reflected shock tunnel operation is the interaction between the reflected shock from the facility endwall and the post incident shock boundary layer flow. Many investigators have attempted to compute and measure the interactions’s effect on hypersonic nozzle flow quality.2 One experimentally observed symptom of this interaction is the premature introduction of cold driver gas to the reservoir region.3 When hydrogen driver gas chemically interacts with an air test gas, water vapor will be an equilibrium product. In the present study, a diagnostic based on water-vapor detection was developed using diode lasers operating near 1.4 µm with the goal of temporally quantifying its presence and simultaneously measuring temperature and velocity. By assuming water is in equilibrium with the test gas, these measurements can be used to infer the temperature and velocity before amounts detrimental to facility performance arrive.

Because some shock-tunnel facilities do not operate with hydrogen, a second diode-laser diagnostic was developed that interrogates a species present in the flow and is unrelated to hydrogen. A candidate species is potassium which has ground-state absorption transitions accessible by commercially available diode lasers, near 766 and 770 nm. Additionally, potassium is the 7th most abundant material in the earth’s crust and is prominent in human sweat and urea. It was anticipated that potassium would be present in the test gas because trace amounts of potassium salts are in commercial-grade materials or found on the internal facility surfaces contacted by workers. Furthermore, even if potassium number densities were small, sufficient absorption signals are possible because potassium is such a strong absorber.

The shock/expansion tube (SET) is another type of impulse facility where traditional measurements are averaged over a steady interval determined by heat flux and pitot pressure surveys (Erdos 1994). Two operational features result in flow unsteadiness and can obscure traditional measurements.

First, a secondary diaphragm in a SET is ruptured via a gasdynamic shock. The inertia and strength of the diaphragm causes a reflected shock, whose strength is coupled to the rupture process, to propagate upstream into the test gas. The presence of a reflected shock was recognized as a potential drawback in the original theoretical studies by Resler and Bloxom (1952) and Trimp (1962). Theoretical and experimental investigations on the interaction between a diaphragm and a shock were first demonstrated in the late 50’s by Meyer (1957). Subsequent

investigations have studied the effect of the reflected shock on the test gas integrity.\(^4\)

Second, the development of boundary layers in a SET flow causes the flow behavior to
depart from simple analytical models. Because the shock tube was developed as a research
tool earlier, much study (both analytical and experimental) has been applied to understanding
the effect of boundary layers on their performance.\(^5\) In summary, boundary layer formation
decelerates the shock velocity and accelerates the contact surface. The boundary layer effect
is more pronounced in SET facilities due to test gas flow through the acceleration tube. As a
result, complex analytical models are needed to predict SET performance.

The SET’s reflected shock causes the test gas near the diaphragm to undergo shock heating
and at appropriate test conditions, temperatures sufficient for ionization and dissociation are
possible. Although the gasdynamics associated with reflected shocks are well understood, the
coupling between the chaotic diaphragm rupture and the reflected shock may generate conditions
which promote the devolution of potassium salts contained in or on the diaphragm to be present
in the test gas.

The features of the reflected shock at the secondary diaphragm and the possibility that
potassium was liberated from the heated diaphragm particles provided the motivation for studying
atomic potassium as a possible spectroscopic target species in shock/expansion tunnels. The
particle path\(^6\) originating near to the secondary diaphragm undergoes the most rapid expansion,
potentially freezing out species such as nitric oxide (Roberts et al. 1994). This thinking was
extended to potassium for it was believed a small amount of frozen atomic potassium would
serve as a spectroscopic tracer. Furthermore by seeding the test gas with water vapor, the same
probe could be used to test in conditions where potassium is not in atomic form.

\(1.2\) Organization of Thesis

This thesis presents the development of diode-laser based probes for non-intrusive measure-
ments of species, temperature and velocity in flows generated by ground-based facilities.
Due to the nature of the flowfield and the recognized limitations of conventional measure-
ment techniques, spectroscopic techniques have been applied to these flows; section 1.3 discusses the
development of past related efforts.

The hypersonic environment related to flight systems offers unique opportunities to spec-
 troscopic sensors, but the sensor must withstand a hostile environment with high stagnation
temperatures and pressures, vibrations, and high-speed particles. A brief discussion of the
unique nature and problems associated with high speed flow is covered in Chapter 2. This

\(^{4}\) Miller 1977; Shin and Miller 1978; Bakos and Morgan 1994; Roberts et al. 1994; Roberts et al. 1995; Wilson

\(^{5}\) Glass and Martin 1955; Duff 1959; Mirels 1963; Mirels 1964; Mirels and King 1966; Mirels 1966; Mirels 1984.

\(^{6}\) Not a actual diaphragm particle but a idealized virtual gas particle which follows the flow.
Chapter also includes operational descriptions of the gas-driven reflected shock tunnel and the shock/expansion tube.

Chapter 3 contains a discussion of the underlying spectroscopic principles for the probe. Additional detailed information relating to the spectroscopy of atoms and molecules is placed in Appendix A. Furthermore, details regarding two potentially relevant lineshape broadening mechanisms, tuning-rate broadening and power broadening, are provided in Appendices, B and C, respectively.

A substantial infrastructure of equipment is necessary for a spectroscopic measurement. Chapter 4 surveys the equipment and operating principles, beginning with diode lasers. Additionally, a description of the data reduction strategy employed in a direct absorption experiment using wavelength modulation is presented.

This thesis departs from the traditional and distinct experimental description and results chapters. The probes' development took an evolutionary path; thus results are presented for each probe design. Furthermore, the results and operational experience had a direct impact on subsequent improvements. As a consequence, Chapter 5 includes the progression of probe designs, results and analysis. Three additional appendices related to this chapter include a discussion regarding selection of the optimal beam angle for Doppler measurements (Appendix D), a detailed analysis of boundary layer effects on radiative absorption (Appendix E), and a brief overview of a test program (Appendix F) which was conducted to determine the source and character of potassium atoms in shock/expansion tube flow.

Chapter 6 presents a summary of the results, reviews the major conclusions and contributions, and outlines suggestions and cautions for future probe development.

1.3 Tunable Laser Measurements in High Speed Flows

The first application of tunable diode lasers (TDL's) in an impulse facility used cryogenically-cooled lead-salt diode lasers in shock-tube flow (Hanson 1977a; Hanson 1977b). In these experiments, the shock tube provided a bath gas at controlled temperatures and pressures to determine linewidth and collision linewidth of carbon monoxide. The necessity of operating these lasers at temperatures below 80 K, their low emission power, general difficulty of use, and spectroscopic complications of strong infrared absorbers such as CO$_2$ and H$_2$O in the atmosphere, prevented their application to high enthalpy facilities until the late 1990's (Mohamed et al. 1996; Mohamed et al. 1998).

A step towards applying TDL's for unsteady flows was conducted in a flame (Hanson and Falcone 1978). A rapid-tuning lead-salt diode laser operating in the near-IR was used to probe rovibrational absorption lines of CO near 4.7 $\mu$m. The ability to monitor unsteady behavior was demonstrated by scanning the transition at repetition rates greater than 1 kHz. Temperature
1.3. TUNABLE LASER MEASUREMENTS IN HIGH SPEED FLOWS

sensitivity was achieved because the continuous-tuning range available with these lasers was large enough to scan multiple lines. The scans were used to determine the ground-state population distribution and corresponding rotational temperatures.

In the late 1980's, the addition of a novel mechanical tuning element to a ring-dye laser permitted modulation of the laser emission at UV and visible wavelengths, enabling study of transitions in the UV. Fluorescence and line-of-sight absorption measurements using OH and NO as molecular tracers in flames or shock heated flows were achieved using these techniques (Chang, Rea, and Hanson 1987; Rea and Hanson 1988). Having established the technique in slowly-changing flowfields, a series of measurements in high speed flows was performed, including simultaneous measurements of velocity and temperature using OH fluorescence in jets near 306.5 nm at a 3 kHz rate (Chang et al. 1990). Additionally, an increased scan rate of 4 kHz was applied for NO absorption measurements near 226 nm in shock tube flows (Chang et al. 1991).

Meanwhile, the use of diode lasers in physics research had been gaining acceptance throughout the 1980's as room-temperature diode laser technology matured (Camparo 1985). By the early 1990's considerable efforts from large optoelectronics companies resulted in commercial availability of inexpensive diode lasers, operable at room temperature, and over wavelengths ranging 0.65 to 1.55 \(\mu m\). Fortuitously, atomic species (Li, Na, K, O, Rb, Sr and Ca) and molecular species (\(O_2\), \(NO_2\), \(H_2\), HCN, CO, CO\(_2\), NH\(_3\) and HCl) have ground-state absorption transitions in this spectral region.

An early TDL experiment relevant to air diagnostics involved \(O_2\) absorption in the A band near 760 nm using derivative spectroscopy (Kroll et al. 1987). Measurements were subsequently reported in a shock tube for a temperature range of 600 to 1100 K and a velocity range of 500 to 1100 m/s using wavelength modulation spectroscopy\(^8\) (WMS) (Philippe and Hanson 1992). WMS techniques are sensitive to small absorption signals and were required due to the weak spin-forbidden transition in oxygen (Philippe and Hanson 1991). Directly applicable to impulse facility testing was the demonstration of WMS at 10 kHz. Weak overtone water transitions are also present in the same spectral region of molecular oxygen and were successfully measured using WMS and frequency modulation spectroscopy (FMS) techniques (Liang-guo et al. 1988).

Often, ground-based facility flows contain chemically frozen atomic oxygen and nitrogen during rapid gasdynamic expansions in the nozzle. These atomic species have also been measured with TDL techniques. For example, measurements of kinetic and population temperatures using direct absorption of atomic oxygen near 777.2 nm with a GaAlAs diode laser were performed in a shock tube from 6900 to 11400 K at a 6 kHz repetition rate (Chang et al. 1993). Similarly

\(^7\) Advances in the shorter wavelengths were motivated for applications in digital storage devices video laser disks and later compact disks (CD) for audio. Development near 1.4 \(\mu m\) was motivated by fiber optic technology. Laser transmission in a fiber possesses a minimum in signal dispersion near 1.3 \(\mu m\) and a minimum in signal attenuation near 1.55 \(\mu m\) (Yariv 1997, pg. 104).

\(^8\) WMS typically refers to high frequency wavelength modulation using the charge carrier density effect superimposed on wavelength modulation using the joule-thermal effect.
atomic nitrogen transitions near 821.6 nm were measured in a shock tube at 8 kHz repetition rates (Chang, Baer, and Hanson 1994).

Diode-laser measurements of water-vapor temperature using a 2-line temperature technique were first made in a shock tube near 1.39 µm (Arroyo et al. 1994a). This scheme used time division multiplexing (TDM). In TDM, lasers are scanned sequentially. For example, while one laser scans a transition, another laser, aligned with the same path, is held just below the threshold current until the first laser is finished scanning. This technique is applicable to environments where the temperature is expected to change very little between subsequent scans. If a line pair is spectrally close enough, they could be probed sequentially during a single scan with negligible time difference between the two. This idea was successfully demonstrated in a shock tube (Arroyo et al. 1994b) for use as a high speed flow sensor by targeting water vapor transitions near 1.4 µm. A drawback is the limited number of spectrally proximate line pairs having the desired characteristics over the range of temperature and pressure of interest. Despite the drawback, the investigators were able to demonstrate the first direct measurements of temperature, velocity, and water vapor partial pressure.

To extend the technique for combustor applications, where many line pairs are required to probe the wide range of temperature conditions, a wavelength division multiplexing (WDM) technique was developed (Baer et al. 1994). In WDM, radiation from multiple lasers, corresponding to separate absorption transitions, is fiber coupled and combined into a single fiber. Once in the fiber, the radiation is routed to a combustor or flame for spectroscopic measurements. The transmitted radiation is collected after exiting the combustor or flame, and the wavelengths are separated using a diffraction grating and then directed into separate detectors. The advancement of WDM opened the way for monitoring multiple transitions of multiple species (Nagali et al. 1995a; Nagali et al. 1995b) in combustion environments. The ability to probe the same volume with multiple lasers is attractive for applications with limited optical access. To detect weak absorption signals (either because the transition is weak or the concentration is low) of multiple gases, frequency modulation multiplexing (FMM) has been applied to CO and CO₂ at 1.548 and 1.558 µm respectively (Oh et al. 1998). In this technique WMS is applied with differing modulation frequencies; then, by applying lock-in amplifiers at the different modulation frequencies, the signal may be demultiplexed. A more detailed overview of some of these measurements and additional ones related to combustion, is provided in a review paper by Allen (1998).

The natural progression of the techniques highlighted above is to incorporate past advances with fiber optics and the commercial availability of laser diodes into self-contained probes. By making the probe small relative to the flow length scales, point-like measurements of temperature, concentration, and target species velocity can be acquired in hypersonic flows such as those studied in this thesis.
1.4 Summary

Many qualities are required of an in situ sensor for high-enthalpy gasdynamic facilities. The sensor must be robust enough to endure the harsh environment which includes the start up and in some cases violent shut down of the facility. For example, during the shut down the high speed flow surrounding the test article breaks down and multiple shock waves generated from the test-section walls subject the test article to varying loads over a wide range of frequencies. The violent duty cycle precludes the use of WDM schemes where precise optical alignment is necessary. Additionally, the sensor must be stable enough to operate for long times in isolation during the multiple-hour operational cycle of large scale facilities.

There are some features in hypersonic flow and the accompanying test facilities that make the use of TDL spectroscopic techniques using direct absorption attractive. The features include an interval of steady operation, a one-dimensional flowfield, and a low pressure environment.

The definition of steady in an impulse facility is equivocal, depending on the goals of the experiment, and to some degree the sophistication of the available instrumentation. From a sensor design viewpoint, a steady condition permits tailoring the selection of absorption transitions for a narrow range of temperatures and pressures. Another feature is that the facilities operate on the principle of applying a Galilean transformation to data. It is expected that the data acquired in the facility can (with proper dimensional similarity) be applied to a vehicle moving at high velocity into quiescent air. As a result, facility designers go to great lengths to produce one-dimensional flow. This permits point-like absorption measurements for small probes. Furthermore, if temporal fluctuations are gradual enough, then the instantaneous axial gradients in the flow can be neglected. These features permit a probe design using relatively simple optics (for robustness and easy realignment) and multiple-passed beams to detect weakly absorbing species or states. These beams need not probe the same volume given the uniformity of the flow.

Finally, most high speed applications occur at very high altitude (>15 km) where the pressure is less than one tenth of an atmosphere. The low pressure conditions reduce collisional effects to yield narrow spectroscopic features. As a result, scans over the entire lineshape at a high repetition rate are achievable, yielding time resolved measurements of temperature, velocity, and species pressure levels.
Chapter 2

Facilities and Hypervelocity Flows

To appreciate the complexities of hypervelocity flows and the ground-test facilities which generate them, this chapter begins with a discussion of the total enthalpy. This quantity is central to understanding the strong coupling between energy and momentum for high-speed flowfields and for characterizing ground-test facilities.

2.1 Gas Dynamics of Hypervelocity Flows

The Mach number, the ratio of the flow velocity to the sound speed, is a means for flow classification. The square of the sound speed, \( a^2 \), is defined as,

\[
a^2 = \left( \frac{\partial p}{\partial \rho} \right)_s,
\]

where \( p \) and \( \rho \) are the static pressure and density, respectively, and \( s \) is the specific entropy. The term static defines the observed property while moving with the flow. Using the ideal gas assumption, the sound speed may be written as,

\[
a = \sqrt{\frac{\gamma R}{M} T},
\]

where \( \gamma \) is ratio of specific heats, \( R \) is the universal gas constant, and \( M \) is the molecular mass [amu]. An informative equation is obtained by assuming the gas is calorically perfect\(^1\) in a definition for the flow’s stagnation enthalpy, \( h_s \). Note that stagnation describes the enthalpy as experienced by a fixed observer with the fluid having been brought to rest adiabatically at

\(^1\)A gas with constant specific heats [Vincenti and Kruger 1986 pg.8].
2.1. GAS DYNAMICS OF HYPERVELOCITY FLOWS

the observer with no work interaction. From the first law of thermodynamics the stagnation enthalpy, \( h_s \), is,

\[
h_s = h + \frac{V_{\text{gas}}^2}{2},
\]

(2.3)

where \( h \) is the flow’s specific enthalpy, defined as the sum of the sensible and chemical enthalpies, and \( V_{\text{gas}} \) is the bulk flow velocity. With rearrangement the following equation for total enthalpy is obtained,

\[
h_s = \frac{a^2}{\gamma - 1} + \frac{V_{\text{gas}}^2}{2},
\]

(2.4)

A contour of constant stagnation enthalpy from equation 2.4 is illustrated in figure 2.1. Though obtained through ideal gas relations, this representation accurately illustrates the different flow regimes. For example, a feature of incompressible flow is that the temperature or sound speed does not change much for low velocities. Thus, the energy and momentum equations are practically decoupled with the only mechanism for change being viscous dissipation. Through the regions of subsonic, transonic and supersonic flow, one observes an increased interdependence between the sound speed and the flow velocity. Hypersonic flows are characterized by relatively constant velocity, but the sound speed can undergo drastic changes. A lower bound for hypersonic flow applies to the Mach number range from 3 to 5. In this range, a number of characteristic phenomena are observable and become distinct from supersonic flow (Anderson 1989). A brief summary of the relevant phenomena follows.

Thermal effects result from the coupling of the gas temperature to velocity. That is, small geometric deviations in hypersonic flow fields result in velocity changes which in turn, generate large temperature changes. This behavior complicates analytical flowfield solutions because
transport properties, namely thermal conductivity and viscosity which possess strong temperature dependencies, couple the energy and momentum equations.

Non-equilibrium phenomena come about as a result of abrupt changes in temperature (i.e. gasdynamic shocks or rapid expansions). Differences between the translational temperature and the temperature associated with internal energy modes (rotational, vibrational, and electronic) result from insufficient time, with respect to flowfield changes, for collisions to communicate the changes between the various modes. Additionally, the short time scales can induce chemical non-equilibrium (both state and species). Thus, hypersonic flows may have composition and temperature gradients in space and time. Analysis requires sufficient understanding of the collisional- and radiative-transfer mechanisms. Due to the vast spectrum of time scales associated with these phenomena, computational models require substantial investments in computer hardware and strong reliance on experimental efforts for validation.

These are only a few of the complexities of hypersonic flow which make it a challenging environment in which to perform measurements and to analyze numerically. Moreover, due to the expense and complexities of flight testing, ground test facilities must be used. However, they suffer from the difficulties mentioned above, and as a result, require flow facility characterization for determining the thermodynamic state, chemical composition, speed, and direction of the flow. Such a characterization should reveal the spatial and temporal distribution of these properties.

There is one more complication to developing diagnostics for a large-scale hypersonic research facility. Often, flows are generated with velocities in excess of 4500 m/s which translates to 10 MJ/kg (via equation 2.3). To test a model of relevant size, a typical mass-flow rate in the Caltech 96-in Hypersonic Shock Tunnel is 4000 kg/s. This translates to roughly a 40 GW power requirement to generate such a flowfield. As a result, the flow-facilities of this scale do not test for very long; in fact test durations are on the order of milliseconds (ms) or 100’s of microseconds (μs). Therefore any diagnostics used in characterizing such flows must have a fast time response (short time constants).

## 2.2 The Gas-Driven Reflected Shock Tunnel

### 2.2.1 Description of Operation

A reflected shock tunnel (RST) consists of a standard shock tube augmented with a converging-diverging nozzle and a test section. The development of the shock tube dates back to Vielle in 1889 (Thompson 1988, pg. 423). Detailed descriptions of shock tube operation can be found in Thompson (1988) and Liepmann and Roshko (1957). A brief description of the operation follows.

Figure 2.2 illustrates the generic RST geometry, shown below an x-t wave diagram. The
2.2. **THE GAS-DRIVEN REFLECTED SHOCK TUNNEL**

The x-t diagram illustrates the axial position of various gasdynamic phenomena as a function of time. The tunnel’s initial state is defined by the conditions in regions 4 and 1. The driver’s initial condition (state 4) is high pressure (and preferably high sound speed) gas. Initially the gas in state 1 is confined to the driven tube which contains the test gas at moderate pressures (0.1 - 2 atm). The primary diaphragm separates the driven tube from the driver while another diaphragm, typically a thin piece of mylar, covers the nozzle throat at the end of the driver (or the endwall). The mylar permits the nozzle and test section to be evacuated and reduces the nozzle start time.

![Diagram](image)

**FIGURE 2.2** A wave diagram and a schematic of the reflected shock tunnel regions illustrate the temporal wave dynamics which generate steady test conditions in region 5.

Shock tunnel operation begins by rupturing the primary diaphragm. Rupture causes a shock to propagate through the driven tube and an expansion fan to radiate outward from the diaphragm location. State 2 refers to the test gas that has been processed by the shock, whereas state 3 is the driver gas which has undergone expansion. The interface of state 2 and 3 is an idealized contact surface which separates gases differing in species and thermodynamic state. While the pressures and velocities in state 2 and 3 are matched, there is a temperature discontinuity. State 2 is relatively hot from shock heating, and state 3 is relatively cool from expansion. The shock reflects off the endwall, re-shocks the test gas, and establishes a high temperature and pressure region, state 5. A small hole in the endwall joins a converging-diverging nozzle to the test section, and the gas in state 5 is accelerated to super/hypersonic conditions in the test section.

Development surrounding the addition of a converging-diverging nozzle to the shock tube to
produce hypersonic conditions was successfully completed in 1959 (Wittliff et al.). The operating principle is based on the near stationary conditions in the reservoir. Reservoir gas is effectively motionless and its thermodynamic state is well defined, establishing the total enthalpy and pressure. However, the presence of a small (with respect to the driven-tube diameter) throat permits mass to flow into the supersonic nozzle. As a result, the wave diagram in figure 2.2 indicates a contact surface with a velocity to reflect the nozzle mass flow rate.

2.2.2 Test Flow Complications

Thermal and Chemical Effects

Ideally, a nearly continuous range of test conditions can be generated with an RST by setting the appropriate reservoir conditions combined with a properly-scaled throat and nozzle, thereby expanding the reservoir gas to the desired conditions of temperature, pressure, and velocity. In practice, developing hardware to perform this function is difficult. For example, to generate test conditions similar to re-entry, the reservoir must be designed to contain gases with temperatures greater than 7500 K and pressures in the thousands of atmospheres. With the rapid expansions occurring in the nozzle, species and state chemistry along with thermokinetics (diffusivity, conductivity and viscosity) become factors in the nozzle design as the reservoir gas relaxes towards natural air.

Another issue is the coupling between the nozzle boundary layer displacement thickness and the Mach number. The coupling extent is largely enthalpy dependent because the freestream enthalpy directly affects the boundary layer recovery temperature. In turn, the viscosity affects turbulence and chemistry alters the gas composition. These effects change the boundary layer displacement thickness which (as an approximation) effectively turns the flow. As a consequence, two separate nozzles may be needed to generate similar Mach numbers if test conditions differ greatly in enthalpy.

Test Time Duration

The steady flow interval contains gas that has undergone a steady expansion from the reservoir region (reflected shock) after an unsteady start-up interval (Smith 1966). The mass flux out of the reservoir is small enough that the reservoir conditions may be assumed constant. The events ending the steady portion of the flow are somewhat equivocal as the definition is dependent on the experiment at hand. Temporal issues regarding test gas composition are treated in section 2.2.2. However, two different gasdynamic events unquestionably cause an end to the useful test time.

The first event is the arrival of the expansion fan head that has been reflected off of the driver end-wall. The expansion causes a rapid reduction in temperature and pressure terminating the
2.2. **THE GAS-DRIVEN REFLECTED SHOCK TUNNEL**

steady reservoir conditions. Generally, RSTs are designed with appropriately long drivers and driven tubes to avoid this issue. The second event is the arrival of the contact surface at the end wall. In a simple one-dimensional model the contact surface arrives at the endwall after all the gas from the reflected shock region enters the nozzle. Its arrival is marked by a rapid change in the reservoir gas composition and temperature. There are however, numerous mechanisms that contribute to premature driver-gas arrival (with respect to consumption of test gas through the throat); these are discussed below.

An additional acoustic process can potentially perturb the steady reservoir conditions. An acoustic impedance mismatch at the contact surface results in either the upstream-traveling reflected shock to re-reflect off the contact surface back into the test gas, or the upstream-traveling reflected shock accelerates causing an expansion fan to propagate downstream into the reservoir. Both phenomena cause temporal fluctuations in pressure and temperature which contaminate the test conditions. Wittliff (1959) developed a technique called “interface tailoring” in which a judicious choice of driver gas composition matches the sound speeds on either side of the contact surface. The reflected shock passes cleanly through the contact surface without generating a disturbance. However, when operating the facility at substantially high enthalpies, where a large incident shock Mach number is required, a pure hydrogen gas driver is generally utilized. At such enthalpies there is no longer any freedom to tailor the driver-gas mixture.

**Test-Gas Contamination Mechanisms**

A number of real-world effects influence the composition of the test gas and are relevant to the development of diagnostics that characterize the freestream conditions based on gas composition. An overview of the mechanisms follows.

As the incident shock passes through the test gas, it imparts momentum to the gas, and the no-slip condition at the tube wall yields a growing boundary layer. The boundary layer acts as a mass sink which decelerates the incident shock and accelerates the contact surface, thereby reducing the available test time in the reservoir region (Mirels 1964). A further reduction in test time occurs through a mixing process when the reflected shock passes through the contact surface. Levine (1978) showed that because a density gradient exists at the contact surface, a condition is established such that Rayleigh-Taylor instabilities promote turbulent mixing at the interface, shortening the length of pure test-gas.

Another consequence of boundary layer formation is the bifurcation of the reflected shock. The reflected shock velocity is set by the near-zero velocity boundary condition at the endwall, and propagates upstream into the shocked test gas accordingly. However, to process the boundary layer flow the shock must bifurcate. As a result, the only way to match the pressure in the core and along the wall is for the boundary-layer flow to “jet” into the reservoir. The bifurcated shock establishes an entropy gradient which induces vorticity and subsequent mixing.
of the gases. When mixing occurs near the contact surface the driver gas jetting prematurely injects the reservoir gas into driver gas. The driver gas alters both the chemical composition and thermodynamic state of the reservoir. Much literature on reflected shock bifurcation has been produced from 1953 when Herman Mark first proposed this effect, to 1991 (Kleine et al.) when color schlieren photographs of the driver gas injection were published.

The cumulative effect of these processes is the premature introduction of driver gas into the test gas, in advance of one-dimensional estimates. Interestingly, conventional heat-flux and pitot-tube measurements have been shown to be largely insensitive to the gas composition (Dunn 1969). However, numerous experimental programs have successfully measured the presence of driver gas in the test flow. Gas sampling measurements of the test gas composition as a function of time were performed using an in situ mass spectrometer tuned to detect helium (Stalker and Crane 1978; Skinner and Stalker 1995). Another interesting technique took advantage of the choking characteristics of a flow through a small channel based on gas composition. By measuring the pressure behind an oblique shock, a change in gas composition causes a transition from the common weak oblique shock to a strong one, enabling the indirect driver gas detection with a pressure measurement (Paull 1995). While each of these methods provide a temporal indication of driver-gas onset, no additional data are obtained.

In the event that the driver gas is hydrogen and the test gas is air, one expects water to be present at some point in time during the operation. Based on the supposed presence of water vapor, an investigation was begun to develop a sensor capable of detecting water vapor as a function of time.

2.2.3 The 96-in HST and the LENS Tunnel

The RST experiments were conducted in two separate facilities located at the Calspan/University at Buffalo Research Center (CUBRC) in Buffalo New York. CUBRC is a not-for-profit organization formed to unify the combined talents of Calspan and the university. The 96-in Hypersonic Shock Tunnel was originally commissioned in 1964. An upgrade, completed in 1992, extended its capability to cover an enthalpy range of 3 to 15 MJ/kg over a Mach number range from 8 to 24 (Albrechinski et al. 1995). The Large Energy National Shock (LENS) Tunnel was commissioned in 1987 and began operation in 1991. The LENS tunnel is operationally identical to the 96-in HST, but its larger size extends the operational test time (Holden 1991; Holden et al. 1993).

Figure 2.3 illustrates the basic components and scale of the facilities. The driver/driver configuration consists of a chambered shock tube with an area ratio (driver/driver) of 2. The 8 \times 0.29 \text{ m} driver is externally heated to 670 K and is capable of holding 2040 atm of hydrogen. The primary diaphragm is a double diaphragm mechanism. Each diaphragm is sized to hold
1/2 the driver pressure. A controlled break is executed by venting the cavity between the diaphragms. Stainless steel diaphragms, 0.61 m in diameter, are used. They are scored in a cross pattern (for cleaner opening), and are as thick as 4 cm. The 17.5-m long driven tube is connected to the 2.44-m diameter test section by a steel-corseted, fiberglass nozzle. The corset enables the use of a fiberglass nozzle despite the 10 to 13 MN (2.3 to 3 million lb.) of thrust generated when the double diaphragm section ruptures. Finally, a fast-acting valve, installed near the endwall, restricts the introduction of diaphragm particles into the test section.

The nozzle has 3 sections, beginning with a beryllium-alloy throat which transitions to a short, conical, stainless steel section and finally to the contoured fiberglass nozzle. The fiberglass portion features a contour design incorporating real-gas effects, finite rate state and species chemistry, and turbulent boundary layers (Chadwick et al. 1996) to produce uniform one-dimensional core flow at the nozzle exit plane.

The test section in both facilities is 2.43-m in diameter, 8.23-m long and rides on a rail system. The large size permits personnel to work directly on test articles and incidentally acts as an inertial damper. Test articles are fixed to a foundation mechanically isolated from the test section.
2.3 The Gas-Driven Shock/Expansion Tunnel

2.3.1 Description of Operation

A shock/expansion tunnel (SET) consists of three tubes operated as two shock tubes in tandem. The idea of augmenting a shock tube with an acceleration tube to generate hypersonic flow was put forth first by Resler and Bloxom (1952). A schematic of the tunnel and the associated gasdynamic wave diagram is shown in figure 2.4. The three tubes are a driver, driven tube, and an acceleration tube. A test section/dump tank is affixed to the end of the acceleration tube where test objects are installed. The initial condition is identical to that of the RST. However, the thin piece of mylar that separates the nozzle from the driven tube in an RST, now separates the acceleration tube from the driven tube and is called the secondary diaphragm. Furthermore, the acceleration tube is filled with a high-speed gas, typically helium, to a prescribed pressure establishing state 10.

![Wave diagram and schematic of shock/expansion tunnel](image)

**FIGURE 2.4** A wave diagram and a schematic of the shock/expansion tube is presented. The wave diagram illustrates the idealized wave dynamics that generate the test conditions in region 5. Additionally, a gasdynamic particle path originating from near the secondary diaphragm is illustrated.

A detailed description of the SET operation is is described by Trimpi (1962). An overview of the operation is as follows. By rupturing the primary diaphragm an incident shock travels down the driven tube establishing states 2 and 3 as in the RST. However, when the shock meets the secondary diaphragm (theoretically causing an instantaneous rupture) a secondary shock with an enhanced Mach number propagates through the acceleration gas establishing state 20.
The breaking of the secondary diaphragm forms a second shock tube.

The simple one-dimensional analysis of the time-space trajectory of a sample particle path in figure 2.4 is an aid to understanding how steady flow is generated. The particle path originates in the driven tube and exits in the test time. In region 2, it has the same velocity as the contact surface (separating states 2 and 3) and intersects a family of expansion waves that originate from the generation of the enhanced secondary shock. These expansion waves are propagated upstream into the test gas but are convected downstream in the supersonic flow. The particle is accelerated through a non-steady constant-area expansion and emerges as state 5. Ideally, the velocity in state 5 is that of the contact surface between acceleration-tube gas processed by the secondary shock. Only a fraction of the test gas near the secondary diaphragm exits as state 5.

The test time begins with the contact surface arrival (between states 5 and 20) and is gasdynamically terminated by one of two events. One possible termination mechanism is the arrival of the expansion fan tail at the secondary diaphragm. The second termination mechanism can be caused by a reflected expansion wave at the intersection of the primary contact surface and the head (i.e. the most upstream portion) of the secondary expansion fan. The respective termination causes are dependent on tube geometry, gas composition, and operational pressures.

In principle, SET's offer substantial gains in both stagnation enthalpy and stagnation pressure together with a decrease in freestream dissociation levels when compared to reflected shock tunnel operation (Trippi 1962). The gains of the SET are mainly due to the total-enthalpy increase affected by the unsteady expansion. Reduced dissociation levels are achieved due to the absence of a high temperature reservoir that exists in a reflected shock tunnel.

### 2.3.2 Test Flow Complications

Four features of SET operation result in flow quality degradation or test time reduction. The most significant feature is the presence of boundary layers which cause a velocity increase at the cost of reduced test time. Theoretical treatments of the flow behind the shock in states 2 and 20, are available. However, due to a gas composition change across the contact surface, test gas velocity analysis requires detailed computations. Additional difficulties arise due to mixing processes that that occur at the secondary contact surface. The presence of the secondary diaphragm and the rupturing of the primary diaphragm both cause additional disturbances affecting flow quality at the beginning and end of the test time respectively. Discussion of the primary diaphragm rupture effects is included for completeness, but this facet of SET operation is not a concern for diode-laser measurements.
Pressure Oscillations

Disturbances in the form of undesirable pressure oscillations can prematurely terminate the test flow (Neely et al. 1991; Paull and Stalker 1992). It is thought that some of the disturbances originate with the primary diaphragm’s rupture. In the laboratory reference frame, pressure fluctuations travel at the gas velocity plus the acoustic velocity. Thus, a portion of gas (in a 1-D sense) near the test flow end is contaminated with pressure oscillations. Strategies involving driver gas composition adjustments have proven to extend the facility operating condition range (Erdos et al. 1994; Bakos and Erdos 1995). One strategy is to reduce the sound speed of the expanded driver gas, thereby impeding the propagation of the disturbances. Another strategy is to enhance the primary shock velocity so as to outpace the disturbances.

