Planar Imaging of a Turbulent Methane Jet

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Introduction

IN this Note, concentration measurements are reported for a round methane jet discharging into air at moderate Reynolds number. The primary objective of this study was to compare concentrations determined by two independent methods, planar digital imaging and gas sampling (physical probe). Since elastic light scattering from small seed particles was used in the optical determination of gas concentration (i.e., marker nephelometry), the experiment also provided information on the adequacy of marker nephelometry at a relatively low Reynolds number.

Experimental

The system studied was a round, free turbulent jet of methane discharging vertically into stationary air. A 2.35 mm diam residential gas furnace nozzle was used. The nozzle was preceded by a large-area-ratio (27:1) premixing section used to insure uniform seeding of the methane with fine marker particles. The jet velocity was 55 m/s and the Reynolds number 7800. A 20 cm diam round exhaust duct was located 20 cm above the exit plane of the fuel nozzle during the imaging experiments. The duct was pulled back an additional 25 cm to accommodate the gas sampling probe.

Gas concentration was measured through gas sampling and planar digital imaging. A slender, 0.5 mm i.d. probe mounted on a three-dimensional traverse mechanism was used for gas sampling. Spatial resolution was ± 0.5 mm. The samples were analyzed on-line by a flame ionization detector (HP 5830A).

Recently, Long et al.[1-3] have developed a technique based on the use of light sheet illumination and a computer-controlled television camera (Vidicon) for two-dimensional imaging of fluid concentration; the method has been applied successfully in elastic light scattering, Ramanography, and fluorescence. Any optical signal of sufficient strength originating in the illuminated plane may be used.

Instantaneous, two-dimensional gas concentration measurements were made by digital imaging of elastically scattered light from small T_iO_2 seed particles uniformly mixed with the fuel. The particles were generated on-line by mixing separate streams of humidified methane and $TiCl_4$ vapor in methane. The elastically scattered light was focused with conventional 35 mm camera lenses onto the face of a computer-controlled silicon intensified target Vidicon detector (PAR 1254 SIT). A high-voltage pulse was used to shutter the image intensifier and expose the detector to the scattered light for a preset period. The detector signal was then digitized as a two-dimensional array (100×100) under computer control and the 10,000 pixel values stored in computer memory or transferred to disk.

Green (0.5145 μm), focused light from an argon ion laser was formed into an 0.3 mm thick light sheet and used to illuminate the jet. The sheet was created by reflection of the laser beam from a rapidly rotating mirror, thus providing a uniform two-dimensional source of illumination.[4] For large fields of view, this method of illumination is preferred over the use of cylindrical lenses, which produce a highly nonuniform light sheet. The exposure was triggered by a photo diode that sensed the arrival of the laser beam at the bottom of the image plane. Exposure time was preset to allow the beam to traverse the desired field of view. The beam velocity exceeded substantially the local velocity, so that the motion was "frozen" at each sampling point. The sampling time was 7 μs for a pixel size of 1.43 mm.

The camera dark noise correction was applied by subtracting a background frame obtained by averaging 1000 blank frames. The average noise level of the background frame was 0.7% or, in absolute terms, about seven counts. Since in a 100×100 format the pixel response was linear to approximately 5000 counts, this background noise introduced an error of 0.14% at full scale (mole fraction unity). The data also had to be corrected for the nonuniform camera response and vignetting in the collection optics. An integrating sphere was used to provide a uniform source of illumination that allowed determination of the overall system response. First, the region of uniform light intensity at the sphere exit orifice (5 cm diam) was defined by imaging small sections of the exit plane for a fixed-frame format, while translating the camera relative to the plane of the exit orifice. It was found that the light intensity was very uniform to within 1 cm of the edge of the orifice. Once this uniform area had been defined, the response frame was measured using the appropriate collection optics and frame format.

A schematic of the system is shown in Fig. 1.

