Planar Imaging of Jet Mixing in Crossflow

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Abstract

A UNIQUE experiment has been developed for the study of jet mixing in crossflow. The scalar mixing of a round jet discharging normally into a ducted flow is studied through planar nephelometry. Simultaneous, multiple-point fluid concentration measurements are made for a variety of flow conditions in a simulated gas turbine combustor. The field measurements are in good agreement with the point-to-point measurements of other investigators. The potential for studying more practical, multijet configurations is evident.

Contents

Jet engine turbine lifetimes depend critically on the gas temperature distribution at the turbine inlet. The gas leaving the combustor primary zone must be cooled and the temperature profile flattened in order to preserve turbine integrity. Cooling is usually achieved by injecting compressor discharge air normal to the hot flow through holes in the combustor liner. The size, geometry, and location of these holes control the combustor exit temperature distribution. An improved understanding of mixing in crossflow is, therefore, of significant practical importance. A new approach to studying mixing in crossflow is described below. A generic experiment consisting of planar digital imaging of a single round jet discharging into a uniform crossflow is described. The study of more complex, multijet configurations is in progress.

Experiment

The configuration chosen for study represents a sector of an annular gas turbine combustor. In these initial experiments, the geometry and flow conditions at the boundaries are simplified to facilitate the interpretation of the data and to allow comparison of the results with those of other investigators.

The apparatus is shown schematically in Fig. 1. The working section consists of three parallel contiguous ducts of rectangular cross section, simulating a sector of an annular gas turbine combustor. Sector width is 30.5 cm. The inner combustor duct is 10 cm high, and side viewing is allowed through a 30.5 cm × 10 cm × 0.16 cm pyrex window. The outer ducts, which supply the injectant gas and simulate gas turbine combustor shroud passages, are each 2.54 cm high and fed by a two-dimensional 2:1 ratio contraction nozzle to provide a more uniform approach flow. These are separated from the inner duct (combustor) by removable 3-mm-thick flat-plates. The injectant is fed to the combustor through holes of various sizes and shapes that are machined into the plates.

In the present experiment, the injectant (air) was fed through a single round hole in the upper plate only. The hole was beveled inward at 40 deg and brought to a sharp edge at the discharge plane. The jet velocity was varied independently of the shroud velocity by regulating pressure drop across the injection orifice through a system of fixed and variable area orifices located downstream of the injection point. Jet velocities are based on the difference between shroud midstream total pressure and combustor static pressure. Velocity profiles at the shroud and combustor inlet planes were measured by hot-wire anemometry. The maximum variation in the mean approach velocity was 6% in the combustor and 10% in the shroud, before contraction. Turbulence levels were about 1.3%. All gas flows were metered using critical flow orifices. The experiments were conducted at suffiently high Reynolds number so that the jet properties, as determined experimentally, were independent of Reynolds number. Jet velocities were sufficiently low to eliminate compressibility effects. Relative combustor, shroud, and jet velocities were varied about representative values for gas turbine engines. The working fluid was air at ambient temperature.

Planar digital imaging has been demonstrated as an effective, quantitative diagnostic technique in small laboratory jets by Long et at.[1] The extension of planar digital imaging to a larger-scale, practical-flow configuration is a new application. Planar nephelometry measurements were made by marking the flowfield with small aerosol particles introduced into the shroud flow upstream of mixing baffles. A thin sheet of light formed by reflecting the beam of an unfocused argon-ion laser into a rapidly revolving mirror illuminated a cross section of the flowfield. The elastically scattered light was imaged onto a low-light-level vidicon camera and digitized. The fluid motion was frozen by exposing the detector for 250 μs coincident with a single sweep of the laser beam through the flowfield. The light sheet was approximately 0.5 mm thick and passed through the midplane of the injection port. The rotation rate of the mirror was sufficiently fast so that all measurements within the frame are considered simultaneous. Each digitized image contains 6700 simultaneous measurements of injectant gas concentration in a 100 × 67 point format. Pixel dimensions were 1.5 × 1.5 × 0.5 mm^3 corresponding to a frame dimension of 10 × 15 cm.

Statistical measurements were based on 300 data frames. This number of trials provides reasonably accurate estimates of both the mean and rms concentration while minimizing the time to conduct the experiments and process the data. The sampling error in the mean and rms concentration measurements, presented below, is about 2 and 7%, respectively.

Mean Properties

The origins of both the Cartesian (X,Y) and curvilinear (X,ξ) systems are located at the center of the injection port. The X axis is aligned with the axis of the injection tube or orifice, and the Y axis is parallel to the direction of the main

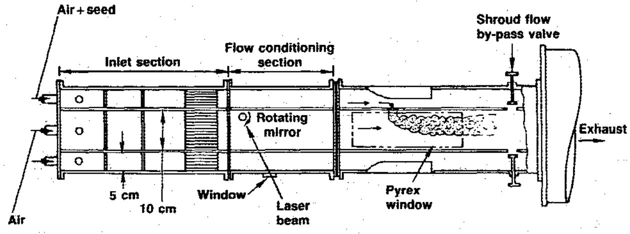

Fig. 1 Schematic of apparatus.

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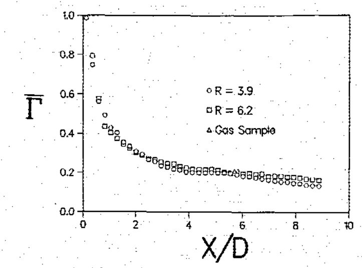

Fig. 2 Effect of velocity ratio on concentration along the trajectory.