Additional disturbances are believed to be generated in the boundary layers that form along the tube walls. This source is especially problematic if the boundary layer is transitional between laminar and turbulent (Erdos and Bakos 1994). The strategy to avoid boundary layer disturbances involves testing at conditions either below or above the transitional Reynolds numbers.

Boundary Layer Effects

The presence of boundary layers in SET facilities is a cause for the gasdynamic performance to depart from one-dimensional predictions. Because the shock tube was developed earlier, much study (both analytical and experimental) has been applied to understanding the effect of boundary layers on their performance. A graphical illustration of the effect of boundary layers on gasdynamic processes is shown in figure 2.5.

![Diagram](image)

**FIGURE 2.5** A wave diagram showing ideal and actual coordinates for the shock wave and contact surface. Boundary layer formation attenuates the shock velocity while causing contact surface acceleration.

The propagation of an incident shock in a driven tube imparts momentum on the test gas

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2 Glass and Martin 1955; Duff 1959; Mirels 1963; Mirels 1964; Mirels and King 1966; Mirels 1966; Mirels 1984.
and, to maintain the no-slip condition at the wall, a boundary layer develops. The boundary-layer thickness grows in time as the shock continues to propagate. Consequently, mass gets entrained in the boundary layer. The removal of mass from the core flow sets up a distributed source of expansion fans which accelerate the contact surface and decelerate the incident shock. After the shock and contact surface travel a long distance (with respect to the tube diameter), the separation distance between the shock and contact surface reaches a limiting value and remains constant thereafter.

A schematic of the mass entrainment process discussed above, as viewed in the laboratory reference frame, is illustrated in figure 2.6a. In figure 2.6b, the coordinate system is fixed on the shock and the gas velocity is zero at the contact surface, yet finite just after the shock. The limiting case is reached when the mass flow passing through the shock equals the flow that moves around the contact surface and through the boundary layer.

![Diagram](image)

**FIGURE 2.6** a) A view of the flow between the shock and contact surface in the laboratory coordinates after the shock and contact surface have achieved steady velocities. b) The same flow as in a) however, viewed in shock-fixed coordinates.

The velocity character of the flow can be understood from this limiting solution. In figure 2.6b, once the gas has been processed by the shock it flows at a lower velocity ($V_{p.s.}$). The core flow at the contact surface has zero velocity in this reference frame. Therefore, in the laboratory reference frame, the velocity of the gas increases from the value behind the shock. Furthermore, for conditions shy of the limiting case, there will be an increase in velocity between the shock and the contact surface.

Boundary layer flow analysis in shock tubes has been studied extensively by the researchers in the above references. Additionally detailed CFD analysis by Sharma and Wilson (1995) including chemistry and assuming axisymmetric flow, was applied to shock tube flow, verifying the analysis of Mires et al enabling one to compute all the primitive variables for detailed analysis. A range of experimental data from various shock tubes is compiled and compared to the numerical results and Mires' theory. The authors concluded that the analytical treatments provide an upper limit on the test time.

The lessons learned from the shock tube studies can be applied to SET flow to conclude
that the acceleration of the test gas by viscous effects occurs throughout the length of the tube. In the SET acceleration tube, the test gas lies behind the contact surface. Mirels' theory can not be applied in this region due to the change in species. Hence, numerical analysis is required to solve for the test gas conditions (Jacobs 1994). Detailed SET flow CFD analysis by Jacobs (1994) and Wilson (1995) confirm the effects of boundary layer formation mentioned above. Both numerical analyses present results indicating that the displacement thickness of the test gas just behind the contact surface was about an order of magnitude larger than for the end of the acceleration-section helium flow. Wilson (1995) states that the displacement thickness depends on the test parameters and tube geometry. Jacobs (1994) presents centerline time histories at the exit of the acceleration tube for the primitive variables along with pitot pressure, Mach number, and density. His results indicate a temporal velocity rise observed at the acceleration-tube exit station.

**Contact Surface Mixing**

The acoustic disturbances mentioned above affect flow quality toward the end of the test interval. The viscous effects will alter the velocity from 1-D theory and reduce the test time duration due to contact surface acceleration and shock deceleration. Additionally, the test interval can be compromised through degradation of the contact surface ahead of the test gas as the test gas moves through the acceleration tube. Mixing of the acceleration and test gas occurs by both Fickian and thermal diffusion processes. Thermal diffusion arises due to the temperature discontinuity (from test gas to acceleration gas) across an ideal contact surface. Note, at the secondary interface the helium has been shock heated and the test gas has been shock heated and subsequently expanded through the secondary expansion fan. Although the contact surface accelerates due to the boundary layer presence, Rayleigh-Taylor instabilities do not play a role because the density gradient is negative with respect to the direction of the gas acceleration.

**Diaphragm Finite Rupture Time**

The wave diagram in figure 2.4 from section 2.3 shows the ideal transmission of the primary shock through a gas interface into the acceleration tube. As early as 1970 it was known that a presence of the secondary diaphragm would affect the test gas quality (Weilmunster 1970). The diaphragm possesses a small mass and strength, and when struck head-on by a shock wave, the resulting difference in pressure between the two sides of the diaphragm causes the material to accelerate in the direction of the incident shock. However, the restraining tensile forces holding the diaphragm in place impede its motion until the material ruptures (in some unknown fashion). The diaphragm's inertia and strength causes the contact surface to have an
accelerating trajectory rather than the straight line depicted in figure 2.4.

Meyer (1957) analyzed a similar scenario: the impact of a shock on a movable wall. His analysis revealed that as time progresses the motion of the diaphragm would send out compression waves into the region downstream and rarefaction waves into the region upstream. Because the diaphragm does not move initially, the incident shock reflects and produces conditions similar to the reservoir region in a RST. The subsequent compression waves would overtake the earlier ones and eventually coalesce to form a shock, whereas the rarefaction waves catch up to the reflected shock and weaken it.

Shin and Miller (1978 pg. 18) presented conclusive evidence of a reflected shock via wall-pressure measurements just upstream of the secondary diaphragm. Roberts et al. (1995) did experiments to study the effect of the secondary diaphragm on the global parameters of test duration and flow quality without regard to the local phenomena surrounding the secondary diaphragm rupture. More extensive measurements of the secondary reflected shock phenomena were done again in 1997 (Roberts et al.) with a heavily instrumented section of the tube just upstream of the secondary diaphragm. These results confirm that the reflected shock velocity is much less than that predicted for a reflection from a solid wall and that its velocity scales with diaphragm thickness.

After Meyer (1957), no analytical treatment of the secondary diaphragm rupture was performed until Morgan and Staller (1992). In this study the researchers noted that to achieve desired test conditions, acceleration-tube pressures had to be an order of magnitude less than theoretical. The reason behind the strong departure from ideal performance was believed to lie in the rupturing process of the secondary diaphragm. Their diaphragm rupture model assumed an instantaneous shearing around the edges upon shock arrival, and the diaphragm's inertia impeded the ideal transmission of the incident shock. Additionally, the region between the diaphragm and the reflected shock was assumed to be of uniform velocity. The diaphragm's trajectory was computed by doubly integrating its acceleration which is driven by the pressure difference across it. The researchers were qualitatively able to confirm the origin of their operational difficulties.

Wilson (1992) was concerned with the possible dissociation problems introduced by the presence of the reflected shock. The test gas very close to the diaphragm goes through the most rapid expansion and therefore, the initial test gas composition could be compromised. A quasi-one-dimensional (with finite rate chemistry) computation of acceleration tube performance was carried out. The goal was to simulate the finite opening time of the diaphragm and subsequently model the effect of the reflected shock on the gas composition. The diaphragm opening process was simulated by noting the primary shock's arrival time at the secondary diaphragm and then instantaneously removing the diaphragm when a specified time had elapsed (approximately 10 μs). Using the simple model for secondary diaphragm rupture, the qualitative features of the
disturbance compared well with the experiments. Wilson (1992) notes that the pitot pressure character (calculated at the exit of the acceleration tube) was altered when the finite diaphragm rupture model was introduced, but failed to include a trace. Additionally, the author included no information on the calculated velocity.

Bakos and Morgan (1994) proposed an improved diaphragm rupture model by modifying the model used by Morgan and Stalker (1992). The modifications entailed more realistic physics between the diaphragm and the reflected shock. First, the flow in the region was treated as compressible. Second, the conditions in this same region were allowed to change as computed by expansion fans propagating from the accelerating diaphragm (as originally put forth by Meyer (1957)). The results of this work showed dissociation levels less than reported by Wilson (1992) and qualitatively good reproduction of the measured static-wall pressure time history just downstream of the diaphragm station.

Predicted dissociation levels are thought to be reduced because in Wilson’s (1992) hold-and-break model, the gas particles near the diaphragm experience a faster expansion rate than the more realistic inertial acceleration model. Because the diaphragm must eventually fragment and leak to achieve observed secondary shock velocities, the calculations using the inertial acceleration model were not carried out for the entire facility simulation. Roberts et al. (1994) improved the model by reducing the secondary diaphragm’s mass linearly over a short time (attenuating inertia model). The modification permitted computation of the tunnel’s entire operation, and the authors note that by adjusting the hold time in their calculations using Wilson’s (1992) hold-and-break model, the static pressure time histories could be made very similar to the attenuating inertia model. The results suggest that the hold-and-break model may be sufficient if dissociation is not an issue.

Strikingly, much of the research regarding the finite secondary diaphragm rupture time fails to consider the effect on flow velocity. The test gas particle paths originating near the diaphragm have a different thermodynamic history than those originating some distance upstream. The gas near to the diaphragm is essentially stagnated and then accelerated while the gas further away is exposed to the more ideal SET process.

The test flow disturbances from the primary diaphragm’s rupture, the diffusive and viscous effects along with the finite secondary diaphragm rupture process all combine to degrade the available test time for experimentation. Ideal analyses yield test-time durations of 10’s to 100’s μs, but non-ideal behavior may reduce this test time substantially.

In hypersonics, velocity is the primary variable of interest due to its relationship to the total enthalpy. However, in studies of non-ideal SET behavior velocity is only rarely reported perhaps because it is difficult to measure directly. Additionally, most numerical analyses have the same deficiency, possibly due to a lack of velocity data for comparison. Using TDLAS techniques, the species-specific nature of the diagnostic can potentially resolve the issues surrounding the
2.3. THE GAS-DRIVEN SHOCK/EXPANSION TUNNEL

blending of the secondary contact surface and directly measure the velocity time history.

2.3.3 Description of the Stanford Expansion Tube

A schematic of the SET is shown in figure 2.7, and a detailed description and initial characterization of the facility has been published by Kamel et al. (1995a). A subsequent characterization study was performed shortly thereafter (Kamel et al. 1995b). The facility consists of four main elements, the driver, driven, and acceleration tubes, plus a test section/dump tank. To achieve repeatable operation, the primary diaphragm station houses two diaphragms in tandem. An intermediate cavity between the diaphragms is loaded to 1/2 the driver pressure and each diaphragm is sized for the differential pressure. Flow in the tunnel is initiated by venting the intermediate cavity. At that time the upstream diaphragm bursts immediately followed by the downstream one.

![Diagram of the Stanford Expansion Tunnel]

**FIGURE 2.7** A schematic of the Stanford University shock/expansion tube. The *emission/absorption* port is located 1.016 m upstream of the acceleration tube exit plane in the test section. The tube section's ID is 9.5 cm.

When the facility is operated with the intention of accelerating a combustible mixture, the driven tube is subsectioned into a buffer and driven section. Both subsections are filled to the same pressure but the buffer section contains inert gas (typically nitrogen) to insulate the combustible test gas from hot rupturing diaphragm particles which may cause unwanted ignition in portions of the tube. The acceleration tube opens into the 27 x 27 cm² test section equipped with optical access via two opposing pairs of 10 x 10 cm² quartz windows.
The test section is hard-mounted to the dump tank, which is turn fixed to the foundation. The test body or probe is mounted on a sting attached to an interior wall of the test section. The acceleration tube is permitted to move axially by means of a radial o-ring seal between the acceleration tube O.D. and the test section. The o-ring seal eliminates the transmission of thrust loads resulting from diaphragm rupture and as a result, no separate inertial foundation is required.

2.4 Summary

Reflected shock tunnels and the shock/expansion tunnels have been in world-wide operation for over 40 years. Yet, issues regarding their ability to generate quality test flow remain. Two pertinent handicaps are associated with reflected shock tunnel operation. First, the expansion of the reservoir gases is so rapid that the test gas may not be in chemical or vibrational equilibrium. As a result, flowfield computation to determine the velocity is computationally intensive due to the wide range in characteristic times (numerical stiffness) introduced by the chemistry and vibrational relaxation processes. The difficulty is compounded by the application of thermo-chemical models over a temperature and pressure range that may extend over orders of magnitude. The second handicap is related to driver gas contamination. The consequences of driver gas introduced into the reservoir region are twofold. First, in the case of hydrogen driver operation, combustion studies are severely impaired if significant concentrations of H, OH, and H2O are present in the freestream test flow. Secondly, computations of the freestream will be affected by alterations in both chemical and vibrational relaxation processes if the temporal increase of hydrogen and its products of combustion are not accounted for.

The operation of the SET suffers primarily from viscous effects. When viscous effects are combined with the unsteady nature of the tunnel operation, axial gradients in velocity translate into temporally changing velocity at the acceleration-tube exit. Additionally, complications of the diaphragm rupture and mixing of the secondary contact surface are confined to the initial portion of the test time. However, when test times are on the order of 100's of microseconds then any additional compromise to the test time duration becomes important to quantify and monitor.
Chapter 3

Absorption Spectroscopy Theory

Diode laser absorption measurements of a gas phase species depend on the spectral position (or line position), the intensity (or linestrength), and the spectral intensity distribution (or line-shape). Absorption measurements are simplified with laser light sources, by taking advantage of their collimated beam and narrow spectral linewidth. When the laser linewidth is narrow compared to absorption linewidth, the light source may be treated as monochromatic. A central feature of spectroscopic measurement is the understanding of the relationship between the environmental parameters (e.g., temperature and pressure) and absorption. Detailed analysis of the position, strength and shape of the absorption feature permits the experimentalist to infer these environmental parameters.

3.1 Line Position

Max Planck put forth the idea that the energy of an oscillator is discontinuous and that any change in its energy content can only occur in discrete amounts, or quanta (Halliday and Resnick 1978, pg. 1094). Furthermore, he suggested that the exchange of energy could be in electro-magnetic form and the radiation’s frequency, $f$, [s$^{-1}$] has the form,

$$f = \frac{\Delta E}{h}, \quad (3.1)$$

where $h$ is Planck’s constant and $\Delta E$ is the energy quanta exchanged. Light frequency is related to the wavelength and wavenumber through the speed of light, $c$,

$$\frac{c}{\lambda} = c \nu = f, \quad (3.2)$$
where $\lambda$ is the wavelength of the radiation and $\nu$ is the wavenumber. Equation 3.2 can be rewritten,

$$
\nu = \frac{\Delta E}{hc}.
$$

In the vernacular of spectroscopy, frequency and wavenumber are often used interchangeably as are the symbols $\nu$ and $f$. When developing the fundamental relations, the innate units of frequency ($f$) will be used. By the end of section 3.2, the convenience of using wavenumbers ($\nu$) will be apparent and used thereafter.

The principles of radiative absorption in a gas can be described using a two level model as shown in figure 3.1. The levels (states) are radiatively coupled where $n_1$ and $n_2$ are the population densities (cm$^{-3}$) in the lower and upper states, respectively. The state energy, in the form of internal energy, consists of nuclear, rotational, vibrational, or electronic modes. Solutions of the time-dependent Schrödinger wave equation for internal energy models describes electromagnetic radiation interaction with the species. By way of their solution, quantum numbers are obtained which discretize the allowable energy levels. Additionally, selection rules (specific to the internal energy models) result which enumerate the allowed quantum number changes (Banwell 1983, pg. 42). The line positions are fixed through the describing the energy separations, $hf$ of allowed transitions.

**FIGURE 3.1** The two level model illustrates the energy separation between a radiatively coupled transition. This model shows 3 radiative processes, stimulated absorption ($1 \rightarrow 2$), stimulated emission ($1 \rightarrow 2$), and spontaneous emission ($1 \rightarrow 2$) where the energy of the photon is $hf$ from equation 3.1. Additionally the radiative transition rates discussed in section 3.2 are shown.

Closer examination of figure 3.1 reveals the radiative processes of emission and absorption. The arrows indicate the direction of population transfer resulting from the following radiative processes: stimulated absorption, stimulated emission, and spontaneous emission, as represented by the rate constants $B_{12}$, $B_{21}$ and $A_{21}$.

If a vector component of the bulk gas motion ($V_{gas}$) is along the direction of the light propagation as shown in figure 3.2, the absorbing molecule will experience radiation at a lower
3.2. **Line Strength**

The line strength describes the propensity of a transition to absorb photons. The goal of this section is to describe the molecular/atomic parameters which influence line strength. The absorption of light can be measured in terms of attenuation with respect to the incident intensity. The spectral intensity of collimated light \( I_f \) is a flux of power per unit spectral frequency:

\[
I_f = \rho(f) \cdot c, \quad \text{(3.5)}
\]

\[
I_f = (n_p \cdot h f) \cdot c \left[ \frac{\text{W}}{\text{area} \cdot \text{Hz}} \right], \quad \text{(3.6)}
\]

where \( n_p \) is the photon number density.

The spectral absorption coefficient \( k_f \) is defined as the fraction of energy absorbed \( (dI_f / I_f) \) per unit length,

\[
k_f = \frac{1}{I_f} \frac{dI_f}{dx}, \quad \text{(3.7)}
\]
Figure 3.3 shows a schematic of an absorption experiment where scattering processes are neglected. Collimated light is attenuated as it passes through a homogeneous gas possessing a spectral absorption coefficient \( k_f \). Assuming that \( k_f \) is independent of the laser intensity, equation 3.7 can be integrated to a position, \( x \), to yield:

\[
I_f(x) = I_f^0 \exp(-k_f x).
\]  

(3.8)

This equation, known as the Beer-Lambert Law, is fundamental for analysis of absorption spectroscopy. Measurements are obtainable through the detailed understanding of \( k_f \).

![Diagram of absorption of radiation through a slab of gas](image)

**FIGURE 3.3** Examination of the absorption of radiation through a slab of gas.

As a beam of light travels through a gas as depicted in figure 3.3, the action of stimulated absorption removes energy from the beam while stimulated emission and spontaneous emission can inject photons. However, spontaneous emission occurs over \( 4\pi \) sr and, by design, a negligible amount is collected. The resulting definition for \( k_f \) from the power absorbed over a small spectral region (\( \delta f \), i.e. the laser linewidth) is,

\[
\frac{1}{I_f} \frac{dI_f}{dx} \equiv -k_f = \frac{hf}{c} \phi(f-f_0) [n_2 B_{21} - n_1 B_{12}].
\]  

(3.9)

Equation 3.9 has two aspects embedded. One, is the spectral dependence on the absorption through the lineshape function \( \phi(f-f_0) \). If the laser intensity is weak, the upper state is negligibly populated and the lineshape can be treated in a straightforward manner as in section 3.3. The second aspect, for large laser intensities, is that the upper state can become significantly populated, meaning that once the radiative system reaches equilibrium, (i.e., \( \frac{dn_i}{dt} = 0 \)) subsequent incoming photons can be absorbed, pass through, or stimulate the emission of an additional photon. The latter process complicates the lineshape and is examined in Appendix C.
3.2. LINE STRENGTH

Equation 3.9 is developed further for a laser probing a system of many atoms or molecules in local thermodynamic equilibrium. The population ratio between the states can be expressed as a ratio of the Boltzmann distributions for each energy level,

\[
\frac{n_2}{n_1} = \frac{g_2}{g_1} \exp\left(-\frac{hf}{KT}\right),
\]

where \( g_i \) is the degeneracy in the \( i \)th energy state, \( K \) is Boltzmann’s constant, and \( T \) is the equilibrium temperature of the system. Furthermore, a relationship between the two Einstein-B coefficients can be obtained by considering the case where the atoms are in thermal equilibrium with a blackbody radiation field at temperature \( T \) yielding,

\[
g_2 B_{11} = g_1 B_{12}.
\]

There is no loss of generality in using equation 3.11 since the magnitudes of the Einstein-B coefficients depend on the atoms and not on the radiation field (Yariv 1989, pg. 171). Substitution of 3.10 and 3.11 into 3.9 yields (for \( hf \gg KT \)),

\[
k_f = \frac{hf}{c} n_1 B_{12} \phi(f - f_s).
\]

The lineshape function, \( \phi(f - f_s) \), is the normalized absorption distribution function about a line center, \( (f_s) \),

\[
1 = \int_{-\infty}^{\infty} \phi(f - f_s) df.
\]

By integrating 3.12 over the line, the propensity of the transition to absorb photons, the linestrength \( (S) \) is,

\[
S_{12} \equiv \int_{-\infty}^{\infty} k_f df = \frac{hf}{c} n_1 B_{12} [\text{cm}^{-1}\text{Hz}].
\]

In this thesis, units of atmosphere [atm] and wavenumber [cm\(^{-1}\)] will be used, so \( S_{12} \) is

\[
S_{12} [\text{cm}^{-2}/\text{atm}] = \frac{S_{12} [\text{cm}^{-1}\text{Hz}]}{c \times P_i[\text{atm}]},
\]

where \( P_i \) is the partial pressure of the absorbing species. Furthermore, \( k_f \) becomes \( k_\nu \) and is equal to \( S_{12} \phi(\nu) P_i \). The natural log of equation 3.8 yields,

\[
-\ln \left( \frac{I_v(x)}{I_v^0} \right) = S_{12} \phi(\nu) P_i x,
\]

and is called the absorbance. In an absorption experiment using a narrow linewidth light source, the left hand side is measured at \( x = L \). With a tunable diode laser, the absorbance can be measured over the lineshape extent rapidly. Applying the knowledge of how the right hand
side behaves with temperature, pressure and velocity, enables the experimentalist to infer their values.

For example, a accurate technique for temperature measurement used in these experiments is obtained by calculating the ratio $R$, of the absorbance for two transitions. The technique is developed in detail by Arroyo and Hanson (1993) and an intermediate result describing the temperature dependence of a single line is,

$$
S_{13}(T) = S_{13}(T_0) \frac{T_0 Q(T_0)}{T Q(T)} \frac{1 - \exp \left( \frac{\hbar \nu_i}{k T} \right) \exp \left( - \frac{\hbar c}{K E''} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right)}{1 - \exp \left( \frac{\hbar \nu_i}{k T} \right) \exp \left( - \frac{\hbar c}{K E''} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right)},
$$

(3.16)

where $Q$ is the species' partition function and $S_{13}(T_0)$ is a known linestrength at a temperature, $T_0$. The result for $R$ is,

$$
R = \frac{S_{13}(T_0, \nu_i^1)}{S_{13}(T_0, \nu_i^2)} \exp \left( - \frac{\hbar c}{K} \left( E''_i - E''_j \right) \left( \frac{1}{T} - \frac{1}{T_0} \right) \right),
$$

(3.17)

where $E''_i$ is the lower-state energy of transition $i$ and $\nu_i^j$ is transition $i$'s wavenumber. $R$ is a single-valued function of temperature and the sensitivity of $R$ can be optimized by selecting a transition pair for an expected temperature range as described in section 3.4.2.

### 3.3 Line Shape

It is observed that radiative transitions between energy levels ($\Delta E$) do not occur precisely at $\hbar \nu_\epsilon$. Loosely speaking, a number of phenomena cause a spreading of the line strength about line center, $\hbar \nu_\epsilon$. The phenomena are expressed in the relation $\phi(\nu - \nu_\epsilon)$ as introduced in equation 3.12. However, the function is really, $\phi(\nu - \nu_\epsilon, P_j, T, \mathcal{E}, \ldots)$ to reflect its dependence on the environmental parameters like the pressure ($P_j$) of collision partners $j$, temperature ($T$), and electromagnetic fields ($\mathcal{E}$). In the literature and most texts, the lineshape is written with a spectral dependence only, $\phi(\nu - \nu_\epsilon)$. This convention will be adopted, too, but the environmental dependence is always implied.

The full width at half maximum (FWHM) of an isolated absorption feature is defined as the linewidth and characterizes the spectral extent of the lineshape. This feature is illustrated in figure 3.4 to negate confusion from references in the literature to a half width at half maximum or 1/e width. Phenomena which contribute to the width of the distribution are called broadening mechanisms and they can be categorized into 3 general classes. The first to be discussed, inhomogeneous broadening, is exhibited when segments of the population fraction experience different radiative interactions. The second, instrumentation broadening, is an artifact of the measurement technique. And finally, there is homogeneous broadening. Homogeneous broadening arises when the radiative interaction is identical for all segments of the population.
3.3. **LINE SHAPE**

![Graph showing the line shape with the integral and expression for $\phi(\nu)$](image)

**FIGURE 3.4** Example of a Doppler broadened lineshape to illustrate the full width at half maximum (FWHM).

**Doppler Broadening (Inhomogeneous)**

Perhaps the most intuitive broadening mechanism is Doppler broadening. It stems from the Gaussian velocity distribution possessed by a gas as put forth by Maxwell (Vincenti and Kruger 1986, pg. 35). Each velocity class in the distribution has a vector component that lies along the laser propagation direction. Because velocity classes interact differently (e.g. possess differing Doppler shifts) with the radiation field, the mechanism is inhomogeneous. The velocity distribution directly translates to a Gaussian lineshape. The lineshape function is,

$$
\phi(\nu) = \frac{2}{\Delta\nu_D} \left( \frac{\ln(2)}{\pi} \right)^{1/3} \exp \left[ -4 \ln(2) \left( \frac{\nu - \nu_0}{\Delta\nu_D} \right)^2 \right],
$$

(3.18)

where the Doppler width is,

$$
\Delta\nu_D = 7.162 \times 10^{-7} \sqrt{\frac{T_k}{M_{amu}}} \nu_0,
$$

(3.19)

and $T_k$ is the translational or kinetic temperature [K], and $M_{amu}$ is the molecular weight [g/mole].

The Doppler width may be less than expected when the number of collisions is high with respect to the time it takes the target species to travel $\lambda_o/2\pi$, where $\lambda_o$ is the line center wavelength. The overall effect of collisions is to slightly retard the velocity in each class (Dicke 1953). Each velocity class is affected differently and the resultant lineshape (neglecting other broadening mechanisms) fails to reflect the Maxwellian velocity distribution. The narrowing of the line profile is properly referred to as motional narrowing to distinguish it from collisional narrowing effects that occur at higher pressures. The effects of motional narrowing can be
CHAPTER 3. ABSORPTION SPECTROSCOPY THEORY

neglected when the condition \(2\pi\Lambda \gg \lambda_s\) (Rautian and Sobelman 1967) is satisfied. An estimate of the mean free path using average molecular properties can be computed using the relation (Vincenti and Kruger 1986 pg. 14),

\[
\Lambda = \frac{1}{\sqrt{2\pi d\bar{d}} n},
\]  

(3.20)

where \(\bar{d}\) is the average collision diameter \((3 \times 10^{-8} \text{ cm, Weast 1974, pg. F-191})\) and \(n\) is the number density. For the Calspan RST test conditions, the static temperature was approximately 600 K while the largest static pressure was 10 torr. The approximate mean free path was 16 \(\mu\text{m}\) and thus the Doppler lineshape accurately reflects the kinetic temperature. In the Stanford SET measurements, the motional narrowing condition was not met, but the Doppler shift (which is not influenced by the broadening mechanism) was the only measured quantity.

Transit-Time Broadening (Instrument)

Transit-time broadening (TTB) is present in all spectroscopic gas measurements where the target species has a bulk velocity. The radiative interaction time is determined by the species’ time-of-flight through a beam of radius \(r_o\). While interacting, the radiative system can be modeled as an oscillator with an amplitude proportional to the radiation intensity (Demtröder 1996 pg. 85). For a laser operating in the fundamental transverse mode, the spatial intensity distribution is Gaussian. The power spectral intensity distribution yields a normalized Gaussian line shape:

\[
\phi(\nu - \nu_0) = \frac{4}{\Delta\nu_t} \left(\frac{2\ln(2)}{\pi}\right)^{1/2} \exp\left[-8\ln(2) \left(\frac{\nu - \nu_0}{\Delta\nu_t}\right)^2\right],
\]  

(3.21)

where the TTB FWHM is,

\[
\Delta\nu_{\text{TTB}} = \frac{V_{\text{max}} \sin\theta}{c r_o} 2\sqrt{2\ln(2)}.
\]  

(3.22)

The definition of \(\theta\) is from Figure 3.2 and \(r_o\) is the \(1/e^2\) radius of the spatial energy distribution. In the Calspan experiments where the bulk gas velocity was greatest, TTB was 2 orders of magnitude smaller than the Doppler broadening and was neglected.

Tuning-Rate Broadening (Instrument)

When a laser is tuning rapidly, an instrument broadening phenomenon similar to transit-time broadening occurs; this is termed tuning rate broadening (TRB) as is mentioned by Kastner and Tacke (1996). Consider a velocity class in a Maxwellian velocity distribution; as the laser’s linecenter is translated, each class’s transition (at a discrete frequency) radiatively interacts for a finite amount of time. Thus, by modeling the radiative system similarly to section 3.3 (as
3.3. LINE SHAPE

shown in Appendix B) the power spectral intensity distribution yields a symmetric exponential lineshape:

\[ \phi(\nu - \nu_{\text{center}}) = \frac{\pi \Delta \nu_b}{a / c} \exp \left( -\frac{2\pi \Delta \nu_b}{a / c} |\nu - \nu_{\text{center}}| \right) \]  

(3.23)

where \( a \) is the laser’s spectral tuning rate magnitude \((d\nu_b / dt)\) of the line-center and \( \Delta \nu_b \) is the spectral width of the laser. The TRB FWHM is,

\[ \Delta \nu_{\text{FWHM}} = \ln 2 \frac{a / c}{\pi \Delta \nu_b}. \]  

(3.24)

In all of the experiments TRB was over two orders of magnitude smaller than the Doppler broadening and was neglected.

**Power Broadening (Instrument)**

A final form of instrument broadening that is pertinent to strong absorbers is power broadening. This occurs for situations where the product of the laser intensity, the Einstein-\( B \) coefficient, and the lower state population density is substantial enough to produce a non-negligible population in the upper state. Specifically, when the laser intensity is such that the population ratio between the upper and lower state is 0.5, the intensity is defined as the saturation intensity \((I_{\text{sat}})\). At intensities near \( I_{\text{sat}} \), equation 3.10 is no longer applicable. Therefore, equation 3.9 must be used to calculate the absorption. Appendix C develops the power-broadened lineshape in detail.

Power broadening is an issue for species with large line strengths like potassium. However, because only the Doppler shift was measured using potassium there is no effect on the measurement. Additionally, water vapor possesses weaker (by 7 orders of magnitude) rovibrational transitions, thus power broadening was not an issue at the low laser intensities associated with cw diode lasers.

**Natural Broadening (Homogeneous)**

Natural broadening results from the finite amount of time the upper and lower state may be populated while the system interacts with radiation. The Heisenberg uncertainty principle relates the energy uncertainty of a state to the amount of time \((\Delta t)\) a state is populated,

\[ \Delta E \geq \frac{h}{2\pi} \frac{1}{\Delta t}, \]  

(3.25)

where \( \Delta t \) is characterized by the 1/e lifetime. Typically, lifetime is a measured quantity inferred from the emission intensity decay time constant. The reciprocal of the lifetime is equal to the Einstein-\( A \) coefficient and in turn the linewidth in wavenumber space is obtained by dividing
equation 3.25 by \( \hbar \epsilon \),

\[
\Delta \nu_N \geq \frac{1}{2\pi \epsilon} \left( \sum_k A_{ik} + \sum_k A_{jk} \right),
\]  

(3.26)

where \( i \) and \( j \) are the upper and lower radiatively coupled states, and \( k \) represents energy states coupled to \( i \) and \( j \) but from lower levels. Since this uncertainty is the same for all resonant atoms, the broadening is homogeneous. The resulting lineshape function can be derived by modeling the system as a damped oscillator and it takes the form of a Lorentzian function (Demtröder 1996 pg. 57),

\[
\phi(\nu) = \frac{1}{2\pi} \frac{\Delta \nu_c}{(\nu - \nu_0)^2 + (\Delta \nu_c/2)^2}.
\]  

(3.27)

For the water vapor transitions probed in this work, natural broadening was significantly less than the aforementioned broadening mechanisms and was neglected. For the potassium transition, the width due to natural broadening width was approximately 6 MHz (0.0002 cm\(^{-1}\)) and was neglected also.

**Collisional Broadening (Homogeneous)**

Collisional broadening can be thought of as an enhancement to natural broadening, where the lifetime of a state is shortened through collisional relaxation. The reduced lifetime is reflected in a broader lineshape.

Nagali (1998) discusses collisional broadening in detail; the results are summarized here. Applying some assumptions for the temperatures and pressures that exist during hypersonic testing simplifies the physics. Namely, the collisions are binary with a negligible duration compared to the time between collisions. The radiative system can be described as a damped oscillator with phase-perturbing collisions. Because the same process applies to all the atoms, the broadening is homogeneous and is described by a Lorentzian profile,

\[
\phi(\nu) = \frac{1}{2\pi} \frac{\Delta \nu_c}{(\nu - \nu_0)^2 + (\Delta \nu_c/2)^2},
\]  

(3.28)

where \( \Delta \nu_c \) is the collision FWHM. For the given assumptions the collision width (at a fixed temperature) is proportional to pressure, and for multi-component ideal gas mixtures the contributions sum linearly as

\[
\Delta \nu_c = P_\infty \sum_i \chi_i (2\gamma_i),
\]  

(3.29)

where \( P_\infty \) is the ambient pressure (in this work the words freestream or static will be applied in the case of a flowing gas), \( \chi_i \) is the mole fraction of the colliding gas, and \( 2\gamma_i \) is the binary
3.4. THE SELECTION OF SPECTROSCOPIC TRACERS

collisional broadening coefficient, which is unique to a collision pair and the specific radiative transition. Typically, the broadening coefficients are determined experimentally. Additionally, the linear pressure dependence is valid up to many 10’s of atmospheres (Dentroder 1996, pg. 82) but a nonlinear temperature dependence correlates the value from a known temperature value as,

\[ 2\gamma_{n} = 2\gamma_{n}\left(\frac{T_{x}}{T}\right)^{n}, \]

(3.30)

where \(T_{x}\) is typically 295 K and the exponent \(n\) is generally determined experimentally (classical analysis yields \(n = 1/2\)).