Experimental Results

Mean Concentration Profiles

The gas sampling measurements were intended to provide, primarily, an independent set of data that could be used to assess the validity of the planar imaging measurements. The results indicate that, with careful calibration, planar imaging/marker nephelometry is an excellent method for measuring gas concentration.

Radial profiles were measured through gas sampling at $x/d_j = 8.5$ and 21. A comparison of the normalized radial profiles, as determined by planar imaging and gas sampling, is shown in Fig. 2. The mean concentrations, determined optically, are averages of 100 realizations. Representative physical pixel size was 1.43 mm (square) at $x/d = 21$ and 0.333 mm ($x/d = 8.5$). The agreement between the two sets of data is generally very good. The centerline concentration profiles (Fig. 3) are in excellent agreement. The overall agreement between the two sets of data also indicates that the Reynolds number is sufficiently high that differential diffusion effects are unimportant. Starner and Bilger[5] have estimated that differential diffusion effects in marker nephelometry are negligible in nonreactive jets at $Re > 10,000$. Our measurements support this conclusion.

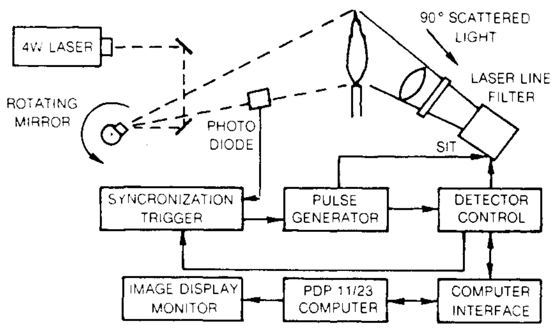

Fig. 1 Planar imaging system.

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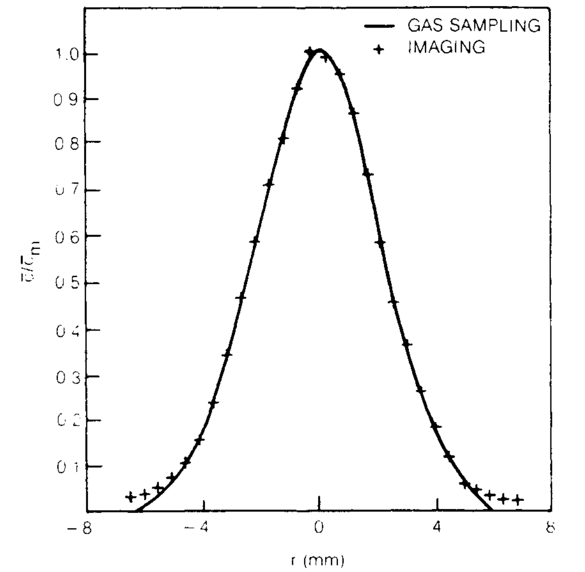

Fig. 2a Comparison of normalized radial concentration profiles, $x = 20$ mm (representative physical pixel dimension is 0.333 mm).

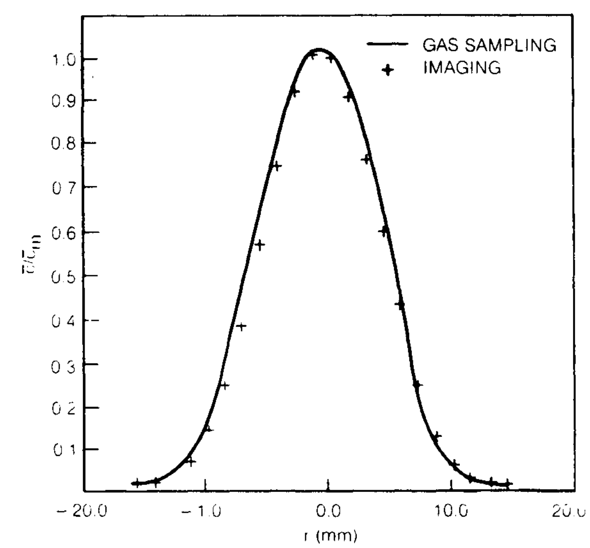

Fig. 2b Comparison of normalized radial concentration profiles, $x = 50$ mm (representative physical pixel dimension is 1.43 mm).

