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Single-pulse temperature measurement in supersonic air flow with predissociated laser-induced thermal gratings

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Abstract

We report single-pulsed, spatially-resolved temperature measurements in unseeded low-speed and supersonic air using the acoustic decay of laser-created thermal gratings. A low energy 193 nm excitation scheme was employed to create thermal gratings by predissociation of O_2 in the flow. The acoustic decay was monitored over a few hundred ns by a continuous-wave argon-ion laser. This technique is insensitive to laser energy fluctuations as it is a frequency rather than an intensity measurement. Single-pulse measurements in Mach 3.9 and Mach 2.0 nozzle flows were analyzed to a temperature uncertainty of better than 7% by use of power spectra of the time domain signals. Higher accuracy is expected with improved calibration measurements. © 1999 Elsevier Science B.V. All rights reserved.

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Remote, spatially-resolved optical measurements of temperature are required in many gas flow environments where reactivity, high temperature, limited access, and high time resolution preclude the use of physical probes. In supersonic flows, nonintrusive optical techniques are of particular importance as the introduction of a probe stagnates the gas in front of the probe and also disturbs the flow behind it. For measurements in many supersonic and hypersonic facilities, single-pulse diagnostics are often required as the duration of a test at the desired conditions may be quite limited. A number of laser-based spectroscopic techniques have been applied successfully to measure gas temperatures in a single laser pulse, but only a small subset of these methods can be applied to air flows. Single-pulse thermometry has been demonstrated with coherent anti-Stokes Raman spectroscopy (CARS) of N_2 [1] and laser-induced fluorescence (LIF) of O_2 [2,3]. We have developed a new technique that is a variant of established transient thermal grating techniques and can be used for single-pulse temperature measurements in air flows. Our approach avoids the complexity and calibration difficulties associated with CARS and LIF. To demonstrate the utility of this technique for temperature diagnostics in aerodynamic test facilities, we

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have performed measurements in a Mach 2.0 and 3.9 flows.

Transient gratings have been used to determine the speed of sound over a wide range of pressures [4] and to measure temperature in reacting flows [5]. Temperature measurement by this technique is particularly attractive in transient flows since the signal occurs over typically short times (hundreds of ns) when compared with flow times, and only the time-dependent relative intensity rather than absolute intensity is needed to determine the gas temperature. Transient thermal gratings have been created by resonant excitation of species of atmospheric interest: NO_2 (via the A^2B_2–X^2A_1 system) seeded in air [4,6], NO (via the $A^2\Sigma^+$–$X^2\Pi$ system) seeded in N_2 [7], OH (via the $A^2\Sigma^+$–$X^2\Pi$ system) in flames [7,8], O_2 (via the weak spin-forbidden $b^1\Sigma_u^+$–$X^3\Sigma_g^-$ system) in O_2–CO_2 and O_2–H_2O mixtures [9], and CO_2 (via Raman excitation of the $\upsilon_1 - 2\upsilon_2$ Fermi dyad) in CO_2–Ar mixtures [10]. Nonresonant electrostrictive transient gratings have been created in air and other gas mixtures [11] and their use has also been demonstrated as a temperature diagnostic [12].

A thermal grating is created when light from regions of high intensity within the interference pattern of two crossed laser beams is absorbed, and the excited-state energy is subsequently thermalized by the surrounding gas. The grating has the same spatial modulation frequency as the interference pattern of the crossed beams. The resulting thermal grating in turn leads to a grating in the index of refraction. The thermal grating can be detected with a CW probe beam phase-matched to Bragg scatter off the spatial modulation in the refractive index. In the case of thermalization of the absorbed energy at near gas-kinetic rates, two counterpropagating acoustic gratings are launched which travel at the sound speed along the grating wave vector, producing a temporal modulation in grating depth as the pressure waves interfere with the stationary thermal grating. In contrast, slow release of the absorbed energy disperses the acoustic perturbation in time and reduces the modulation depth of the temporal interference with the stationary grating. Of diagnostic utility is the fact that the frequency of this temporal modulation is proportional to the speed of sound, which, for a perfect gas, is proportional to the square root of the temperature. It is, therefore, of distinct advantage when measuring the modulation frequency to resonantly excite a state which is rapidly quenched by the surrounding gas. Providing the thermalization process produces only minor density perturbations, the gas translational temperature can be determined by measuring the modulation frequency f with a knowledge of the molecular mass and specific heat ratio for the gas. The temperature is given by [5]:

$$T = (fd)^2 \frac{M}{\gamma R}, \tag{1}$$

where d is the grating fringe spacing, M is the molecular mass of the gas, γ is the specific heat ratio, and R is the universal gas constant.

