Measurements of a Zero-Pressure-Gradient Boundary Layer Blown by an Asymmetric Jet

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Abstract

MEASUREMENTS were made in a two-dimensional wall jet submerged under a thick upstream boundary layer and advancing into a zero-pressure-gradient flow with the ratios of jet velocity to the freestream velocity confined to a practical range (<2). The effect on the flow development of an asymmetric wall jet velocity profile with a relatively higher concentration of momentum away from the wall was investigated. The flow was computed using an existing method for blown boundary layers and the results show good agreement with experimental data.

Contents

The flow of a wall jet mixing tangentially with an external stream finds its primary application in the control of boundary-layer separation. Most earlier work on wall jets has been concerned with the case where the ratio of jet velocity to freestream velocity is in the range of 2 to infinity, with the resulting profile consisting of only a local maximum. However, the practical range of velocity ratios is between 1 and 2 and the wall jet usually mixes with a thick upstream boundary layer that is approaching separation, resulting in a velocity profile with both local velocity maximum and minimum. For this case the available data, especially the turbulence properties, are limited. Hence, the present study concentrates on the mean velocity and turbulence properties of such an incompressible two-dimensional turbulent wall jet advancing into a zero-pressure-gradient flow.

Most investigators of wall jets have used jet velocity profiles which were symmetric about the centerline of the slot. However, it is interesting to examine the effect on the flow development of an asymmetric jet velocity profile with a higher concentration of momentum near the slot lip for a given value of the total jet momentum. Such a jet velocity profile would not only energize the momentum-deficient upstream boundary layer better but also result in relatively less frictional loss due to smaller velocity gradients at the wall: this conclusion is supported by the experiments of Joshi and Yu[1] on jet-noise reduction. In comparison, in the case of a symmetric jet velocity profile a large momentum-deficit region may develop downstream and away from the wall, leading to eventual earlier wall separation.

The wind tunnel, including the wall jet system, is described in detail by Simpson and Saripalli.[2,3] The tunnel has a test section 24-cm wide and 196-cm long, with a nominal freestream turbulence intensity of 0.2%. The wall jet issued from a two-dimensional nozzle (slot height y_c of 2.72 mm) designed to provide an asymmetric mean velocity profile at the nozzle exit.

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References 2 and 3 document experimental data taken at several streamwise stations, a brief summary of which is presented here. Figure 1 shows the mean velocity (U) and turbulence profiles at $x/y_c = 0.292$, where x is the streamwise distance from the slot and U_∞ the freestream velocity. The velocity profile in the jet is asymmetric and a thick, turbulent upstream boundary layer exists above the slot. The turbulence in the wall jet is typical of a two-dimensional channel flow. The representative mean velocity profiles (Fig. 2) show that the upstream boundary layer is completely absorbed by the jet as the flow proceeds in the downstream direction.

The variation of the profile parameters y_{max}, y_{half}, y_{min}, U_{max}, and U_{min} and the integral parameters C_f (skin friction coefficient), δ_2 (momentum thickness), and δ_l (displacement thickness) are presented in Fig. 3. U_{max} and U_{min} are the maximum and minimum velocities, y_{max} and y_{min} the corresponding y locations, and y_{half} the location where $U=(U_{max}+U_{min})/2$. Previous research on wall jets showed that y_{max}/y_c can be expressed as a univeral linear function (Fig. 3a) of the distance x/y_c for self-preserving wall jet flows. The data also indicate that for symmetric injection through the slot, the development y_{half} is not universal; and its growth rate is always higher than that of y_{max}. The present non-self-preserving wall jet flow has a growth rate of y_{max}, higher than that of the universal distribution, and the growth rate of y_{half} is approximately equal to that of y_{max} instead of being higher as shown in Fig. 3a. Both are attributed partially to the asymmetric jet velocity profile.

The inner layer for an asymmetric profile spreads outward more rapidly because of the greater velocity gradient between the inner and outer flows. Therefore, the position of maximum velocity (y_{max}) in the case of an asymmetric profile moves more rapidly into the outer layer than that of a uniform jet velocity profile. On a similar basis, the outer layer tries to extract more momentum from the inner layer rather than from the freestream, resulting in a slower growth of the outer layer and, hence, a slower growth rate of y_{half} compared to that of y_{max}.

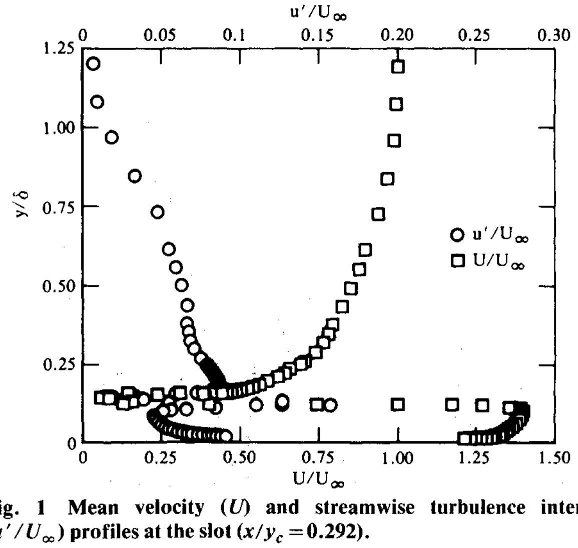

Fig. 1 Mean velocity (U) and streamwise turbulence intensity (u'/U_∞) profiles at the slot ($x/y_c = 0.292$).

