Thermal Measurements for Jets in Disturbed and Undisturbed Crosswind Conditions

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Abstract

JETS of low-temperature air are introduced into the aft sections of gas turbine combustors for the purpose of cooling the high-temperature gases and quenching the combustion reactions. Research studies, motivated by this complex flowfield, have been executed by introducing a heated round jet into the cross stream of a wind tunnel. The investigation by Kamotani and Greber[1] stands as a prime example of such investigations and it serves as the principal reference for the present study. Recent references which provide for the reader's access to related literature are provided by Holdeman et al.[2] and Andreopoulos.[3]

The low disturbance level of the cross stream in the Kamotani and Greber study and in similar research investigations is compatible with an interest in identifying the basic features of this flowfield. The influence of the prototype's strongly disturbed crossflow is not, however, made apparent in these prior investigations. The present study provides a direct comparison of the thermal field properties for a low-disturbance ($\tilde{u}/V_\infty = 0.67\%$) and a high-disturbance ($\tilde{u}/V_\infty \simeq 34\%$) level condition. The latter disturbance field was established near the edge of a large shear layer and it served to buffet the jet at a low frequency ($fd/V_\infty \lesssim 1$).

A novel technique was used for this experimental investigation (Fig. 1). Sixty-four fast response thermocouples were simultaneously sampled and corrected for their time constant (λ) effect (see Wark and Foss[4] for details) at a downstream plane close to the jet exit ($x_o/d = 3$-4). Various measures were used to characterize the thermal fields for the disturbed and undisturbed conditions, for two different ranges of the momentum flux ratio ($J = \rho_j V_j^2/\rho_\infty V_\infty^2 = 17$-$21$ and 67-84), and for three overheat conditions ($T_j - T_\infty = 22.2$, 47.1, and $61.1°$C). The cross stream speed V_∞ was 2 m/s and the jet diameter d was 10 mm.

Two forms of data acquisition were used for this study. Stochastic values were obtained from triplet values $T_k(t - \delta t)$, $T_k(t)$, and $T_k(t + \delta t)$, where $k = 1....64$ is the thermocouple designation and the $\pm\delta t$ ($\delta t = 0.64$ ms) values were used to form the central difference time derivative from which the corrected temperature value $[T_k(t)]_c$ was determined.

$$[T_k(t)]_c = \lambda \frac{dT_k}{dt} + T_k \cong \lambda \frac{[T_k(t+\delta t) - T_k(t-\delta t)]}{2\delta t} + T_k(t) \quad (1)$$

where λ is the thermocouple time constant. Temperature variance contours are provided in the companion report of Wark and Foss.[4] Instantaneous samples $\delta t = \Delta t = 0.64$ ms and $N = 1225$ were stored for $J = 21$ and 84 and for $T_j - T_\infty = 61.1°$C.

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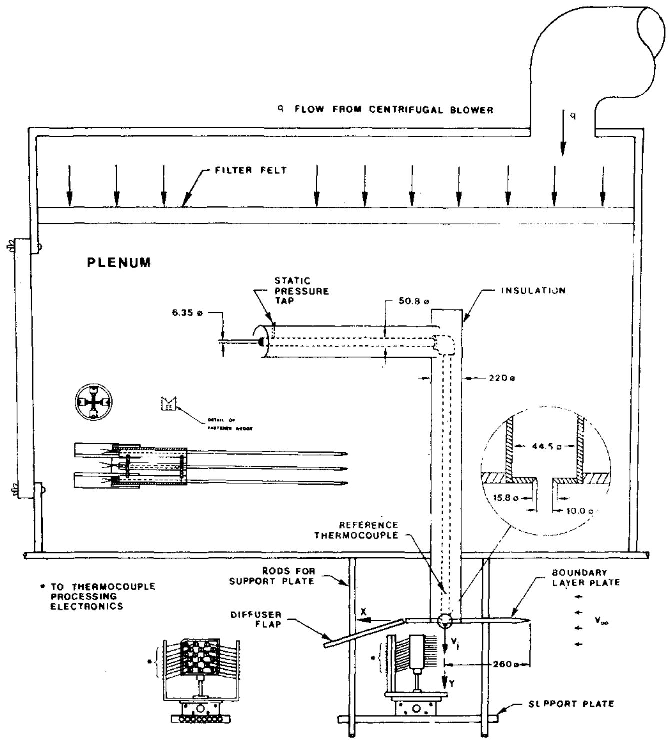

Fig. 1 The experimental facility.

