Hypersonic Mass Flux Sensing

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Motivation

Mass flux is an important parameter in air-breathing propulsion, and is used in calculations of inlet and combustor performance as well as thrust and drag. Measurement of mass flux can aid in propulsion test facility operation and provide test conditions to more accurately evaluate engine performance. The current goal is to develop a tunable diode laser sensor for mass flux based on wavelength modulation absorption spectroscopy of water vapor.

The sensor described here is designed to measure mass flux in a high-temperature, supersonic flow in a combustion-driven facility (Fig. 1), where hypersonic flight conditions are produced by expansion of hot, high-pressure air. In such facilities, the gas is typically vitiated (heated by combustion of hydrogen with oxygen-replenishment). The use of H_2O as the target species in the gas allows the sensor design to exploit mature telecommunications diode lasers in the 1.4 µm region, which can access the $2\nu_1$, $2\nu_3$, and $\nu_1 + \nu_3$ absorption bands of water vapor.

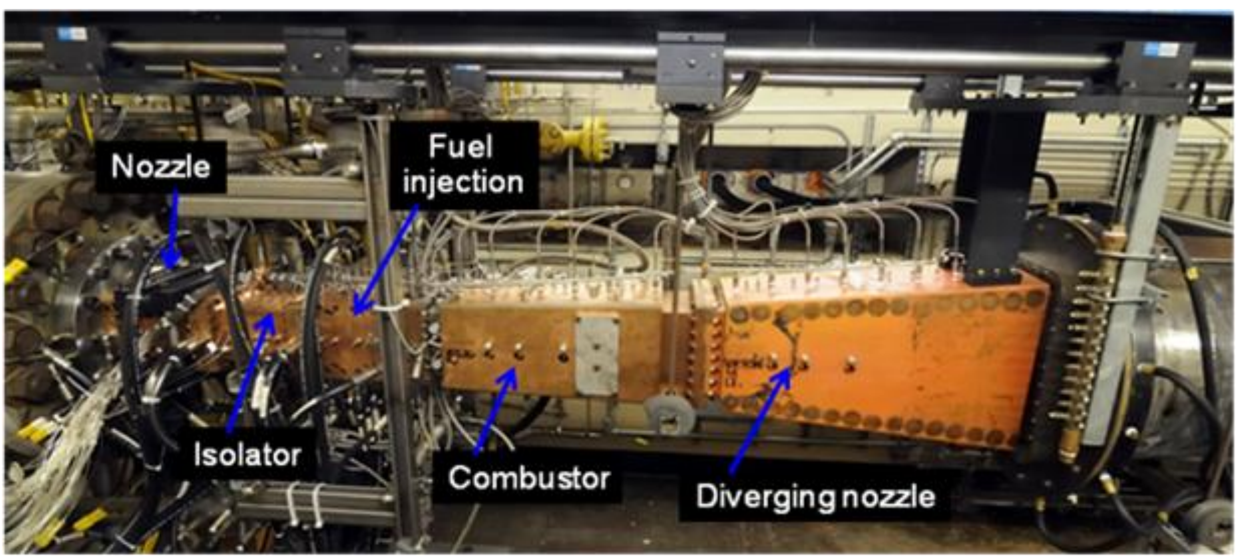

Figure 1: NASA Langley Direct Connect Supersonic Combustion Test Facility (DCSCTF).

Overview

Mass flux is determined from the product of measured velocity and density. Velocity is obtained from the relative Doppler shift of an absorption transition for beams directed upstream and downstream in the flow. Temperature is determined from the ratio of absorption signals of two transitions and is coupled with a facility pressure measurement to obtain density. The sensor exploits wavelength-modulation spectroscopy with second-harmonic detection (WMS-2*f*) for large signal-to-noise ratios. Additionally, the sensor utilizes optimization of the modulation for 1*f*-normalized WMS-2*f* (WMS-2*f*/1*f*) signals for velocity sensing. A schematic of the sensor architecture is presented in Fig. 2.

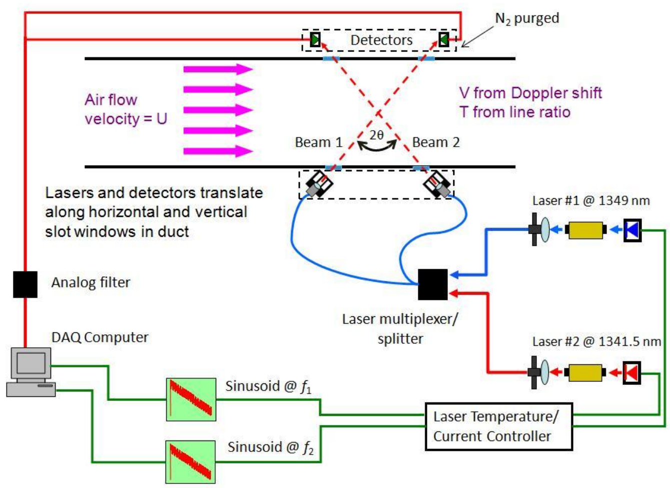

Figure 2: Two-laser frequency-multiplexed WMS sensor for mass flux at H_2O wavelengths λ_1 and λ_2 (~1349 and 1341.5 nm). The two lasers are combined on a single fiber and then split to be directed upstream and downstream in the supersonic flow with a crossing angle 2θ. Velocity is determined from Doppler shifts of the absorption lineshape and gas temperature by the ratio of the two absorption signals.