Voigt Lineshape

The Voigt lineshape function describes the normalized lineshape when broadening phenomena causing Lorentzian and Gaussian lineshapes dominate over all others and is a convolution (in light frequency space) of the two,

\[ \phi(\nu) = \frac{2}{\Delta\nu_{D}} \sqrt{\frac{\ln 2}{\pi}} V(a, w), \]

(3.31)

where \(V\) is the Voigt function, \(a\) is termed the Voigt-a parameter and indicates the relative significance of the Lorentzian and Doppler broadening mechanisms,

\[ a = \frac{\sqrt{\ln 2} \Delta\nu_{L}}{\Delta\nu_{D}}, \]

(3.32)

and \(w\) is a nondimensional relative-line position,

\[ w = \frac{2\sqrt{\ln 2}(\nu - \nu_{x})}{\Delta\nu_{D}}, \]

(3.33)

where \(\Delta\nu_{D}\) and \(\Delta\nu_{L}\) are the Doppler and sum of the Lorentzian line widths. The numerical algorithm by Scheer (1992) is used to approximate the value of the Voigt function and has a worst-case point error of ±100 ppm.

3.4 The Selection of Spectroscopic Tracers

Three features are required of a spectroscopic tracer in flowfield measurements using laser absorption. First, it must be present, either naturally or as a result of intentional seeding. Second, its line positions must be accessible by available laser sources. Third, its linewidth in combination with the expected number density and pathlength must yield sufficient absorption for detection. Additionally, the occurrence of spectrally isolated transitions for a tracer is not a requirement but a feature, which make its selection more attractive.
3.4.1 The Selection of an Atomic Spectroscopic Tracer

Several atomic species have potential to be spectroscopic tracers and are shown in Table 3.1. Each of the species have different spectral characteristics due to differences in nuclear configuration (i.e., nuclear charge, mass, and spin quantum number). The ideas presented in sections 3.1 and 3.2 are developed further in Appendix A with an emphasis on atoms and the results are discussed below.

Because aluminum, copper, and iron are used in the construction of many facilities, their presence in the gas phase can result from ablation and vaporization. Lithium, copper, and sodium are observed in emission spectra from the planetary probe's stagnant region in Figure 3.5. Additionally, because sodium and potassium are the sixth and seventh most abundant elements comprising just under 2.5% of the Earth's crust (McQuarrie and Rock 1984 pg. 2), it was expected that potassium would be present, too. Many of the species were rejected simply because diode lasers are not available in the correct wavelength region.

Atomic ground state transitions in lithium, potassium, rubidium, and calcium are promising candidates tracers because each of these transitions spectrally overlap with commercially available diode lasers. However, to avoid the issues surrounding seeding a tracer into the flowfield, Ca was rejected because it was about 6000 times weaker than the remaining candidates.

\(^1\)The planetary probe aerodynamic model is described by Srinivasan and Boyd (1995).
3.4. THE SELECTION OF SPECTROSCOPIC TRACERS

<table>
<thead>
<tr>
<th>Species</th>
<th>Wavelength [μm]</th>
<th>Line Strength 10^6 [cm⁻²/atm]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>308</td>
<td>3.84</td>
<td>Laser Unavailable</td>
</tr>
<tr>
<td>Cu</td>
<td>325, 327</td>
<td>4.8, 9.6</td>
<td>&quot;</td>
</tr>
<tr>
<td>Fe</td>
<td>382, 388</td>
<td>0.106, 0.510</td>
<td>&quot;</td>
</tr>
<tr>
<td>Na</td>
<td>589.1, 589.7</td>
<td>14.1, 7.1</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>657.3</td>
<td>0.0011</td>
<td>Weak Line Strength</td>
</tr>
<tr>
<td>Li</td>
<td>670</td>
<td>16.2</td>
<td>Isotopic Interferences</td>
</tr>
<tr>
<td>K</td>
<td>766</td>
<td>14.7</td>
<td>Cooling Difficult</td>
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<td>780</td>
<td>7.431</td>
<td>Selected Transition</td>
</tr>
<tr>
<td></td>
<td>794</td>
<td>7.2</td>
<td>Laser Unavailable</td>
</tr>
</tbody>
</table>


The spectra of each species was computed including the effects of isotopes and nuclear spin (see Appendix A). Figure 3.6 illustrates the results of the computations. Examination of the spectra reveals that potassium possesses spectral features that are the most narrow and isolated. A narrow spectral feature permits a faster laser scanning frequency and yields better temporal resolution. Additionally, less complicated absorption features permit easy identification of Doppler shift. The latter feature is important when considering the counter propagating absorption technique as discussed in section 3.4.2.

3.4.2 The Selection of Water Line Pairs

Water vapor line selection in an absorption experiment is largely governed by the availability of laser sources (Langlois et al. 1994). Figure 3.7 illustrates the many transitions between 0.7 and 3 μm that are accessible, given the availability of current laser diode materials. Generally speaking, the higher wavenumber transitions in figure 3.7 are largely made up of overtone transitions, the middle region consists of combination and difference vibrational modes and the transitions near 3 μm are made up of the fundamental vibrational modes where Δν1,2, or 3 = 1 (see Appendix A.3).

The spectral regions for available diode laser wavelengths are superimposed on figure 3.7 (Hecht 1992). Recently, the emergence of InGaAsSb lasers permit access to the strong fundamental bands near 2.7 μm (Menna et al. 1998; Garbuzov et al. 1999). An experimental version of a Fabry-Perot InGaAsSb laser operating in the 2.3 μm water window is being examined as a potential combustion-gas sensor (Wang et al. 2000). The constraint of commercial availability introduces an economic restriction as to what can be developed into a sensor. Because of the
FIGURE 3.6 Calculated absorbance line shapes [left axis] and HFS oscillator strengths [right axis] for a) lithium, b) potassium and c) rubidium. From these figures one can see that potassium has the most isolated absorption features of the three selections.

strong demand in the communications and digital storage market, there are only a few spectral windows where laser diodes are readily available. A survey of H₂O absorption bands in the spectral region between 0.7 and 1.6 μm, where diode lasers can be purchased, revealed the strongest absorption will occur near 1.4 μm in the 101-000 combination band (Arroyo and Hanson 1992). For a modest fee, approximately $2000, lasers can be purchased in this spectral region.

Recalling that equation 3.17 (shown below) will be instrumental in determining the temperature, the room-temperature line strength and the lower state energy (Eᵢ) are important quantities to optimize when selecting transitions.

\[
R = \frac{S_{12} (T, \nu_1)}{S_{12} (T, \nu_2)} \exp \left( -\frac{hc}{K} \left( E_{1}^{\nu_1} - E_{2}^{\nu_2} \right) \left( \frac{1}{T} - \frac{1}{T_e} \right) \right) \tag{3.17}
\]

When computing the absorbance ratio of two lines to compute the temperature, the lineshape function and the partial pressure of the target species cancel, but the pathlength does not. As a result R in equation 3.17 is modified by the ratio of pathlengths between two lines, becoming:

\[
R_k = R \frac{L_1}{L_2} \tag{3.34}
\]
3.4. THE SELECTION OF SPECTROSCOPIC TRACERS

![Diagram of the selection of spectroscopic tracers](image)

**FIGURE 3.7** A plot of the line strength vs. wavenumber for water vapor transitions from 0.7 to 3 µm [Rothman et al. 1992].

However, when comparing a pair of lines, it is assumed the respective pathlengths are the same for each of the line pairs. Thus, $R$ is used for comparison purposes.

Temperature sensitivity is based on the derivative of $R$ with respect to temperature. The most accurate temperature measurement is achieved when,

$$\frac{\partial R}{\partial T} = R \frac{hc}{K} \left( E^\prime_{1} - E^\prime_{2} \right) \frac{1}{T^2}$$

is large. High enthalpy facilities are designed to operate with a duration of steady conditions (i.e., steady temperature). A steady operating temperature allows the designer of a temperature sensor to tune the selected line pair to maximize $\partial R/\partial T$.

The temperature where a given line pair will perform best is obtained by evaluating,

$$\frac{\partial^2 R}{\partial T^2} = 0$$

which yields the following relation when solving for the lower state energy separation between two lines ($\Delta E^\prime_{12} = (E^\prime_{1} - E^\prime_{2})$),

$$\Delta E^\prime_{12} = \frac{T}{hc} \frac{2K}{\partial R}$$

For a given temperature, equation 3.36 calculates what lower state energy separation will yield optimal performance. There may be other linepairs with a better sensitivity at the prescribed temperature but their peak temperature sensitivity occurs elsewhere. As a result, this relation is to be thought of as a guideline rather than a constraint.
The best line pair to determine temperature for a given test condition is selected using the following strategy. First, plot the linestrength at a given temperature versus lower state energy for transitions which overlap spectral regions accessible by available lasers. Second, superimpose a pair of curves that represent the minimum line strength necessary to obtain an acceptable signal to noise ratio (SNR) for each pathlength. The curves are computed accounting for the anticipated noise and water levels. Candidates lying above the superimposed curves (which are approximately straight lines) indicate transitions possessing sufficient strength-pathlength product to overcome noise.

![Graph showing line strength vs. lower state energy](image)

**FIGURE 3.8** The top line in each tag reports an index for convenient reference in the text. The line strengths for tagged transitions (Toth 1994) are calculated for a temperature of 550 [K]. The lower state energy and linestrengths for untagged transitions are as reported by HITRAN (Rothman et al. 1992). Each of the tagged transitions are from the 101 \([v_1, v_2, v_3]\) combination band. The rotational transition quantum numbers are reported with the arrow pointing in the direction of the upper state \((J'_{K_C} K_C)\). Calculations for the minimum strength curves (dashed lines) incorporate the line center Doppler broadened lineshape and an absorbance noise floor of 0.001. Finally, the transitions shown in doubleboxes were used in this work.

The above analysis was applied to the Calspan condition and is shown in figure 3.8. In referring to the abscissa (x-axis), transitions which possess small lower state energies are referred to as low-temperature lines and those possessing higher lower state energies are high-temperature
lines. The two dashed horizontal curves represent the minimum acceptable line strength required to achieve a unity signal to noise ratio for a 22 cm path and a 89.2 cm path. The two pathlengths were chosen based on physical constraints associated with the size of the test section and concurrent experimental hardware. The 22 cm pathlength is a single pass through the sample volume, while the longer pathlength is achieved by passing a beam 5 times.

A number of transitions would yield an acceptable SNR for the shorter path and more transitions are acceptable for the longer pathlength. However an energy separation between the two transitions is necessary to obtain temperature sensitivity (see equation 3.36). Line pairs with the greatest temperature sensitivity and linestrengths were selected. Two different test conditions were encountered where temperature was to be measured. Each was at a low enough pressure so that collisional broadening was negligible. The first condition had an expected freestream temperature of 650 K while the second was 550 K.

A single line pair (identified by their indices) 441-413 was identified as the pair with the best sensitivity and SNR for both test conditions. However, lasers were not available for the initial experiments and a second pair was identified and used in the first rotational temperature measurements, 340-202, which possessed a slightly worse signal to noise ratio. Temperature sensitivity for both line pairs are approximately the same as the lower-state energy difference for both is approximately 1000 cm$^{-1}$, but the 441-413 pair possesses a better signal to noise ratio.
Chapter 4

General Elements of an Absorption Experiment

A number of optical elements are needed to perform an absorption measurement. For the experiments reported, the layout of the optical elements in each of the systems was very similar. However, in each experiment some individual components were in principle the same but operated in a slightly different fashion. The component selection was based on a combination of component availability or the needs of the individual experiment.

Figure 4.1 illustrates layouts of two typical TDLAS systems. The system in the top panel is one channel of a two-transition water system where each transition represents a channel. The laser energy from two $1 \times 3$ fiber splitters come together in a reference cell to ensure tuning is over the line center. The bottom portion of figure 4.1 shows the channel from the potassium system. This figure serves as a map through the detailed the discussions below regarding operation of different components required for a TDLAS measurement system.

4.1 Semiconductor Diode Lasers

The first diode lasers were developed in 1962. These early devices required operation at cryogenic temperatures. The limited availability of gain material rendered emission to the far infrared ($\lambda > 3 \mu m$). The development of room-temperature devices in the late 1970’s hastened their acceptability as laser sources. However, when diode lasers met acceptable performance levels in the lucrative markets of fiber-optic communication, compact-disk audio players, and laser printers, the pace of development accelerated (Hecht 1992, pg. 297).

Since different commercial systems (primarily communications and digital storage) have
Laser output is approximately 10 mW at 1.4 µm. The fiber optic cable has a 8.5 µm core with a 125 µm cladding for single mode operation.

Laser output is approximately 10 mW at 0.77 µm. The fiber optic cable has a 4.5 µm core with a 125 µm cladding for single mode operation.

FIGURE 4.1 A diagram illustrating the elements for two separate laser systems in a diode laser absorption experiment. On top is 1/2 of a set-up to measure two-line temperature. On bottom is a system to measure potassium.
different needs, disparate structures and materials have been developed. Ironically, the consequences of improved manufacturing techniques, quality control and well defined commercial markets has limited the wavelengths available to the spectrosocist (Lawrenz and Nie\textsuperscript{max} 1989).

Despite the development being largely limited to the communications and data storage industries, a few companies will produce lasers at a specific wavelengths within limited ranges. Figure 4.2 (Murray 1997) illustrates the multitude of laser models commercially available. The communications industry has selected 1300 and 1500 nm lasers for their systems due to minimal losses and dispersion in fiber optics. Printers, optical storage devices and displays make up the bulk of the of the demand between 600 and 1000 nm. For example, compact disc technology uses lasers at 780 nm to achieve 650 MB storage per side. The market for digital video disc (commercially referred to as DVD) drove the development of 650 nm lasers in order to increase the information density to a level of 4.7 GB per side. Additionally, the success of hi-definition television will stimulate the development of even shorter wavelength lasers to obtain the required 15 GB (per side) storage capacity. To that end, Toshiba and Cree Research have developed a 415 nm pulsed laser using Gallium Nitride (GaN) as the gain material. Laser development in the blue is also a response to the demand to complete the Blue-Green-Red combination for color displays.

### 4.1.1 Diode Laser Operation

A schematic illustrating the diode-laser architecture is shown in figure 4.3. As in other semiconductor devices, current is carried by electrons free to move within a crystal when an electric field is applied, and by holes migrating in the opposite direction. The semiconductor is doped with impurities to control the type (holes or electrons) and density of current carriers. Material doped with elements that yield holes are denoted p-type (positive carrier) and those
that yield donor electrons are denoted n-type (negative carrier). Application of a negative voltage to the n-type material and a positive voltage to the p-type material creates a local excess of minority carriers on each side of the junction. Between the junctions, in the active region, some of the electrons recombine radiatively with holes to produce photons with an energy roughly equal to the energy difference between the conduction and valence bands (also called band-gap energy). Passing a drive current through a diode laser produces a population inversion in the active layer and optical feedback comes from reflective structures on the forward and back faces, defining the resonator length.

### 4.1.2 Diode Laser Wavelength

The composition of the materials determines the band-gap energy and as a consequence, the emission wavelength. For example Gallium-Aluminum-Arsenide (GaAlAs) lasers have a range of wavelengths from 620 nm to 895 nm and Indium Gallium Arsenide Phosphorous (InGaAsP) lasers have a range between 1100 to 1650 nm. A particular component mass ratio will set the band-gap energy. Additionally, slight alterations in the laser’s environment will affect the lasing wavelength. It is this latter property that makes the laser diode such an attractive spectroscopic light source. An understanding of the environmental sensitivity permits one to tune to a desired wavelength.

The family of wavelengths produced by the laser is determined by the cavity length. During laser operation, radiative gain establishes standing waves within the resonator and the following
relation must be satisfied (Sharp 1988),

\[ L = q \frac{\lambda_0}{2n}, \]  

where \( L \) is the length of the cavity, \( \lambda_0 \) is the wavelength, \( n \) is the active layer’s index of refraction and \( q \) must be an integer value. Multiple standing waves (that is multiple values of \( q \), called longitudinal modes) can be supported in the cavity. For example a laser, with typical dimensions as in figure 4.3, operating at 770 nm, with a typical index of refraction (\( n = 3.5 \)), the neighboring \((q \pm 1)\) longitudinal modes would be 0.35 nm (or 5.9 cm\(^{-1}\)) away. Lasing within the active layer dominates at the wavelength with the maximum gain, thereby selecting \( q \).

To refine the wavelength selection to a single mode, a number of methods are employed. Two of the most common are through interference or diffraction effects. The latter is achieved in one of three ways. Two are internal, where a diffraction grating is either distributed along the active layer (distributed feedback, DFB) or affixed along an extended region of the semiconductor substrate (distributed bragg reflection, DBR). The third, is to align a diffraction grating externally to the laser which selects the wavelength fed back into the lasing medium. This latter method requires mechanical elements to tune/optimize the laser.

A Fabry-Perot laser uses interference to select the mode. The ends of the cavity are cleaved so they are nearly parallel and a high reflectance coating is applied on each end to improve the finesse (spectral narrowness of the emission). Although simpler to construct, Fabry-Perot lasers are not as efficient as DFB lasers in selecting a single lasing mode. To quantify this ability, the side mode suppression ratio \( R_{sms} \) is defined as,

\[ R_{sms} = -10 \log \left( \frac{I_0}{I_{\pm 1}} \right) \text{[dB]}, \]  

where \( I_0 \) is the intensity of the primary mode and \( I_{\pm 1} \) is the intensity of an adjoining mode. Note, the coefficient is 10 rather than 20 because the intensity is proportional to the laser power.

For molecular spectroscopy applications, \( R_{sms} \) is an important parameter. For insufficient \( R_{sms} \), neighboring radiative transitions may absorb the side modes and alter the desired transition’s measured lineshape. As a result, the lasers used for the initial water vapor measurements were of the DFB type and had values of 20 dB (Langlois et al. 1994). Subsequent water vapor experiments used lasers with values greater than 40 dB (Sensors- Unlimited 1997).

For velocity measurements using atomic absorption, \( R_{sms} \) is less critical because the neighboring transitions are typically far away (e.g., 59 cm\(^{-1}\) for potassium). It was estimated that \( R_{sms} \) of the Fabry-Perot laser used for potassium was greater than 20 dB. The estimate was achieved by using an optically thick potassium-seeded flame (FWHM < 0.5 cm\(^{-1}\)) to selectively block the dominant mode. Subsequent blocking of the laser produced no offset in the detector signal. Thus, the sidemode’s intensity is estimated to be no larger than the detector’s 20 to 30 mV noise level.
4.1. SEMICONDUCTOR DIODE LASERS

Modern manufacturing techniques produce lasers in batches (> 1000) which are within 1 nm of the target wavelength. As a result, coarse adjustments to the lasing wavelength are required to target a specific transition. Because the active layer's index of refraction is temperature sensitive, careful adjustment of the laser's operating temperature (from equation 4.1) can alter the lasing wavelength in a precise manner.

The laser temperature is controlled by mounting the laser in a block possessing high thermal conductivity. Typically, the block is a metal such as copper or aluminum. In turn, the metal is in thermal contact with a Peltier device which uses temperature feedback to maintain temperature to within ± 0.01 °C over periods exceeding an hour. Thus wavelength stability is assured. Most commercial room-temperature lasers can operate over a range of ±30 °C which often yields ±10 nm. The absolute wavelength (to 7 significant figures) is measured using a Michelson-interferometer-based wavelength meter.

Tunable diode laser spectroscopy is enabled by the controllable variation in emission wavelength. Wavelength adjustments (order of pm, 10⁻¹² m) result from joule heating which alters the active layer's index of refraction. Heating the laser shifts the emission to the red, however a simultaneous opposite shift occurs by increasing the charge carrier density (Schleerth 1996). The fluctuations in the charge carrier density at low frequencies (< 10 MHz) render the joule-thermal effect dominant (Petermann 1988, pg. 119).

4.1.3 Diode Laser Linewidth

The linewidth of an ideal continuous-wavelength (CW) laser, operating in single longitudinal mode will have a finite spectral width due to spontaneous emission in the laser medium. Photons generated by stimulated emission will add in phase to the lasing field, whereas the phase associated with a spontaneously emitted photon is random and is a principal cause of broadening. Analysis that considers the spontaneous emission rate and the photon density in the laser cavity yields a relation for the width of the diode laser linewidth:

\[ \Delta f_{\text{las}} = \frac{R}{4\pi I} \left(1 + \alpha^2\right), \]  

(4.3)

called the Shawlow-Townes-Henry linewidth. \( R \) is the average rate with which the spontaneous emission is transferred into the lasing mode and \( I \) is the light intensity. The term in parenthesis is a diode-laser correction factor. The factor accounts for linewidth broadening originating from the relationship between the active layer's charge carrier density and the refractive index.

For low powers, equation 4.3 accurately predicts that the laser linewidth decreases with increasing laser intensity (Petermann 1988, pg. 64). However, at large laser intensities (typically many times the threshold intensity) a linewidth floor is reached and laser-line broadening is

---

1 Ohtsu 1996, pg. 4 gives the relation in equation 4.3 however, Amann and Buus 1998, pg. 68 provides a detailed analysis with equation 4.3.
observed for higher intensities. The causes for the floor and broadening are not yet fully understood (Ohtsu 1996, pg. 9). However, several mechanisms have been put forth to explain such behavior including side-mode interaction, $1/f$-noise, spatial-hole burning, nonlinear gain, and current noise (Agrawal and Dutta 1993, pg. 275).

In the other extreme, when diode lasers are modulated at very high frequencies or with step increases in current (pulsed laser operation), a rapid shift in laser linecenter occurs. This behavior is of importance to communications engineers as the rapid shift will increase dispersion of the signal in fiber-optic transmission. Altering the charge carrier number density changes the index of refraction, hence emission wavelength. An additional shift as a consequence of carrier-density unsteadiness is called chirp and is described by (Vasil’ev 1995, pg. 196),

$$\Delta f(t) = \frac{a}{4\pi} \left( \frac{d \ln P(t)}{dt} + \frac{4\pi \Gamma \epsilon}{V \eta h \omega} P(t) \right),$$  

where $P$ is the laser power, $\eta$ is the laser differential quantum efficiency, $\Gamma$ is the optical confinement factor (which a property of the laser construction), $\epsilon$ is the nonlinear gain coefficient, $\omega$ is the stripe width (see figure 4.3) and $V$ is the volume of the active layer. The additional frequency shift is due to the time rate of power change. Some literature refers to the shift as an increase in width.

An indication of which chirping does to the instantaneous laser linewidth is difficult to ascertain. Some texts simply indicate that the linewidth of an individual longitudinal mode increases considerably during dynamic operation (Agrawal and Dutta 1993, pg. 70). Often the increase in width is due to the tendency for lasers to operate multimode under dynamic conditions. In this case the larger width is attributed to the presence of additional side modes.

### 4.1.4 Observed Linewidth Broadening

Transient flowfield features are frozen by scanning across absorption features rapidly. Laser linewidth estimates, using a confocal etalon, indicated a linewidth increase over the spectral-tuning interval for a Fabry-Perot InGaAs diode laser. Figure 4.4 illustrates the measured laser linewidths during 10- and 40-kHz scans over a tuning interval of approximately 1 cm$^{-1}$.

During the 10 kHz case, the injection current and intensity at the end of the scan was higher than the beginning (ramp modulation). However equation 4.3 predicts the laser linewidth to narrow towards the end of the scan. The increase in laser-linewidth scatter increased from ± 20 MHz to ± 50 MHz over a laser scan rate range of 0.25 to 2.5 PHz/s (10$^{15}$Hz/s). The scatter is most likely an artifact of the single-mode diode laser exhibiting dynamic multi-mode behavior (Agrawal and Dutta 1993, pg. 70).

The explanation for the increase in observed linewidth during the 10 kHz scan is due to insufficient frequency response in the data acquisition hardware for the etalon channel. Figure
4.1. SEMICONDUCTOR DIODE LASERS

4.5 shows the power spectral density (PSD) functions for an etalon fringe while scanning at 0.25 and 0.39 PHz/s. The two laser tuning rates were selected based on extremes observed during the 10 kHz scan in figure 4.4. Each PSD function is normalized by the most powerful frequency component. The etalon detector’s bandwidth was 98 MHz while the analog bandwidth of the data acquisition (A/D) system was 2.5 MHz. As an aid in comparing the two PSD’s, arrows on the frequency axis indicate the A/D bandwidth. A substantial amount of high-power frequency components were attenuated above 2.5 MHz for the 0.39 PHz/s scan rate.

FIGURE 4.4 Spectral width of a 770 nm Fabry-Perot laser as a function of laser tuning rate in PHz/s \(10^{1.5}\)Hz/s. The increase is scatter is believed to be due to dynamic-multimode behavior.

FIGURE 4.5 Power spectral density functions for an etalon fringe while scanning the laser at 0.25 and 0.39 PHz/s. Arrows on the frequency axis indicate the limiting frequency response of the acquisition system.
Two consequences result from inadequate bandwidth. First, there is signal distortion exhibited as laser linewidth broadening. Second, there is a delay in determining the measured peak location. Figure 4.6 illustrates the two consequences. In this figure, the etalon signal is synthesized assuming a finesse of 50 (see section 4.4) and a laser tuning rate of 0.39 PHz/s. Additionally, it is assumed that the laser width is much less than the etalon width. The filtered signal is obtained by passing the etalon signal through a 12 dB/octave Butterworth filter.

For a constant laser tuning rate, the linewidth increase is observed in time by the increase in FWHM width of the filtered fringe. A 150% increase is calculated from this analysis and is consistent with the observed increase in spectral width for the 10 kHz scans in figure 4.4 where the measured linewidth increased from about 35 MHz to 60 MHz.

For a 2 GHz free spectral range etalon (see section 4.4), a 20 ns peak delay translates into a 0.4% relative frequency error while scanning at 0.39 PHz/s. Doppler shifted absorption is to the blue (see section 5.3) and as a result, occurs early in the scan while the laser is scanning more slowly where there is no delay.

The analysis now turns to the observed linewidth increase while scanning over the spectral interval at 40 kHz. During this measurement, the limiting frequency response was the PMT detector, f_{-3dB}=79 MHz, whereas the data acquisition system had a 200 MHz frequency response. The fringe PSD for a laser scanning at the fastest rate, 2.5 PHz/s, is shown in figure 4.7. An arrow on the frequency axis indicates the f_{-3dB} point and illustrates that the system was more than adequate to resolve the etalon signal, yet an increased linewidth is observed.

The laser linewidth increase may be caused by temperature gradients in the active layer while rapidly thermal tuning. A simplified energy balance states that the thermal power leaving
the laser must equal the stored power (neglecting Joule heating),

$$- \dot{E}_{\text{out}} = \dot{E}_{\text{st}},$$

(4.5)

where $\dot{E}_{\text{out}}$ is through heat transfer at the base of the laser and $\dot{E}_{\text{st}}$ is the rate of thermal energy storage. A estimate of the effect can be obtained by applying a lumped capacitance model (Incropera and DeWitt 1985, pg. 174) to a diode laser cube:

$$-k_T A \frac{dT}{dx} = \rho V c_T \frac{dT}{dt},$$

(4.6)

where $k_T$ is the thermal conductivity, $\rho$ is the mass density, $c_T$ is the thermal specific heat, and $V$ is the laser volume. By approximating the laser as a cube with an active layer 0.01 the thickness of a side (Sharp 1988, pg. 16) equation 4.6 becomes:

$$-k_T L \times L \frac{\Delta T}{0.01 L} = \rho L^3 c_T \frac{\Delta T}{\tau},$$

(4.7)

yielding a laser thermal time constant,

$$\tau = \frac{0.01 L^2}{\alpha_T},$$

(4.8)

where $\alpha_T$ is the average thermal diffusivity of the laser. An approximation for an AlGaAs laser can be made by assuming the thermal diffusivity is equal to that of aluminum (90 m$^2$/s Incropera and DeWitt 1985, pg. 755) and $L$ is equal to 250 $\mu$m. A time constant of 7 $\mu$s is obtained or a frequency response of 23 KHz. The simple analysis yields a result consistent with a value of 1 $\mu$s given by Amann and Buus (1988 pg. 67) and implies a significant gradient in index of refraction.

![Figure 4.7](image)
may occur across the active layer for sufficiently fast laser scan rates. A distribution in index of refraction would result in a continuous range of laser emission given by equation 4.1.

The observed linewidth for the 10 kHz scans was attributed to insufficient data acquisition frequency response. The effect on velocity measurements was shown to be minimal (< 0.4%). However in the 40 kHz case, it was surmised a thermal effect may be responsible for the enhanced laser linewidth. Although the cause of the spectral rebroadening with thermal tuning may not be well established, if the overall magnitude is small, then the phenomenon is of little concern when performing velocity measurements. However, when performing significantly rapid lineshape measurements, an unsteady laser width results in a time dependent (and hence spectrally varying) Lorentzian lineshape component.

4.2 Faraday Isolator

A small amount of unwanted feedback into the diode laser cavity can have a drastic effect on the diode laser’s performance (Camparo 1985). A source of unwanted feedback is poor or scratched anti-reflective coatings on optics. The effects on performance can be wavelength shifts, linewidth variations and reductions in side mode suppression.

To isolate the laser from optical feedback a Faraday isolator which consists of a terbium-gallium garnet crystal housed in a strong homogeneous magnetic field, is placed between the laser and the optical system. Wynands et al. (1992) discusses in detail the operation of a Faraday isolator. A brief review of its operation using an example is discussed below.

Typically an isolator consists of a Faraday-rotator situated between two rotatable, polarizing beamsplitter cubes. The operation of the isolator is best described by tracing the light path through the instrument. The maximum laser energy is transmitted by rotating the input polarizer to match the polarization of the laser emission, 0°. The laser polarization, after passing through the Faraday rotator, is rotated +45°. The exit polarizer is properly matched (oriented at +45°) so that the maximum beam intensity is transmitted.

The isolation properties are apparent when light with mixed polarization meets the exit polarizer. Only the light with matched polarization leaves it (i.e. enters the instrument at +45°). The nonreciprocal nature of the Faraday effect (Yariv 1997 pg. 29) results in the reflected light being rotated by an additional +45° or a total of +90°. Finally the reflected light meets the input polarizer and it is diverted.

Typically, the effectiveness, \( \eta \), of an isolator is measured in decibels,

\[
\eta = 10 \log \left( \frac{I_l}{I_o} \right) \quad [dB],
\]

where 10 is used as the coefficient because the laser intensity is proportional to the power, \( I_o \) is the intensity of the incident laser intensity and \( I_l \) is the laser intensity leaving the isolator when
operated in the reverse direction. Values of $\eta$ between -35 and -40 dB are usually sufficient.

4.3 Radiation Transmission in an Optical Fiber

A central attribute of diode-laser techniques lies in their compatibility with fiber optics. However, transmission of light through a fiber suffers from practical limitations. Radiative power losses occur in fiber connectors, combiners and splitters. Losses also occur as a result of liner and nonlinear scattering phenomena. An additional concern is dispersion phenomena over large distances when transmitting rapid pulses of light as in the communications industry. The damaging effects result in pulse distortion and are scaled by kilometers. Furthermore, the communications industry transmits pulses in the tens of GHz. However for the experiments conducted herein the fiber length was merely 30 meters and the laser scanning frequencies were from 8 to 30 kHz. As a result, dispersion effects are negligible. However, geometrical dispersion, also called multimode operation, is of importance to the spectroscopist.

Figure 4.8 shows an operational schematic of a fiber possessing azimuthal symmetry. A cladding with a slightly higher index of refraction surrounds a core (diameter $d$) possessing a lower index of refraction. From Snell’s law, light will propagate with total internal reflection for angles less than $\theta_{\text{max}}$. Transmitted rays with different angles can be thought of as modes. Because a degree of coherence is maintained in the fiber over the short transmission lengths (30 m) multiple modes will exhibit detectable interference (3 or 4% of the signal) while tuning. As a result, single-mode fiber is required for tuning experiments.

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2 See Senior (1992), Chapters 2 and 3 for a practical discussion whereas Yariv (1997) Chapter 3, offers a more rigorous approach.
To achieve single-mode operation the diameter of the core must be of the same order as the wavelength. The two different wavelengths used, 1.4 \( \mu \text{m} \) for water and 0.77 \( \mu \text{m} \) for potassium, required different single mode fibers. For small diameter cores, geometrical optics fails to describe the transmission of light. Instead, Maxwell's equations are required (Jackson 1998, pg. 385).

Analysis of cylindrical waveguides (e.g. fiber optic) results in a parameter \( V \), the normalized cutoff frequency, defined as,

\[
V = \pi \frac{d}{\lambda} \sqrt{n_1^2 - n_0^2},
\]

where \( d \) is the diameter of the core and \( n_i \) are defined in figure 4.8. For \( 0 < V < 2.405 \) the fiber will operate in single mode. Standard communications fiber \( (d = 8.5 \mu \text{m}) \) was used for the water experiments at 1.4 \( \mu \text{m} \) whereas 4.5 \( \mu \text{m} \) diameter fiber was used for the potassium experiments at 0.77 \( \mu \text{m} \).

### 4.4 Interferometers

These measurements probe gasdynamic environments with a laser that is spectrally scanned as a function of time. However, the desired spectroscopic parameters (e.g., Doppler shift and lineshape) are functions of light frequency. Therefore the data must be converted from time space to light-frequency space. Interferometers are used for this transformation and operate on the principle of interference. Fringes are provided at a constant light-frequency spacing. By recording the time interval between fringes, a time-to-frequency transfer function is generated.

