Measurements in a Large-Angle Oblique Jet Impingement Flow

J.F. Foss*
Michigan State University, East Lansing, Mich.

Abstract

THE flowfield associated with the oblique impingement of an axisymmetric jet (see Fig. 1) is of interest as a result of its presence in numerous technological problems. Prominent among these is the externally blown flap (ebf) configuration for STOL aircraft. An extensive study of the shallow angle ($0 \leq \alpha \lesssim 15$ deg) case has been summarized by Foss and Kleis.[1] The present communication is concerned with a more complicated large-angle case, viz., $\alpha = 45$ deg. Prior experimental studies provide some insight into the structure of the large-angle flowfield. Donaldson and Snedecker[2] investigated a wide range of Mach numbers, jet-plate spacings, angles, and impact plate dimensions via surface pressure and centerplane velocity measurements. Westley et al.[3] provide surface rms pressure measurements. Fink[4] has examined the acoustic characteristics of the large-angle impinging jet flows and has advanced some interpretations of the probable turbulence structure associated with them. Given the information base of these studies, and recognizing the motivation of the ebf configuration, a detailed study of the $\alpha = 45$ deg, $h/d = 4.95$ oblique jet impingement flow was deemed to be appropriate. The Reynolds number, $u_0 d/\nu$, was 4.8×10^4; this value is considered to be sufficiently large that qualitatively similar results are expected for larger Reynolds numbers which may be found in flows of technological interest. The jet Mach number was approximately 0.1.

Contents

The experimental configuration allowed radial and vertical traverses with respect to the intersection of the jet centerline ($\alpha = 45$ deg) and the horizontal impact plate. The computer-controlled probe positioning system allowed the angle of the time-mean velocity vector, $\langle \beta_0 \rangle$, to be determined as well as the velocity components U_r, U_θ, $\overline{u_r^2}$, $\overline{u_\theta^2}$, $\overline{u_r u_\theta}$. Details are given in the full paper. [Note: ($\tilde{}$) denotes rms fluctuation intensity of ( ).]

The results of the experimental investigation are summarized in Figs. 2-6. A numerical tabulation of these results is presented in the full paper. The vertical traverse data of Fig. 2 showed that the maximum velocity, and hence the "dividing plane" between the positive and negative, transverse, mean vorticity ($\bar{\omega}_T \equiv \partial \bar{U}_s / \partial z - \partial \bar{W} / \partial s$ where $\bar{W}$ is the time mean vertical velocity component), is located at approximately $z/d = 0.05$. A series of radial velocity traverses were executed near this elevation to document the velocity field in this near-wall region; these results are presented in Fig. 3. The flowfield revealed by these traverses can be described in terms of two non-axisymmetric, apparent-source points. The velocity vectors within $\simeq 1$ diameter of the geometric origin appear to originate from $r/d \simeq 1$ and $\theta = \pi$. A second apparent origin at $r/d = 0$ describes the velocity field for large ($\gtrsim 3$) r/d

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*Professor, Dept. of Mechanical Engineering. Member AIAA.

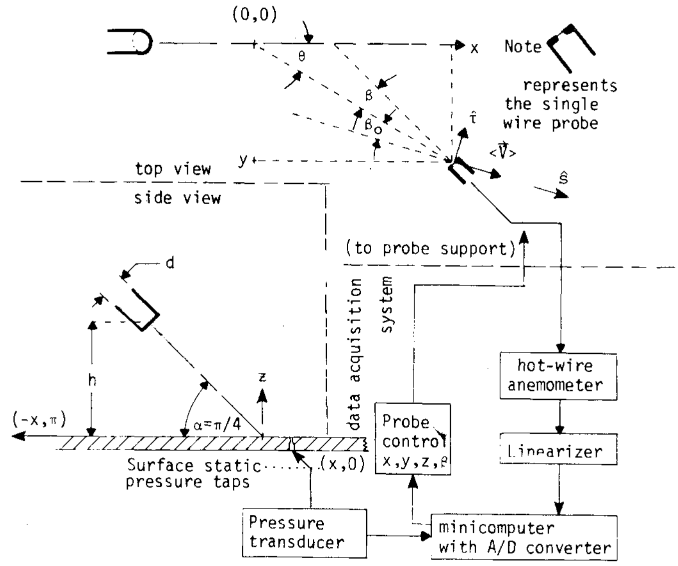

Fig. 1 Schematic of experimental system and definition of terms. Note: $r^2 = (x^2 + y^2)$ and $\theta = \arctan y/x$.