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Stochastic temperature values $\bar{T}_{m,n} = \bar{T}(x_o, y_m, z_n)$ were acquired at $x_o/d = 3.9$ for $J \le 21$ and at 3.5 for $J \ge 67$. These values were used to prepare mean and instantaneous isothermal contours for the above noted J and T_j values. Figure 2 provides an example of each set of contours for a disturbed crossflow condition. The mean isothermal contours for the same J and T_j values in an undisturbed crossflow (results not included herein) show a significantly higher maximum value than the maximum value (approximately 90) of Fig. 2. The approximate parity of the peak values ($\simeq 130$) in the instantaneous data sets (undisturbed case is not shown here), however, suggests that the difference in the mean values should be attributed to the jet column migration and not to enhanced molecular diffusivity effects.

The jet centerline, identified by the centroid of the thermal field, is shown as a function of the momentum flux ratio (J) in Fig. 3. The location of the centerline, at a given streamwise location, is taken as a measure of the "jet penetration". The primary J variation is provided by two different volume flux values at the inlet to the heater tube, and the secondary variations are provided by the density variation as a result of the change in the jet temperature. An instructive result, from this figure, is the lesser penetration for the disturbed case; the larger disturbance level can be considered to provide larger Reynolds stresses in the jet crosswind interaction region.

The boundary conditions for the present study and for the Kamotani and Greber study differ as a result of the bound-

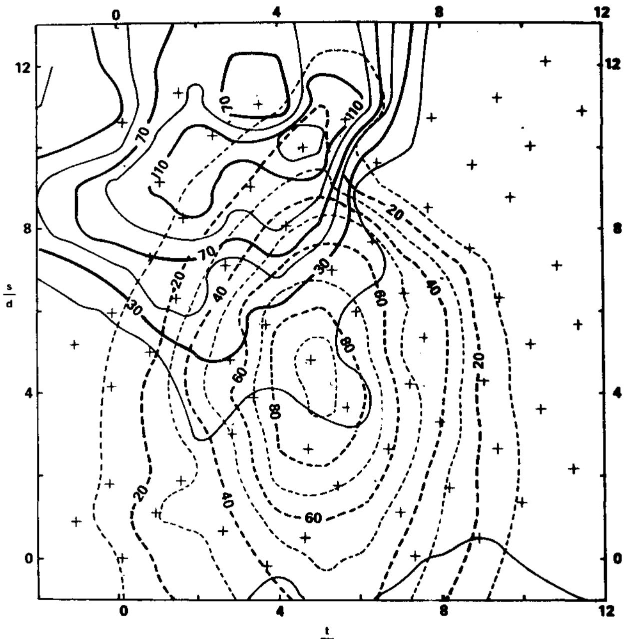

Fig. 2 Time mean (dashed) and instantaneous (solid) isothermal contours for the disturbed crossflow condition $J = 84$, $T_j - T_\infty = 61.1°C$. The symbol "+" shows the locations of the thermocouples in the vertical (s) and lateral (t) directions. The array is positioned such that $(s/d) = 16.8\ (\pm 0.7) - z/d$ and $(t/d) = 4.2\ (\pm 0.5) - y/d$. Indicated contours are $\{[T(x,y) - T_\infty]/[T_j - T_\infty]\} \times 1{,}000$.