In our approach, thermal gratings are formed by collisional thermalization of the kinetic energy of O (^3P) photofragments released following predissociation of O_2. Laser light at 193 nm is used to pump highly-predissociated rotational transitions in the $\upsilon'(4)$–$\upsilon''(0)$ band of the $B^3\Sigma_u^-$–$X^3\Sigma_g^-$ Schumann–Runge system of O_2. The O atom photofragments are released with total kinetic energy of approximately 1.3 eV [13] for each absorbed 193 nm (6.4 eV) photon. The crossed beams of an injection-locked ArF excimer laser with a bandwidth of 1 cm^{-1} were used to create the thermal grating. The experimental geometry is shown in Fig. 1. To create two pump beams, two slots were placed in an aluminum mask that blocked the rectangular beam profile of the ArF laser. A 240 mm focal length lens (at 193 nm) focused both beams that emerged from the slots in the mask so that they crossed at the focus of the lens. The two beams were in a plane perpendicular to the primary flow vector; the interference fringes at the focal region are parallel planes oriented to be parallel to the primary flow vector. The ArF laser was tuned far off (~ 3 cm^{-1}) exact resonance with the predissociative O_2 rotational lines to reduce attenuation of the pump beams from propagation through the laboratory air. The total pulse energy of the two pump beams was measured to be approximately 1 mJ, and no significant attenuation of the beam over approximately a 3 m path was detected. The intensity at the focus was approximately 35 MW/cm^2. Calculations indicate that less than 0.1% of the O_2 is dissociated, which results in a negligible temperature rise in the surrounding gas. The formation of a population grat-

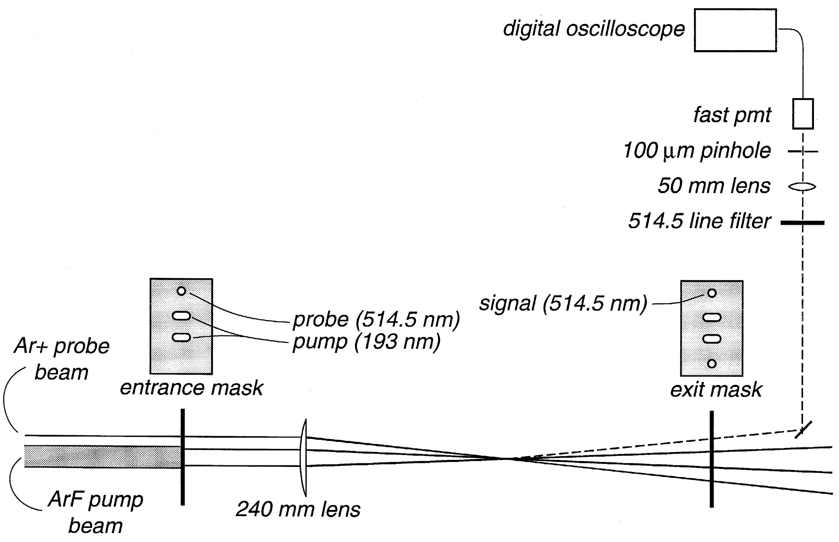

Fig. 1. Experimental configuration for transient grating measurements in a supersonic flow. Flow direction is into the page. PMT: photomultiplier tube.

ing, a precursor to thermal grating production, was confirmed by degenerate four-wave mixing with a third beam from the excimer laser as a probe [14]. The CW probe beam for the transient grating measurements was the 514.5 nm output from a single line argon-ion laser. The output power was approximately 1 W. The probe beam was directed through a third hole in the mask and through the same focusing lens. The pump and probe beams were passed through an identical mask that was reflected and inverted on the opposite side of the focus, so that the probe beam crossed the focal region at the angle required for proper phase matching to the ArF pump beams. The use of slots for the ArF beams enlarged the lateral dimension of thermal grating to offset the reduction in residence time due to the high convective velocities. The diffracted light of the transient grating signal was directed through a 514.5 nm line filter, a 100 µm spatial filter, and onto a fast (0.7 ns rise time) photomultiplier tube. The large difference in wavelength between the pump and probe beams forces a relatively large phase-matching angle for the probe beam, which, in turn, permits easier spatial discrimination of the signal from scattered pump beam light. Transient grating signals were recorded on a digital oscilloscope where they were stored for later analysis. The pump beam crossing half angle (0.7°) was defined by the vertical hole spacing in the aluminum mask and by the focal length of the lens. As with all four-wave mixing processes, the spatial resolution along the beam paths is limited by the beam diameters and this crossing angle. We conservatively estimated our spatial resolution to be a cylinder 3 mm long with a nominal diameter of 75 µm. The crossing angle forms a grating fringe spacing d of approximately 8.0 µm. To determine this more precisely, a series of calibration measurements was obtained in atmospheric air. The temperature was measured independently with a thermocouple, and the modulation frequency was measured from the transient grating signal.