Second Moment of Concentration

Concentration fluctuations (rms) were also measured in this experiment and compared with the point measurements in a methane jet at Reynolds number 16,000 determined through Raman scattering by Birch et al.[6] For the sake of brevity, these results are not discussed here, but will be presented in a future publication. However, excellent agreement was found for $x/d_j > 20$. It is believed that differences in nozzle geometry and possibly other experimental variables led to higher values in this experiment for $x/d_j < 2$; this was consistent with a more rapid decay of the mean concentration along the jet axis than reported in Ref. 6.

Conclusions

Mean gas concentrations, determined by two independent methods, planar imaging/marker nephelometry and gas sampling, are in overall good agreement. Fluctuations in the rms concentration agree qualitatively with other published data. Thus, it is concluded that planar imaging/marker nephelometry may be used with confidence in the quantitative measurement of gas concentration in jets. Differential diffusion effects in marker nephelometry are not important in the methane/air jet at a Reynolds number of 7800 and, furthermore, the turbulent transport is convectively controlled.

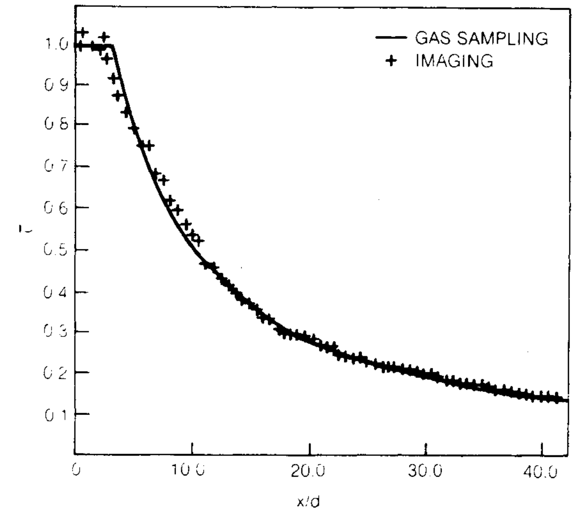

Fig. 3 Comparison of concentration profiles along the jet centerline.

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References

[1]Chang, R. K., Long, M. B., Murphy, D. V., and Chu, B. T., "Laser Scattering for Concentration and Temperature Determination in Turbulence and Combustion Studies," Paper presented at International Conference on Lasers, Beijing, 1980.

[2]Long, M. B., Chu, B. T., and Chang, R. K., "Instantaneous Two-Dimensional Gas Concentration Measurements of Light Scattering," *AIAA Journal*, Vol. 19, Sept. 1981, pp. 1151-1157.

[3]Long, M. B., Fourquette, D., and Escoda, M. C., "Instantaneous Ramanography of a Turbulent Diffusion Flame," *Optics Letters*, Vol. 8, May 1983, pp. 244-246.

[4]Lysaght, A.J.P., Bilger, R. W., and Kent, J. H., "Visualization of Mixing in Turbulent Diffusion Flames," *Combustion and Flame*, Vol. 46, No. 1, April 1982, pp. 105-108.

[5]Starner, S. H. and Bilger, R. W., "Differential Diffusion Effects on Measurements in Turbulent Diffusion Flames by the Mie Scattering Technique," *AIAA Progress in Astronautics and Aeronautics: Flames, Lasers, and Reactive Systems*, Vol. 88, edited by J. R. Bowen, W. Manson, A. K. Oppenheim, and R. I. Soloukhin, AIAA, New York, 1981.

[6]Birch, A. D,, Brown, D. R., Dodson, M. C., and Thomas, J. R., "The Turbulent Concentration Field of a Free Jet," *Journal of Fluid Mechanics*, Vol. 88, Pt. 3, 1978, pp. 431-449.