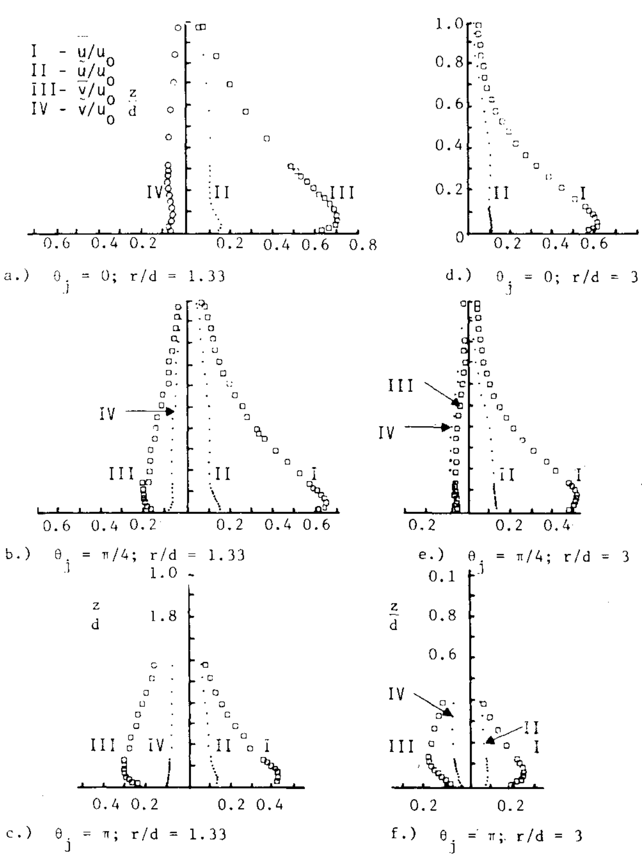

Fig. 2 Vertical traverses to record the mean and fluctuation intensities at selected (r, θ) locations. Conditions: $h/d = 4.95$; $u_0 d/\nu = 4.8 \times 10^4$, $\alpha = 45$ deg.

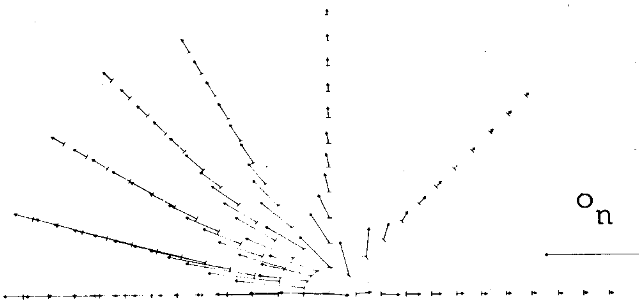

Fig. 3 Composite view of the time-mean velocity field in the plane $z/d=0.053$. Conditions as in Fig. 2; length scale of plot: data points acquired for each 2 $d/3$ along the radial lines shown.

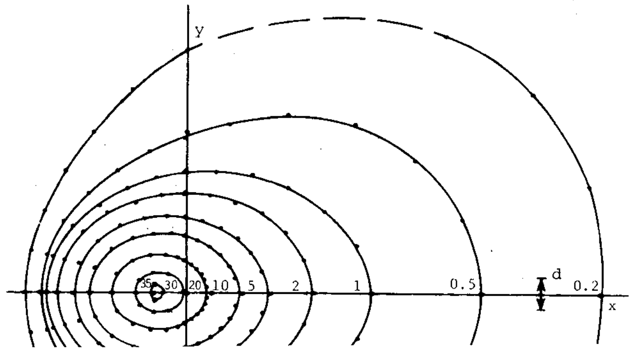

Fig. 4 Surface pressure isobar contours. Level curves shown represent $(p-p_{atm})\times 100/(\rho u_0^2 \lambda \sin\alpha)$ where $\lambda=\int_{A_{jet}} (u/u_0)^2 \, dA/A_{jet}=0.809$.

locations. Isobars, formed from surface static pressure measurements, show that the upstream source point (i.e., the kinematically defined stagnation point) is also the location of the maximum static pressure (see Fig. 4). This is in contrast with the shallow angle observations in which the stagnation point is quite far upstream of the maximum pressure location (see Foss and Kleis[1]).

The oil-streak, flow visualization observations of Westley et al., reveal similar effects in the near-wall region of the large-angle, jet impingement flowfield. The flowfield above the surface will recover a dominant streamwise character; the vertical velocity traverses of Fig. 2 partially reveal these changes in the flow direction.