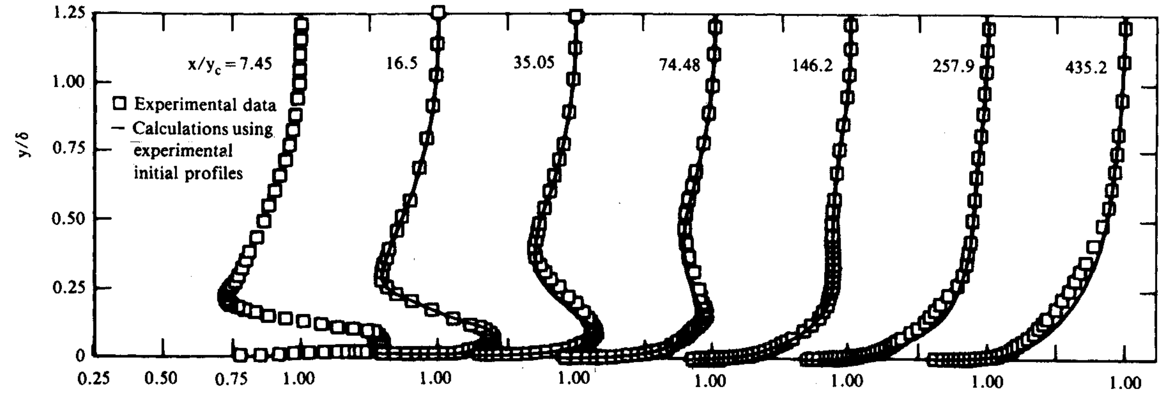

Fig. 2 Mean velocity profiles downstream of the slot.

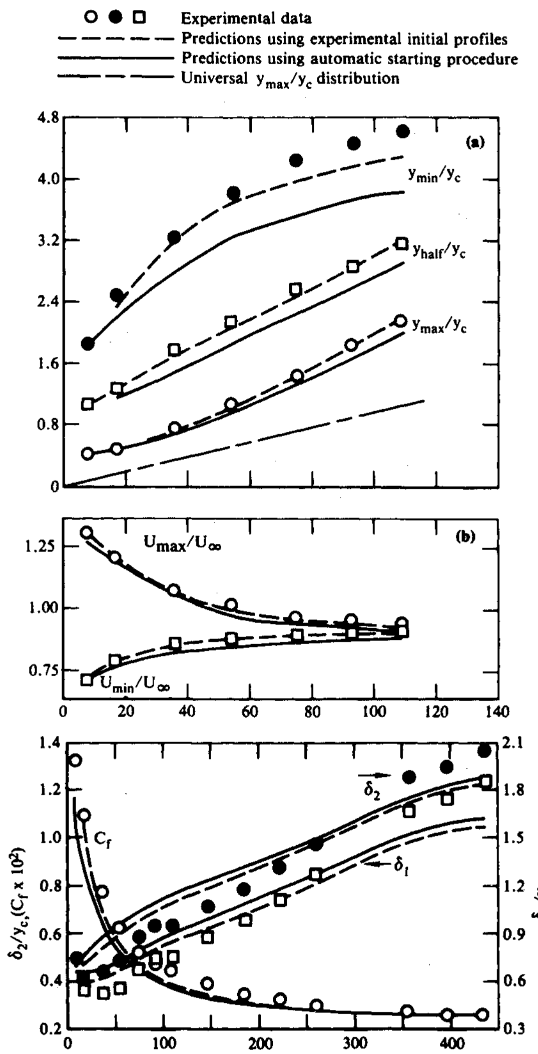

Fig. 3 Variation of the profile and integral parameters.

The turbulent shear stress data measured with a slant-wire probe show two points of zero crossing near the velocity maximum and minimum, respectively. The shear stress data confirm the well-documented result that the inner point of zero shear is always closer to the wall than the point of maximum velocity. The data also reveal that the outer point of zero shear is closer to the wall than the point of minimum velocity. This particular shear stress behavior results in regions of singularity in the distributions of eddy viscosity and length scales, both of which, along with the spectral data, are presented in detail in Refs. 2 and 3.

The subject flow was calculated using the procedure of Irwin[4] which solved a set of equations for the mean flow and the Reynolds stresses. Two types of starting procedures were used to examine the effects of the jet velocity profile. One used the available experimental data as the starting profiles; the other used Irwin's "automatic starting" procedure[4] which developed the initial profiles from a given set of integral parameters at the jet slot while conserving the jet momentum. The resultant automatic starting velocity profile[2-4] which was assumed to represent the case of a uniform jet velocity profile, consists of a uniform velocity profile in the jet, a power law profile for the upstream boundary layer, and a cosine profile for the intermediate mixing layer.

Figures 2 and 3 show the computed representative velocity profiles and the integral and profile parameters, respectively, using different starting procedures. In general, the agreement between the calculations using the experimental initial profiles and the experimental data is generally good; the calculations using the uniform jet velocity profile are in slightly poorer agreement. Both sets of calculations indicate that Irwin's method is somewhat sensitive to initial input profiles and produces results in good agreement with measured data. On the other hand, the level of confidence in the calculation method is not high enough to conclude that the δ_2 and C_f distributions are weakly dependent on the initial jet profile, as Fig. 3 would suggest.

Acknowledgments

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