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Technical Notes

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Mach-Number Measurement with Laser and Pressure Probes in Humid Supersonic Flow

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Introduction

LASER-BASED vapor screen [1] is commonly used for flow visualization in some high-speed wind tunnels, including NASA Langley Research Center's (LaRC) unitary plan wind tunnel (UPWT) [2]. Vapor-screen visualization is accomplished by adding water to the wind-tunnel circuit; the cooled supersonic flow condenses the H_2O vapor into small H_2O droplets or ice crystals. Flow visualization is possible by illumination of the H_2O particles with a laser light sheet. However, adding H_2O to a supersonic wind tunnel alters the flow conditions in the test section compared with otherwise identical, but dry, conditions. Hence, typical aeronautical testing with pressure probes is done under dry tunnel conditions. Some flow facilities have measured (with pitot and static probes) and specified the effect of flow humidity on tunnel Mach number (e.g., see p. 87 of [2]), so that facility users will know the effect of high humidity.

Another optical technique, laser-induced thermal acoustics (LITA), has been recently demonstrated for Mach-number measurement in a supersonic flow. No seeding is required with this approach. LITA-based, nonintrusive, time-averaged, and simultaneous measurements of Mach number, static temperature, and static pressure at a localized point in the freestream flow of UPWT are demonstrated and described in [3]. The present Note describes a novel comparative study of pressure-probe and LITA-based Mach-number measurements versus humidity in the UPWT.

Method

A more detailed description of LITA velocimetry at LaRC can be found for supersonic [3], transonic [4], and subsonic [5] flows, and the work of other groups is summarized in a recent review [6]. LITA is a laser diagnostic that typically measures sound speed and one directional component of velocity, simultaneously, in a flow volume defined by crossed laser beams. If the flow composition is known, then translational temperature can be derived from the sound speed, and gas pressure is measurable under certain restricted circumstances [3,7].

In LITA, two focused and crossed 1.06-μm laser beams from a Q-switched Nd:YAG (150 mJ/pulse/beam) induce two counter-propagating sound-wave packets in the sample volume defined by the crossing region. These sound waves constitute gas-density gratings in the fluid. The $\sim$100 dB (re 20 μPa) sound pressure level corresponds to a fractional density change of $\sim 10^{-4}$. Thus, the technique can be characterized as nonintrusive. Flow velocity and sound speed are determined from distinct Doppler shifts of Bragg-scattered light from a third laser beam (probe at 532-nm) that intercepts the sound-wave packets. The sound packets reflect a tiny fraction of the incident probe intensity to a detector positioned at the Bragg-scattering angle. All LITA measurements presented here are time-averaged over 17 s (500 laser pulses at a rate of 30 Hz).

Results

Freestream results comparing measurements of Mach number M by a pressure probe and LITA are given in [3] for dry airflow (dew point $= -35°$C) at Reynolds number per unit length $R = 6 \times 10^4$/m. Figure 1 summarizes some of those results and shows exceedingly good agreement (typical differences in M of 0.003) between time-averaged measurements from both techniques for the Mach-number range 1.6–2.2. Open circles are from one day of testing, the solid triangle is from a second day, and the solid line represents perfect agreement between the two techniques.

Results comparing Mach number measurements versus steady-state water content are given in Fig. 2, at approximately $M = 2$. Pressure-probe results are from [2] (Fig. 27, p. 87), and the LITA results were obtained during the work of [3]. Pressure-probe results were obtained at $M = 2.17$, and LITA results were obtained at $M = 1.97$. This is the closest Mach-number match that is possible for the limited humidity studies from the two unrelated works of [2,3]. Results at other Mach numbers, illustrated in [2] (p. 87), suggest that one expects only a small change in the effect of adding water between these two slightly different Mach numbers. Thus, it appears reasonable to compare these two data sets.

Pressure-probe results are plotted using the right-hand Mach-number scale, and LITA results use the left-hand Mach-number scale. Offsetting the two scales by $M = 0.2$ provides a simple comparison of the relative change in Mach number at the two slightly different Mach numbers. Open squares are probe results at $R = 6 \times 10^4$/m, open diamonds are probe values at $R = 12 \times 10^4$/m, and solid triangles are LITA results at $R = 6 \times 10^4$/m. The leftmost triangle is the same lone triangle plotted in Fig. 1. The abscissa gives the dew point of the airflow. A dew point of $-12°$C corresponds to a water concentration of 0.5% at the stagnation conditions 70 kPa (0.7 atm) and 52°C. As water concentration in the flow is increased, the difference between the two methods increases for the change in Mach number, illustrating a potential error in one or both techniques. LITA measures a factor-of-5-larger change in Mach number due to the addition of water, as the humidity varies from the driest dew point of $-35°$C ($-30°$F) to $-12°$C ($+11°$F). Along with the decrease in Mach number, LITA also measures the freestream static temperature T to increase (data omitted for brevity) from -90 to $-83°$C as dew point varies from -35 to $-12°$C. This temperature increase and Mach-number decrease come from the heat release during water vapor condensation into particles.

Uncertainties in the LITA data [3] are typically $\pm 0.2\%$, or $\Delta M = \pm 0.004$. Uncertainties in the pressure-probe data are not

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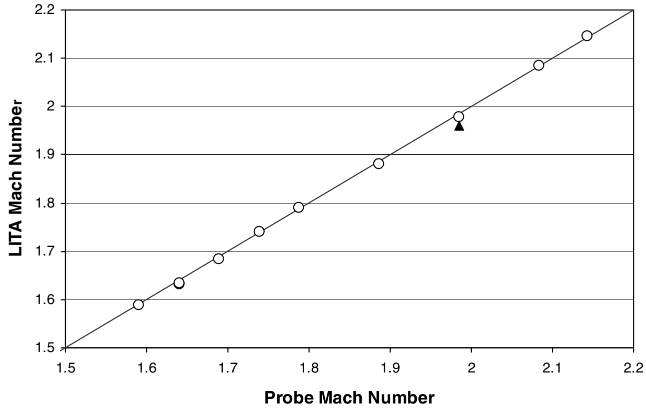

Fig. 1 Probe and LITA-based Mach number for dry air (dew point = −35°C).