The sensor temperature and velocity measurements were validated under controlled conditions at Stanford facilities prior to deployment in the NASA DCSCTF. Water vapor temperature was measured in a quartz cell placed in the center of a three-zone furnace to provide a uniform (~1%) temperature as measured by thermocouples at the center and each end of the cell. The sensor-measured temperature is in good agreement with the thermocouple reading as shown in Fig. 3a. Velocity measurements were conducted in a low-velocity (18 m/s maximum), high-uniformity tunnel at Stanford operating with ambient air. As seen in Fig. 3b, the sensor-measured velocities are within 0.5 m/s of the tunnel set point.

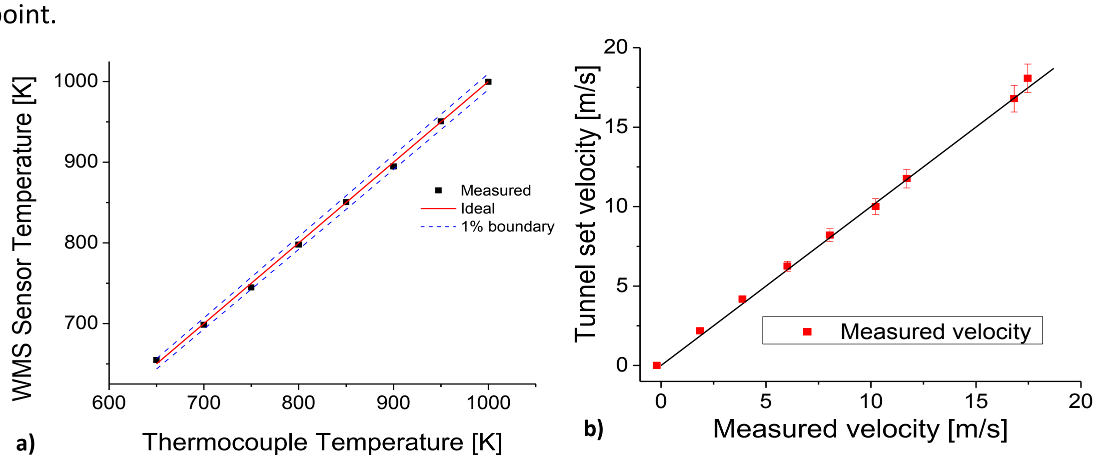

Figure 3: a) Sensor temperature measurement in Stanford high-uniformity furnace. b) Sensor velocity measurement in Stanford low speed wind tunnel.

Next Steps

The sensor was successfully deployed in the NASA DCSCTF in September 2009 and spatially- and temporally-resolved mass flux data was collected. Mass flux measurements were in good agreement with the facility Mach 6 and Mach 7 flight enthalpy set points (see Fig. 4). Currently efforts are underway to examine the effects of flow non-uniformities (boundary layers, regions of stagnant gas, etc.) on the WMS signals and to develop a method to minimize these effects in order to accurately recover the gas properties in the core flow. The accuracy of the sensor at both low velocities and hypersonic conditions now leads to the possibility for deployment in other ground test facilities or in-flight testing.

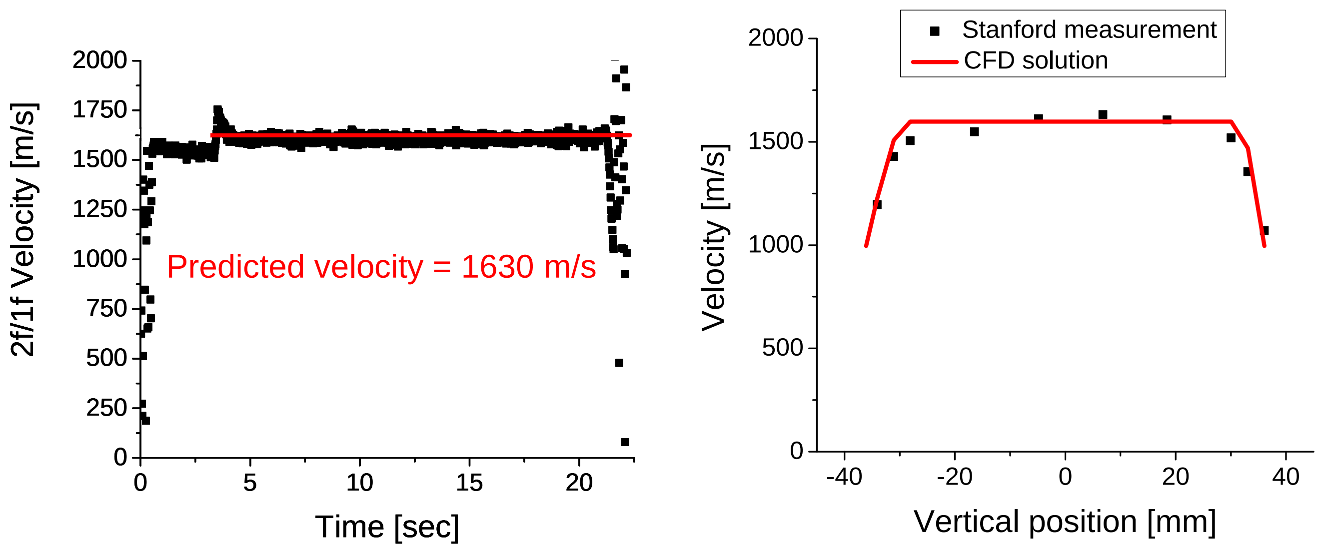

Figure 4: Measurements of velocity in the DCSCTF during a measurement campaign at NASA Langley in September 2009. Left panel: velocity versus time is quite stable after initial transient; Right panel: velocity versus vertical position in good agreement with CFD prediction with potentially a slightly thicker boundary layer.