To demonstrate the use of the technique in aerodynamic supersonic flows, the static temperature was measured at the exit of pressure-matched Mach 2.0 and Mach 3.9 nozzle flows. In each the air was exhausted into a large tank held at approximately atmospheric pressure. The exit diameters of the Mach 2.0 and 3.9 nozzles were 3.18 mm and 20 mm, respectively. The interaction region was centered on the jet axis approximately 1 mm downstream of the exit for both nozzles. Fig. 2 shows single-shot transient grating signals obtained in atmospheric air (296 K) for calibration and for Mach 2.0 and 3.9 nozzle flows. The oscillation period is observed to decrease

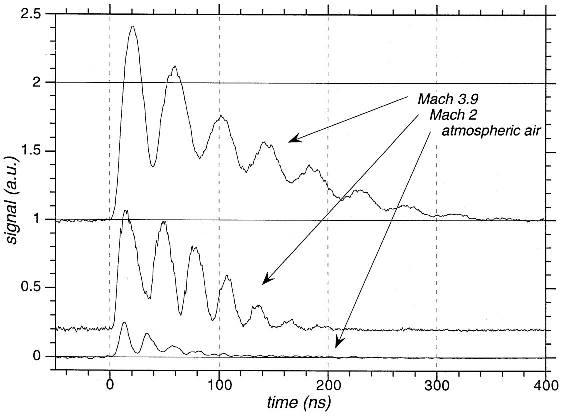

Fig. 2. Transient grating signals recorded in atmospheric air (calibration) and Mach 2 and 3.9 nozzle flows. The three signals are offset for clarity.

with increasing Mach number due to the decrease in static temperature. The diffracted signals are proportional to the square of the density [4], and the increased density of the jet at this lower temperature is apparent when comparing the relative intensity of the three signals. However, an accurate determination of density was not possible as the intensities of the lasers were not monitored for each pulse.

The modulation frequencies were determined from the power spectra of the transient signals. The temperature was calculated from a ratio of the measured frequencies at the unknown and calibration conditions under the assumption that the crossing angle (i.e., grating fringe spacing), gas molecular weight, and specific heat ratio were constant:

$$T = T_c \left(\frac{f}{f_c} \right)^2 . \tag{2}$$

Here, T is the nozzle flow gas temperature, T_c is the calibration gas temperature, and f_c is the calibration gas modulation frequency. The power spectra of the transient signals for the calibration in ambient air and the two nozzle flows are shown in Fig. 3. The uncertainty in each temperature measurement was estimated from the uncertainty of the peak frequency of the sideband feature obtained from the power spectra. At the higher densities of the cooler gas flows, the greater signal intensity and lower acoustic damping rate result in a larger number of oscillations and a well-resolved peak for the sideband; conversely, the faster decay at atmospheric conditions increases the width of the sideband. The uncertainty in the modulation frequency was computed as 1/10 of the full-width at half-maximum of the sideband; from Fig. 3 these are 1.6%, 1.8%, and 2.5% for the Mach 3.9, Mach 2.0, and calibration measurements, respectively. Propagation of errors from Eq. (2) lead to the temperature measurement uncertainties listed in Fig. 3. The measured temperatures agree within their uncertainties with temperatures calculated from perfect gas isentropic flow relations and measured stagnation temperatures. To our knowledge, this is the first demonstration of single-pulse thermometry in unseeded air using resonantly-excited thermal gratings, both under static conditions and at supersonic velocities. Better estimates of the modulation frequency approaching 0.1% uncertainty have been quoted from the use of nonlinear curve fitting to a system model in the time domain that adequately describes the grating evolution [7,15]. Such a fitting procedure requires an accurate knowledge of the experimental conditions including the temporal pulse shape, laser beam profile, detector response, and the correct functional form of the grating formation by thermalization. Without confidence in the fidelity of the system model, the error estimates obtained from nonlinear curve fits may be misleading.