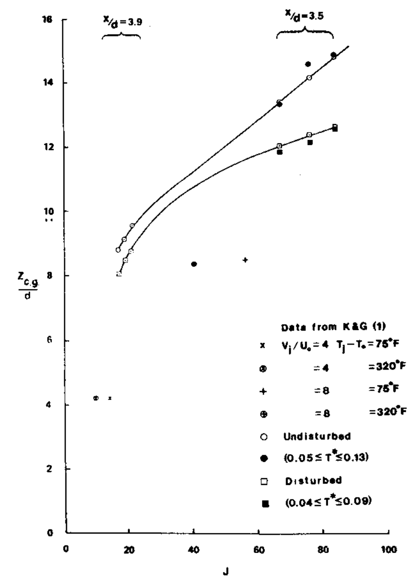

Fig. 3 Centroidal positions of the jet's thermal field.

ary-layer thickness at the orifice [$\delta/d \simeq 1.3$ for the present investigation compared to a "thin" $(\delta/d) < 0.1$ boundary layer for Kamotani and Greber] and the use of a sharp edge orifice (present) compared to a contoured nozzle (Kamotani and Greber). The influence of these factors may be assessed by comparing the penetration distance for the two studies at the same x/d for a given J value. By interpolating to the J value of 56.5, which is inferred to describe the Kamotani and Greber $R = 8 = V_j/V_\infty$ case, and by incorporating the nominal value of $z_{\max}$ (maximum temperature)/$z_{c.g.} \simeq 1.03$, which is inferred from the present data, $z_{\max}/D$ values at $x/d = 3.5$ can be obtained for the two studies. For Kamotani and Greber, $z_{\max}/d = 8.7$, whereas $z_{\max}/d = 12.5$ (a 44% increase) for the present study. Hence, the boundary condition differences are seen as quite significant.

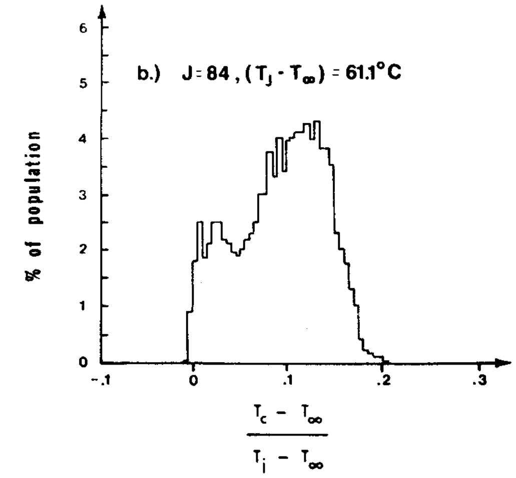

Fig. 4 Histograms of the temperature time series recorded at $s/d = 5.5$, $t/d = 3.7$ for the disturbed crossflow condition.

The mean isothermal contours (Fig. 2) did not exhibit the kidney shape pattern that is evident in the plane perpendicular to the centerline trajectory of the Kamotani and Greber isotherms initially observed by Keffer and Baines[5] in their velocity field contours. Since other jet studies have shown the expected shapes at similar measurement planes and momentum flux values, it is inferred that the absence of the kidney shape may be caused by the sharp-edge orifice of the present study, or (as suggested by a referee) the relatively large boundary layer ($\delta/d \simeq 1.3$) may strongly alter the secondary flow associated with the bound vortices.[5]

Histograms, formed from independent samples, were sufficiently smooth to approximate a probability density function. An example is shown in Fig. 4 for a thermocouple from the central region of the jet. A striking result, from all such histograms, is that the peak (nondimensional) temperature did not exceed 0.25. Hence, even at the relatively close x/d locations of the present study, molecular diffusivity has played a dramatic role in the reduction of the temperature for the fluid elements of the jet.

The instantaneous planes of the temperature field allow the centroid to be computed using the temperature values as discrete mass points. The standard deviations σ of the centroidal position in the z and y directions were computed. The larger migration of the disturbed case is evident in the numerical values of $\sigma_z/d = 0.34$ and 0.233 compared to 1.84 and 1.16 for the undisturbed and disturbed $J = 21$ and 84 conditions, respectively. Similarly, the larger migrations are shown by the results $\sigma_y/d = 0.25$ and 0.23 compared to 1.45 and 1.12 for the undisturbed and disturbed $J = 21$ and 84 conditions, respectively.

Acknowledgments

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