Precise Time-Resolved Temperature Measurements in Shock-Heated Flows

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Motivation

The design and optimization of combustion systems relies heavily on accurate predictive modeling. These combustion models provide information regarding performance such as efficiency and pollutant emissions. An important component of any combustion model is the reaction mechanism that describes the chemistry of the combustion event. The constitution of a reaction mechanism requires a database of accurate chemical reaction rate constants for the temperature range of interest. The development of such a mechanism requires careful experiments to determine ignition times and species concentration time-histories in reacting or combusting flow with well-controlled temperature, pressure, and reaction time. Shock tubes can provide well-defined initial temperatures and pressures for such kinetic investigations. While ignition-delay times provide an overall measure of the performance of kinetic mechanisms, refinement and validation of the detailed chemistry of the system requires a time-dependent picture of temperature and the species concentrations. This project seeks to develop an ultra-sensitive temperature sensor capable of more precise time-resolved gas temperature measurements than achieved in any previous reactive shock tube experiments.

Overview

We have developed a new tunable diode laser sensor for measuring temperature behind reflected shock waves using wavelength modulation spectroscopy with 1*f*-normalized second harmonic detection (WMS-2*f*/1*f*). The sensor probes the R(28) and P(70) transitions of the $\nu_1+\nu_3$ combination vibrational band of CO_2 near 2.7 μm. This band offers absorption strengths that are 1000 and 50 times stronger than the CO_2 bands used in previous sensors near 1.5 μm and 2.0 μm, respectively. The well-separated lower-state energies of the selected transitions enable sensitive temperature measurement over a wide range of temperatures. The two lasers are modulated at 100 kHz and their modulation depths are optimized to maximize the WMS-2*f* signal for the target conditions in the shock tube (P ~ 1 – 2 atm, T ~ 800 – 1600 K). The lasers are characterized for actual laser performance to determine laser parameters for the specific modulation frequency and modulation depth. The WMS-2*f* signal is normalized by the 1*f* signal. The sensor has negligible sensitivity to pressure variations in the pressure range of interest. The existence of a cold boundary layer in the shock tube and changes in gas composition do not induce significant uncertainty to the temperature measurements.

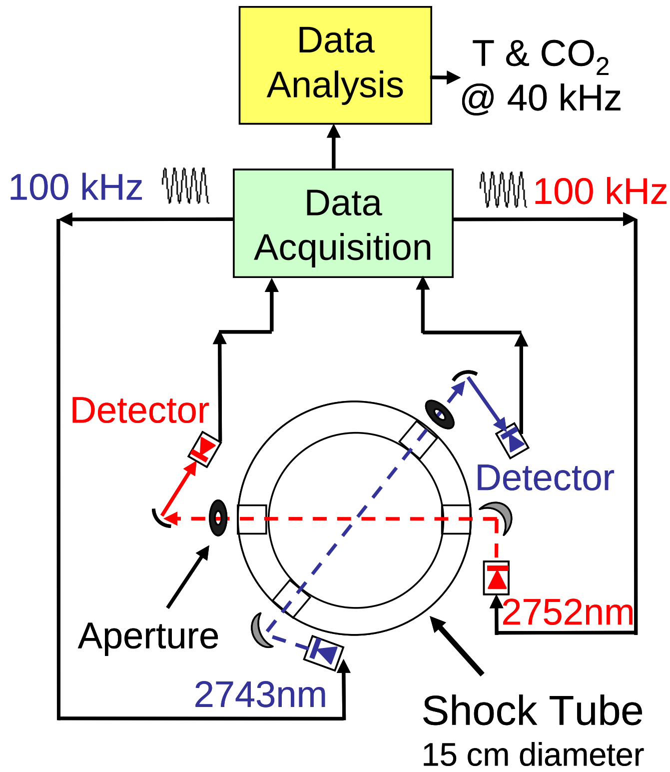

Figure 1: Schematic diagram of the experimental setup used for WMS-2*f* sensor measurements in the shock tube.

The fixed-wavelength WMS-2*f* sensor is validated in heated static cell experiments and the measured temperatures agree well with thermocouple readings, with a standard deviation of 9 K. Temperatures measured by the TDL sensor agree with calculated reflected-shock temperatures within 1% in non-reactive CO_2-Ar shocks. For the case shown in Figure 2, a standard deviation of ~3 K is achieved which translates to an uncertainty of only 0.32% at the measured temperature of 952 K. Measurements of CO_2 and temperature are subsequently carried out behind reflected shock waves in ignition experiments of heptane-O_2 system. Pre-ignition temperature histories are also measured by seeding a small quantity of relatively inert CO_2 in the initial fuel-oxidizer mixture. The sensor offers improved temperature sensitivity, better accuracy, and excellent SNR, relative to past optical sensors, owing to the relatively large CO_2 absorption strength near 2.7 μm and the use of 1*f*-normalized WMS-2*f* strategy.

Next Steps

Future work will extend this strategy to use in the presence of fuel aerosol, which produces significant scattering interference.

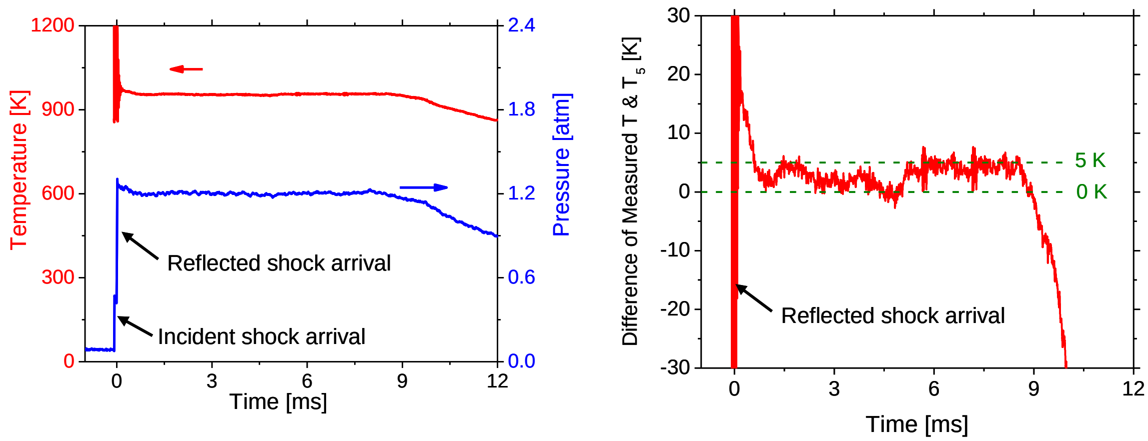

Figure 2. Left panel: Measured temperature and pressure behind a reflected shock wave arriving at t = 0. Reflected shock conditions 952 K, 1.20 atm, 2% CO_2 in Ar, tailored driver 40% N_2 in He with driver insert. Right panel: Difference in measured T and calculated T_5 (reflected shock temperature)

References

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