The ability to determine the modulation frequency from the Fourier transform technique is practically

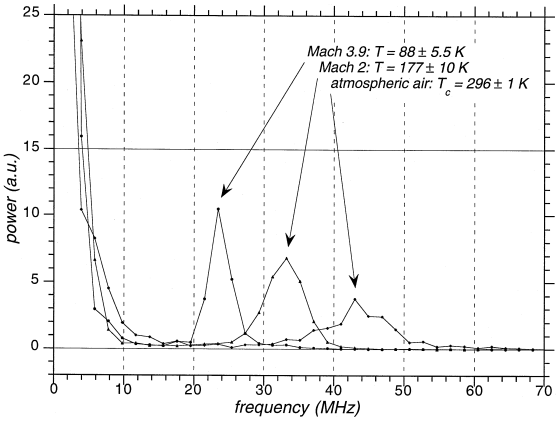

Fig. 3. Power spectra of transient grating signals of Fig. 2. The modulation features are indicated, and the gas temperatures derived from the measured frequencies in the Mach 2 and 3.9 are shown.

limited by noise, and fundamentally by the finite duration of the decaying oscillation. The uncertainty of the modulation frequency can be minimized by increasing the number of resolvable oscillations which, in turn, reduces the spectral overlap between the large component at zero frequency and the sideband at the modulation frequency of interest. Obtaining this condition is a compromise between the modulation frequency, laser pulse duration, acoustic and thermal decay rates, and beam diameter. The upper limit to this approach is determined by the bandwidth of the detection system (detector speed, sampling rate, and sampling record length). In our measurements, the duration of the transient signals is limited by the finite beam size and not by thermal diffusion. Pump beams with a larger diameter were found to produce signals with lower computed frequency measurement uncertainty but also with an accompanying decrease in spatial resolution.

Systematic error in the temperature measurement can result from changes in grating fringe spacing produced by refractive index variations along the beam paths. In particular, the turbulent shear layer between the flow and the ambient air was suspected to cause pulse-to-pulse fluctuations of the pump beam crossing angle. This effect was inferred to be negligible in comparison to the measurement uncertainty. The frequencies obtained from a series of single-pulse measurements were reproducible well within the uncertainty of any single measurement, indicating that refractive index fluctuations through the thin shear layer near the nozzle exit did not contribute any systematic error. In other experiments, however, path-integrated changes in beam angle accumulated over longer distances with index gradients normal to the beam can introduce a significant source of error.

We have demonstrated that thermal gratings in air can be readily created by laser-induced photolysis of oxygen and that single-pulse temperature measurements can be obtained from the transient signal of a Bragg-diffracted probe laser. The utility of this approach for thermometry in aerodynamic test environments was demonstrated with single-pulse measurements in a supersonic flow. Translational temperature measurements using this technique are attractive as unseeded air flows are most commonly used for aerodynamic testing. The pulse power density required for creation of thermal gratings by photolysis of O_2 is small when compared to that typically required for the creation of nonresonant electrostrictive gratings [7,11] with comparable reflectivity under similar conditions. This may be important for temperature measurements in high density flows or flows with significant particulates where the optical breakdown threshold may be exceeded at the focus of the crossed, high-power laser beams. Since the absorbed photon energy (minus the bond energy) is driven directly into the translational energy of the photofragments, the extent of thermalization at near gas kinetic rates is expected to be limited only by collisional excitation by the hot O atom photofragments of long-lived conditions of vibrational and chemical nonequilibrium; relaxation rates of these modes are typically several orders of magnitude smaller than gas kinetic and do not contribute to acoustic wave formation. Such slow thermalization has been observed by other authors and results in the delayed creation of a stationary density grating [9,10]. For our experiments, the available translational energy not promoted to other modes was estimated to be thermalized in less than 1 ns, a time which is faster than the laser pulse and acoustic and diffusive decay. Our measurements illustrate that the most favorable aspect of thermometry with transient grating spectroscopy is that detailed knowledge of the thermalization process is not necessary, providing that it is sufficiently rapid to generate the acoustic waves which modulate the grating reflectivity with maximum efficiency.

Acknowledgements

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