that this study further demonstrates the many potential benefits of this technique for propulsion applications.

Acknowledgments

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Associate Editor

Streamwise Vortices in the Outer Layer of Wall Jets with Convex Curvature

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Introduction

WALL jets appear where tangential blowing from a slot is used to delay or prevent flow separation in diffusers or on trailing-edge flaps. They also appear on circulation-control airfoils[1] where tangential blowing is used to move the upper-surface stagnation point around the well-rounded trailing edge to produce high values of lift coefficient. In circulation control and often in other applications, the wall jets have substantial convex curvature.

A definition sketch of a wall jet appears in Fig. 1. It can be seen that when there is convex curvature the radial gradient of angular momentum, $\partial(ur)/\partial r$, is negative in the outer layer ($y > y_m$), corresponding to centrifugal instability.[2] Such instability is well known to give rise to Goertler vortices[2] in conventional boundary layers with concave curvature. One of the authors has long suspected that similar streamwise vortices are present in the outer layer of wall jets on convex surfaces.

This suspicion was triggered by measurements of the spanwise distribution of maximum total pressure in the wall jet on the trailing edge of a circulation-control airfoil.[3] Typical data are shown in Fig. 2. The distributions were very nonuniform, with a spanwise distance between successive peaks about equal to the local thickness of the wall jet. Blowing slot thickness and slot-exit total pressure were uniform within 0.5% and 0.25%, respectively, and the trailing edge was smooth to the touch. The particularly large perturbation about 50 mm (2 in.) from midspan corresponds to the spanwise position of a streamlined spacer in the plenum upstream of the slot. There was a contraction ratio of 17 : 1 between the spacer and the slot exit; slot-exit conditions downstream of the spacer were thus very nearly the same as elsewhere. All attempts to eliminate or reduce the spanwise perturbations seen in Fig. 2 were unsuccessful. They were present when freestream velocity over the airfoil was both zero and finite. Very small flow perturbations present at the slot exit were clearly being amplified with distance downstream of the slot. Similar observations were made years later on another apparatus.[4] There is also mention of difficulties with spanwise nonuniformities in the work of Guitton[5] and co-workers. The aforementioned instability mechanism appears to be a plausible cause.

It is well known that the growth rate of wall jets on convex surfaces is much higher than that for plane wall jets; it is generally accepted that this is due to the enhanced turbulent mixing that results from the aforementioned centrifugal instability. The existence of relatively steady streamwise flow structures has, on the other hand, not previously been confirmed and indeed has not been mentioned as a possibility by most authors. If they exist, such vortices could be an important mechanism for radial transport of momentum flux, and they could thus have an important influence on flow development.

This Note reports measurements of crossflow velocity components that support the existence of streamwise vortices in the outer layer ($y > y_m$) of turbulent wall jets flowing over convex surfaces.

Apparatus and Experimental Methods

The measurements were done on a wall jet flowing over an existing 127-mm-diam circular cylinder in still air. The cylinder span was 495 mm, and end plates were present. The blowing slot height b was 0.95 mm. Velocity at the slot exit, U_J, was about 90 m/s, dictated by the available blower. The Reynolds number $U_J b/\nu$ was thus about 4700. The upper lip of the slot was ground square, with a thickness of 0.25 mm. A somewhat more detailed description of the cylinder is available in Ref. 4.

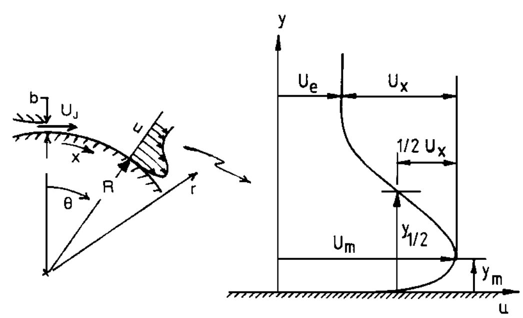

Fig. 1 Definition sketch of a wall jet.

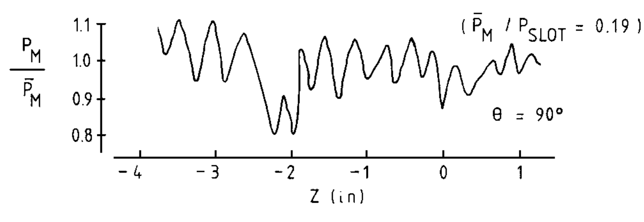

Fig. 2 Spanwise distribution of maximum total pressure P_M in the wall jet on the circular trailing edge of a circulation-control airfoil (still air, $R = 14.3$ mm, $b = 0.75$ mm, $U_J b/\nu = 3500$; $\bar{P}_M$ = spanwise average of P_M) (figure from Ref. 3).