Three different types of interferometers are used during the dynamic measurements: the solid Fabry-Perot interferometer (SFPI), the confocal Fabry-Perot interferometer (CFPI), and the ring fiber-interferometer (RFI). The choice of which one was determined largely by availability for the given spectral range.

**Fabry-Perot Interferometer**

A Fabry-Perot interferometer consists of two plane parallel partially reflecting surfaces separated by a distance \( d \). The SFPI used during the water vapor measurements had reflecting surfaces polished on a rod of fused silica which were coated with a highly reflective film optimized for 1.4 \( \mu \text{m} \) light. A summary of Yariv’s (1997, pg. 121) detailed development of optical resonator theory follows.

When a laser beam that is aligned well with the interferometer’s axis enters from one end, the internal reflections off the surfaces will set up a standing wave. The action of tuning the laser causes interference to occur at a fixed frequency spacing called the free spectral range (FSR).
given by,

\[ f_{\text{res}} = \frac{c}{2nd} \text{ [Hz]}, \]

(4.11)

where \( c \) is the speed of light and \( n \) is the index of refraction. The narrowness of the fringes or the finesse (\( \mathcal{F} \)) is given by:

\[ \mathcal{F} = \frac{\pi \sqrt{R}}{1 - R'}, \]

\[ = \frac{f_{\text{res}}}{\Delta f_{\text{fringe}}}, \]

(4.12)

where \( R \) is the reflectivity of the surface, and \( \Delta f_{\text{fringe}} \) is the full width at half maximum of a fringe. The reflectivity is usually enhanced by a dielectric film coating.

The transmission through the etalon is (Demtröder 1996, pg. 148),

\[ \frac{I(f)}{I_0} = \frac{1}{4\pi^2 \sin^2 \left( \frac{\pi f}{f_{\text{res}}} \right) + 1}. \]

(4.13)

A CFPI operates on the same principle, however the FSR has a 4 instead of a 2 in the denominator due to the spherical surface geometry (Demtröder 1996, pg. 147),

\[ f_{\text{res}} = \frac{c}{4nd} \text{ [Hz]}. \]

(4.14)

When the interferometer is operated near resonance, the argument of the \( \sin^2 \) term in the denominator effectively becomes zero. The transmission behavior of the interferometer can be examined by expanding \( \sin^2(x) \) in a Taylor series about zero. By neglecting higher order terms (\( \geq x^6 \)), the transmission becomes Lorentzian. The effective Lorentzian transmission function permits a high-finesse Fabry-Perot interferometer to be used to measure the laser linewidth. The resulting combined instrument/laser lineshape is Lorentzian and the width will be the sum of the Lorentzian laser linewidth and the instrument Lorentzian linewidth.

A CFPI was used during the potassium experiments. An experimentally determined finesse of 50 was measured at 789 nm using an external cavity diode laser with a linewidth of 300 kHz used by Mihalcea et al. (1996). Because the finesse of the instrument rolls off rapidly for wavelengths longer than 650 nm (Spectra-Physics 1976) a finesse of 50 at 770 nm is conservative.

**Ring-Fiber Interferometer**

Cedolin (1997) describes the operation of the fiber-ring interferometer (FRI) in detail. An overview of the operation is included below and a schematic is shown in figure 4.9 to aid the discussion. The FRI is a four-port directional fiber coupler composed of single mode fiber. A portion of the laser output is routed to port 1 while the output of port 4 is monitored with a
FIGURE 4.9 A schematic of a fiber ring interferometer (FRI) illustrates the feedback loop between ports 3 and 2 which provides for interference along the junction.

detector. The interference is obtained by feeding back the output of port 3 into port 2. Inside the instrument two single-mode fibers are brought into close proximity (along the junction) such that their evanescent fields overlap. Interaction along the junction results because the condition of the total internal reflection condition is frustrated due to the overlapping fields. The consequence is a coupling between the fields and power can be transferred between the fibers (Neumann 1988, pg. 184).

The light coupled from port 3 to 2 undergoes a phase shift with respect to the light entering at port 1. Thus the free spectral range of the FRI is,

$$f_{FSR} = \frac{c}{nd} \ [Hz],$$

(4.15)

where \(d\) is the length of the loop from ports 2 to 3 and \(n\) is the index of refraction of the fiber core. Simply by providing a long length of fiber, a high spectral resolution (small FSR) can be obtained inexpensively.

An FRI requires calibration because a precise method to measure length of the return loop (ports 3 to 2) is unavailable. The FRI was calibrated using the fringe spacing from a SFPI as a reference. The FSR of the SFPI was calculated to be 2.0008 GHz ± 500 kHz from data provided by the interferometer manufacturer (Temer 1992).

The calibration procedure entailed scanning the laser while simultaneously recording the interference fringes from the SFPI and the RFI. The fringe centers were determined by (boxcar) smoothing the data, differentiating, and determining the derivative’s zero crossing for each fringe. Since the FSR of each instrument is constant over the wavelength range scanned, a FSR was chosen for the RFI which minimized the sum of the root mean squared errors, between the relative frequency calculated by the SFPI and the FRI. Figure 4.10 illustrates a calibration result. A plot of the errors for a series of guesses is shown in figure 4.11. A FSR of 182.564 MHz was determined by this method. Considering the accuracy of the SFPI’s FSR and the accuracy in determining peak centers, the last digit was dropped. In a similar manner, a FSR of 405.80
MHz was measured the second FRI used in the two-channel water absorption experiments.

The reflected shock tunnel water-vapor experiments were at low pressures (3 - 10 torr) and relatively cool freestream temperatures (600 K) yielding narrow lineshapes. To acquire finer temporal/spectral resolution the RFI’s were used instead of the 2 GHz SFPI. However, while performing SET measurements with water, the increased scan rates required use of the SFRI to meet the frequency response limits of the 10 MHz InGaAs detector.

4.5 Data Reduction Algorithm

To calculate the spectral absorbance from the measured transmission which is acquired in time, time must be converted to light frequency. Additionally, because the incident intensity is not measured, it must be estimated. The data reduction procedure which leads to the measured spectral absorbance, is illustrated in figure 4.12. Panel a) shows example transmission and interferometer signals acquired in time. To calculate the instantaneous laser frequency (or wavenumber), the centers of the interferogram fringes are used calculate the transfer function between light-frequency space and time space (b). For experiments using a PMT to record the interferometer signal, a 22 ns electron transit time (Hamamatsu 1998, No. R928) is subtracted from the interferometer signal’s time base.
To calculate the spectral absorbance, the incident laser intensity is estimated by fitting a polynomial through the non-absorbing portion of the transmission signal as in panel c). A correction for the detector offset and/or background emission (see section 5.1.2) is applied to the data and the absorbance can be calculated as in panel d.
4.5. DATA REDUCTION ALGORITHM

FIGURE 4.12 A plot illustrating the data reduction procedure. (a) The interference and transmission data is acquired in time. (b) The interference fringe centers (e.g., 7) are used to calculate the relative frequency. (c) The estimated incident intensity, $I'_i$, is found by fitting a polynomial through the non-absorbing portion of the data, $I_o$. $I_{os}$ is the recorded detector offset voltage when the laser light is blocked. (d) A correction due to detector offset, $I_{os}$, permits calculation of the spectral absorbance which is equal to $-\ln(I_i/I_o)$. 
Chapter 5

Experimental Results

5.1 Mark 0 Probe,

Is Water Vapor Present?

The first experiment was designed to test the concept of detecting hydrogen driver gas contamination (see section 2.2.2) with a fiber-coupled probe installed directly into a reflected-shock-tunnel core flow. The proof-of-concept experiments validated the probe concept and revealed the presence of water vapor earlier in the test time than expected.

5.1.1 Mark 0 Probe Design

A simple, yet rugged probe was designed to pitch and catch a laser beam perpendicularly through the hypersonic reflected shock tunnel’s flowfield core. The probe’s salient optoelectronics are illustrated schematically in figure 5.1. The 18-cm pathlength was the maximum allotted so as to not gasdynamically interfere with concurrent experiments. Wedged (3°) windows were used to avoid interference effects. To reduce beam steering effects, a 1.25 cm (0.50 in) focal length lens focused the laser beam onto 3-mm diameter InGaAs detector. The detector monitored the transmission intensity with a frequency response, $f_{\text{3dB}} = 250$ kHz. Two 2.8-mm (1/8-in) thick $- 6.4 \times 6.4$-cm (2.5 x 2.5-in) structural steel tubes (referred to as legs) housed the optics and detectors. All leading edges were stainless steel to prevent damage from diaphragm particles. Additionally, the leg-leading edges possessed 42° inclines to maintain an attached shock in the Mach-9 flow.

Figure 5.2 shows a photo of the Mark-0 probe (foreground) installed in the reflected shock tunnel test section. The facility-survey rake is mounted above and to the rear of the probe. The probe pathlength was limited to provide clearance for concurrent rake installations. The probe
5.1. MARK 0 PROBE, IS WATER VAPOR PRESENT?

was affixed to a pair of struts connected to a 2000-lb. seismic mount. The seismic mount was affixed to a facility-isolated foundation to avoid vibration transmission into the probe.

The use of fiber optic cable permitted the operator to have direct access to the laser system while safely distanced from the reflected shock tunnel. Figure 5.3 shows the plan view of the facility layout and illustrates the remote location of the probe with respect to the laser systems. During the time required to load the (reflected shock tunnel’s) driver tube to operating pressure (as long as 2 hours) the laser operator, safely located in an adjacent building, could make adjustments and corrections.

5.1.2 Water vapor absorption measurements

A total of seven experiments were run, of which the first two used hydrocarbon-free air as a test gas while the remaining five used dry nitrogen. Table 5.1 shows the nominal freestream conditions for the experiments.

The diode laser was tuned to $1.40074 \mu m$ (index number 202 in figure 3.8, pg. 40) and scanned at 8 kHz over $1.2 \text{ cm}^{-1}$. The signals were recorded on a DATALAB digital recorder with 10-bit resolution sampled at 5 MHz. The probe successfully detected water vapor in the test flow and figure 5.4 verifies that the absorption recorded through the water-vapor reference cell is simultaneous with the flow’s absorption signal. Furthermore, the narrowness of the feature
FIGURE 5.2 A photo shows the proof-of-concept probe in the foreground of the Calspan 96" HST. Shown above and to the rear is the facility-survey rake containing total pressure and total temperature probes. Just behind the bottom leg of the probe is a light collection optic focused on the stagnation region on a hemisphere located just behind the probe's upper leg.

FIGURE 5.3 A plan view of the Calspan-facility layout to illustrate the remoteness of probe relative to the safe location of the diode laser system and operator.
reflects the test flow’s low-pressure condition.

Figure 5.5 shows recorded traces from a facility pitot tube and the probe’s raw transmission signal. A hand-drawn curve through the unfiltered pitot signal illustrates the mean character. The rapid oscillations result from an acoustic effect inside the pitot probe and are not representative of the flowfield. This figure indicates the overall facility timing beginning from the double diaphragm rupture. The test-time interval was determined by the facility operators.

The bottom trace is the raw signal recorded by the probe detector. When the airflow begins to turn on, the baseline lifts up from zero. This additional signal is believed to be broadband emission associated with hot dust particles and the multiple stagnation regions located on the adjacent survey rake. However, it appears that the transmitted intensity’s signal simply rides on top of a the smooth emission signal.

The smooth behavior of the emission signal and the lack of signal attenuation permits construction of an estimated emission signal from the raw signal. The process of creating the emission signal is illustrated in figure 5.6. Emission points are selected during the scan when no absorption occurs. Thus, the points represent the laser intensity plus background emission. By
subtracting the average of the values before the flow starts up, the set of points represents the emission signal. The emission signal is fit with a cubic spline and this signal is subtracted from the raw signal to yield an emission-corrected signal.

The pre-airflow data points do not have identical values because of noise and were averaged together. Results of the raw-signal correction are displayed in figure 5.7 for a series of 3 scans. The figure illustrates the effectiveness of the emission correction and that the water vapor absorption is quite distinct.

Kinetic temperature, which is inferred from the Doppler width, yielded inordinately large temperatures. The reason for this problem was determined from an analysis of the acquisition system frequency response. The frequency response of the acquisition system was simulated using approximately 30 m (100 ft.) of RG-58A/U cable. Figure 5.8 illustrates power spectra of a synthesized transmission trace using the calculated freestream conditions, and the acquisition systems measured gain profile is superimposed. The synthesized data incorporated the maximum scan rate of the laser (14.6 km\textsuperscript{-1}/s) and a Doppler broadened lineshape. The figure indicates that a considerable amount of the high-frequency information is attenuated.

An attempt was made to equalize the experimental data by compensating for frequency distortion. The compensation was made by dividing the measured transmission in Fourier space by the measured frequency response curve. The results were less than favorable and it is thought...
5.1. MARK 0 PROBE, IS WATER VAPOR PRESENT?

![Graph showing emission subtraction process.](image)

**FIGURE 5.6** A plot illustrating the emission subtraction process. The raw signal which contains both the laser intensity and background emission, is corrected by subtracting out an emission curve. No absorption due to water vapor is present during the illustrated time interval.

That the measured frequency response on the bench top did not simulate that of the detector as installed with the long signal lines and multiple junctions. However, the equalization exercise indicated the peak heights were attenuated by approximately 25%. By using the line strength at the calculated freestream temperature (from Table 5.1), an estimate of the water partial pressure as a function of time is obtained and shown in Figure 5.9.

The experiment was successful in that water was detected during the test time when operating with an air test gas and a hydrogen driver gas. Equally significant is the fact that no water was detected when nitrogen was used as the test gas. The latter result eliminates outgassing from the tunnel and nozzle surfaces as a possible water source.

This first-generation probe performed well mechanically. In each of the seven runs the probe endured multiple hits from diaphragm particles and suffered minor cosmetic damage. Furthermore, the optical alignment was well preserved from run to run; however, minor window surface cleaning was required.

Finally, background emission did affect the signal, but it varied smoothly and did not overwhelm the laser intensity. The emission signal can be subtracted out, but the introduction of spatial filtering in subsequent detector-module designs reduced its contribution.
FIGURE 5.7 A plot of three selected laser scans from figure 5.5 to illustrate the laser transmission (a) before the airflow, (b) at the first sign of water absorption and (c) when the absorption signal reaches its maximum,
5.1. MARK 0 PROBE, IS WATER VAPOR PRESENT?

FIGURE 5.8 An illustration of the measured detector gain curve superimposed on the power spectra of a synthesized transmission signal.

FIGURE 5.9 Estimated water-vapor pressure fraction calculated in the Calspan 96-in HST as a function of time. The test time interval was provided by Calspan and the error bars account for fluctuations in determining the baseline and uncertainty in the line strength. Changes in temperature and static pressure which may be related to the presence of water are not accounted for.
5.2 Mark I Probe, 
Measurements of $P_{\text{H}_2\text{O}}$, $T$, and $V$

Detection of water vapor during an interval of concern to facility operators motivated probe enhancements to enable temperature, velocity and concentration measurements. Improvements included pitching a second laser that targeted a transition originating from a different lower-state energy for rotational temperature measurements. By pitching one of the beams at an angle with respect to the bulk gas velocity, the resulting Doppler shift could be used to infer the velocity. In summary, the two laser beams permit 2 measurements of kinetic temperature and 1 of rotational temperature. Additionally, 2 measurements of water pressure are obtained along with velocity.

5.2.1 Mark I Probe Design

Multiple layouts and strategies are available to pitch two laser beams. Wavelength division multiplexing and temporal division multiplexing would permit measurements to be made along an identical gas path. However, such a criterion is not necessary when one considers: (1) the flow is nearly one dimensional (see section 2.2.3), (2) an absorption measurement is pathlength- and time$^1$-averaged, and (3) a beam must be pitched at an angle, to measure velocity, providing additional probe axial path averaging. These three points suggest it is sufficient for the laser beams to probe nearly the same test gas, nearly simultaneously.

Permitting the laser beams to interrogate nearly the same test gas allows the selection of two lines possessing more disparate lower state energies. Generally, a line with a higher lower-state energy possess a smaller population fraction, yielding a smaller linestrength. To use the high-temperature weak transitions, multiple passes are required. Figure 5.10 illustrates the use of two laser beams in the new design.

The design of the multipass system was intended to achieve the greatest pathlength while maintaining a reasonable level of effort for optical alignment. Additionally, to make multiple passes, a finite angle (with respect to the bulk gas velocity) is required resulting in a finite Doppler shift. A requirement for the design is to achieve identical Doppler shift with each pass. Multiple passes at different angles would contribute to broadening due to the different Doppler shifts. By maintaining a large angle, the absolute shift in each pass is minimized in addition to the differences in each shift.

While developing the multipass subsystem, minimal alignment effort was required for three passes while 7 was challenging. Furthermore, 3 or 7 passes required an additional mirror when compared to 5 passes, to guide the beam into a detector. While five passes required some effort

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$^1$In the time it takes the laser to scan the absorption feature ($\sim 15\,\mu s$) 7 axial cm of gas have passed by.
to align, it was more stable than 7 and permitted the use of a prism on the catch window to guide the beam into the detector housing. The use of a prism instead of a mirror reduced the degrees of freedom available for alignment, but in this situation the reduction turned out to be an advantage. To get the beam to hit the prism and the detector, the beam angles needed to be nearly exact. Thus, the 5-pass system yielded the most robust optical system.

The detector housing shown in figure 5.11 contained a lens in order accommodate subtle beam steering effects. To reduce background emission collection, a field stop was placed in front of the lens and the housing interior was painted flat black.

New detectors were purchased with a measured frequency response \( f_{\text{MAX}} \) of 1.5 MHz which is more than adequate to resolve the absorption features (see figure 5.8). Additionally, the laser
scan breadth was reduced to 0.7 cm\(^{-1}\) from 1.2 cm\(^{-1}\) used in the proof-of-concept experiment (Mark 0). By reducing the spectral scan breadth, the transmitted intensity's power spectral density is shifted to frequencies lower than indicated in figure 5.8, and therefore provides more than adequate frequency response.

### 5.2.2 Measurements in the LENS Tunnel

Table 5.2 shows the nominal test conditions for the water absorption tests. These tests were executed in the Calspan LENS tunnel with test gases composed of either hydrocarbon-free air, dry nitrogen, or nitrogen seeded with water vapor.

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Temperature (K)</th>
<th>Pressure (torr)</th>
<th>Mach No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4500</td>
<td>650</td>
<td>8.0</td>
<td>8.9(^\dagger)</td>
</tr>
</tbody>
</table>

\(^\dagger\) Estimated assuming \(\gamma = 1.35\)

The parameters for the laser operation are shown in table 5.3. The diode lasers were current-tuned at 8 kHz over approximately 0.7 cm\(^{-1}\). The signals were recorded at a 5 MHz sample rate on a Hytechnique digital recorder with 12-bit resolution.

<table>
<thead>
<tr>
<th>Desc.</th>
<th>Index</th>
<th>Transition Quant. No.</th>
<th>(\lambda_e) ((\mu)m)</th>
<th>(S_e) cm(^{-1})/atm</th>
<th>(E^{\prime}) cm(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\angle)ed Beam</td>
<td>202</td>
<td>4_{94} \leftrightarrow 5_{95}</td>
<td>1.40074</td>
<td>0.232</td>
<td>325.35</td>
</tr>
<tr>
<td>n-pass</td>
<td>340</td>
<td>7_{71} \leftrightarrow 7_{70}</td>
<td>1.39509</td>
<td>0.00330</td>
<td>1294.81</td>
</tr>
</tbody>
</table>

\(S_e\) from Toth (1994), \(E^{\prime}\) from Rothman et al. (1992)

For these experiments the interferometers were of the fiber ring type (see section 4.4) whose transmission signals were monitored with \(f_{\text{3dB}} = 10\) MHz InGaAs detectors.

Figure 5.12 illustrates the emission correction signal normalized to the mean signal level. The background emission is subtracted from the raw probe detector signal before data reduction. After the initial start-up transient, the largest correction to the detector signal was 12%.

Figure 5.13 presents measured unshifted and Doppler-shifted absorption lineshapes recorded from a single scan at \(t = 3.6\) ms in a 10-MJ/kg-enthalpy airflow. The test gas was seeded with water at its room-temperature saturation pressure (6% by partial pressure) prior to firing the
5.2. MARK I PROBE, MEASUREMENTS OF $P_{H_2O}$, $T$, AND V

![Image of graph](image-url)

**FIGURE 5.12** (Top) The pitot signal is shown to indicate the facility timing. (Bottom) The emission correction, normalized by the average signal level, is subtracted from the raw probe detector signal. The source of the precursor radiation is from the reflected shock region which has a temperature of approximately 6000 K.

...tunnel to increase the absorption signal-to-noise ratio. The pressure trace (top-left) was recorded using a pitot probe affixed to the probe to indicate the flowfield timing. The test time was defined as the interval in which the pressure remained relatively constant.

Representative absorption traces (recorded at $t = 3.6$ ms) are shown in the bottom left ($\lambda_s = 1.401 \, \mu$m) and right ($\lambda_s = 1.395 \, \mu$m) of figure 5.13. Collisional broadening was negligible because the flowfield static pressure was about 8 torr, rendering the lineshapes Gaussian. The smaller amplitude (unshifted $\lambda_{1,401}$) absorption is due to absorption by (static) gas contained within the probe. The larger amplitude (Doppler-shifted $\lambda_{1,401}$) absorption is due to relative motion of the test gas in the direction of beam propagation. The relative frequency shift corresponds to a freestream velocity of 4630 m/s. Dots represent measured data points. Solid lines represent the best-fit Gaussian lineshapes to each data set. Translational temperatures were determined from the width of each (Doppler-broadened) lineshape [$T_{\text{trans}} = 561 \, \text{K} \ (\lambda_{1,401})$, $544 \, \text{K} \ (\lambda_{1,285})$] and were in excellent agreement with the rotational temperatures determined from the two-line temperature ratio [$T_{\text{rot}} = 560 \, \text{K}$].

The estimated total measurement uncertainties are shown in table 5.4. The uncertainty in baseline determination contributes to the uncertainty in each of the measurements. Through a process of selecting different baseline regions and different order baseline polynomials, the sensitivity for each of the measurements to the baseline determination is included in the uncertainties. Additionally, measurement uncertainty calculations included the uncertainty in spectroscopic

---

2 This refers to the non-absorbing portion of the transmission in figure 4.12c.
parameters ($S_e$, $E^*$, and $v_e$), pathlengths, and measured beam propagation angles.

TABLE 5.4 Estimates of total measurement uncertainties.

<table>
<thead>
<tr>
<th></th>
<th>$\lambda_{1.48 \mu m}$</th>
<th>$\lambda_{1.395 \mu m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta V$ (m/s)</td>
<td>$\pm 50$</td>
<td>$\pm 50$</td>
</tr>
<tr>
<td>$\Delta P_{H_2O}$ (torr)</td>
<td>$\pm 0.03$</td>
<td>$\pm 0.06$</td>
</tr>
<tr>
<td>$\Delta T_{\text{trans}}$ (K)</td>
<td>$\pm 15$</td>
<td>$\pm 35$</td>
</tr>
<tr>
<td>$\Delta T_{\text{rot}}$ (K)</td>
<td></td>
<td>$\pm 13$</td>
</tr>
</tbody>
</table>

Figure 5.14 presents time histories of the measured total pressure (measured with a facility pitot probe), H$_2$O partial pressure, gas temperature, and gas velocity in the LENS tunnel for test run using hydrocarbon free air seeded with water vapor (6% by partial pressure). The signal from a pitot probe illustrates the facility timing and is traditionally used to infer the steady test time interval ($t = 3 - 9$ ms). The three ordinate axes (y-axes) share the same time axis. The first data points plotted correspond to the first laser transmission traces that could be reliably interpreted after the intense flash of broadband emission following facility start up.

The initial data points reflect the starting process of the nozzle. The initial measured
5.2. **MARK I PROBE, MEASUREMENTS OF $P_{H_2O}$, T, AND V**

![Graph showing measurements of temperature, velocity, and $H_2O$ partial pressure recorded simultaneously in free stream with a flow enthalpy of 10 MJ/kg in air seeded with 6% $H_2O$ (by pressure). The test time defined as the interval in which the pilot pressure value was relatively constant, began at t = 3 ms and lasted approximately 6 ms. Measured values of translational and rotational temperature, and velocity are in agreement with CFD-calculated steady-state values (650 K and 4500 m/s, respectively) for a period of approximately 1.0 ms near the test time beginning.](image-url)
CHAPTER 5. EXPERIMENTAL RESULTS

temperatures (t < 3 ms) indicate the presence of hot H₂O (near 900 K) vapor behind the initial shock wave. The fluctuations in the temperature and pressure measurements prior to the test time indicate rapid temporal changes in the flowfield during the tunnel start-up. The measured velocities indicate a relatively gradual increase to a steady value, of 4500 m/s equal to the CFD determined value. The scatter in the temperature measurements are most likely due to the fluctuations (temporal gradients) present in the flow. Section 5.2.3 evaluates the sensitivity of the measurements to fluctuation.

The measurements reach relatively constant values between t = 3.2 ms and t = 4.2 ms and are consistent with free-steam conditions (T∞ = 650 K, V∞ = 4500 m/s) calculated using CFD models of the nozzle flow which neglected the presence of water in the reflected shock region. During the initial start-up and test-time intervals the rotational and translational temperatures are within 150 K of each other. As the temperature decreases below 420 K, the SNR of the absorption measurement near 1.395 μm (the multiple-pass high-temperature transition) decreases substantially, thus no rotational temperature measurements are reported. Additionally, the velocity increase from 4500 m/s to 5000 m/s near 4.2 ms is accompanied by a temperature decrease. It appears the facility is not operating in a steady fashion. However, assuming that the total enthalpy is steady and the test gas is calorically perfect at the nozzle exit, the associated temperature change would be,

\[ \Delta T = \frac{1}{2c_p} \left( V_t^2 - V_i^2 \right) \]  

where \( c_p \) the test gas specific heat at constant pressure. The velocity change contributes over 2 MJ/kg in enthalpy change. This simple model yields a 2000 K temperature drop, which is impossible starting from 650 K, and thus indicates enthalpy from chemically frozen species or internal states may have been released into the flow or simply added to the reflected shock region.

Figure 5.15 presents measurements from a 10-MJ/kg enthalpy run with a hydrogen-gas driver and a test gas composed of dry hydrocarbon-free air. Due to the relatively low H₂O concentrations present, only the results from the stronger (1.401 μm) H₂O absorption line are meaningful. At t = 4.3 ms, the water levels are greater, however the temperature has decreased such that the transition near 1.395 μm is too weak to measure an absorption signal.

Measurable H₂O levels were detected as early as t = 3.6 ms, or about 500 μs after the steady interval (i.e., test time) begins. These results are consistent with proof-of-concept H₂O measurements recorded in the Calspan 967 HST. In runs of similar enthalpy using dry nitrogen as as the test gas, no H₂O was detected in either facility flowfield.

The measurements of water-vapor partial pressure and translational temperature indicate a period of steady conditions that deteriorates after t = 4.2 ms. For later times, the water-vapor partial pressure increases to 0.40 torr and the temperature decreases to near 400 K. The gas
5.2. MARK I PROBE, MEASUREMENTS OF $P_{H_2O}$, $T$, AND V

![Graph showing measurements of temperature, velocity, and $H_2O$ pressure.]

**FIGURE 5.15** Measurements of temperature, velocity and $H_2O$ pressure recorded simultaneously in free stream with a flow enthalpy of 10 MJ/Kg in hydrocarbon-free air. The test time defined as the interval in which the pitot pressure value was relatively constant, began at $t = 3$ ms and lasted approximately 6 ms. Measured values of translational temperature and velocity are in agreement with CFD-calculated steady-state values (650 K and 4500 m/s, respectively).
velocity however is nearly constant for the entire measurement interval greater than \( t = 3.5 \) ms.

### 5.2.3 Evaluation of Unsteady Measurements

The goal of this section is to investigate the sensitivity of fluctuating properties such as temperature, velocity, and water partial pressure on their measurement. The overall measurement uncertainty reported previously is quantifiable in terms of uncertainties in: linstrength, lower-state energy, line position, pathlength, angle, and baseline determination. However, the data reduction strategy assumes the flow is frozen during the time absorption is monitored. To examine the consequences of a fluctuating property, line shapes are synthesized using equation 3.15 shown below,

\[
- \ln \left( \frac{I_\nu(x)}{I_\nu} \right) = S_{12} \phi(\nu) P_1 x. \tag{3.15}
\]

The area under equation 3.15 is called the integrated absorbance and the effect of a fluctuating property will manifest itself as a distortion in \( \phi(\nu) \). Although the property fluctuates in time, a spectral-frequency/time transfer function will yield a spectrally fluctuating property for use in evaluating changes in, \( V_{gas} \), \( T \) and \( S_{12}(T) \), \( \phi(\nu - \nu_\epsilon, T) \), and \( P_1 \).

Figure 5.14 indicates that the measured properties are unsteady. The rate of change in a property between scans provides an indication of a property's rate of a change. There is an obvious danger in using a measured rate of change to in turn infer the measured property's sensitivity to that change. However, the following analysis qualitatively contributes to an understanding of the measurement behavior during such transients.

The spectral-frequency/time transfer function is derived from the fact that both the laser line position (\( \nu_{las} \)) and the fluctuating property are now assumed to vary linearly with time. Figure 5.16 displays an example absorbance for a complete scan where the absorbance is plotted against both laser wavenumber (linear bottom axis) and time (non-linear top axis) to illustrate the relative time between scanning and absorption. The Doppler-shifted absorption occurs over a 15-\( \mu \)s interval while the 0.65-cm\(^{-1} \) scan lasts 125 \( \mu \)s. So, for the short time that absorption takes place, the assumption of linearly varying properties is reasonable.

To calculate the perturbation due to a temporally fluctuating property, an estimate of the spectral rate of change is needed to calculate the varying properties for use in equation 3.15. Dividing the measured change between scans by the spectral tuning range provides the spectral tuning rate. For the largest velocity change, 250 m/s, observed between scans, 125 \( \mu \)s of time passes while the laser scans 0.65 cm\(^{-1} \). Thus, the spectral rate of velocity change (\( V_\nu \)) is,

\[
V_\nu = \frac{\Delta V}{\Delta \nu_{scan}} = \frac{250 \text{ m/s}}{0.65 \text{ cm}^{-1}} = 385 \text{ m/s/cm}^{-1}. \tag{5.2}
\]
5.2. **MARK I PROBE, MEASUREMENTS OF $P_{H_2O}$, $T$, AND $V$**

The distortion to a Doppler-shifted lineshape is calculated by letting the linecenter change ($\Delta \nu_0$) with velocity,

$$\phi(\nu) = \phi(\nu - \Delta \nu_0 [V(\nu)]),$$

where $\Delta \nu_0 (V)$ is spectrally dependent and follows from the Doppler equation:

$$\Delta \nu_0 (V) = \frac{V(\nu)}{c} \nu_0,$$

and where $V(\nu)$ is,

$$V(\nu) = V_0 \times \nu_{nss}.$$  \hspace{1cm} (5.5)

Two distorted lineshapes are presented in figure 5.17 for an increasing and decreasing velocity and an undistorted lineshape is shown for a constant velocity flow ($4200$ m/s) and a beam angled ($45^\circ$) to the flow. The spectral velocity fluctuations are purposefully large ($\pm 10$ km/s/cm$^{-1}$) to qualitatively illustrate the lineshape distortion.

Figure 5.17 illustrates that a linearly varying velocity contributes no velocity error. The symmetric line shape yields the correct average velocity at the correct time. Furthermore, if the velocity were to increase and then decrease during the scan, the resulting velocity error is equal to $1/2$ the fluctuation.

The lineshape distortion directly affects the measured kinetic temperature ($T_k$), via the Doppler width. The distorted lineshape’s Doppler width was calculated for a range of $V_0$, and is shown in figure 5.18. The percent change in measured $T_k$ is linearly proportional to $V_0$. For
the maximum observed $V_o$, 385 m/s/cm$^{-1}$ (see equation 5.2), the effect on $T_k$ is approximately 2%. Typically, the average contribution to $T_k$ uncertainty is less than 1%.

The lineshape distortion due to velocity fluctuation also affects the rotational temperature ($T_r$) measurement by perturbing the integrated absorbance ratio. The fractional change in integrated absorbance is illustrated in the top axis in figure 5.19 by $\Delta R/R_o$. The resulting fractional change in $T_r$ is shown on the bottom axis for average temperatures of 500, 600, and 700 K. The fractional change in $T_r$ is less than 1% when $V_o$ is less than 385 m/s/cm$^{-1}$

The temperature dependence of the $T_r$ error is clarified by examining figure 5.20. The bottom axis shows a range of integrated absorbance ratios, $R$. The top axis presents $T_r$ corresponding to $R$ from equation 3.17. The curve indicates the temperature derivative with respect to $R$. For lower temperatures, the line pair is more sensitive to errors in determining the absorbance ratio. However, from 500 to 700 K, the fractional change in $R$ from the top plot in figure 5.19 overwhelms the decreased sensitivity to integrated absorbance ratio. Thus $T_r$ errors increase as the average temperature increases.

The lineshape distortion resulting from temperature fluctuations was computed using,

$$\phi_{\text{int}}(T) = \frac{S(T)}{S(\overline{T})} \phi(\Delta \nu_r(T)),$$

where $\Delta \nu_r(T)$ is given in equation 3.19 and $\overline{T}$ is the average temperature. The dominant contribution to lineshape distortion is due to the lineshapedependence on temperature for the low temperature transition (angled beam). This functionality is illustrated in figure 5.21 for the two strongest low-temperature lines used in this work. The 413 line has a steeper temperature gradient and is thus used to illustrate the distortive effect from temperature fluctuations.

FIGURE 5.17 The computed lineshapes for large velocity fluctuation, $\pm 10$ km/s/cm$^{-1}$ illustrate the lineshape distortion that results.
5.2. MARK I PROBE, MEASUREMENTS OF $P_{H_2O}$, $T$, AND $V$

FIGURE 5.18 The percent change in kinetic temperature as a function of spectral velocity fluctuation is shown.