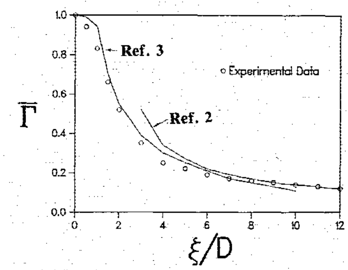

Fig. 4 Comparison of concentrations along the trajectory.

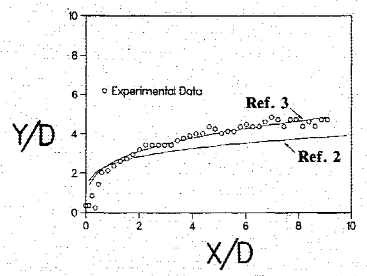

Fig. 3 Comparison of trajectories.

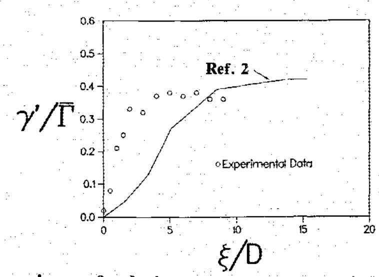

Fig. 5 Comparison of relative concentration fluctuation intensities along the trajectory.

flow. The local coordinate ξ, which defines the jet trajectory, is the locus of points of maximum mole fraction along the Y axis.

An important characteristic of the system is the rate at which the jet mixes with the surrounding fluid. The mixing is characterized by the rate at which the concentration along the trajectory changes with X or ξ. For practical purposes, where combustor length is an important consideration, the rate at which the concentration along the trajectory decreases with X must be considered. Typical results are shown in Fig. 2, where concentration along the trajectory is plotted as a function of X/D for $R = 3.9$ and 6.2. It is seen that the mixing rate, in the sense of concentration decay with X, is only a weak function of velocity ratio over this range of R. The decrease in concentration is initially very rapid as the mole fraction of injectant decays to 0.5 in about one jet diameter. For $X/D \geq 3$ the decrease is much slower. It is noted that an independent check on the optical measurements was made by gas sampling. The jet was seeded with methane and the flow sampled with a small sampling probe at a downstream position. The injectant mole fraction was inferred from methane concentration, as measured by a flame ionization detector, and is shown in Fig. 2.

The field measurements have been compared with the point-to-point measurements of other investigators. Although exact comparisons are precluded because of differences in experimental conditions, the results are generally supportive of the field measurements.

Jet trajectory for pipe-fed injection at $R = 3.9$ (symbols) is compared in Fig. 3 with empirically based correlations developed by Rathgeber and Becker[2] and Kamotani and Greber.[3] The present data are correlated reasonably well by the expression given in Ref. 3:

$$\frac{Y}{D} = 0.76\left(\frac{\rho_j V_j^2}{\rho_0 V_0^2}\right)^{0.52}\left(\frac{\rho_j}{\rho_0}\right)^{0.11}\left(\frac{X}{D}\right)^{0.29} \tag{1}$$

The expression given in Ref. 2 represents a large body of nephelomentry measurements for crossflow injection of air through a tube into a fully developed turbulent pipe (air) flow, whereas that of Ref. 3 represents mean temperature measurements for injection of slightly heated air from a nozzle into an infinite duct with uniform approach flow. In view of the differences in geometry and approach flow conditions, the agreement with the results of other investigators is satisfactory. As a practical matter, trajectories were compared at two levels of shroud velocity with orifice pressure drop held constant. Little effect of shroud velocity was found in the range studied. It is felt that the experimental conditions of Ref. 3 more closely resemble those of the present investigation. This becomes more apparent in the comparison of mean concentration profiles along the trajectory.

Mean concentration $\bar{\Gamma}$ along with jet trajectory for pipe-fed injection at $R = 3.9$ is compared in Fig. 4 with correlations developed in Refs. 2 and 3. The choice of ξ/D as the independent variable is consistent with that presented by these investigators. The curve corresponding to Ref. 3 represents data for the decay of maximum temperature from a slightly heated jet and thus provides a valid measure of the rate of scalar mixing. The agreement with the data of both Refs. 2 and 3 is quite reasonable. In the near field, $\xi/D \geq 4$, the differences relative to the data of Ref. 3 are most likely due to differences in experimental conditions, described above.

Fluctuations

Relative concentration fluctuation intensity $\gamma'/\bar{\Gamma}$ along the ξ axis at $R = 3.9$ is compared in Fig. 5 to that reported in Ref. 2. It is encouraging that the present data approach the same asymptotic limit, 0.4, found in Ref. 2. Spatial integral scales, determined from spatial covariance measurements, agreed with those reported in Ref. 2.

Conclusions

A unique experimental apparatus has been designed for the study of crossflow jet mixing. The utility of planar digital imaging/marker nephelometry in the quantitative measurement of scalar mixing in a complex flow has been demonstrated in this very practical application. Results are in agreement with point-to-point measurements of other investigators. The technique may be applied to more complicated flows for the study of jet interactions and to study the influence of variable fluid properties. Indeed, experiments of this nature are being performed at this time and are proceeding with no special difficulties.

References

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