The presence of the plate with the consequent no-slip condition and the strong velocity gradients might lead to the a priori expectation that the turbulence energy level near the plate is greater than that to be expected if the plate were absent. This expectation is not supported by the data. Figure 5 is a composite plot of the turbulence intensity information from the radial traverses. In order to compare the turbulence levels near the plate with the turbulence level of the jet itself, the data for the condition $z/d=0.053$ and $\theta=90$ deg have been plotted on the same figure with the radial traverse data of $x/d=6$ and 8, from Kleis and Foss[5] (see Fig. 6). This comparison appears to be the most reasonable basis from which to evaluate the relative turbulence level created by the impingement process given the avaliable experimental data. However, it is not unambiguous. A preferable comparison would be on the basis of a volume integral of the turbulence energy in a given streamwise domain. Such an integral could be readily formulated for the axisymmetric case, but would require an extensive series of traverses in the three-dimensional impingement flow. The vertical traverse data of Fig. 2 show that the turbulence intensity magnitudes in the plane $z/d=0.053$ are representative of the maximum values for these quantities in the impingement flow, albeit there is a slight increase in the steep gradient $(\partial U_r/\partial z)$ region for

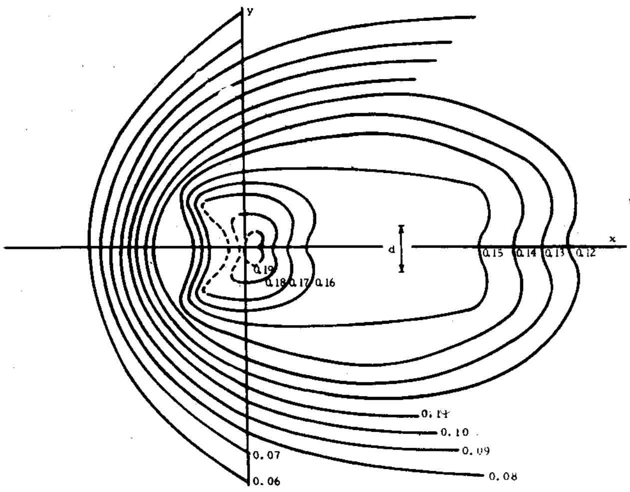

Fig. 5 Turbulence intensity contours at $z/d=0.053$. Conditions as in Fig. 2; level curves shown represent $[\tilde{u}_r^{2}+\tilde{u}_\theta^{2}]^{1/2}/u_0$.

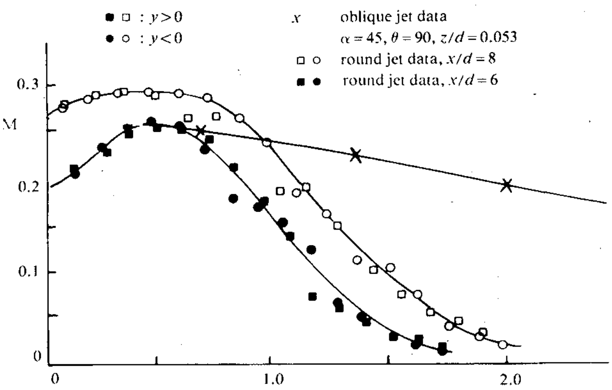

Fig. 6 Comparison of turbulence intensity level for impinging and free jets. Note: $M=(\tilde{u}_x+\tilde{u}_r)/u_0$ for the free jet and $(\tilde{u}_r+\tilde{u}_\theta)/u_0$ for the impinging jet.

$z<0.053d$. The suppression of the turbulence intensity and the Reynolds stresses by concave curvature is discussed at length by Bradshaw[6] along with numerous other effects. The present observations regarding the maximum turbulence intensity values are compatible with these considerations. The rms surface pressure data of Westley et al.[3] indicate two maxima located up and downstream of the origin. Apparently, these are related to the stagnation point and to the local maxima in the turbulence intensity magnitudes observed in the present data.

Acknowledgment

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References

[1] Foss, J.F. and Kleis, S.J., "Mean Flow Characteristics for the Oblique Impingement of an Axisymmetric Jet," *AIAA Journal,* Vol. 14, June 1976, p. 705.

[2] Donaldson, C. DuP. and Snedecker, R., "A Study of Free Jet Impingement, Part 1. Mean Properties of Free and Impinging Jets, *Journal of Fluid Mechanics,* Vol. 45, 1971, p. 2.

[3] Westley, R., Woolley, J.H. and Brosseau, P., "Surface Pressure Fluctuations from Jet Impingement on an Inclined Flat Plate," AGARD Symposium on Acoustic Fatigue, AGARD, CP-113, 1972.

[4] Fink, M.R., "Mechanisms of Externally Blown Flap Noise," AIAA Paper 73-1029, Seattle, Wash., Oct. 1973.

[5] Kleis, S.J. and Foss, J.F., "The Effects of Exit Conditions on the Development of an Axisymmetric Turbulent Free Jet," Third Year Tech. Rept., Grant No. NGT 23-004-068, 1974.

[6] Bradshaw, P., "Effects of Streamline Curvature on Turbulent Flow," AGARDograph No. 169, Aug. 1973.