FIGURE 5.19 Fractional change in area ratio (top y axis) and rotational temperature measurement (bottom y axis) is illustrated as a function of spectral velocity fluctuation.
FIGURE 5.20. The rotational temperature rate-of-change is plotted with respect to integrated absorption area ratio.

FIGURE 5.21. The linestrength as a function of equilibrium temperature for the absorption transitions used in this work.
The lineshape dependence on temperature fluctuations is illustrated in figure 5.22 for an exaggerated temperature range. For example, in this figure the average temperature is 500 K and the temperature fluctuates from 100 to 900 K. The exaggerated temperature fluctuation reveals both the line-center shift and peak-height alteration.

Similarly, the influence of temperature fluctuations on the measured velocity is illustrated in figure 5.23. Calculations were made over a wide range of fluctuation rates, however the maximum observed temperature fluctuation between scans was 150 K yielding spectral temperature fluctuation, \( T_\nu \), of 230 K/cm\(^{-1} \), where the subscript \( \nu \) indicates the spectral rate. An inset in the figure illustrates a velocity shift of just over 8 m/s. However, typical fluctuations are much less than this.

Measured \( T_\nu \) is influenced by changes in the integrated absorbance also. However, the affect of temperature fluctuations on the integrated absorbance was less half a percent for the low-temperature transition (angled beam). Additionally, the high-temperature line (multiple-pass beam) possesses a negligible linestrength temperature dependence over this range and results in negligible integrated absorbance change. Thus, as indicated by the top axis in figure 5.19, small integrated absorbance changes have a negligible effect on the measured \( T_\nu \). Additionally, the effect of temperature fluctuations on \( T_\nu \) were less than 0.1 percent.

The final parameter which may affect the lineshape analysis is the fractional change in the target species’ pressure. Lineshapes were synthesized for varying water pressure levels in the following manner. The spectral rate of fractional pressure change (\( \Delta P_e \)) is characterized by,

\[
\Delta P_e = \frac{\Delta P}{\Delta \nu_{1\text{mm}}} \quad [1/\text{cm}^{-1}],
\]
where $\Delta P$ represents the water vapor partial pressure change during the scan and $P$ represents the average water vapor partial pressure during the scan. The instantaneous deviation from the average water vapor partial pressure $(\eta_p(\nu))$ is,

$$\eta_p(\nu) = \Delta P * \nu_{\text{inert}}.$$  

(5.8)

Finally, the equation used to describe the distorted lineshape is,

$$\phi(P_{\text{water}}, \nu) = \eta_p(\nu)\phi(\nu),$$  

(5.9)

where $\phi(\nu)$ is the standard Doppler-broadened lineshape. Kinetic temperature was calculated for a series of lineshapes obtained for a range of pressure fluctuations. The resulting lineshapes are qualitatively identical to distorted lineshapes in figure 5.22. No effect on measured $T_\nu$ is observed because the integrated absorbance perturbation for both transitions is identical. A minor perturbation to $T_k$ is observed for the low-temperature transitions (angled beam) and is illustrated in figure 5.24. For example, if the average partial pressure of water was 0.25 torr and the fluctuation was 0.5 torr, $(P_{\text{water}})_\nu = 3$ and the effect on $T_k$ is less than 1 percent.

The largest observed water pressure fluctuations were approximately 0.25 torr between scans while the average pressure was approximately 0.6 torr. The corresponding spectral fluctuation is 0.75 $1/cm^{-1}$ and contributes less than 450 ppm uncertainty to $T_k$. On the other hand, the influence on measured velocity is more extreme, by as much as 30 m/s at high temperatures as illustrated in figure 5.25.

The increased velocity shift exhibited at higher temperatures is due to the decreased linesstrength and results in an increased fractional change in absorbance for a fluctuating water pressure level.

The increased fractional change in absorbance results in an increased shift from line center.
5.2. MARK I PROBE, MEASUREMENTS OF $P_{H_2O}$, $T$, AND $V$

![Graph](image1.png)

**FIGURE 5.24** Fractional change in the kinetic temperature measurement is illustrated as a function of spectral water pressure fluctuation.

![Graph](image2.png)

**FIGURE 5.25** Change in the measured velocity is illustrated as a function of spectral water pressure fluctuation. The temperature dependence results from an increasing line strength with decreasing temperature.
Based on the preceding analysis, measurements of kinetic temperature and velocity are most sensitive to fluctuations. More specifically, kinetic temperature measurements are most sensitive to fluctuations in velocity. If the spectral velocity fluctuations are less than 230 m/s/cm**2** the perturbation is less than one percent. Velocity measurements are the most sensitive to target-species partial pressure fluctuations.

### 5.2.4 Measurements in the 96-in HST

A third set of diode-laser based measurements was collected at the invitation of Calspan. Calspan staff were concerned with the timing of water vapor detection in the LENS and the 96-in HST in relation to the timing associated with abrupt microwave interferometer transmission changes during magnetogasdynamic (MDG) experiments. The goal of these measurements was to confirm water vapor's arrival in the test gas and provide velocity and temperature information.

Diode-laser measurements were obtained at a 10 kHz rate, in freestream conditions similar to previous experiments, during Calspan airflow calibration tests prior to MGD experiments. The freestream velocity was calculated to be on average 4150 m/s, while the freestream temperature and pressure were 490 K and 3 torr respectively. The Mark I probe was used again, however with two modifications. First the collection optics in the probe were modified slightly. The collection lens aperture was reduced by blacking out all but a 4-mm diameter hole in the middle to reduce the collection of background emission further. Figure 5.26 illustrates the success of the reduced lens aperture when compared to figure 5.12 where signal corrections up to 12% were required. Because corrections appear random and are less than a percent, no emission correction was made.

The second modification was a change in the laser line-pair selection due to the availability of new lasers. Section 3.4.2 discusses the merits associated with the new 441-413 line pair (figure 3.8 pg. 40). To summarize, the new 441-413 line pair offers both increased temperature sensitivity and signal strength over the 202-340 pair used previously (section 5.2.2).

Table 5.5 displays the TDLAS-measured and calculated values of temperature and velocity during the steady-flow interval. The calculated values are derived from CFD calculations using a commercial CFD code, GASP, with a Calspan-generated grid. The model assumes steady mass flow originating from an equilibrium reflected shock region through a contoured-nozzle. The reflected shock region is computed from the conditions generated by measuring incident shock Mach number and reflected shock total pressure for an air test gas. Note, no consideration is given for hydrogen chemistry. Also shown are the measured freestream conditions of kinetic temperature and velocity using the water-based TDLAS probe.

The measurements of temperature generally agree well with the calculated results with the exception of run numbers 9 and 15 where the measured temperatures are respectively 200 and
5.2. MARK I PROBE, MEASUREMENTS OF $P_{H_2O}$, $T$, AND $V$ 85

![Graph of emission correction against facility timing](image)

**FIGURE 5.26** The normalized value of the emission correction signal using the modified collection optic. Because the correction would be less than 1/2 percent and appears random, no emission correction was necessary.

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<td>n/a</td>
<td>n/a</td>
<td>620$^\dagger$</td>
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<td>9</td>
<td>486</td>
<td>4.17</td>
<td>700$^\dagger$</td>
<td>4.53</td>
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<tr>
<td>15</td>
<td>485</td>
<td>4.16</td>
<td>540$^\dagger$</td>
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| Calculated (CFD) | Measured (TDLAS) |

130 K higher. Additionally, run number 7 had a temperature in line with 7 and 15, but due to a trigger malfunction, Calspan did not acquire data and could not calculate conditions. It is observed in the time history plots (described below) that the early introduction of water vapor is associated with an increase in gas temperature. In runs 7, 9, and 15, where the gas temperature is high, the initial observed water vapor levels are greater. In runs 4, 5, and 6, the initial observed water vapor partial pressures are lower and so are the temperatures. In general, the measured temperatures are greater than the calculated values. Measurements of velocity are consistently larger by an average of 6%.

Two typical time histories of the TDLAS measured data are presented in figures 5.27 and 5.28. The time histories include the total pressure (measured with a pitot probe and low-pass filtered at 8 kHz), $H_2O$ partial pressure, gas temperature, and gas velocity from the angled
beam. The water vapor partial pressure is normalized to the calculated (steady) static pressure of 3 torr. The Calspan-determined test time is indicated in the pressure trace. Spectral data from the multipass beam were rendered unusable due to a detector problem. The detector problem was linked to inordinately wide Doppler widths and indicated an inadequate detector-acquisition system frequency response for that channel. However, because the laser used for the multiple-beam detection probed a high-temperature transition, the marker :math:`\lambda_2` serves to indicate the initial detection of higher temperature water vapor.

Two tunnel behaviors are observed related to the initial water vapor level detected. In figure 5.27 the initial water vapor level and temperature is low. Consistent with this measurement is the delay in the first detectable water level from :math:`\lambda_2`. Contrast the behavior in figure 5.28 where the initial measured water vapor levels are higher as is the temperature. Consistent with the higher temperatures in figure 5.28, :math:`\lambda_2` (from the high temperature line) indicates that water
vapor was present earlier, but at a temperature too high and a level too low to be detected by the Doppler shifted channel.

Additionally, a behavior in contrast to the LENS tunnel performance is observed. In the LENS facility, an increase in water vapor level was associated with a decrease in freestream temperature. However, in the 96-in HST the temperature either dropped as in figure 5.27, or held nearly steady as in figure 5.28. These results indicate that hydrogen levels introduced into the reflected shock region may not be repeatable.

In a single test during this series, argon was used as the test gas with hydrogen as the driver gas. No measurable water levels on either channel were detected. This test further confirms that the introduction of water vapor into the test flow does not originate from facility hardware outgassing.
5.3 Mark II Probe,

Potassium Velocity Measurements

The primary motivation for developing a probe based on a species other than water was that water is not present in all test facilities. For example, oxygen-free test gases or the use of helium driver-gas does not generate water. In section 3.4.1 many potential candidates were reviewed and potassium was selected. Attractive features of a potassium sensor are that it can be smaller due to the large line strengths of the atomic-electronic transitions and the absorption features are narrow relative to those of other atomic absorbers.

5.3.1 Miniaturized Probe Design

A decision as to the size of the probe was based on the desire to build something small so as to be able to be run with other test programs or fit in smaller university-sized facilities. The question became, "how small?" If the pathlength is too small, then most of the it is taken up by the boundary layer. Considering a 2.5-cm (1-in) pathlength, 100's of ppb can be detected if monitoring ground-state potassium atoms, but no near-infrared spectral surveys in high-enthalpy facilities were available. However, experience with emission measurements has shown that sodium and lithium emission is always observed in spectra from stagnation point flow. Based on the assumption that sodium is deposited on the surfaces located in the reflected shock region,\(^3\) it was assumed that potassium would be deposited, too. Another assumption was that potassium atoms would be chemically frozen in the freestream due to the rapid nozzle expansion. The strategy then assumed that potassium existed at the level of 100's of ppb, and if needed, additional potassium could be deposited in the reservoir of the reflected shock tunnel to increase the absorption signal.

The issue of gasdynamic interference between the water-based probe and the surrounding Calspan diagnostics were a significant concern during its design. However, due to the large test-section size these issues are practically of no concern in the case of a miniaturized probe. As a result, the beam used to measure the Doppler shift could be at virtually any angle. In Appendix D, a discussion and analysis of beam angle considering velocity sensitivity, error minimization, and reflection losses shows that a 45° angle is optimal.

A probe was developed incorporating a 44° pitch angle. Figure 5.29 shows a plan and a side view of the miniaturized probe. The leading edge wedges were 41° for the Mach-9 flow at Calspan. Additional material was provided in anticipation of reducing the angle to 34° for use in Mach-3 shock/expansion tunnel flow. The side view illustrates the trajectory of the leading edge Mach waves. The probe height was selected to accommodate the high-pressure gas spillage.

\(^3\)A high-speed valve, located in this region, is worked on extensively by mechanics and technicians.
originating from the leading edge oblique shock so as to not interfere with the angled absorption measurement.

The plan view illustrates the optoelectronics used within the probe. One single-mode fiber couples the probe to a diode laser centered at 770 nm. A cube beamsplitter provides two beams yielding an in-situ reference absorption and an angled Doppler-shifted absorption beam. Both pitched beams pass through the same catch window and are directed to two 2.5 mm diameter silicon detectors (f_{-3dB} = 2.5 MHz) by a mirror and a right-angle prism. The prism faces were antireflection coated (optimized for 770 nm) and the detectors contained no windows to minimize interference effects. A number 29 Wratten filter (long-pass cutoff λ = 630 nm) was affixed to the inside of the single catch window, served to attenuate background emission.

The detectors were unable to drive the long signal lines when installed in the Calspan facilities. To remedy the problem the detectors were connected to instrumentation amplifiers (f_{-3dB} = 1.5 MHz) that possessed unity gain and performed as line drivers.

5.3.2 Measurements in the 96-in HST

Potassium measurements were obtained simultaneously with the water vapor results discussed in section 5.2.4. The wavelength of the (AlGaAs) diode laser was current tuned at a 10-kHz repetition rate over the potassium D1 (2S_{1/2} → 2P_{1/2}) transition near 770 nm to record a Doppler-shifted absorption feature every 0.1 ms. Figure 5.30 presents representative absorption line shapes (bottom) recorded from a single laser scan with air as the test gas. The facility
conditions are shown in the top-right of the figure and the pitot pressure trace is shown to the left to give facility timing. The left-hand trace was obtained from a beam directed at a 43.8-deg. angle with respect to the bulk gas flow. The right-hand trace was obtained from a beam directed at a 90.0-deg. angle with respect to the bulk gas flow.

Initially, it was believed there were two absorption features in the Doppler-shifted absorption trace, owing to absorption in the nearly stationary boundary layer close to the wall (near 0.68 cm⁻¹) and absorption by potassium frozen in the freestream. Data reduction based on this interpretation leads to Doppler widths with kinetic temperatures near 4000 K. This temperature value was much greater than the Calspan-determined value of 550 K and the simultaneously measured values (see section 5.2.4) using the water vapor probe. Possible causes of the questionable Doppler widths were investigated including broadening mechanisms such as transition broadening, tuning-rate broadening (Appendix B), and power broadening (Appendix C). Furthermore, the addition of the instrumentation amplifiers eliminated inadequate frequency response as a cause.

Further investigation of the boundary layer’s influence on potassium absorption was needed. To analyze the boundary layer in more detail, the equations for compressible boundary layer flow
were solved following the procedure outlined by Anderson (1989) and White (1991) (pg. 239 and pg. 502 respectively). Details of the analysis can be found in Appendix E. The boundary-layer solution yielded profiles of temperature and velocity. Due to the reduced velocities and elevated temperatures within the boundary layer, equilibrium potassium-chemistry was assumed. The calculated temperature profile provided a means to compute the potassium concentration profile. Finally, Beer’s law was numerically integrated through the variable-property boundary layer and freestream. Figure 5.31 illustrates the comparison between the calculated and measured absorbance based on this model.

Three key absorption features are now observed. First, the smallest amplitude feature (near 0.68 cm\(^{-1}\)) in figure 5.30 (bottom-left) is due to absorption by nearly stationary hot gas adjoining the wall along the probe boundary layer. Second, the larger-amplitude feature includes the combined absorption of cold freestream (chemically frozen) potassium and that of the relatively hot potassium in the outer portion of the boundary layer, that is, the thermal recovery zone. Thirdly, the reduced absorption between the outer boundary layer and the inner boundary layer (adjoining the wall) is due to ionization of the potassium atoms by the high recovery temperatures. As a result of the boundary layer absorption, velocity uncertainty is estimated to be approximately ± 200 m/s, which is much larger than the estimated ± 50 m/s for water vapor absorption.

Figure 5.32 presents time histories using both the water vapor and the potassium based
FIGURE 5.32 Measurements of the facility pitot pressure and velocity (recorded using the potassium-based diode-laser sensor) during a 9.53 MJ/kg test. For comparison, simultaneous results using the water-vapor probe are shown, too (run 15 from table 5.5). To aid comparison, lines through the data indicate average values of the measured quantity and the temperature and velocity values calculated by Calspan are shown in boxes to the right.

probe during a test with a total enthalpy of 9.53 MJ/kg and a freestream temperature of 485 K. To aid the comparison, lines through the respective data indicate average values of the measured quantity during a nearly steady interval. The total pressure measurements were recorded at a 100-kHz rate using a nearby pitot probe.

The measured velocity (using potassium) during the steady interval was approximately 4400 m/s (± 200 m/s) while the calculated steady state velocity was 4160 m/s. The velocity difference is just outside the estimated uncertainty. However, the average velocity measurement obtained from the water-vapor probe was 4350 m/s (± 50 m/s). The agreement between the measured velocity trends is good, however there is a difference in the initial average levels. The difference in average values may be due to the measurement location differences. The potassium probe was located closer to the nozzle center line while the water-vapor probe was located closer to the edge of the core flow (as measured by radial pitot-rake surveys).
5.4 Mark III-a Probe, Boundary Layer Signal Abatement

To further develop the diode-laser probe technique, a strategy to ameliorate radiative absorption in the boundary layer by potassium atoms was developed. This section contains a brief discussion regarding the options available to mitigate boundary layer absorption and presents an overview of the subsequent sections which detail the features and experiments leading to the development of a new probe.

To mitigate boundary layer potassium absorption, two options are available: one can alter the conditions in the boundary layer fluid or one can alter the concentration of potassium atoms. Altering the potassium atoms in a non-intrusive manner could be done through the use of a light source with sufficient power spectral density near 282 nm to radiatively ionize the potassium or near 770 nm to saturate the transition\(^4\).

An alternative strategy is to change the boundary layer conditions to inhibit the formation of atomic potassium, reduce the potassium atom number density or remove the boundary layer. By nature, changing the conditions is intrusive and involves either suction to remove the boundary layer or injection/mixing to alter the thermodynamic state in the boundary layer.

Suction works well locally to remove the boundary-layer gases, but it would be impractical to deploy. Incorporating suction in a probe which is used in conditions of low static pressure requires either a large pumping capacity or large (near-vacuum) reservoirs and would increase the size and complexity of the probe dramatically.

The literature presents fluid injection strategies to mitigate issues related to the high temperatures associated with compressible boundary layers for three types of problems. The thermal protection of a surface (i.e., an optical window or an engine/turbine blade wall), flow separation prevention and reduction of skin friction. However, a fourth problem area is the removal of optical interference. There is a dearth of studies involving the latter topic, probably due to its relevance to classified missile intercepter technology.

One strategy for fluid injection is transpiration. Due to the need for optical access, transpiration would have to occur upstream of a window. However, transpiration can introduce boundary layer instabilities which can make viscous dissipation more severe adjacent to the window. The alternative is direct tangential injection (slot cooling). This method results in a three pronged attack on the problem of radiative absorption by potassium atoms in the boundary layer. First, injection substitutes potassium contaminated gas near the wall by the cooling gas thus removing radiative absorption near to the wall. Second, injection provides a slip stream for the freestream gas to flow over thereby, reducing viscous dissipation and hence temperature rise in the freestream gas. Third, by way of mixing, the outer boundary layer can be affected by

\(^4\) See the discussion on power broadening in Appendix C.
the injection gas. The effect on the outer boundary layer from mixing of a cold injectant, or an injectant containing a component which pyrolyzes endothermically, is to cool the outer boundary layer allowing the potassium atoms to relax to a salt. Alternatively the gas may contain a scavenger species which is more likely to bond at higher temperatures, fluorine for example.

Ideally, injection of a fluid would be preceded by suction to remove the hot boundary layer gas, then the process of injection could inhibit the formation of a boundary layer containing optical contaminants. Suction has been addressed above, however, so the abatement strategy concentrates on injection.

Two goals are intended to be achieved through tangential injection of a gas upstream of the window. First mixing of the injected gas with the hot gas in the thermal recovery zone should cool it so that potassium atoms recombine with their oxidizer partners. Second, is to provide a slip zone, that is a layer of injected gas which is absent of potassium which will make up most of the boundary layer, permitting the freestream gas to flow over it without slowing down and undergoing viscous dissipation.

Ideally, the modified probe (Mark III-a) with slot cooling would be installed in the Calspan facilities to compare and contrast its performance. Unfortunately, there were no more opportunities for Calspan testing. Therefore, the experimentation was developed for application in a Stanford facility. The Stanford shock/expansion tube (SET) facility provided a test bed for Mark III-a development. Before slot injection development could begin, however, it was necessary to define a test condition in the SET containing potassium. Section 5.4.1 discusses preliminary experiments where the presence of potassium in the Stanford SET was investigated using the Mark II probe. The experience in the SET revealed that velocities with useful test time are in the vicinity of 2000 m/s. This motivated modification to the optical train to enhance the velocity measurement. Details of the modification are presented in section 5.4.2. Additionally, the SET experience revealed that swept-shock/boundary-layer (SSBL) interaction should be accounted for in the design, and details of the interaction and consequences to the design are presented in section 5.4.3.

Discussion of the slot injection analysis is presented in section 5.4.4, however before probe construction could begin, it was necessary to investigate a flowfield featuring the following: slot injection and SSBL interaction. Schlieren imaging was used for flowfield analysis and as a design tool, and the results are discussed in section 5.4.5. Finally, the results of the schlieren imaging experiments were used to complete the Mark III-a design. An experiment examining the influence of slot cooling on radiative absorption in the boundary layer is discussed in section 5.4.6.
5.4.1 Test Condition Identification and Characterization.

During a series of experiments (outlined in Appendix F) in the SET, potassium-atom absorption was measured during the test flow over a range of operating conditions. The results, summarized below, were used to determine that the potassium source was the secondary diaphragm. Additionally, based on the Calspan experience with potassium absorption measurements, further tests determined that absorption was dominated by potassium atoms in the boundary layer. Finally, a coarse velocity measurement from the radiative transmission data confirmed the calibrated facility performance.

The source of potassium was linked to the presence of the secondary diaphragm through a simple experiment. In this experiment the SET was operated as an open-ended shock tube at a high enthalpy condition with and without a diaphragm. A laser beam, tuned to the potassium $D_1$ transition (near 0.77 $\mu$m), was pitched through an optical port near the test section and potassium atoms were detected solely when a secondary diaphragm was installed. Furthermore, the absorption signal began when the contact surface (initially defined by the diaphragm location) passed the port location as confirmed by pitot pressure measurements. However, the spatial distribution of potassium atoms was uncertain.

To determine if potassium was frozen in the freestream or confined to the boundary layer's thermal recovery zone, additional experimentation was required. The strategy was to measure the absorbance ($-\ln (I/I_0)$) across two different pathlengths using a laser fixed at line center. Figure 5.33 illustrates the experimental setup and indicates a laser beam pitched perpendicularly to the bulk gas velocity in two locations. One location is in the test section where the Mark II probe is used to pitch and catch the beam through the SET core-flow. The Mark II probe's leading-edge angle was reduced from 41° used in the Mach-9 Calspan flow to 34° to be compatible with the Mach-3 flow. The second location is the emission/absorption port (see figure 2.7). Although the locations are not coincident, given the SET's unsteady nature, each location sees a similar aerodynamic time history delayed by the time-of-flight.

If significant absorption occurred in the freestream then the absorbance should scale with pathlength, but if the absorption is confined to the boundary-layer then absorbance would scale with the boundary-layer thickness. Figure 5.34 illustrates an absorbance time history for both locations at a calibrated test condition (Ben-Yakar et al. 1998), called the Mach-10 condition. The operation of the SET dictates that the same freestream condition passes by each measurement location. This operational feature is indicated by similarities in the absorbance time-history character. The average absorbance over the same initial feature is indicated in the figure. If the absorption was due to freestream potassium, the absorbance ratio should scale.

---

5 The pressure ratio across the secondary diaphragm was unity.
with the pathlength as,
\[
\frac{l_{p_{\text{set}}}}{l_{p_{\text{probe}}}} = 7.
\]

On the contrary, the measured absorbance ratio is about 1.6 while the pathlength ratio is 7. This result implies that radiative absorption from potassium atoms is primarily in the boundary layer.

A velocity estimate was obtained by identifying similar features (e.g., peaks and valleys) on each location’s absorbance trace and recording the time-of-flight (± 10μs) between each feature’s respective arrival. It is assumed that the mass-sink effect of a growing boundary layer entrains freestream flow, so the recorded absorbance in the boundary layer qualitatively reflects the freestream potassium salt concentration. Thus, the velocity inferred from the time-of-flight measurement is an estimate of the core-flow velocity. The estimated velocity of approximately 2400 m/s confirms this test condition’s prior characterization (Ben-Yakar et al. 1998). Furthermore, velocity measurements using the Doppler shift as performed in sections 5.2.2 - 5.3.2 yielded velocities near 1800 m/s. The lower velocities recorded using the Doppler technique supports the conclusion that radiative absorption is confined to the boundary layer as found in section 5.3.2.

5.4.2 Optical Train Modification

The test velocities in the Stanford SET are less than in the Calspan RST facilities. As a result, modifications to the optical train were made to increase velocity sensitivity and reduce measurement error. This was achieved by simultaneously providing a velocity reference and measurement with a single counter propagating beam. A schematic of the new optical train is shown in figure 5.35.

As the beam emerges from the GRIN lens and passes through the gas stream, a vector
FIGURE 5.34 A test in the expansion tube at a calibrated condition [Ben-Yakar et al. 1998] yields time histories of the measured potassium absorbance using a diode laser at 0.77 μm. The test gas was nitrogen with a 0.25-mil (6.4 μm) mylar (secondary) diaphragm cleaned with acetone and deionized water. The velocity measurements (solid circles) were inferred by identifying similar absorbance features in each of the traces and calculating the time-of-flight.

FIGURE 5.35 A schematic of the Mark III-a diode laser probe with slot cooling capabilities and the counterpropagating dual pass optical train to enhance the velocity measurement.
component of the bulk gas velocity is opposite the laser propagation (red-shifted absorption). Subsequently, after passing through a retroreflector the beam is translated upward (with respect to the page’s outward normal) and passes through the gas stream again, yielding an opposite shift (blue-shifted absorption). Once inside the probe, the beam travels over the prism and into the detector module. This optical train design maintains the presence of an in situ pressure-shift reference, as the pressure shift is identical for each pass, and requires one less detector. Furthermore, the alignment of the optical train is simplified because the orientation of both mirrors is fixed, and the self-correcting retroreflector requires a single adjustable optic; the pitch lens.

Synthesized absorbance traces for the counter-propagating beam and the angle/reference beam strategy is displayed in figure 5.36. The trace displayed in the top axis indicates a single curve as the data is obtained from one detector. Two traces are displayed in the bottom axis as they are derived from two detectors, one for the angled beam and one for the reference (perpendicular beam). A factor of 2 increase in sensitivity to velocity is achieved from the counter-propagating beam system as shown by the following equations,

\[ V_{a/r} = \frac{\nu_a - \nu_r}{\nu_0} c, \quad V_{c0} = \frac{\nu_b - \nu_0}{2\nu_0} c, \]  

(5.10)

where the left equation is for an angle/reference strategy and the right equation is for the counter-propagating strategy, and \( V_{a/r} = V_{c0} \). Additionally, the subscripts, \( r \) and \( b \) in the right equation indicates the red- and blue-shifted absorbance, and the \( a \) and \( r \) represent the angled and reference absorbance. The variables in the numerator are measured, and the subscript \( c \) indicates the absolute line position. Similarly, a factor of 2 increase in velocity measurement error reduction (\( \delta V \)) is also achieved,

\[ \delta V_{a/r} = \frac{2\delta \nu}{\nu_0} c, \quad \delta V_{c0} = \frac{\delta \nu}{\nu_0} c \]  

(5.11)

where it is assumed that error in determining shift between line centers, \( \delta \nu \), is equal in each case.

5.4.3 Swept-Shock/Boundary-Layer interaction

The interaction between the probe’s 2-D boundary layer, injectant gas, and the attached oblique shock along the leading edge of the probe's keel was of concern regarding the modified probe design. The interaction between the boundary layer flow and the wedge flow is called swept-shock/boundary-layer interaction. Figure 5.37 delineates the flow's topology and the relationship to the probe geometry.

Settles and Dolling (1990) present a review on the results of 20 years of research on swept
FIGURE 5.36 The top axis illustrates the enhanced Doppler shift using the counter propagating optical train in the Mark III-a probe. The bottom axis serves to display the shift for an angled/reference optical train used in the Mark II probe.

FIGURE 5.37 A schematic illustrating the gasdynamics of the interaction of the swept shock attached to the probe keel and the probe boundary layer. The detached shock envelope is of concern when determining window positions.
shock/boundary-layer (SSBL) interaction. Additionally, Panaras (1996) presents a similar review with additional numerical results and experiments. The feature of most concern to absorption measurements is the upstream extent of the detached shock envelope. The envelope is produced from the presence of subsonic flow in the boundary layers on both the probe face (flat plate), and the probe keel (wedge). The pressure jump across the keel's attached oblique shock drives the flow upstream in the subsonic region. It is important that the downstream window is not within the detached shock envelope since the elevated pressures may break it. The concept of the interaction's affect on absorption measurements arose when the Mark II probe was used during the initial SET-potassium experiments (in section 5.4.1). In these tests, the reference beam's linecenter fluctuated from scan to scan unlike the Calspan tests. The interference was thought to be a result of beam steering as the reference-laser beam passed through the recirculation region.

The literature contains SSBL studies emphasizing supersonic freestream velocities and turbulent boundary layers\(^6\) interacting with structures emanating from flat-plate-like surfaces. Practical applications are the junctions between wing/body or fin/body and struts located in engine intake ducts. The transition Reynolds number for a turbulent boundary layer in Mach 3 flow can be estimated from Bowcut et al. (1987),

\[
\log_{10} (Re_T) = 6.421 \exp \left[ 1.209 \times 10^{-4} \cdot M_e^{0.641} \right],
\]

(5.12)

is approximately 2.7 million. However, the Reynolds number over a 4 cm-long probe in 2.4 km/s nitrogen flow at 1200 K, is approximately 360,000 and as a result the probe boundary-layer flow is estimated to be laminar.

Despite the dearth of research for laminar SSBL interaction, an order of magnitude estimate is needed for design purposes. The study most relevant to this work, Sedney and Kitchens (1977), presents data for cylindric protuberances perpendicular to a flat plate. The size of a detached shock envelope was described for flows ranging in Mach number from 1.5 to 3.5 and for \(Re_e\) of 9.8 \(\times 10^6\). The length of the detached shock envelope was between 0.5 and 2 cylinder-diameters in Mach 3 flow. A 35° half angle wedge (i.e., the probe keel) will have a less severe disturbance than a cylinder. However, in the absence of a protuberance diameter, a default characteristic length scale in the presence of a wedge, is the probe's boundary layer thickness. Thus, an allowance for positioning the window upstream of the wedge was set between 2 to 2.5 cm giving more than 20 length scales to accommodate the separated flow. Furthermore, the action of slot cooling adds momentum to the boundary layer further attenuating the detached shock separation distance, thus making the estimate more conservative.

\(^6\)The reason being, the transitional length \(L_{trans}\) for 1 km/s air flow is approximately 4 cm therefore most of the boundary layer flow over a large supersonic vehicle is turbulent
5.4.4 Slot Injection Design Parameters.

The goal of the slot injection is to introduce an appropriate mass flow rate such that, when mixed with the probe boundary layer, the recovery temperature is reduced to one where potassium relaxes to a salt. Figure 5.38 illustrates the pertinent parameters considered in the design. The laser needs to pass through the mixing region at a distance (x in the middle panel) far enough downstream such that the coolant is mixed with hot gas associated with the boundary layer recovery zone. An additional constraint is that the injection pressure needs to be close to the freestream static pressure to avoid additional shocks or expansions that would adversely alter the freestream flow.

There is no simple analytical equation available to design a slot injection system to achieve a particular goal. This is made obvious by examining the variables associated with slot injection. There are 2 fluid streams each possessing a viscous and an inviscid region. Furthermore, each stream possesses different temperatures, pressures, species and velocity. Additionally, there is the injection geometry specification which includes a lip height (thickness of a splitter plate), slot height, and potentially an injection angle. A minimum of 11 parameters (considering individual freestream and injection gases) need to be accounted for. The practical approach was to find a model for the mixing layer, apply scaling laws to get an initial estimate for the proper spacing of the injector with respect to the window. Finally, by applying a mass and energy balance to the mixture of boundary-layer flow and injectant, an injector mass flow rate estimate to cool the thermal recovery zone was made.

The boundary layer mass flow rate and average specific enthalpy (per unit width) is calculated by integrating the mass and energy conservation equations through the energy and velocity profiles. The profiles were calculated using the compressible boundary layer solution method described in Appendix E for the freestream conditions identified in section 5.4.1. The enthalpy in the boundary layer was 163 kJ/(m·s) and the mass flow rate was 0.156 kg/(m·s) (N₂).

Based on the atom fraction present at 500 °C (see figure E.1) and assuming complete mixing, the required injectant mass flow rate (per unit width) was calculated for helium, hydrogen, and nitrogen injectants. To calculate the slot height, choked flow was assumed at the slot exit, room temperature was assumed for the slot reservoir. Additionally, an estimate of the boundary layer thickness for the slot injection flow was made, using the compressible boundary layer solution, to correct the slot height for viscous effects. To reduce the influence of viscous dissipation a light molecular-weight gas was favored due to the high sonic velocity and helium was chosen over hydrogen for safety reasons.

The width of the slot/probe body must accommodate the lateral Mach waves originating from the leading edge to avoid interfering with the laser. Thus, the placement of the window, slot width and body width depends on the stream distance (shown as x in the middle of figure 5.38) required for the injection to mix with the freestream.
FIGURE 5.38 A schematic of the diode laser probe with slot cooling capabilities to highlight the various parameters related to the design. (top) The plan view shows 1/2 of the probe structure to illustrate the Mach waves originating from flow disturbances. (middle) The side view is a cutaway detailing the qualitative velocity profiles for the freestream and slot injected flow. (bottom) The expanded injection region details velocity profiles.
5.4. MARK III-A PROBE,  BOUNDARY LAYER SIGNAL ABATEMENT

![Graph showing mixing layer thickness vs. stream distance for a range of compressible Mach numbers.]