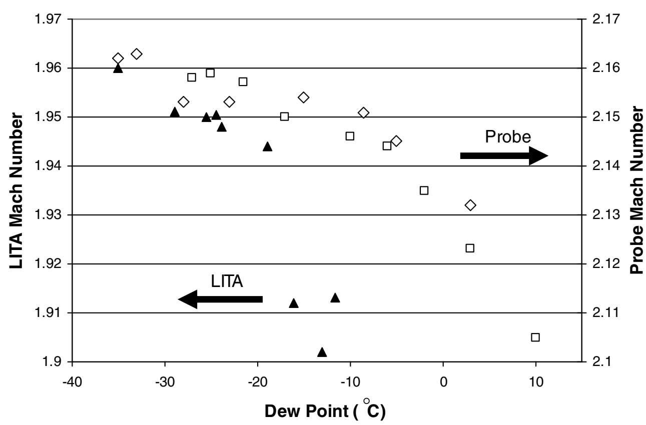

Fig. 2 Probe and LITA-based Mach number versus water concentration.

quoted in [2], but the precision is estimated to be $\Delta M = \pm 0.005$ from the point-to-point variation from an imaginary smooth curve through the probe data. Thus, the difference in ΔM for the two techniques, at -12°C, exceeds the estimated combined uncertainty of $\Delta M \approx = \pm 0.009$ of both measurements by a factor of 5. The good agreement of the two methods in Fig. 1 is typical of comparisons of LITA and many traditional methods performed at LaRC over one decade, and so the disagreement of Fig. 2 is unusual.

One potential reason for the discrepancy is an error in the LITA measurement due to an unknown effective molecular mass m after adding water vapor to the air. The highest humidity in Fig. 2 is equivalent to ≈2% water vapor before supersonic expansion. This H_2O concentration reduces the mass by 1% and increases sound speed V_s by 0.5% ($V_s^2 \propto T/\mu$). Furthermore, most water vapor is condensed into particles and is not in vapor phase in the test section. Conservatively, assuming no knowledge of H_2O density, the error in measured M is less than 0.5% and negligible.

In the dry airflow of Fig. 1, LITA generates only acoustic gratings from a purely electrostrictive effect. Solid, liquid, and vapor phases of water have weak absorptions at the pump-laser wavelength of 1064 nm. Gas heating after an optical absorption leads to a second possible error in the humid LITA measurements of Fig. 2: a LITA-generated thermal-based grating in gas density. In fact, in humid flow, we do observe that LITA generates a weak thermal grating (in addition to the acoustic grating). The thermal grating increases in strength as the humidity increases. At -12°C, the thermal-grating signal is about equal to the acoustic-grating signal. An absorption coefficient of $\sim 10^{-4}$ cm^{-1} is inferred by an estimated (not measured) thermal-grating reflectivity of $\sim 10^{-9}$. The absorbed energy is more than enough to heat the gas by 7°C and reduce M from 1.96 to 1.91, if it is assumed that all absorbed energy were to be transferred to the gas (e.g., by vaporization of the ice particles). If the crystals do not vaporize and only a small fraction of the energy absorbed by the crystals is transferred to the gas in the LITA observation time of 1 ms, the thermal grating is unlikely to account for the Mach-number discrepancy. The estimated laser peak intensity of 10^{11} W/cm^2 and our observation of rare laser-induced breakdown (once every 1000 laser pulses) suggest that a majority of the water particles survive the laser pulse [8]. Although this potential error should not be ruled out yet, the best evidence for asserting that it is negligible is that the strength of the thermal grating is about the same as the strength of the acoustic grating, which is known [9] to exhibit fractional changes in gas density and temperature of $\sim 10^{-4}$.

A third explanation for the difference of Fig. 2 is an error in the pressure-probe measurement, related to the particle-laden freestream. As particles transit the shock from the pressure probe, they are heated. Immediate (or delayed) evaporation of these H_2O particles, directly behind the probe shock (or in the probe duct), would anomalously alter the flow conditions sampled by the probe. In this scenario, the disagreement in humid flow is speculatively attributed to the probe because of the heating and evaporation of the water particles that are entrained in the cold freestream flow. Two different estimates of the probe error can be made. First, the energy available to heat the gas (if all H_2O in the flow condenses into crystals in the nozzle expansion and then all particles vaporize as they cross the probe shock) is given by the heats of fusion and vaporization. This estimate gives $\Delta T \approx 8$°C for 0.5% fractional water vapor, more consistent with the LITA measurement of $\Delta T \approx 7$°C than the inferred probe measurement of $\Delta T \approx 1$°C at dew point $= -12$°C. This inferred ΔT from the probe was estimated using isentropic expansion tables to convert ΔM to ΔT. Second, ideal one-dimensional flow with heat addition in a constant-area duct [10] predicts $\Delta M \approx 0.06$, more consistent with LITA's measurement of $\Delta M \approx 0.05$ than the probe measurement of $\Delta M \approx 0.01$.

Conclusions

Pressure-probe and noninvasive LITA-based Mach-number data were compared and found to disagree in humid supersonic airflow, although they agree well in dry flow. Additional work would be useful to unambiguously determine that the difference in the two methods is due to an error in the pressure probes.

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