**Figure 5.39** A plot of the mixing layer thickness vs. stream distance for a range of compressible Mach numbers bracketing the SET experimental conditions.

Stream distance engineering estimates were obtained from compressible shear layer measurements (Island 1997). The probe’s geometry is different than the compressible shear layer measurements. Specifically, in the measurements, the mixing layer was enveloped between two freestreams. It is assumed that the presence of a lower wall (probe body) will make the length estimates conservative. The mixing layer thickness (\(\delta_{\text{mix}}\)) scales by the convective Mach number and for flows with equal ratios of specific heats (\(c_p/c_v\)) this ratio is defined as,

\[
M_c = \frac{V_1 - V_2}{a_1 + a_2}
\]  

(5.13)

For the purposes of obtaining an engineering estimate, equation 5.13 is evaluated as 0.90 (for freestream \(N_2\) and sonically injected helium) in conjunction with Island’s (1997, pg. 146) experimental results, graphically illustrated in figure 5.39. A mixing length estimate of 1.5 cm provides a mixing layer thickness equal to the thickness of the freestream boundary layer, 1 mm.

5.4.5 Schlieren Studies:

**Slot Cooling – Swept-Shock/Boundary-Layer Interaction**

Schlieren imaging was used as a design tool to examine the viscous flowfield phenomena related to swept-shock boundary-layer interaction with slot cooling injection. Using the engineering estimates regarding the boundaries describing the proper window placement, the Mark III-a probe body was built including slot cooling passages, but not internal optics. SET tests
FIGURE 5.40 A schematic illustrating top and side views of the slot cooled diode laser probe installed in the SET expansion tube exit plane. The top view illustrates the location of the leading edge Mach waves, and those emanating from the edges of the slot injection. The side view locates the relative placement of the imaging window.

were run at the condition discussed in section 5.4.1 to examine the viscous interaction/mixing length scales.

The schlieren system used in the experiments is configured in the standard Toepler z-configuration. The optical train used a xenon flash lamp with two f/10, 20-cm diameter concave mirrors to collimate the light through the test section and refocus it onto a horizontal knife-edge. The test object was imaged with an f/6, 76 mm lens onto a 578 × 384 intensified CCD array. An intensifier upstream of the CCD array acted as a fast shutter effectively freezing the image over a 200 ns exposure.

Figure 5.40 shows a schematic of the Mark III-a blank installed at the acceleration tube exit plane. The top view illustrates the location of the leading edge Mach waves and those emanating from the slot injection edges. The purpose of the tests is to determine the placement of the window inside the region bounded by the intersection of the Mach waves, the slot injection mixing distance, and the upstream edge of the detached shock envelope.

A set of results from three tests are shown to illustrate the flowfield features with and without slot cooling. Figure 5.41 shows a schlieren image and a schematic which indicates the features observed without slot cooling. From this figure it is observed that the shock-envelope leading edge is 0.70 in (1.78 cm). The shadow in the top right of the schlieren image appears to be the Mach wave originating at the probe leading edge. Expansion fans surrounding the
leading edge wedge give the mach wave a three dimensional structure, thus, a distinct Mach wave is not present in the image.

Figure 5.42 shows a schlieren image and the related schematic for a test with helium injection. The pressure in the probe’s injection reservoir was adjusted so that the flow was choked and the pressure was approximately equal to the freestream pressure of 145 torr. A consequence of the helium injection is the shock detachment origin has been moved back to 0.85 in (21.6 mm) compared to 0.63 in (16 mm) as illustrated in figure 5.41 when no injection was present. Additionally, there is no evidence of the expansion fan originating from the slot position as there is in figure 5.41. This suggests that the expansion fan is now very weak due to the injection of helium at nearly the correct pressure.

Helium has the same index of refraction as nitrogen at the freestream temperature of 1200 K.
FIGURE 5.43 (left) A schlieren image of the flow surrounding the probe body in an expansion tube run with He/N₂ slot cooling. (bottom) A schematic indicates the detached shock origin and wave phenomena exhibited during the test.

As a result, no image of the injection is present due to the similar indexes of refraction. Twenty percent room air was added to the injectant to achieve enough of an index of refraction change for imaging purposes. Figure 5.43 illustrates the results of the helium/air mixture injection. The movement of the shock detachment origin is a bit more severe, 0.88 in (22.4 mm) due to the increased density associated with the air/He injectant. The increased density yields a greater momentum contribution near the boundary layer and impedes the projection of the recirculation region upstream. Most important to determining the window placement is the presence of the white region in vicinity of the slot. After about 0.50 in (12.7 mm) the light intensity is nearly equal to the background indicating substantial mixing has occurred.

5.4.6 Slot Cooling Diode Laser Results Using Potassium

The optics to pitch a counter propagating beam at 45° were incorporated into the Mark III-a probe body using the information regarding the shock separation distance and the estimate of the mixing length distance. Figure 5.44 illustrates single sweeps without slot injection on the left and with slot injection on the right during the steady flow portion of SET operation.

These results indicate that slot injection successfully removed the absorption that occurs near the wall. The center peak which is pronounced in the left trace in figure 5.44 (slot injection off) was eliminated in the right trace (slot injection on). However, it appears that slot cooling was unable to remove the radiative absorption that occurs in the outer region of the boundary layer. This conclusion is supported by analysis of the shifted absorptions while repetitively scanning the diode laser using the Mark III-a probe. The same velocities (~ 1800 m/s) with and without blowing were measured and were equal to the velocities were recorded using the Mark II probe for the same condition (freestream velocity = 2400 m/s). These results lend
further support to the assumption, that the origin of the shifted absorption was in the outer portion of the boundary layer.

This concludes diode-laser probe development based on atomic absorption. An important conclusion is that absorption measurements of any species that is generated in the boundary layer will not be successful unless absorption in the boundary layer is circumvented.

5.5 Mark III-b Probe,

SET Velocity Measurements Using H$_2$O

Water makes a favorable spectroscopic tracer for shock/expansion tunnels because it is easily seeded in the test gas and, by a judicious transition selection, radiative boundary layer absorption can be minimized. However, a limited range of conditions are available for water vapor absorption measurements over a 2.7 cm pathlength. Figure 5.45 illustrates linecenter signal-to-noise (S/N) ratio contours for four of the strongest transitions capable of making absorption measurements over a range of temperatures and pressures which have been calibrated in the Stanford SET (Morris et al. 1995; Ben-Yakar et al. 1998). Doppler and collisional broadening were considered in calculating the linecenter absorptions using data from Delaye et al. (1989). The transition near 1.393 μm (No. 413) offers the greatest S/N ratio over the a temperature range from 300 to 500 K. Furthermore, its strength decreases in the boundary layer thermal recovery zone, thereby reducing absorption in the region.
The influence of radiative boundary layer absorption for line No. 413 on velocity measurements was calculated using the same technique applied for potassium as in Appendix E. However, no consideration was necessary for H$_2$O chemistry as the recovery temperatures are much lower in the relatively (with respect to the Calspan RST) low-enthalpy flow. The results of the boundary layer calculation for line No. 413 was that the measured velocity would be biased lower by approximately 12 m/s.

The desire to use the miniaturized Mark-III probe for measurements using water vapor was anticipated. As a result, the inside window surfaces and the retroreflector were not anti-reflection (AR) coated for a specific wavelength. However, it was necessary to replace the GRIN lens, the right-angled prism,\textsuperscript{7} and the detector for components optimized for 1.4 $\mu$m light.

A scan rate of 30.3 kHz was achieved by changing the modulation function from a ramp to a saw-toothed one. The saw-toothed function permits greater utilization of the modulation duty cycle because less time is used waiting for the laser to cool. For example, in the Calspan experiments, 20% of the duty cycle was used for the laser to cool and reheat prior to each scan. Conversely, the time consumed for a saw-toothed modulation consumes approximately 5% of the duty cycle. As a result, the average laser-linecenter tuning rate is reduced, thus shifting the absorption PSD to lower frequencies. Additionally, a consequence of the greater freestream

---

\textsuperscript{7} To reduce etalon from the retroreflector and GRIN lens surfaces, the prism faces need to be AR coated for the wavelength of interest.
5.5. MARK III-B PROBE, SET VELOCITY MEASUREMENTS USING H₂O 109

![Graph showing absorption profiles and velocity measurements](image)

**Facility Conditions**
- \( V = 2100 \text{ m/s} \)
- \( T = 340 \text{ K} \)
- \( P = 140 \text{ torr} \)

**Figure 5.46** Reduced absorption profiles obtained from a single laser scan (near 1.393 \( \mu \text{m} \)) in air seeded with 3% water vapor by partial pressure. The velocity is determined from the Doppler shift between peaks. The peak in the center is due to water vapor contained inside the probe.

Pressures was to enhance collisional broadening. A broader absorption lineshape also shifts the transmission signal’s PSD to lower frequencies. The cumulative result of the saw-toothed modulation function and a broader lineshape, was the ability to scan faster while using the same detection system.

Figure 5.46 shows an example reduced water lineshape near 1.393 \( \mu \text{m} \) for SET test-gas traveling near 2100 m/s and a laser scanning at a 30.3 kHz rate. The scan occurred 66 \( \mu \text{s} \) after the contact surface arrived at the probe location. The duration of absorption is 6 \( \mu \text{s} \) as indicated by the bracket located on the wings of the shifted absorption traces. The contact surface was identified when the initial absorption occurred. Three peaks are identified in figure 5.46. The outlying peaks are the Doppler-shifted absorptions for the upstream and downstream passes of the laser beam. The peak in the center is from water vapor contained inside the probe. The center peak was present before the test flow began and while it is not an advantage to the measurement, it serves as check on line center. The measured Doppler shift between the outermost peaks yields a velocity of 2110 m/s. In figure 5.46 each of the absorption traces the Doppler-shifted peak heights were the same to within the noise levels. This was true for all of the lineshapes, and suggests that the laser scan rate was sufficient to freeze temporal fluctuations in the flow. Thus, the contributions to the velocity uncertainty are limited to baseline determination, beam-angle measurement, and a contribution from boundary layer absorption.

Typical velocity time histories are shown in figures 5.47 and 5.48 for two SET tests at the same initial condition (i.e., initial pressure settings). Each figure contains three sets of data. A solid line indicates the calculated helium velocity measured from secondary shock speeds.
The error bar ($\pm 25$ m/s) is a consequence of the secondary shock time-of-arrival measurement uncertainty ($\pm 2$ $\mu$s).

The second piece of data is the velocity as measured using time-of-flight (TOF) data for this test condition. The TOF velocity is obtained from calibration data measured by a combination absorption/pitot pressure measurement (Morris et al. 1995). Briefly, the technique assumes the gas behind the contact surface travels at the contact-surface velocity. By seeding the test gas with 5% CO a broadband absorption measurement at the emission/absorption port (see figure 2.7) detects the contact surface arrival. The contact surface arrival is also indicated from a pitot tube located at the acceleration-tube exit. A change in molecular weight between helium and nitrogen results in a sudden pitot pressure increase and indicates contact surface arrival. The error bar ($\pm 100$ m/s) indicates the measurement uncertainty in identifying the contact surface time-of-arrivals and the distance between the pitot tube location and the fixed optical port. The calibrated test duration is indicated by the length of the dashed line (approximately 160 $\mu$s).

Finally, the data points indicate the measured velocity from the individual scans using the Mark III-b probe. Each data point has its own vertical error bar, whose magnitude is determined from baseline determination (see section 4.5, pg. 59), angle and pathlength uncertainty. The uncertainty from the laser angle measurement is $\pm 7$ m/s and is a constant throughout the test. The horizontal error bar is 6 $\mu$s wide, the average duration of the absorption during a scan. Additionally, a bias of 12 m/s is added to the error bars to account for boundary layer absorption.

The absorbance peak heights from the first to third scan also increased indicating the water concentration or gas temperature was changing. Within a scan however, the peak heights of the blue and red shifted peaks were the same to within the noise level. The consistency in peak height indicates no additional uncertainty contribution is appropriate for the temporally changing velocity and water vapor concentrations (see section 5.2.3).

The features of each velocity time history are similar. First, a rapid velocity increase from close to the post-secondary-shock helium velocity to a nearly steady velocity occurs. Numerous SET computational models, as discussed in section 2.3.2, indicate that a velocity rise should be observed due to test-gas boundary layer formation. Wilson’s results (1995) indicated the viscous effects in the helium gas are much less than the test gas. Additionally, the influence of a finite diaphragm opening time (see section 2.3.2) may enhance the initial velocity rise.

The steady levels in the two cases differ by 50 m/s, while the secondary shock velocity in each case is measurably identical. The cause of the difference may be due to differences in water vapor levels in the test gas as result of wall adsorption. Additionally, the velocity appears to drop off at a faster rate than suggested from calibration runs. The cause for this is uncertain, however it is consistent with the velocity decrease associated with the arrival of the rarefaction fan originating from the secondary diaphragm location.
5.5. Mark III-B Probe, Set Velocity Measurements Using H₂O

**Figure 5.47** Measurements of velocity $V_{\text{T.O.F.}}$ recorded in the Stanford shock/expansion tunnel using the miniaturized probe. The helium flow velocity $V_{\text{He}} = 1847 \pm 25$ m/s is calculated from the secondary shock velocity. The time of flight velocity $V_{\text{T.O.F.}} = 2100 \pm 100$ m/s is obtained from calibration runs using CO absorption data.

**Figure 5.48** Measurements of velocity $V_{\text{T.O.F.}}$ recorded in the Stanford shock/expansion tunnel using the miniaturized probe. The helium flow velocity $V_{\text{He}} = 1847 \pm 25$ m/s is calculated from the secondary shock velocity. The time of flight velocity $V_{\text{T.O.F.}} = 2100 \pm 100$ m/s is obtained from calibration runs using CO absorption data.
The miniaturized probe successfully measured velocity in a SET using a Doppler shift measurements obtained in a counter propagating beam configuration. The discrete nature of the measurements reveal temporal details of the flow development previously unavailable.

5.6 Velocity Measurement Performance Envelopes

A methodology to evaluate the counter-propagating beam technique to measure velocity is presented. Results are given for potassium and water vapor as spectroscopic tracer species. Performance envelopes have been generated accounting for Doppler and collisional broadening effects which influence velocity measurement resolution. First, the ability to resolve velocity (Doppler Shift) is examined with respect to the breadth of the lineshape (width). Second, the freestream pressure and temperature impose a requirement on how far the laser needs to be scanned to acquire sufficient baseline. Third, signal to noise ratio is a concern for the weaker rovibrational transitions of water vapor.

The spectral relationship between a double passed beam (at 45° and 225°) and a velocity measurement is illustrated in figure 5.49. The shaded line depicts the absorbance from a single pass. The Doppler shift between the two passes is indicated by the spacing of \( \Delta \nu_{\text{dop}} \) and the full width at half maximum (FWHM) of a single Voigt lineshape is indicated by \( \Delta \nu_{\text{FWHM}} \).

\[
\eta = \frac{\Delta \nu_{\text{FWHM}}}{\Delta \nu_{\text{dop}}} = 1.4
\]

![Graph](image)

**FIGURE 5.49** A calculated lineshape simulating the passing a pair of counter propagating beams (at 45° and 225°) through a sample of moving gas. As the width of the absorption feature \( \Delta \nu_{\text{dop}} \) gets to be approximately 1.4 times the velocity shift \( \Delta \nu_{\text{dop}} \) it becomes difficult to distinguish the peak features.
The ability to measure velocity is characterized by the parameter $\eta$,

$$
\eta = \frac{\Delta \nu_{\text{FWHM}}}{\Delta \nu_{\text{trans}}},
$$

(5.14)

When $\eta = 1.4$ it becomes visually difficult to distinguish the individually shifted lineshapes. However, lineshape-fitting techniques are able to distinguish lineshapes for values $\eta \leq 10$ with nominal levels of noise. Thus, 10 serves as a threshold for describing the potential operational envelope for velocity measurements.

The shift is simply dependent on the velocity and for a $45^\circ/225^\circ$ inclination angle, the shift is determined as,

$$
\Delta \nu_{\text{shift}} = \nu_c \frac{V \sqrt{2}}{c},
$$

(5.15)

where $\nu_c$ is the energy of the transition (cm$^{-1}$), $V$ is the bulk-gas velocity and $c$ is the speed of light. The Doppler and collisional widths have been defined in equations 3.19 and 3.29. An approximation for the FWHM for the Voigt-lineshape from Whiting (1968) is,

$$
\Delta \nu_{\text{FWHM}} = \frac{\Delta \nu_c}{2} + \sqrt{\frac{(\Delta \nu_c^2}{4} + \Delta \nu_D^2}. 
$$

(5.16)

The accuracy of equation 5.16 is determined by comparing a numerically determined FWHM of a Voigt lineshape to White's approximation. The numerically determined Voigt FWHM was calculated from the fractional height of the Voigt function, $V_{\text{trans}}$,

$$
V_{\text{trans}} = \frac{2V(\nu, a)}{V(\nu_c, a)} - 1,
$$

(5.17)

where $\nu_c$ is line center. $V_{\text{trans}}$ is equal to zero when $\nu$ is equal to the half-width at half maximum. The difference between White's approximation and the computed width (normalized by the numerically determined FWHM) as a function of the Voigt-a parameter is shown in figure 5.50. The largest error for this approximation is 1 percent, which is sufficient for calculating performance envelopes.

Equation 5.14 is evaluated considering equations, 3.19, 3.29, 5.15 and 5.16 for a velocity of 1.0 km/s and a 2.7 cm pathlength. Contours of $\epsilon \eta a$ (equation 5.14) are plotted in figure 5.51 to illustrate the operational envelope as a function of temperature and static pressure for both potassium and water. A point is annotated in each plot indicating the freestream conditions in the Stanford shock/expansion tube experiments. Both plots illustrate that the width-to-shift ratio ($\eta$) is not the limiting factor when testing with velocities greater than 1 km/s.

The consequences of increasing the spectral scan width to acquire sufficient baseline as the pressure or temperature increases is examined. Potassium possesses a large broadening coefficient (see figure C.2) and as a result the scan range must be large to accommodate the
FIGURE 5.50 The normalized difference between the calculated FWHM ($\Delta \nu_{FWHM}$) and the approximate width, $\Delta \nu_{FWHM}$, by Whiting (1968), is plotted as a function of the Voigt-$a$ parameter. The error using the approximation is at worst, 1 percent.

Absorption signal and baseline. Inexpensive Fabry-Perot diode lasers are commercially available to access the potassium transitions, but spectral scan ranges over a wavenumber (cm$^{-1}$) become difficult due to mode hops. Typically, 30 times the lineshape FWHM is sufficient to acquire a baseline. To reflect this scan-breadth issue graphically, a _width contour_ equal to,

$$1 = 30 \times \Delta \nu_{FWHM} [\text{cm}^{-1}],$$

is superimposed in figure 5.51 for both potassium and water. The limiting factor in the case of potassium is the required spectral scan width for baseline determination. The DFB lasers used for water vapor are able to scan much further than a wavenumber. However, the motivation for including the _width contour_ equal to 1 cm$^{-1}$ for water is to make the point that the presence of neighboring transitions may interfere and need to be considered at larger pressures and temperatures.

Typically, the linecenter signal-to-noise ratio decreases as the temperature and pressure increase due to Doppler and collisional broadening. For strong absorbers like potassium, a decreased signal is mitigated by adding tracer. However, water vapor needs to be present at percent-like levels$^8$ to have sufficient signal, and increases in water concentration would diminish the tracer-like character.

---

$^8$The level is pathlength and pressure dependent. For example, percent levels were recorded using a 22 cm pathlength in a freestream environment of 10 torr and 600 K while 27 cm was sufficient for 140 torr and 340 K.
In the Water Vapor Performance plot of figure 5.51, a temperature-pressure envelope results when considering percent seeding levels in the Stanford SET facility and a diminishing lineshade for a strong, low-temperature transition. Signal-to-noise ratio contours are plotted for the $2_{03} \leftarrow 3_{03}$ (index No. 413) transition at a 5% (by partial pressure) level in a 140 torr test condition. The contours illustrate that as the temperature increases the signal to noise ratio drops off rapidly.

Contours of signal-to-noise ratio, scan breadth and width-to-shift ratio presented in figure 5.51 are specific to a given species and probe design. However, the contours graphically indicate the pertinent issues to be aware of when investigating high-speed flow velocity measurements with a diode-laser probe. Namely, the temperature and pressure influences on lineshape, strength and number density, need to be considered against the characteristics of the laser, neighboring transitions and the tolerance level for tracer species.
Chapter 6

Summary/Conclusions and Future Work

This thesis presented the development of a probe containing the required optoelectronics to pitch and detect laser beams targeting the following resonance transitions: potassium near 0.77 μm and water vapor near 1.4 μm. Measurements of temperature, velocity, and target species partial pressure were obtained by capitalizing on the species and quantum-state specific nature inherent to spectroscopic techniques, and the availability of room-temperature tunable-diode lasers and fiber-optic components. The laser scan rate yielded radiative absorption measurements over short-enough time intervals to freeze unsteady flow features during the time absorption takes place. A series of scans during a test provided a time history of the probed parameters in two impulse-type facilities, the gas-driven reflected-shock tunnel and the shock/expansion tunnel.

6.1 Summary and Conclusions

Summaries of six test programs are shown in table 6.1. The parameter in the last column, $\eta_{\nu}$, indicates the ability of each probe’s optical-train to measure velocity normalized by the maximum obtainable shift,

$$\Delta \nu_{\nu, \max} = 2 \frac{\nu_{\text{gas}}}{c} \nu_0.$$  \hspace{1cm} (6.1)

Thus, $\eta_{\nu}$ is independent of the velocity and resonant transition wavenumber, and a comparison can be made between the probes while independent of the facility and test condition. The ability to measure velocity in high-enthalpy flows is important because the velocity comprises a large
fraction of the flow enthalpy. It is believed that a probe with $\eta_v = 0.71$ is the best velocity measurement one can obtain without applying anti-reflection coatings to the windows.

TABLE 6.1 Summary of velocity measurement performance and test programs conducted for the development of a tunable diode laser probe

<table>
<thead>
<tr>
<th>Program</th>
<th>Facility Name</th>
<th>Probe</th>
<th>Species</th>
<th>$f_{\text{Laser}}$ kHz</th>
<th>Meas. Parameters</th>
<th>$\eta_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cal. 96-in RST</td>
<td>0</td>
<td>H$_2$O</td>
<td>8</td>
<td>$T_L$, $V$, $P_{\text{H}_2\text{O}}$</td>
<td>0.29</td>
</tr>
<tr>
<td>2</td>
<td>Cal. LENS RST</td>
<td>I</td>
<td>H$_2$O</td>
<td>8</td>
<td>$T_L$, $V$, $P_{\text{H}_2\text{O}}$</td>
<td>0.29</td>
</tr>
<tr>
<td>3</td>
<td>Cal. 96-in RST</td>
<td>II</td>
<td>K</td>
<td>10</td>
<td>$V$</td>
<td>0.35</td>
</tr>
<tr>
<td>4</td>
<td>S.U. SET</td>
<td>III-a</td>
<td>K</td>
<td>33</td>
<td>$V_{BL}$</td>
<td>0.71</td>
</tr>
<tr>
<td>5</td>
<td>S.U. SET</td>
<td>III-b</td>
<td>H$_2$O</td>
<td>30.3</td>
<td>$V$</td>
<td>0.71</td>
</tr>
</tbody>
</table>

RST = Reflected Shock Tunnel, SET = Shock Expansion Tunnel
Cal = Calspan, S.U. = Stanford University

Test programs 1 through 3 represent the first measurements using tunable diode laser absorption to measure the influence of hydrogen driver gas contamination on gas-driven reflected-shock tunnel performance. Measurements from the proof-of-concept Mark 0 probe in test program 1, indicated that water levels could be 5% or more by partial pressure. Furthermore, water arrival was detected during an interval generally considered to be steady. While the arrival of water may not be detrimental when performing standard aerodynamic measurements (heat flux and stagnation pressure), measurements dependent on flow chemistry, for example combustion or electron number density, may be compromised.

Results from test programs 2 and 3 were obtained using a refined probe design, Mark I, which permitted simultaneous temperature, velocity and water concentration measurements. Three significant conclusions are drawn from the two test programs. First, early temperature and velocity measurements indicate that facility operation is consistent with current steady CFD facility models, for the times during which water vapor levels are low. Second, after elevated water partial pressures are observed, the facility operation departs from the performance predicted by models which assumed the tunnel operated steadily. Namely, there is an increase in velocity but inconsistent temperature behavior. Thirdly, it was confirmed that simultaneous pitot and heat-flux measurements do not indicate a change in conditions concomitant with the arrival of water vapor. Finally the measurements presented from test programs 1 through 3 have resulted in a computational program on the part of Calspan$^1$ to model the introduction of hydrogen in the reservoir and the effects on the test condition.

A possible source of water vapor, outgassing from facility walls, has been eliminated. In test program 1 no water vapor was observed using a nitrogen test gas driven by hydrogen.

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$^1$ Now called Veridian Engineering.
Furthermore, in test program 3 no water vapor was observed when using argon as a test gas
driven by hydrogen. Water vapor was detected only when a chemical source was present, a
hydrogen driver gas and an oxygen-containing air test gas.

The fourth test program, which occurred simultaneously with the third, demonstrated the
use of a miniature probe (Mark II) based on potassium atom absorption. The results of the
Mark II probe independently confirmed the velocity measurements made using the the Mark I
probe based on water vapor. That is, current computational models accurately predict facility
performance, but when hydrogenated species are present, the Mark II probe measured the same
flowfield velocity increase as the Mark I probe. Additionally, test program 4 was the first
measurement using potassium as a spectroscopic tracer to measure velocity in a reflected shock
tunnel.

It was also determined that substantial radiative absorption occurs in the boundary layer
adjacent to the probe window when using species which may be generated in the hot boundary
layer. A simple boundary layer compressible flow model was used to explain each of the radiative
absorption zones that occurred in the chemically reactive boundary layer. It was learned that
high temperature thermal recovery zones can produce atomic species, but despite the short
length scales associated with boundary layer flow, the target species’ elevated number densities
can be orders of magnitude larger than in the freestream. The result is radiative absorption in
the boundary layer can mask the desired freestream absorption.

Test program 5 investigated the ability to ameliorate radiative boundary layer absorption
using a slot cooled diode-laser probe (Mark III-a) in the Stanford shock/expansion tube fa-
cility. Initial time-of-flight absorption measurements targeting potassium absorption at two
locations along the expansion section, indicated velocities (2400 m/s) consistent with facility
calibrations. However, the same measurements indicated that atomic potassium is confined to
the hot boundary layer. Measurements using the Mark III-a probe indicated that slot cool-
ing successfully removed the near-wall absorption but was unable to remove potassium in the
boundary-layer region near the freestream. The latter conclusion was inferred from Doppler-
shifted velocity measurements which were 25 percent less than the time-of-flight measurements.
The reason potassium absorption measurements were successful in the Calspan experiments was
that a sufficient potassium atom number density was chemically frozen in the freestream for
detection.

The experience in test programs 4 and 5 strongly suggest that the application of the diode-
laser probe technique to any species generated, or energy state populated in the boundary layer,
will suffer from boundary layer radiative absorption. Thus, atomic species such as the alkali
(K, Rb) and alkaline earth (Ca, Sr) metals and radicals such OH, CN and CO which may be
available as tracers in the future, should be considered only with due attention to the boundary
layer.
6.2. FUTURE WORK

Test program 6 successfully demonstrated the ability of the counter-propagating beam technique to rapidly acquire velocity measurements (30.3 kHz rate) using a miniaturized probe. The demonstration was in a shock/expansion tube flow using a water-seeded nitrogen test gas. The laser scan rate was sufficient to freeze fluctuations associated with a velocity and target species concentration increase, as the contact surface marking the transition between pure helium expansion tube gas and nitrogen/water test gas passed over the probe. The measured velocity, \( \sim 2100 \text{ m/s} \) agreed well with the calibrated velocity using time-of-flight techniques.

When scanning a laser at a sufficiently fast rate, the velocity measurement uncertainty is based on the beam-angle and Doppler-shift uncertainties. The latter uncertainty originates from systematic (e.g., etaloning) and random noise in determining the baseline. Thus, the total velocity uncertainty resulting from a probe design is velocity independent, and the measured \( \pm 25 \text{ m/s} \) velocity uncertainty for the Mark III probe design would be applicable to the 4500 m/s flow examined in the first three test programs. That results in a \( \pm 0.5\% \) uncertainty and suggests that the diode-laser probe technique should be developed as part of an impulse facility performance survey.

A lineshape was developed in Appendix B which quantifies the tuning rate broadening mechanism as predicted by the Heisenberg uncertainty principle. A natural tendency is to try and improve the temporal resolution and freeze temporal gradients (parameter fluctuations) better by scanning the laser source more rapidly. However, the process of increasing a measurement’s temporal fidelity cannot increase without consequences to the lineshape and should be considered. Additionally, analysis of the power broadened lineshape in Appendix C showed for the purposes of velocity measurements, an average laser intensity of \( 1/2 \) the saturation intensity has little effect on the ability to measure velocity. However, to measure kinetic temperature inferred from a power-broadened lineshape to within 1\%, a saturation intensity ratio of 0.05 cannot be exceeded.

6.2 Future Work

This thesis lays the ground work for developing a laser diagnostic suite of probes to fully characterize the test flow in a high-enthalpy impulse facility. In large-scale facilities, multiple probes situated across the facility exit plane could simultaneously measure the velocity and temperature exit-plane profile. The profiles could be used to validate current nozzle flowfield computational models. Furthermore, the results of design improvements, to inhibit driver-gas contamination, could be checked directly.

The test gas compositions can be quantified as transitions are accessible with commercially available tunable lasers for all the major test-flow species (NO, \( \text{O}_2 \), and \( \text{H}_2\text{O} \)), with the exception of molecular nitrogen. However, in order to measure some of the weaker transitions,
molecular oxygen for example, frequency modulation or wavelength modulation spectroscopy techniques should be investigated using a probe. Similarly, as laser diodes become available for longer wavelengths, fundamental modes of water vapor will be accessible near 2.6 µm. The strongest transitions in this region possess a factor of 10 increase in line strength, and will permit measurements over a short pathlength to achieve finer spatial resolution. To detect even smaller quantities of water vapor, longer pathlengths could be applied.

The use of a miniature diode-laser probe based on water vapor yielded discrete velocity measurements using DFB diode lasers. However, the scan rate was limited by the data acquisition system frequency response. The laser is capable of tuning across sufficient spectral widths at frequencies approximately a factor of 5 to 10 greater. Application of commercially available multi-gigasample per second data recorders with GHz analog bandwidths and high-frequency response detectors could yield 0.1-MHz velocity measurement resolution in shock/expansion tube flowfields.

The successful demonstration of the high-fidelity velocity measurement suggests using the technique for CFD validation. The shock/expansion tunnel offers a unique test facility which suffers from the presence of a secondary diaphragm, species diffusion and viscous effects. However, the facility’s ease of use and simple geometry, combined with a diode laser velocity probe offers a test bed to validate unsteady compressible flow computations. Of particular interest would be to examine the effect of boundary-layer growth on the contact surface and velocity. An ensemble of tests with the probe located at a series of axial positions would yield both an axial velocity profile and contact surface location as a function of time for comparison to numerical models.

A motivation for developing a diode laser probe technique based on potassium was its natural presence and large line strength. While, velocity measurements using the miniaturized probe were successful, the resolved lineshapes were compromised by radiative absorption of potassium atoms in the boundary layer. A method to remove boundary layer radiative absorption by atoms or radicals generated in the boundary layer is necessary for further development. A solution is to investigate saturating the target transition in the boundary layer by pitching a spectrally fixed, high-power laser centered on the resonant transition across the window surface. For example, a commercially available cw diode laser\(^2\), at 770 nm, with a 2 nm spectral width (33 cm\(^{-1}\)) and 16 watts of power, provides a spectral power density over 400 mW/cm\(^2\) which is more than enough energy density to saturate potassium. The required spatial intensity could be met by using multiple lasers. Thus, by saturating the transition in a region confined to the boundary layer, the region becomes transparent to the probe laser beam interrogating the freestream.

A second motivation for developing a diode laser probe technique based on potassium was its presence in the flow independent of the driver gas species. Similarly, the extension of the

\(^2\)The laser is manufactured by Coherent Semiconductor.
6.2. FUTURE WORK

diagnostic to hydrogen fluoride (HF) should be investigated as a spectroscopic tracer. The HF-probe technique could be used when water vapor is not tolerable or generated naturally during facility operation. An advantage HF has over potassium (or other atomic species) as a tracer is spectral access to low-temperature rovibrational transitions. The selection of a transition with small lower-state energy offers weakened radiative absorption in the high-temperature boundary layer which minimizes the uncertainty in velocity measurements. Finally, it can be seeded in the test gas to examine conditions during steady flow, or seeded in the driver gas to examine rates associated with driver gas infiltration.

Two advantages of HF over H₂O are its spectral accessibility near 1.3 µm with less expensive DFB communications diode lasers and its large line strength (compared to transitions near 1.4 µm). The strongest low-temperature transitions are 5 times stronger than the equivalent low-temperature water transitions used in this work. A disadvantage of using HF is its toxicity and corrosive nature. However, its toxicity is similar to nitric oxide (NO) which is commonly generated in ground-based test facilities using an air test gas at high enthalpies or seeded in low-enthalpy flows or inert flows for diagnostics involving laser induced fluorescence. Thus, toxic-gas handling practices and facility purge procedures are already established. The corrosive properties of HF would have no effect on highly polished interior steel surfaces. However the use of HF would not be advised for use in aluminum-based facilities as it readily reacts with oxidized aluminum exposing the former subsurface to additional oxidation.

An additional motivation for a hypervelocity diode laser probe based on HF is that comparison of the water vapor probe results with computational models is currently hampered by three issues. First the computations are numerically stiff due to the need to account for hydrogen chemistry in addition to the well-characterized air chemistry. Second, a boundary condition is a time varying/unknown hydrogen concentration. Third, there is large uncertainty as to the chemical mechanism's accuracy over the vast range of temperatures and pressures existing between the reflected-shock reservoir and the nozzle exit plane. The use of small concentrations of uniformly seeded spectroscopic tracer in an inert test gas or driver gas would permit computational analysis of the driver-gas influence separately from chemical effects. Subsequently, measurements using a high-fidelity water-vapor probe could commence to investigate the effects of water vapor more thoroughly.
Appendix A

Atomic and Molecular Spectra

A.1 Electronic Transition Line Positions

The dynamics of an electron moving about a nucleus is described by quantum mechanics. Thus, to calculate an electron’s trajectory and energy one calculates the accompanying particle-wave motion using quantum mechanical theory. A detailed presentation of the theory is not necessary; only a brief review of the results is presented to reveal the origins of the unique spectroscopy exhibited by different atomic species.

A function related to the probability that a particle with frequency $f$, will be found at a position is,

$$\Psi = \psi \exp(-2\pi ft),$$

where $\psi$ is the amplitude of the standing wave at a position in space. The probability for the particle to be at a given location is given by $|\Psi|^2$. A physical interpretation of $\Psi$ comes from examining De Broglie Waves for the circular orbits of an electron about the nucleus of an atom as described in Herzberg (1944). The wavefunctions of the electron particle exist for integral frequencies such that the wave functions reinforce one another, that is a standing wave results. Those solutions with frequencies other than particular integral numbers (i.e. quantum numbers) will destroy each other through interference. As a direct consequence of equation 3.1, each integral frequency corresponds to unique energy level.

An orbital is defined as the three dimensional shape within which the electron spends most of its time. There are 4 quantum numbers that result for the three dimensional solution to electron particle-waves about the nucleus of an atom and are summarized in table A.1.

The quantum number $l$ is used to indicate the electronic angular momentum. For $l = 0$, the orbital of the electron is labeled s, when $l = 1$, the orbital is labeled p, when $l = 2$ or 3 the
TABLE A.1 The atomic quantum numbers for an electron-particle about the nucleus of an atom

<table>
<thead>
<tr>
<th>Quantum No.</th>
<th>Name</th>
<th>Permitted Values</th>
<th>Governing Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>Principal</td>
<td>$1, 2, 3, \ldots$</td>
<td>The energy and size of the orbital</td>
</tr>
<tr>
<td>l</td>
<td>Orbital</td>
<td>$(n - 1), (n - 2), \ldots, 0$</td>
<td>The shape of the orbital and its electronic angular momentum</td>
</tr>
<tr>
<td>m</td>
<td>Magnetic</td>
<td>$\pm 1, \pm (l - 1), \ldots, 0$</td>
<td>The direction of an orbital</td>
</tr>
<tr>
<td>s</td>
<td>Spin</td>
<td>$1/2$</td>
<td>The electron axial angular momentum</td>
</tr>
</tbody>
</table>

Letters used are d and f, then for larger numbers, sequential letters from the alphabet are used. Uppercase letters are used to identify the state of an atom as opposed to a single electron. A value of $l$ equals zero does not imply a motionless electron, just that the electron’s motion yields zero angular momentum; the orbital in this case is spherical in shape.

The angular momentum is quantized because energy states are. The electronic angular momentum is from Schrödinger’s equation,

$$L = \sqrt{l(l+1)} \frac{j}{2\pi},$$

(A.2)

where the boldface $L$, indicates that momentum is a vector. In accordance with quantum theory, the direction of the angular momentum may be such that components projected along a reference direction are integral multiples of $\hbar/2\pi$. There are $(2l + 1)$ possible directions and they are identified with the magnetic quantum number, $m$. In the absence of an external magnetic field, the orbital energy of the electron depends only on the magnitude and not the angular momentum direction.

The spin quantum number, $s$, indicates the electron axial angular momentum. It can be shown to have only values of $s = 1/2$ and the spin angular momentum is,

$$s = \sqrt{s(s+1)} \frac{j}{2\pi},$$

(A.3)

where the boldface $s$ indicates that the spin angular momentum is a vector.

The electron axial momentum and the electronic angular momentum interact to form a total orbital angular momentum of the atom. For light to medium sized atoms, the coupling between the spin and the orbital angular momentum is weak, and their interaction can be neglected (Bernath 1995, pg 130; Banwell 1983 pg 174). This approximation is called Russel-Saunders coupling permitting the spin and orbital momentum to be summed independently, and then combined to yield the total orbital angular momentum:

$$L = \sum L_i,$$

(A.4)
and
\[ S = \sum s_i, \]  
(A.5)

where the summation of the orbital contributions and axial contributions must be expressible as
\[ L = \sqrt{L(L+1)} \frac{\hbar}{2\pi}, \]  
(A.6)

and
\[ S = \sqrt{S(S+1)} \frac{\hbar}{2\pi}. \]  
(A.7)

The boldface type indicates they are vector sums. The sums must be integral and in the case of spin momentum, if the number of spins is even then the sum is zero or integral but if the number of spins is odd, then the sum is half integral. Finally, the total orbital angular momentum \( J \) is:
\[ J = L + S, \]  
(A.8)

which has a quantum number \( J \) such that the vector sums as,
\[ J = \sqrt{J(J+1)} \frac{\hbar}{2\pi}, \]  
(A.9)

where \( J \) is integral if \( S \) is integral and \( J \) is half-integral is \( S \) is half-integral. The quantum numbers for \( J \) are then,
\[ J = L + S, L + S - 1, \ldots |L - S|. \]  
(A.10)

From the above equation when \( L \geq S \) there are \( 2S+1 \) different values of \( J \), or different values of total orbital angular momentum. Otherwise if \( L < S \) then there are \( 2L + 2 \) different values of total orbital angular momentum. It is these differences in energy possessed by each electronic state which give rise to the fine structure. Thus, the quantity, \( 2S+1 \) is important, and is called the multiplicity. The use of multiplicity makes for a convenient classification label because transitions between different multiplicities is forbidden according to Schrödinger’s equation. Thus, designating the multiplicity indicates immediately to which other levels a transitions may take place. However this is not entirely true, for a cross multiplet transition is well documented for calcium where a singlet-triplet transition occurs near 657 nm.

All the energy of the atom is accounted for, with the exception of the nucleus, and the state of the atom is defined using a term symbol:
\[ ^{2S+1}L_J, \]  
(A.11)

where the numerical subscript gives the total electronic-angular-momentum quantum number, and the superscript states the multiplicity. For hydrogen and the alkali metal atoms the letter
$I$ represents the orbital quantum number. The orbital quantum number takes on the letters $S$, $P$, $D$, $F$, ..., corresponding to the quantum numbers, $0$, $1$, $2$, $3$, .... The allowed transitions between energy states of an atom with multiple electrons are given by the selection rules (resulting from solving the Schrödinger equation) shown in table A.2.

The presence of nuclear spin contributes additional energy and angular momentum to an atom, and its quantization yields additional line splitting. The splitting is called hyperfine structure (HFS) because the splitting is much smaller than the fine splitting of the total orbital angular momentum. An additional quantum number is required to account for the angular momentum of the nucleus when nuclear spin is present, and its spin is quantized with $I$ such that,

$$I = \sqrt{I(I+1)} \frac{\hbar}{2\pi},$$

where $I$ may be zero, integral or half-integral, and the value is a physical property of a particular nucleus. This is in contrast to say, all electrons which which have spins of $\pm 1/2$.

The nuclear spin $I$ combines with $J$ to form the total angular momentum, which is given by their vector sum,

$$\mathbf{F} = \mathbf{J} + \mathbf{I},$$

where $\mathbf{F}$ is the total angular momentum of the atom. The coupling between the nuclear spin and the total orbital electronic angular momentum for the species considered in this work, follows the Russel-Saunders coupling approximation (Herzberg 1944; Bernath 1995). Thus, the quantum number $F$ can take values,

$$F = J + I, J + I - 1, \ldots |J - I|.$$

Physically, the magnetic moment of the nucleus produces a precession of $\mathbf{J}$ about the total angular momentum (F) axis. Because the magnetic moment of the nucleus is approximately 2000 times smaller than that of the electron, the resulting precession is much slower, and corresponds to similarly smaller scaled energy differences.

A non-standard addition to the term symbol shown in equation A.11, will be the quantum number $F$ in the superscript position shown below:

$$^2S+1 F^I \frac{P}{L},$$

to completely define the energy state of the atom.

When considering isotopes an additional effect due to the presence of different numbers of neutrons in the nucleus is sometimes referred to as splitting because it is associated with slight

---

1 Not to be confused with the total orbital angular momentum, $\mathbf{J}$
changes in the levels of angular momenta. It is properly classified as an isotope shift (Shevelko 1977) and is related to the mass and size of the atomic nucleus. The angular momentum of an electronic state has a definite fixed value which is defined by quantum mechanics as $P$ and for a classical rotator the momentum is (Banwell 1983),

$$P = \sqrt{2EI},$$

where, $I$ is the moment of inertia of the rotator, so if the mass of the atomic nucleus is changed, by substituting one isotope for another, the energy of the level will have to change so that the angular momentum can remain the same. This change in energy is called the mass shift.

The isotope shift is sometimes referred to as a volume shift in the literature because the energy of an electronic state depends on the nucleus spacial distribution of the electrical charge (Sobelman 1979). There is an adjustment of the charge distribution associated with an addition or subtraction of a neutron which contributes to the electric field and thereby affects the electronic energy levels. A change in the levels arising from differences in the field is called a field shift. The respective shifts of these two effects are opposite to another (Shevelko 1977) and to a good approximation, the total isotope shift is a linear superposition of the two.

Two additional effects can further complicate the atomic spectrum. They are the Zeeman Effect and the Stark Effect. They become apparent when there are externally applied magnetic (Zeeman) and electric fields (Stark) present. However since no applied or natural fields were present these phenomena are not accounted for in the modeling of atomic spectra.

Taking into account the interaction of the electrons with the angular momentum of the nucleus, leads to the hyperfine splitting of the fine split transitions. For example, the potassium transition near 770 nm ($D_1$) is from the ground state $^2S_{1/2}$ to the first excited state $^2P_{1/2}$. Both states are split into two finer levels $F = 1$ and $F = 2$ according to equation A.14. The additional splitting is referred to as hyperfine splitting (HFS). The quantum numbers $J, I$, and $F$ are sufficient to calculate the extent of the splitting with respect to the energy level of the fine split, $E_J$.

The total energy of an atomic level is approximated as the sum of:

$$E_F = E_J + E_{Dipole} + E_{Quadrupole}$$

(A.17)
where \( E_J \) is the energy of the level unperturbed by the nuclear spin, \( E_{Dipole} \) is the interaction energy for the system electrons-nuclear dipole moment, and \( E_{Quadrupole} \) is the interaction energy for the system electrons-nuclear quadrupole moment,

\[
E_{Dipole} = \frac{h}{2} \kappa
\]

\[
E_{Quadrupole} = \frac{3h}{8} B \kappa \frac{(k + 1) - 4/3(I(I + 1)J(J + 2))}{I(2I - 1)J(2J - 1)} \quad I, J \geq 1,
\]

where \( \kappa \) is computed from,

\[
\kappa = F(F + 1) - I(I + 1) - J(J + 1).
\]

The constants \( A \) and \( B \) are the hyperfine splitting constants of the atomic energy levels. The quadrupole interaction constant \( B \) is zero for states where \( J \leq 1/2 \) due to the spherical symmetry of the charge distribution. In fact, rather than give values for \( A \) in these cases, some tabulations will simply report the amount of the split (Radzig and Smirnov 1985).

Table A.3 illustrates the values of the constants used in generating the positions of the hyperfine split lines. By applying the equations A.18 to A.20 one can calculate the energy displacement of the hyperfine split level with respect to the fine split level.

Calcium which is a potential spectroscopic tracer, possessed no nuclear spin thus no hyperfine splitting calculations are necessary. However, it does have two naturally present isotopes, and the ground energy state of the less abundant isotope lies 995 MHz below the more prevalent one (Röhe-Hansen and Hellvig 1992).

### A.2 Strengths of Atomic Electronic Transitions

The strengths and positions of atomic lines can be found in large compilations as in Wiese et al. (1969) with about \( \pm 5\% \) accuracy. However, more accurate/recent measurements and \textit{ab initio} calculations can be found for the individual species in the literature. For example, the efforts in this work concentrated on the potassium \( 4^2 S_{1/2} \rightarrow 2^2 P_{3/2} \) transition and some line strength results (in terms of oscillator strengths) are shown in table A.4.

In the literature, most data for atomic line strengths are tabulated as the oscillator strength as shown in table A.4. A conversion is developed below in equation A.24 which converts the oscillator strength to a line strength with units cm\(^{-2}\)/atm.

The relation between the line strength and the oscillator strength can be expressed as (Hanson and Webber 1998; Lucht 1978)

\[
S_{12} \text{[cm}^{-1}\text{s}^{-1}] = \frac{\pi e^2 m_e}{m_e c} n_{f1} n_{i2} \left( 1 - \exp \left( \frac{-h \nu_0}{k T} \right) \right).
\]
TABLE A.3  Hyperfine splitting and isotope data for candidate spectroscopic tracers. I is the nuclear spin quantum number.

<table>
<thead>
<tr>
<th>Species</th>
<th>Mass No</th>
<th>Natural Abnd. [%]</th>
<th>I</th>
<th>Magnetic Dipole [MHz]</th>
<th>Nuclear Q-pole [MHz]</th>
<th>$\Delta E^2 S_{1/2}$ [cm⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>6</td>
<td>7.59</td>
<td>1</td>
<td>125.136814 17.375 -1.155 -0.1</td>
<td>0.625</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>92.41</td>
<td>3/2</td>
<td>401.752043 45.91 -3.055 -0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>39</td>
<td>93.2581</td>
<td>3/2</td>
<td>230.85986 27.8 6.13 2.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>41</td>
<td>6.7302</td>
<td>3/2</td>
<td>127.00694 15.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rb</td>
<td>85</td>
<td>72.17</td>
<td>5/2</td>
<td>1011.911 120.7 25.0 26.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>87</td>
<td>27.83</td>
<td>3/2</td>
<td>3417.3413 400 84.9 12.6 -0.00534</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Natural abundance data is by atom (IUPAC 1989)

$\Delta E$ is the energy difference with respect to the predominant isotope (Radzig and Smirnov 1985)

Magnetic and nuclear splitting data for Li and $^{39}$K is from Sher et al. 1996

Magnetic and nuclear splitting data for $^{41}$K and Rb is from Radzig and Smirnov 1985

TABLE A.4  Potassium (D₁) oscillator strength ($f_{12}$) measurements

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$f_{12}$</th>
<th>±Δ%</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Wiese et al. 1969)</td>
<td>0.339</td>
<td>5</td>
<td>1969</td>
</tr>
<tr>
<td>(Shabanova and Khlystalov 1985)</td>
<td>0.324</td>
<td>3</td>
<td>1985</td>
</tr>
<tr>
<td>(Volz and Schmoranzer 1996)</td>
<td>0.332</td>
<td>0.2</td>
<td>1996</td>
</tr>
</tbody>
</table>

In the case of potassium, $\nu_e = 12984$ cm⁻¹ and

$$\exp\left(\frac{-h\nu_e}{kT}\right) < 2.6 \times 10^{-12}, \quad 300 \text{ K} < T < 1200 \text{ K},$$

thus:

$$S_{12} [\text{cm}^{-1}\text{s}^{-1}] = \frac{\pi e^2}{m_e c} n_1 f_{12}. \quad (A.22)$$

To convert the line strength shown in equation A.22 to the units, cm⁻²/atm at a reference temperature of 296 K, requires dividing equation A.22 by the speed of light and 1 atmosphere:

$$S_{12} [\text{cm}^{-1}\text{s}^{-1}] = \frac{\pi e^2}{m_e c} \frac{n_1 f_{12}}{P \text{[atm]}}. \quad (A.23)$$
where:
\[
\frac{\pi e^2}{m_e c} = 0.0265 \text{ cm}^2 \text{s}^{-1},
\]
\[
n_1 = \frac{P}{kT},
\]
\[
= \frac{P[\text{atm}] 101325 N/m^2}{1.3805 \times 10^{-23} \frac{J}{K \cdot m^2}} \frac{3}{296[K]} \frac{1 \text{m}^3}{(100 \text{cm})^3}
\]
\[
= P[\text{atm}] 2.481 \times 10^{13} \text{ cm}^{-3}/\text{atm}.
\]
Substituting the above into A.23 yields:
\[
S_{12} [\text{cm}^2/\text{atm}] = 0.0265 \text{ cm}^2 \text{s}^{-1} \frac{P[\text{atm}] 2.481 \times 10^{13} [\text{cm}^{-3}/\text{atm}]}{e P[\text{atm}]} f_{12}.
\]
Simplifying yields,
\[
S_{12} (T = 296 \text{ K}) = 2.193 \times 10^7 f_{12} \text{ [cm}^{-2}/\text{atm}]. \tag{A.24}
\]

The literature presents line strengths for an atom that are measured or calculated for the fine splitting (considering only changes in total orbital angular momentum \(\Delta L = 1\)). Proper use of these data, requires consideration to the presence of isotopes and hyperfine splitting due to nuclear spin. In the case of an isotope, because the line strength is an electronic property, the line strength of in each isotope is identical. However, the presence of the target species is assumed to be in proportion to the natural abundance (by atom percentage), in turn the line strength is apportioned by the natural abundance as given in the commission on atomic weights and isotopic abundances report (IUPAC 1989).

The relative intensities of the separate hyperfine-split lines are determined by quantum-mechanical sum rules as derived by Dirac and reported in White (1934, pg. 206). The sum rules are presented below in a slightly different form than presented in White (1934). The equations have been modified so as to be applied to hyperfine splitting. This is done by replacing the quantum numbers: \(S\) by \(I\), \(L\) by \(J\) and \(J\) by \(F\). Additionally, corrections for temperature and \(\nu^4\) dependence are not necessary for hyperfine structure (White and Elliaison 1933) and so their functionality has been eliminated.

The possible summation rules to calculate the relative intensity, \(Y_i\), for a hyperfine transition is shown below. For \(J \to J\) transitions,
\[
(J + F + I + 1) (J + F - I) (J + F - I) (J - F - I) \frac{F}{F}
\]
\[
= \frac{[J(J + 1) + F(F + 1) - I(I + 1)]^2 (2F + 1)}{F(F + 1)}
\]
\[
- \frac{(J + F + I + 2)(J + F - I + 1)(J - F + I)(J - F - I - 1)}{2F + 1}
\]
\[
\text{for } F \to F; \tag{A.25}
\]
\[
\text{for } F - 1 \to F; \tag{A.26}
\]
\[
\text{for } F + 1 \to F; \tag{A.27}
\]
and for $J - 1 \rightarrow J$ transitions, the partial strengths are

\[
\frac{(J + F + I + 1)(J + F + I)F}{(J + F - I)(J + F - I - 1)} \quad \text{for } F - 1 \rightarrow F,
\]

\[
- \frac{(J + F + I + 1)(J + F - I)(J - F + I)(J - F + I - 1)(2F + 1)}{F(F + 1)} \quad \text{for } F \rightarrow F,
\]

\[
\frac{(J - F + I)(J - F + I - 1)(J - F + I - 2)}{F + 1} \quad \text{for } F + 1 \rightarrow F,
\]

(A.28) \hspace{2cm} (A.29) \hspace{2cm} (A.30)

An HFS line strength ($S_l$) is determined by multiplying the line strength for the fine split by the ratio of the relative intensity for an HFS line to the sum of relative intensities for all allowed HFS lines for the given fine split transition,

\[
S_l = S_{12} \frac{T_i}{\sum_j T_j},
\]

(A.31)

where $S_{12}$ is the line strength for the fine split transition, and $j$ represents each of the allowed HFS transitions. Note, the index $j$ includes $i$.

A number of atomic ground state transitions were considered as potential atomic tracers in hypervelocity flows. The influence of isotopes and nuclear spin was considered when constructing a species spectroscopy in order to evaluate a species’ potential as a tracer species. The results of the analysis are shown in 3.4.1.

### A.3 Strengths and Positions of Molecular Transitions

Water is the molecular species of direct interest in this research. The relatively simple structure of the molecule fails to portend the complicated spectra of the many lines that exist. To understand the line positions a brief outline of the properties and quantum-mechanical description of rotating-vibrating oscillator is presented.

The line positions of a rotational-vibrational (rotvibrational) transitions are a result of a combinational transition between energy states. The energy states involve internal energy modes of vibration and rotation. A schematic illustrating the energy levels of a simple diatomic molecule (e.g. carbon monoxide) is shown in figure A.1. The schematic serves to illustrate the large spacing between the vibrational energy levels when compared to rotational energy levels. The quantum numbers $v$ and $J$ are vibrational and rotational modes respectively. The energy levels of both the rotational and vibrational levels are obtained from solutions to the time independent Schrödinger equation for an anharmonic oscillator (vibration) and a non-rigid rotator (rotational-angular momentum). Furthermore, selection rules are obtained for specifying the changes in $v$
and $J$. These rules prescribe all the possible energy changes for a transition but are dependent on the molecular structure and the classical model used.

A complication arises when considering the vibrational spectra of a polyatomic molecule; there can be multiple modes of vibration. For a non-linear molecule with N atoms, 3N-6 fundamental vibrations exist (e.g., 3 vibrations for water). Each mode is infrared active for a dipole change during vibration, and the changes may take place along the line of symmetry axis (parallel) or at right angles to it (perpendicular). These modes are identified in figure A.2 for water vapor.

The selection rules for an anharmonic oscillator allow for incremental changes in $v$ greater than or equal to 1. Changes greater than 1 are called overtones. Furthermore, combinations of the different modes are permitted and these may form sum or difference combinations. For example, transitions in this work were selected from the $v_1 + v_3$ band; the denotation for vibrational state is 101. A detailed discussion of vibrational transitions can be found in Herzberg (1991).

The rotational spectra of water vapor is complicated because water is an asymmetric top. That is, it has three unique moments of inertia as shown in figure A.3. The most common method of analysis for this type of molecule is to consider the asymmetric top as falling somewhere between the oblate and prolate symmetric top (Banwell 1983). For the case of the symmetric top, the quantization of the angular momentum yields two quantum numbers, $J$ and $K$. $J$ represents
the total angular momentum of the molecule and $K$ serves to quantify the contribution from angular momentum about the minor axis. Extending the same idea to an asymmetric top yields an additional quantum number for the angular momentum about the remaining minor axis. The end result is three quantum numbers $J$, $K_a$, and $K_c$. The rotational-state denotation is $J_{K_a K_c}$. For an extensive analysis of the ideas applied to an asymmetric top consult Zare (1988) (Ch. 6). The resulting selection rules are shown in Table A.5.

TABLE A.5 Selection rules for rotational-vibrational energy transitions in an anharmonic, polyatomic, asymmetric top molecule.

\[
\begin{align*}
\Delta v_i &= 0, \pm 1, \pm 2 \ldots \\
\Delta J &= 0, \pm 1 \\
\Delta K_a &= 0, \pm 1, \pm 2, \ldots \\
\Delta K_c &= 0, \pm 1, \pm 2, \ldots
\end{align*}
\]

A complicated spectra is a result of all the various permutations of these rules. Fortunately, extensive tabulations of spectroscopic data for water vapor are available. The tables used in this work were the HITRAN molecular data base (Rothman et al. 1992) and a set of results from measurements of line positions and strengths of water vapor by Toth (1994). Past experience in this laboratory (Langlois et al. 1994) has revealed the line strengths and positions of Toth (1994) to be more reliable and the HITRAN data base is useful for obtaining the lower state energy of the transitions.

The value of lower state energy is important in determining the change in linestrength of a given line to temperature as in equation 3.16. Furthermore, the lower state energy is important when calculating the temperature from the ratio of the absorbances of two different transitions as in equation 3.17.
FIGURE A.3 The 104.5 bond angle prompts the classification of water as an asymmetric top.
Appendix B

Tuning Rate Broadening

Tuning-rate broadening (TRB) is similar to the more common transit-time broadening (TTB) mechanism which results from the finite interaction time between molecules and laser radiation as molecules pass through a laser beam via their bulk gas velocity. An analysis of the TRB broadening mechanism is presented below.

Consider the situation where a laser (with spectral width $\Delta f_\lambda$) scans through a predominantly Doppler broadened lineshape as shown in figure B.1. Molecules located in the beam have a transition at $f_\lambda$, however due to the presence of a Maxwellian velocity distribution, there are molecules in a velocity class with a discrete transition at $f_d$. As the laser scans, the molecules in a velocity class experience a time dependent radiation intensity that is a function of the laser scan rate. If the laser is scanning rapidly, the interaction time is short and additional broadening called tuning-rate broadening (TRB) can occur in an analogous fashion to TTB.

B.1 TRB Lineshape

A derivation of the lineshape generated by the laser tuning-rate is developed following the procedure outlined by Demtröder (1996, pg. 84) for transit-time broadening. When a laser is tuned at a constant rate, the transfer function between light-frequency space and time space is:

$$f - f_d = a (t - t_d), \quad (B.1)$$

where $a$ is the line-center tuning rate [Hz/s]. The laser’s spectral intensity distribution is modeled as a Lorentzian:

$$\phi(f) = \frac{1}{2\pi} \frac{\Delta f_\lambda}{(f - f_\lambda)^2 + \left(\frac{\Delta f_\lambda}{2}\right)^2}. \quad (B.2)$$
FIGURE B.1 A schematic of the time/frequency relationship for tuning-rate broadening is shown. The position of a laser which is scanning from left to right at a tuning rate $\alpha$ [Hz/s] towards a transition, has its line center at $\nu_0$. 
However, from the perspective of the particular velocity class, \( f_L \) becomes \( f_d \) and equation B.2 becomes a function of time,
\[
\phi(f_d(t)) = \phi(t) = \frac{1}{2\pi^2 \alpha} \frac{\Delta f_L/\alpha}{(t - t_d)^2 + \Delta f_L/\alpha^2},
\]
where \( \Delta f_L/\alpha \) is the laser’s full width at half maximum in time-space. Neglecting natural decay processes, the oscillator amplitude \( g(t) \), at frequency \( f_d \) is proportional to the laser’s intensity:
\[
g(t) = \phi(t) \cos(2\pi f_d t),
\]
and the frequency spectrum is obtained from the Fourier transform,
\[
G(f) = \text{FT} g(t) = \int_{-\infty}^{+\infty} g(t) \exp(-i2\pi f t) \, dt.
\]
To apply the transform, let \( t_d = 0 \) (because the integral is over all time), and use the modulation theorem (Bracewell 1986, pg. 122):
\[
\text{FT} f(x) \cos(2\pi s_o x) = \frac{1}{2} \left[ F(s - s_o) + F(s + s_o) \right],
\]
and the transform pair (Bracewell 1986, pg. 418):
\[
\exp(-a|x|) \supset \frac{2a}{(2\pi a)^2 + a^2}.
\]
The power spectral intensity \( I = G^2 \), for \( |f - f_d| < f_d \), is,
\[
I(f) = \frac{1}{4\alpha^2} \exp\left(\frac{2\pi \Delta f_L}{\alpha} |f - f_d|\right).
\]
The lineshape function resulting from rapidly tuning the laser is obtained from the definition:
\[
1 = C_o \int_{-\infty}^{+\infty} I(f) \, df,
\]
where \( C_o = 4\pi \Delta f_L \alpha \) satisfies equation B.9 and yields the lineshape function in wavenumber space:
\[
\phi_{\text{TRB}}(\nu) = \frac{\pi \Delta \nu_L}{\alpha/c} \exp\left(-\frac{2\pi \Delta \nu_L}{\alpha/c} |\nu - \nu_o|\right),
\]

### B.2 TRB Linewidth

The extent of TRB, like all broadening mechanisms, is characterized by the FWHM of the resulting lineshape:
\[
\Delta \nu_{\text{TRB}} = \ln2 \frac{\alpha/c}{\pi \Delta \nu_L} \text{ [cm}^{-1}\].
\]
An interesting symmetry property is realized by applying the Heisenberg uncertainty principle, as done for natural broadening in section 3.3, to TRB. The Heisenberg uncertainty principle is repeated below:

$$\Delta E \geq \frac{\hbar}{2\pi} \frac{1}{\Delta t}$$  \hspace{1cm} (3.25)

The characteristic time ($\Delta t$) the laser spends at any given frequency is equal to $\Delta \nu \cdot \kappa$ thus, dividing equation 3.25 through by $\hbar \kappa$ yields:

$$\Delta \nu_{\text{FWHM}} = \frac{a/c}{2\pi \Delta \nu_{\kappa}} \text{ [cm}^{-1}] .$$  \hspace{1cm} (B.12)

This value is not equal to the value in equation B.11, however it is equal to the 1/e halfwidth of equation B.10. This is expected as there is a symmetry between the calculation for natural broadening width and TRB. The relationship between equations B.11 and B.12 is shown graphically in figure B.2. When the Heisenberg uncertainty principle is applied to the measured 1/e lifetime of a decaying radiative transition, the principle yields the FWHM of a Lorentzian in light frequency space. Likewise, in the case of TRB, the FWHM of the Lorentzian laser in time space yields the 1/e halfwidth in light frequency space.

### B.3 Example Lineshape

In these experiments the Fabry-Perot and the DFB laser linewidths were approximately 100- and 10-MHz respectively. Each were tuned over 1 cm$^{-1}$ at 33 kHz. Neglecting all other broadening mechanisms, an example lineshape produced by tuning the Fabry-Perot laser is shown in figure B.3. TRB is negligible with respect to the Doppler width encountered in this thesis (0.02 $< \Delta \nu_D < 0.04$ [cm$^{-1}$]). However, by increasing the scanning rate by a factor of 10 and simultaneously reducing the width of the laser by a factor of 100, tuning rate broadening could become an issue.
Radiative Lifetime
\[ C_0 \exp\left(-\frac{1}{\tau} t\right) \]

\[ I_0 / e \]

\[ \tau \]

\[ t \]

\[ \alpha = \delta v_t / \delta t \]

\[ \Delta v_t = \Delta v_L / \alpha \]

Lorentzian Lineshape

\[ \Delta v_{\text{FWHM}} \]

TRB LineShape

\[ C_0 \exp\left(-1/\Delta v_{1/e} |v-v_0|\right) \]

\[ \frac{1}{2} \Delta v_{1/e} \]

**FIGURE B.2** A schematic of the time/frequency relationship between natural (top) and tuning-rate broadening (bottom). The power spectral density (PSD) of the Fourier transform yields the lineshape function.
B.3. **EXAMPLE LINESHAPE**

\[ \phi(\nu) = \frac{\Delta \nu}{\alpha} \exp\left(\frac{2\pi \Delta \nu}{\alpha} |\nu - \nu_0|\right) \]

\[ \Delta \nu_L = 100 \text{ MHz} \]
\[ \alpha = 1 \text{ cm}^{-1} (1/33 \text{ kHz}) \]
\[ = 990 \text{ THz/s} \]

\[ \Delta \nu_{\text{TRB}} = 0.0000728 \text{ cm}^{-1} \]

**FIGURE B.3** A calculated lineshape considering tuning-rate broadening using the parameters from a Fabry-Perot AlGaAs tunable-diode laser.
Appendix C

Power Broadening

The action of a laser tuned to a wavelength which is resonant with a difference in energy levels $(\Delta E/\hbar)$ increases the number density associated with the upper energy level through absorption. In section 3.2 a detailed radiation balance for a two-level model yielded the absorption coefficient in equation C.1,

$$-k_{\nu} = h\nu\phi(\nu)(n_2 B_{21} - n_1 B_{12}),$$  \hspace{1cm} (C.1)

where the subscript $\nu$ on $k$ and $\phi(\nu)$ on the right-hand side are included to account for the distribution of absorption about $\nu$. Subsequent development was based on the assumption of local thermodynamic equilibrium (LTE) which permitted one to neglect the upper-state population. However, if the laser strength is intense (large photon flux density, Hz/cm²), relative to the ability for natural processes (spontaneous emission and collision) to repopulate the lower state, the upper state becomes significantly populated.

In an absorption measurement, when the upper state is significantly populated, stimulated emission becomes an issue, and the detector is unable to discriminate between incident photons or photons resulting from stimulated emission. As a result the measured absorption is reduced and the lineshape differs from one predicted considering the effects listed in section 3.3. Equation C.1 is further developed in this appendix, considering the effects of a finitely populated upper-state on lineshape.

C.1 Saturated Absorbance

The process of saturation is the population of the upper state. To aid in the analysis, the number density of the target species in each state is written in terms of the total number of
C.2. POPULATION RATIO

atoms, \( n_\tau \), originally in the lower state,

\[
n_\tau = n_1 + n_2. \tag{C.2}
\]

The goal will be to find a function \( F \) (called the population ratio) which is a function of the laser intensity and describes the ratio of the number density in the upper state to that in the lower state,

\[
F = \frac{n_2}{n_1}. \tag{C.3}
\]

Thus, the populations in each of the states can be found in terms of \( F \) and \( n_\tau \),

\[
n_1 = \frac{n_\tau}{1 + F}, \tag{C.4}
\]

\[
n_2 = n_\tau \frac{F}{1 + F}. \tag{C.5}
\]

Equations C.4 and C.5 can be used with the relation, \( g_2 B_{21} = g_1 B_{12} \) in equation C.1 to rewrite it as,

\[
-k_\nu = \hbar \nu_\nu B_{12} n_\tau \phi(\nu) \left[ \frac{F - 1}{1 + F} \right], \tag{C.6}
\]

or in differential form analogous to equation 3.9,

\[
\frac{1}{L_{\nu, x}} \frac{dI_{\nu, x}}{dx} = \hbar \nu_\nu B_{12} n_\tau \phi(\nu) \left[ \frac{F - 1}{1 + F} \right]. \tag{C.7}
\]

C.2 Population Ratio

The population ratio is an expression for the number density ratio in the upper and lower states in terms of the laser frequency and laser intensity. Baer (1993) expressed a relation for \( F \),

\[
F = \left( \frac{4 \ln 2}{\pi} \right)^{1/2} \frac{1}{\Delta \nu_{\omega, \omega}} \frac{B_{12}/c}{A_{21} + Q} \left( 1 - \exp \left(-\frac{\hbar \nu_\nu}{kT}\right) \right) \sqrt{\frac{L_0}{1 + L_0/I_{5at}}} V(a_s, D), \tag{C.8}
\]

where \( \Delta \nu_{\omega, \omega} \) is the sum of the Lorentzian broadening widths, \( Q \) is the collisional quenching rate which is proportional to the collision frequency of the target species with all other molecules. \( V \) is the standard Voigt function where \( a_s \) is a modified Voigt-a parameter:

\[
a_s = a_s \sqrt{1 + I_L/I_{5at}}, \quad a_s = \sqrt{\ln 2} \frac{\Delta \nu_{\omega, \omega}}{\Delta \nu_{\omega}}, \quad D = 2 \sqrt{\ln 2} \frac{\nu - \nu_\nu}{\Delta \nu_{\omega}}.
\]
Additionally, $I_s$ is the instantaneous laser power (at frequency $\nu_c$) while $I_{sat}$ is a specific laser intensity defined (Yariv 1989, pg. 180) as,

\[
I_{sat} = \frac{\pi c}{2} (\Delta \nu_{sat} c) A_{21} + \frac{Q}{\nu_c} \frac{g_2}{g_1 + g_2},
\]

(C.9)

where $\Delta \nu_{sat} c$ is the sum of all the Lorentzian broadening mechanisms. With some manipulation the population ratio can be re-written in terms of the ratio of the laser intensity to saturation intensity, called the saturation intensity ratio,

\[
F = a_s \sqrt{\frac{I_s}{I_{sat}}} \frac{1 - \exp \left( -\frac{\nu_c}{K T} \right)}{\sqrt{1 + \frac{I_s}{I_{sat}}}} \exp \left( \frac{g_2}{g_1 + g_2} \right).
\]

(C.10)

Note, $F$ goes to zero as the saturation intensity ratio goes to zero (i.e. a weakly perturbing laser) and the absorption coefficient reduces to the former linear form.

Dividing the equation C.7 by the constant $I_{sat}$ gives,

\[
\frac{1}{I_{sat} / I_{sat}} \frac{dI_{\nu, s}/I_{sat}}{dx} = h \nu_c B_{12} n_{g} \phi(\nu) \left[ \frac{F (I_{\nu, s}/I_{sat}) - 1}{1 + F (I_{\nu, s}/I_{sat})} \right],
\]

(C.11)

a non-linear differential equation which can be numerically integrated along an absorbing path. Note, $I_s$ is replaced by $I_{\nu, s}$ to reflect the spectral dependence of the laser’s transmitted intensity when integrating the equation along a path. The spectral dependence is brought about because more absorption occurs near line center than in the wings thereby changing the saturation intensity ratio with spectral position. Furthermore, after integrating through the pathlength, the solution, $I_{\nu, s}/I_{sat}$ can be divided by the initial saturation intensity ratio, $I_{\nu, s}/I_{sat}$, to yield the absorption, $I_{\nu, s}/I_s$. The calculated absorption can be used to determine the effect of saturation on the resulting absorbance and compared to the linear line shape function.

### C.3 Estimation of $I_{sat}$

To calculate a value for $I_{sat}$, some of the parameters in equation C.9 need to be estimated. Values for, $B_{12}$, $A_{21}$, $\Delta \nu_{sat}$ are functions of the oscillator strength as found from the following relations (Hanson and Webber 1998) where $1 - \exp(-h\nu_c/K T) \ll 1$:

\[
B_{12} = \frac{\pi c^2}{m_e c} f_{12} \frac{1}{h\nu_c^2},
\]

(C.12)

\[
A_{21} = \frac{\pi c^2}{m_e c^2} 8\pi \nu^2 f_{12},
\]

(C.13)

\[
\Delta \nu_{sat} = \frac{1}{2\pi c} \sum_k (A_{2k} + A_{1k}),
\]

(C.14)
where \( \pi e^2/m_e c \) is 0.0265 \( \text{cm}^2\text{Hz} \) and the degeneracy in the upper and lower states is equal and where \( k \) (in equation C.14) are states less than level 1 and 2. The relations in equations C.12 to C.14 are substituted into C.9 yielding:

\[
I_{\text{sat}} = \frac{\pi e^2}{2} \left( C_1 f_{12} + \Delta \nu_{\text{sat}} \right) \frac{C_2 f_{12} + Q}{C_3 f_{12}},
\]

where \( C_i \) are coefficients for \( f_{12} \) which absorb all the constants. The behavior for \( I_{\text{sat}} \) is shown in figure C.1. For strong atomic-electronic transitions (large \( f_{12} \)) such as potassium, \( I_{\text{sat}} \), increases linearly with oscillator strength. However for much weaker transitions (small \( f_{12} \)), such as water vapor, values for \( I_{\text{sat}} \) are very large power broadening is very rarely an issue. For potassium,

\[
I_{\text{sat}} = \frac{\pi e^2}{2} \left( C_1 f_{12} + \Delta \nu_{\text{sat}} \right) \frac{C_2 f_{12} + Q}{C_3 f_{12}}
\]

**FIGURE C.1** A plot illustrating the dependence of \( I_{\text{sat}} \) on the oscillator strength. For weak rovibrational transitions, the saturation intensity is very high. As the oscillator strength increases the saturation intensity reduces but then increases again for very large oscillator strengths as in potassium.

\( f_{12} = 0.332 \) (Volz and Schiemanzer 1996):

\[
B_{12} = 1.023 \times 10^{37} \left[ \frac{\text{cm}^3\text{Hz molecule}}{\text{Js}} \right]
\]

\( A_{21} = 37.3 \) [MHz]

\( \Delta \nu_{\text{sat}} = 0.000196 \) [cm\(^{-1}\)]

The collisional quenching rate \( (Q) \) is estimated to be equal to the collisional frequency between potassium and all other species which is expressed as (Vincenti and Kruger 1986, pg. 54):

\[
Q = \sqrt{8 \pi K T n_{N_2} d_{K N_2}} \sqrt{\frac{1}{m_K} - \frac{1}{m_{N_2}}}
\]
where \( m \) is the mass of the species in kg. For a temperature and pressure of 650 K and 3 torr respectively the collisional quenching rate is approximated to be 11.1 MHz.

The remaining necessary term to examine is the homogeneous broadening contribution from collisions. Collisions with oxygen and water vapor are neglected so the collisional width becomes:

\[
\Delta \nu_{\text{coll}} = P \frac{2\gamma_{\text{N}_2}}{T}.
\]  \hspace{1cm} (C.17)

Because only nitrogen collisions are considered, the \( \text{N}_2 \) subscript is dropped and the temperature dependence for of the collisional broadening is,

\[
2\gamma = 2\gamma_0 \left( \frac{T_0}{T} \right)^x,
\]  \hspace{1cm} (C.18)

where \( T_0 \) and \( 2\gamma_0 \) are the reference values for temperature and broadening, and \( x \) is classically 1/2. Values for \( 2\gamma_0 \) are well documented for potassium/noble-gas collision partners however this is not true for other gas species. Figure C.2 shows the available data for nitrogen/potassium broadening data. A curve fit through the data yields an estimate for \( \gamma \) as 0.0017 ± 0.0007 cm\(^{-1}\)/atm.

![Figure C.2](image-url)  \hspace{1cm} FIGURE C.2  A plot of the estimated \( \gamma \) for \( \text{N}_2\)-K collisions versus temperature from various sources in the literature.

Substituting the various parameters into equation C.9 yields an estimate for \( I_{\text{sat}} = 0.65 \pm 0.22 \text{ mW/mm}^2 \) at 600 K and 3 torr of \( \text{N}_2 \).

### C.4 Estimation of \( I_0 \)

Because there is a power distribution across the beam diameter only the most intense portion of a beam will cause power broadening effects. For a laser operating in the fundamental
C.5 Lineshape Distortion

In the transverse mode, the power distribution is Gaussian and only the center portion of the beam will cause saturation. Below describes how the measurement of the beam diameter yields an estimate of the maximum laser intensity in the experiments.

The power distribution in a Gaussian beam is described by the following relation:

\[ I(x, y) = \frac{2P_0}{\pi r_0^2} \exp \left( -\frac{x^2 + y^2}{r_0^2} \right) \]  \hspace{1cm} (C.19)

where \( P_0 \) is the total power [W], \( 2P_0/\pi r_0^2 \) is the maximum intensity at beam center [W/area], and \( r_0 \) is the \( 1/e^2 \) beam radius. The process of passing a knife edge across the beam cross section through the (arbitrarily defined) x-axis of the beam yields an equation for the power reaching the detector as a function of x:

\[ P(x) = \int_{-\infty}^{\infty} \frac{2P_0}{\pi r_0^2} \left( \int_{-\infty}^{\infty} \frac{1}{r_0^2} \exp \left( -\frac{2y^2}{r_0^2} \right) dy \right) \exp \left( -\frac{2x^2}{r_0^2} \right) dx \]  \hspace{1cm} (C.20)

After integration, the transmitted power, normalized by the total laser power is:

\[ \frac{P(x)}{P_0} = \frac{1}{2} \text{erfc} \left( \frac{\sqrt{2}x}{r_0} \right) \]  \hspace{1cm} (C.21)

A plot of the normalized power verses the translation position of a knife edge across the beam diameter is shown in figure C.3 and a fit to the data using equation C.21 gives a beam diameter of 0.229 mm. The average laser power used in the Calspan experiments was 25 \( \mu \)W. Thus, the maximum intensity, or \( I_0 \) from equation C.19 is 0.30 mW/mm\(^2\) giving a saturation intensity ratio of 0.5.

C.5 Lineshape Distortion

The saturation intensity ratio is approximately 0.5 and equation C.11 is integrated across the pathlength encountered in the Calspan experiments, 3.6 cm, to determine the effect of power broadening on a predominantly Doppler broadened lineshape. Figure C.4 shows the calculated absorbance for four different saturation intensity ratios, including 0.5. The linear absorbance is shown for comparison to a weakly probing laser. As the laser intensity increases, the absorbance does not extend beyond the linear case, instead, due to the bleaching effect of populating the upper state (stimulated emission), the absorbance profile is flattened and the width (FWHM) increases.

For the purposes of velocity measurements, an average laser intensity of 1/2 the saturation intensity has little effect on the ability to measure velocity. However, this numerical analysis shows that a kinetic temperature inferred from a power-broadened lineshape is accurate to within 1\% for an intensity ratio less than 1/20 for the conditions at Calspan.
FIGURE C.3 A plot of the normalized laser power as a knife edge is translated (x-direction) across the beam diameter. Also shown is a fit to the measured data where the 1/e beam diameter is 0.229 mm.

FIGURE C.4 A plot of the calculated absorbance illustrating the effect of increase saturation intensity on the lineshape.
Appendix D

Choice of Optimal Beam Angle

When choosing the angle for the beam used to measure Doppler shift, a number of factors have to be weighed: the size of the probe, the accuracy of the velocity measurement and the power loss through the optical train.

The beam angle's effect on the size of the probe is made clear by examining the Doppler equation from section 3.1,

$$\Delta \nu_{\text{vel}} = \frac{V_{\text{gas}} \cos \theta}{c} \nu_0.$$  \hspace{1cm} (3.4)

A reduced inclination angle $\theta$, increases the Doppler shift and reduces the measurement error in light-frequency space. As a consequence, the probe length increases to accommodate the beam. Furthermore, the increase in length requires an increase in the probe width. By examining the side views in figures 5.10 and 5.29, the leading Mach wave, which defines an enveloped of undisturbed flow, must not be allowed to intersect the laser beam. Thus, as the length is increased to pitch and catch a reduced inclination angle ($\theta$), the width must increase to keep the leading edge effects from disturbing the beam path.

The measurement accuracy is also a factor. The sensitivity of the velocity measurement to inclination angle is illustrated after solving for the velocity in equation 3.4, taking the differential, and normalizing result by the bulk gas velocity,

$$\frac{\delta V_{\text{gas}}}{V_{\text{gas}}} = \frac{\delta \nu_{\text{vel}}}{\Delta \nu_{\text{vel}}} + \tan \theta \delta \theta.$$  \hspace{1cm} (D.1)

From equation D.1 the sensitivity of the velocity measurement is dependent on the uncertainty in the Doppler shift measurement ($\delta \Delta \nu_{\text{vel}}$). However the sensitivity is also dependent on the angle of the beam and, like equation 3.4, the trigonometric term also drives the angle to smaller values in the interest of increasing the Doppler shift. However, the accuracy of
the velocity measurement is linearly dependent on the angle measurement accuracy, \( \delta \theta \). From trigonometry, the tangent of the beam angle is simply the length between the probe legs (1) divided by the dimension along the leg between the beam pitch and catch windows (\( x \)),

\[
\theta = \tan^{-1} \frac{1}{x}. \tag{D.2}
\]

By taking the differential of equation D.2 one obtains:

\[
\delta \theta = \frac{x \delta l - 1 \delta x}{x^2 + 1^2}, \tag{D.3}
\]

and assuming the measurement accuracy for distance 1 is equal to \( x \) (\( \delta l = \delta x \)) the velocity uncertainty contribution from angle uncertainty in equation D.1 is:

\[
\frac{\delta V_{gas}}{V_{gas}}(\theta) = \frac{1}{x} \left( \frac{x - 1}{x^2 + 1^2} \right) \delta l. \tag{D.4}
\]

At 45°, \( l = x \) and the angle uncertainty contribution is minimized. As an example, during the water vapor measurements in the expansion tube, the distance between the probe legs, \( l \), was 0.750 ±0.001 in and \( x \) was 0.75 ± the measured beam diameter 0.229 mm or 0.01 in. Substitution of these values in equation D.3 gives the \( \delta \theta \) 0.7%. When using the larger water vapor probe (Mark I), the dimensions of the probe were large compared to the measurement uncertainty (\( x = 5.23 \pm 0.03 \) in, \( l = 7.004 \pm 0.02 \) in) and as a result equation D.3 gives a smaller contribution of 0.4%.

Another factor relating to the laser inclination angle is the loss of laser power at each surface. The Fresnel equations express the ratio of the reflected amplitudes for transverse electric (TE) and transverse magnetic (TM) polarization (Fowles 1975, pg. 43):

\[
r_s = \frac{\cos \phi - \sqrt{n^2 - \sin^2 \phi}}{\cos \phi + \sqrt{n^2 - \sin^2 \phi}}, \tag{D.5}
\]

\[
r_p = \frac{-n^2 \cos \phi + \sqrt{n^2 - \sin^2 \phi}}{n^2 \cos \phi + \sqrt{n^2 - \sin^2 \phi}}, \tag{D.6}
\]

where \( r_s \) and \( r_p \) are the reflected amplitude ratios for the TE and TM polarization respectively, and \( n \) is the ratio of index of refraction at the interface. That is \( n \geq 1.76 \) for an external reflection and \( n \geq 0.568 \) for an internal reflection. Note the index of refraction (\( n \)) for air is effectively unity and 1.76 for sapphire. \( \phi \) is the angle of incidence which is equal to 90 − \( \theta \), where \( \theta \) is the inclination angle. The average fraction of reflected energy is,

\[
\overline{R} = \frac{r_s^2 + r_p^2}{2}. \tag{D.7}
\]

Equation D.7 is plotted in figure D.1 as a function of the inclination angle (\( \theta \)) along with a schematic insert illustrating the laser propagation through a 3° wedge window. The impact of
the reflected losses accumulate as a beam must pass across 8 surfaces for the counter propagating probe design in sections 5.4 and 5.5. Thus, a 45° angle beam suffers 52% attenuation on its round trip while at 30°, the attenuation is about 78%.

When considering each of these factors a 45° inclination angle yields substantial Doppler shift, while minimizing the uncertainty associated with measuring the angle. Additionally, 50% laser-power attenuation is acceptable and the probe dimensions can remain reasonably small.
Appendix E

Boundary Layer Analysis

Initially, as discussed in section 5.3.2, it was thought there were two absorption regions in the Doppler-shifted absorption trace. The regions were identified as absorption in the nearly stationary boundary layer close to the wall and absorption from frozen potassium in the freestream. Data reduction incorporating this assumption leads to Doppler widths yielding kinetic temperatures near 4000 K. This temperature value was much greater than the facility calculated value of 550 K and the simultaneously measured values (see section 5.2.4) using the water vapor probe.

To examine the boundary layer effect on the absorption signal in the Calspan potassium experiments, 3 constitutive calculations must be considered. First, is a solution to the boundary layer equations for compressible flow. Second, is a chemical equilibrium calculation for salt (KCl) as the most likely source of potassium. Third, is a numerical calculation of Beers law considering spatial dependencies of Doppler shift and width, concentration, and temperature that result from the first two calculations.

The governing partial differential equations for a compressible boundary layer are greatly simplified using the following transformation of variables (White 1991, pg. 502).

\[
\xi = \int_{0}^{\infty} \rho_0(x) \nu_c(x) \mu_0(x) \, dx \\
\eta = \frac{\nu_c(x)}{\sqrt{\rho_0}} \int_{0}^{\infty} \rho(x) \, dy
\]

The momentum and energy equations for uniform freestream flow ($\nu_c \neq \nu_e(x)$) over a flat plate transform to the following set of non-linear coupled differential equations,

\[
(Cf^\prime)^\prime + f f^\prime = 0 \tag{E.3}
\]
\[
\left( \frac{C}{F} \right) f^\prime + f f^\prime + \frac{V_e^2}{h_e} (f)^2 = 0 \tag{E.4}
\]
where the primes indicate derivatives with respect to $\eta$ and:

$$f' = \frac{U}{U_e}, \quad g = \frac{h}{h_e}, \quad C = \frac{\rho \mu}{\rho_e \mu_e}$$

where $C$ is the Chapman-Rubesin factor, $\rho$ and $\mu$ are the gas density and viscosity respectively. Note, the subscript "e" denotes an evaluation of the parameter in the freestream, and $C$ is a local point variable (e.g., $C = C(\xi, \eta)$). Additionally, Pr is the Prandtl number,

$$Pr = \frac{\mu_c \rho_c}{k},$$

where, $c_p$ and $k$ are the specific heat at constant pressure, and the thermal conductivity of the gas respectively. The Pr number is also a point variable. To simplify the analysis molecular nitrogen was considered as the bath gas.

The applicability of this similarity solution is subject to a wall boundary condition of uniform temperature, or uniform heat transfer. The impulse character of the test facility lets one approximate the wall boundary condition as a constant temperature.

The set of equations are solved using a 4th order Runge-Kutta method (Gerald and Wheatly 1984, pg. 308) with a shooting technique as discussed in Anderson (1989) ([1989], pg. 238). The introduction of $C$, $Pr$, and their derivatives introduce non-linear coefficients in equations E.3 and E.4 which are mitigated by iteration. Additionally, the spatial step size is fixed to facilitate high-accuracy interpolation values for the non-linear coefficients in the intermediate Runge-Kutta spatial steps.

To account for the spatial variation in potassium through the boundary layer it was assumed that potassium and its salt are in the vapor phase. The equilibrium fraction of potassium was calculated considering KCl, K, Cl, K$^+$, e$^-$, and $N_2$. In figure E.1 the mole fraction of potassium atoms ($\chi_k$) is normalized by the initial mole fraction of salt ($\chi_{KCl_\infty}$). From this figure the equilibrium fraction of potassium increases as the temperature increases due to dissociation of the salt. At temperatures greater than 2000 K, due to potassium ionization, the concentration of neutral potassium atoms begins to decrease.

Because of the small equilibrium levels in the freestream, when using the results in the boundary layer model, it is assumed that the potassium in the freestream was frozen out at some temperature $T_{fref}$.

The potassium partial pressure in the boundary layer $P_K$ is:

$$P_K = P_{KCl_\infty} \frac{\chi_k(T)}{\chi_{KCl_\infty}}, \quad (E.5)$$

where the freestream potassium chloride partial pressure, $P_{KCl_\infty}$, is given as,

$$P_{KCl_\infty} = \frac{P_{K\infty}}{\chi_{KCl_\infty}}, \quad (E.6)$$
and where $P_{K_{\infty}}$ is an estimate of the frozen freestream potassium partial pressure. When computations were made near the outer boundary layer edge, if the temperature is below the frozen value, the potassium partial pressure is simply an estimated value. On the contrary because of the lower velocities within the boundary layer, equilibrium chemistry is assumed.

Figure E.2 illustrates the velocity, temperature and potassium mole fraction profiles found after numerically integrating the boundary layer equations. Note, at this point in the explanation, the wall temperature and the temperature at which potassium freezes out are arbitrary. However, once the flow field is determined, a differential form of Beer’s Law is integrated through the profiles using a Runge-Kutta-Fehlberg method (Gerald and Wheatly 1984) which optimizes the stepsize to maintain an error below a given tolerance. The values of wall temperature, the frozen temperature and the estimated freestream potassium partial pressure are adjusted to minimize the error between the measured absorbance and the numerically integrated absorbance.

The definition of the spectral absorption coefficient is integrated numerically to determine the calculated absorbance through the boundary layer flowfield. Recalling from section 3.2:

$$k_\nu \equiv \frac{dI_\nu/L_\nu}{dy}$$

(3.7)

where the functional dependence is changed to $y$ to reflect the integration path in standard
boundary layer coordinates and $k_v$ is defined as:

$$k_v = -S \phi(\nu) P_t$$

Modifications to the above parameters are:

$$S = S(T(y))$$
$$P_K = P_K(T(y))$$
$$\phi = \phi_{D_{ps}}(\nu - \nu^*, T(y))$$
$$\nu^* = \nu_0 \left(1 - \frac{V(y)}{c}\right)$$

$$\Delta \nu_{D_{ps}} = 7.162 \times 10^{-7} \sqrt{\frac{T(y)}{M_{atm}}} \nu_0$$  \(3.19\)

The numerical integration of equation 3.7 at multiple values of $\nu$ yields the effect of the radiative absorption in the boundary layer on the spectral absorbance. The best solution is shown in figure E.3 where a wall temperature of 402 K and a frozen temperature ($T_{froz}$) of 1350 K yields a minimum in the residual between the measured absorbance and the numerically calculated absorbance.

The simple numerical model infers the presence of 4 distinct absorption regions concealed within the two apparent peaks. From left to right, in figure E.3, the first apparent peak contains
a small peak due to fastest moving potassium atoms in the freestream. The next region can be described as hot potassium atoms absorbing in the outer region of the boundary layer. The gap between the two apparent peaks is due to potassium ionization occurring at the high recovery temperatures. The ionization region is made clearer by examining the right-most plot in figure E.2. Finally, the right-most apparent peak is due to the nearly-stationary hot potassium adjacent the window surface.
Appendix F

Identification of Potassium in Shock/Expansion Tube

The flowfield generated in the shock/expansion tube (SET) (described in section 2.3) was found to contain potassium over a range of operating conditions. This appendix describes a test program to examine the source and nature of potassium atoms detected by absorption spectroscopy in the Stanford SET. The test program was conducted over three phases. The goal of the first phase was to determine whether potassium atoms could be detected in SET flow, and what its source was. The second phase was, an attempt to map the SET conditions where potassium was detectable. The third phase was initiated to examine the ability to control the potassium levels.

F.1 Is Potassium Present?

Initially, the experiments were aimed at finding a test condition which would generate potassium atoms in the test gas. Having found such a condition, it was important to determine the source of potassium to understand how the diagnostic would perform at different conditions. Two possible sources were: (1) minute quantities of potassium salts in secondary diaphragm material or (2) in particles adhering to the acceleration tube side-wall. In either case a two step process was surmised. First, the particles in the high temperature reflected shock region proximate to the secondary diaphragm, deposit potassium salts/atoms into the test gas region through pyrolysis. Second, the test gas proximate to the secondary diaphragm station propagates through an expansion fan after having been shock heated, where the gas closest to the diaphragm station experiences the most rapid expansion and may freeze potassium in atomic form.
Figure F.1 illustrates the experimental arrangement used to examine the potassium’s presence in the Stanford SET. The Mark II leading edge angle was reduced from 41° used in the Mach-9 Calspan flow to 34° to be compatible with the lower Mach number flows (M > 3). During the experiments absorption was measured in the SET core-flow using the Mark II probe. The probe was fiber coupled to a remotely located diode laser which was tuned to D₁ potassium transition near 770 nm. A flame seeded with potassium chloride served as a check on the laser wavelength. Additionally, by scanning the laser rapidly, 30 kHz, the transition was probed on- and off-line to ensure the reduced transmission was from radiative absorption of potassium atoms and not by particles or beam steering effects.

The SET experiments are outlined in Table F.1 and tests, a through d, outline the salient expansion tunnel tests during the first phase. Tunnel conditions were set to establish a hot reflected shock region and freestream (T₃) condition. Potassium absorption was measured in the first test using the Mark II probe. Subsequently, for tests b and c, the tunnel was run in shock tube mode without a secondary diaphragm at conditions hot enough to see if potassium was from the tube walls or helium. No absorption was measured thus eliminating that the absorption was related to the test gases or the facility walls. The remaining source was the secondary diaphragm, and test d was a repeat of test c while operating the tunnel in shock tube mode. However, the secondary diaphragm was inserted in this test with P₁ = Pₙ₀. The presence of the secondary diaphragm was successful in producing conditions necessary to generate potassium absorption at the Mark II probe location. Thus, it is assumed that its presence is directly involved in generating potassium.

The second testing phase began to map a range of test conditions over which potassium absorption was detected. Freestream temperatures were reduced to a level of 500 K as shown in test e of Table F.1. At this condition, only a few scans indicated Doppler-shifted potassium absorption. The measured velocity was 1910 m/s and the freestream velocity was estimated to be greater than 2500 m/s, where 2500 m/s is the velocity from ideal 1-dimensional theory.
TABLE F.1 A summary of selected SET tests used to examine test conditions with detectable potassium in the test gas. Columns labeled $P_4$, $P_1$, and $P_{10}$ indicate the pressure levels and gas species for the tunnel initial conditions. Columns labeled $T_2/T_R$ indicate the theoretical temperature behind the initial shock and the temperature behind a reflected shock from a stationary endwall. $T_2$ indicates the test gas temperature when operating the facility in SET mode and $K_{\text{al}}$ indicates the maximum absorbance observed.

<table>
<thead>
<tr>
<th>Test</th>
<th>$P_4$ [psig, Sp.]</th>
<th>$P_1$ [psia, Sp.]</th>
<th>$P_{10}$ [torr, Sp.]</th>
<th>$T_2/T_R$ [K]</th>
<th>$T_2$ [K]</th>
<th>$K_{\text{al}}$ Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>21.4, He</td>
<td>3.62, N$_2$</td>
<td>1, He</td>
<td>2600/6100</td>
<td>1300</td>
<td>$&gt;&gt;1$</td>
</tr>
<tr>
<td>b</td>
<td>1.80, He</td>
<td>2.59, He</td>
<td>1</td>
<td>2300/-</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>c</td>
<td>21.4, He</td>
<td>2.59, N$_2$</td>
<td>1, N$_2$</td>
<td>2500/-</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>d</td>
<td>21.4, He</td>
<td>2.59, N$_2$</td>
<td>2.59, N$_2$</td>
<td>2500/-</td>
<td>-</td>
<td>$&gt;&gt;1$</td>
</tr>
<tr>
<td>e</td>
<td>21.4, He</td>
<td>103, N$_2$</td>
<td>5, He</td>
<td>1150/2000</td>
<td>500</td>
<td>0.1</td>
</tr>
<tr>
<td>f</td>
<td>21.4, He</td>
<td>12.9, N$_2$</td>
<td>10, He</td>
<td>1830/4100</td>
<td>1200</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Viscous effects are expected to raise the velocity in the test gas above that value. The concurrent analysis of the Calspan tests indicated, radiative absorption in the boundary layer dominated the absorbance signal. Additionally, velocity measurements using Doppler-shifted lineshapes in test condition e, contradicted what one-dimensional theory predicted the minimum velocity could be. Thus, it was conjectured that the radiative absorption was confined to the slower moving region of the thermal recovery zone in the boundary layer.

The value of $K_{\text{al}}$ was found to vary from values of 0.1 to values much greater than 1 over the range of test conditions examined. Fluctuations in the absorber concentration hinder the ability to measure velocity, as was shown in section 5.2.3. However, the absorbance time history recorded for a well calibrated test point, f (Ben-Yakar et al. 1998), yielded a range of absorbance which never surpassed one. Thus, test point f was selected to examine the possibility of controlling the atom population in phase 3, through seeding or change in diaphragm material.

### F.2 Potassium Seeding Strategies

The diode laser wavelength was fixed to line center of the potassium D$_1$ transition and the absorbance was recorded as the flow developed. Figure F.2 depicts the recorded absorbance time history using the Mark II probe in the SET configured to test condition f with a mylar secondary diaphragm installed. Additionally, a trace from a pitot tube located in the facility boundary layer is useful to illustrate the facility timing. The pitot tube indicates the arrival of the secondary shock which is followed by a steady flow of helium. After helium flow, the contact surface (CS) which defines the separation between the helium acceleration gas and the nitrogen test gas, passes over the probe location. More importantly however, the arrival of the contact surface coincides with the detection of potassium atoms. The test time is terminated, in this
The absorbance time history indicates that the presence of potassium coincides with the arrival of the contact surface between helium acceleration gas and nitrogen test gas. The test time is terminated, in this case, by the arrival of an expansion fan (EF).

The absorbance trace clearly indicates that the concentration of potassium is fluctuating. Note, that the absorbance is a logarithmic scale and the signal fluctuations represent changes in concentrations by factors of two or more. A number of physical treatments to the diaphragm were attempted with the intention of causing the absorbance signal to become more smooth.

Before attempting seeding strategies, however, the effect of cleaning the diaphragm surface on the absorbance time history was examined. Before cleaning, the diaphragms were installed in a frame so installation could be performed without handling the material. Cleaning consisted of rinsing the surfaces with research grade acetone and deionized water. The order was selected such that bodily oils deposited though prior physical handling would be removed first. Subsequently, the deionized-water rinse would remove salts left on the surface. Figure F.3 illustrates that diaphragm cleaning was effective at retarding the onset of potassium by approximately 100 μs. Additional cleaning steps included soaking the mylar in boiling deionized water and placing the diaphragm in a capacitively-coupled radio-frequency plasma etcher to remove the surfaces of the mylar after cleaning. Qualitatively, the absorbance time histories displayed the same behavior. These results indicate that potassium or salts of potassium must be minor constituents of the diaphragm material.

Next, it was thought that seeding the diaphragm surface or the walls near the diaphragm surface with a potassium salt may smooth out the absorbance signal’s high-frequency character.
To control the amount of potassium placed on a wall or diaphragm surface, measured quantities of potassium salt were dissolved in measured volumes of deionized water. After thoroughly stirring, a syringe was used to deposit metered volumes of saline on a surface and allowed to dry. Figure F.4 illustrates a typical absorbance time history at condition f (as in table F.1) with 150 ± 50 pg of potassium chloride deposited on the upstream side of the secondary diaphragm.

The result of seeding the diaphragm surface was to increase the initial amounts released during the first 100 µs, however after 200 µs the absorbance increased to a value of 2. The temporal character displayed in figure F.4 was consistent despite attempts to change the amount of potassium deposited or whether it was placed on the upstream or downstream side. Changes in the amount of potassium deposited simply changed the levels while the fluctuations remained. Additionally, tests where run with saline placed near the edge of the diaphragm in the shape of a ring, and in the center. No qualitative change in the high-frequency nature was achieved. Seeding the upstream and downstream tunnel walls had no effect on the absorbance character. The absorbance traces were nearly identical to figure F.3, where a cleaned diaphragm was used.

Additional tests were run using diaphragms made of different materials to see if they would release potassium into the flowfield and if the character of the absorbance time history would change. The following materials were tried: kapton, copper, stainless steel, and aluminum. All the tests exhibited the same qualitative character consistent with being seeded with potassium salt or cleaned.
F.3 Radiative Absorption in Boundary Layer

At this point phase three began with the intent of determining if potassium atoms were frozen in the free stream or confined to the thermal recovery zone in the boundary layer. The idea was to measure the absorbance \((-\ln I/I_0)\) with the laser fixed at line center across two pathlengths. The Mark II probe interrogated the SET core flow while another beam (from the same laser), pitched across the optical port, interrogated both the core and facility boundary layer flows. If significant absorption occurred in the freestream, then the absorbance should scale with pathlength, but if the absorption is confined to the boundary layers only the absorbance would scale with the boundary-layer thickness.

Figure F.5 illustrates an absorbance time history for the probe location and the optical port location during the test (condition f). The operation of the SET dictates that the same freestream condition passes by each measurement location. This feature of operation is indicated by the similar characteristics of the absorbance time history. The average absorbance over the same initial feature is indicated in each time history. If the absorption was due to freestream potassium, the ratio of the absorbance ratio should scale with the pathlength as,

\[
\frac{I_{\text{port}}}{I_{\text{probe}}} = 7.
\]

On the contrary, the ratio is about 1.6 while the pathlength ratio is 7. This result implies that radiative absorption from potassium atoms is confined to the boundary layer.
F.3. RADIATIVE ABSORPTION IN BOUNDARY LAYER

An estimate of the velocity was obtained by identifying similar features (e.g., peaks and valleys) on the absorbance trace from each location and recording the time-of-flight (± 10 µs) between the features respective arrivals. It is assumed that the recorded absorbance in the boundary layer indicates the freestream potassium salt concentration. Thus, the velocity inferred from the time-of-flight measurement is an estimate of the core-flow velocity. The estimated velocity of approximately 2400 m/s confirms this test condition's prior characterization (Ben-Yakar et al. 1998). Furthermore, velocity measurements using the Doppler shift as performed in sections 5.2.2 - 5.3.2 yielded velocities near 1800 m/s. The lower velocities recorded using the Doppler technique supports the conclusion that radiative absorption is confined to the boundary layer as found in section 5.3.2.
Bibliography


Letters 19(22), 1900–1902.