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The flowfield measurements were taken with an available seven-hole pressure probe having a 60-deg apex-angle conical tip of diameter 2.4 mm. The probe was traversed in three radial planes, $\theta = 80$, 120, and 160 deg downstream of the slot exit, using a computer-controlled, two-axis traverse gear. The probe was used in the non-nulling mode with its axis oriented perpendicular to the radial plane of each traverse. In the $\theta = 160$ deg plane, crossflow angles obtained with the probe are estimated to be accurate within ± 2 deg and coefficients of total and dynamic pressure within $\pm 6\%$ and $\pm 10\%$ respectively; accuracy is better nearer the slot, where flow velocities are higher. These inaccuracies are sufficiently small that they do not cast doubt on the conclusions. The relative position accuracy in the radial planes is estimated at ± 0.01 mm. Details of the probe and its calibration are available in Ref. 6.

The present wall jet could be expected to be nominally two dimensional. That is, except for perturbations due to radial transport of momentum, etc., by crossflow structures, time-average flow parameters in any radial plane should have the same values at all spanwise stations along lines of constant y. The data reduction scheme took advantage of this by subtracting the spanwise ensemble average of parameters measured at a particular y from the individual values. The differences thus obtained would represent the perturbations due to crossflows. This technique would eliminate most of the bias errors due to the radial static pressure and velocity gradients in the basic two-dimensional flow, probe misalignment, finite size of the probe, wall proximity effects, and bias error in the calibrations.

Results and Discussion

Preliminary measurements confirmed that the total pressure at the slot exit was uniform within about $\pm 1\%$ across the span and that static pressure distribution on the cylinder surface in the measurement region downstream of the slot agreed well with that found by Fekete.[7] Spanwise-ensemble-average thickness values $y_{1/2}$ measured in the traverse planes also agreed quite well with those reported by Fekete[7] and Kind[3] at corresponding positions. The parameter $y_{1/2}$ is defined in Fig. 1. The data are also consistent with Guitton's[5] correlation for growth of $y_{1/2}$ along log spiral surfaces. This indicates that behavior of the present wall jet was not atypical of that of other convex wall jets.

Figure 3 shows crossflow velocity vectors in the three measurement planes. It is clear from these data that organized crossflow structures do exist. They appear to consist of pairs of counter-rotating streamwise vortices. Their size is comparable to the thickness of the shear layer at each θ position, with larger and accordingly fewer vortices farther downstream of the blowing slot. The mechanism by which the number of vortices per unit span decreases with downstream distance is not clear. It is plausible, however, that the large turbulent eddies in the outer layer of the wall jet break up the smaller, weaker streamwise vortices such that their vorticity becomes more or less randomly oriented.

Figure 4 juxtaposes crossflow vectors and total-pressure data for the $\theta = 120$ deg plane. It is clear that the streamwise vortices are directly responsible for the spanwise variations in total pressure seen in the present and previous experiments. Total pressure is relatively high where the streamwise vortices produce an upwelling of fluid and vice versa, consistent with the fact that $\partial u / \partial y$ is negative for $y > y_m$.

The relative importance of momentum transport due to the streamwise vortices can be assessed by evaluating $u''v''/\overline{u'v'}$. This is the ratio of radial transport of momentum associated with the steady perturbation velocity field (u'', v'', w'') of the vortices to that by the turbulent fluctuation velocities (u', v', w') or Reynolds shear stress ($-\overline{u'v'}$); $\overline{u'v'}$ was estimated using k–ϵ flow development computations. Values of the ratio are between 0 and 0.1 over more than 85% of the shear layer cross section in each of the three measurement planes. At $\theta = 80$ deg the value rises as high as 0.7 in three localized areas, corresponding to the relatively strong crossflows seen in Fig. 3 at $z = -55$, $+50$, and $+120$ mm. Local peak values of the ratio decrease to about 0.4 and 0.2 at $\theta = 120$ and 160 deg, respectively. Thus the radial transport of momentum by the streamwise vortices is significant but not dominant.

It was found that the spanwise locations of the strongest crossflows of Fig. 3 coincided with small deposits of dirt, about 0.05 mm thick, on the inside upper surface of the nozzle, just upstream of the slot exit. Similar placement of small ($\sim$3 mm wide) pieces of 0.06-mm-thick adhesive tape on the cleaned surface was found to initiate streamwise vortices. Vortices could also be initiated by using small ($\sim$1 mm wide) solid objects to just barely disturb the upper surface of the flow where it left the slot. On the other hand, no major downstream effects were produced by disturbances, either inside or outside the slot exit, on the convex wall that forms the lower boundary of the flow. Introduction of a new nozzle-exit upper edge, in the form of the cleanly sheared edge of a 1-mm-thick piece of sheet steel, produced an entirely new pattern of streamwise

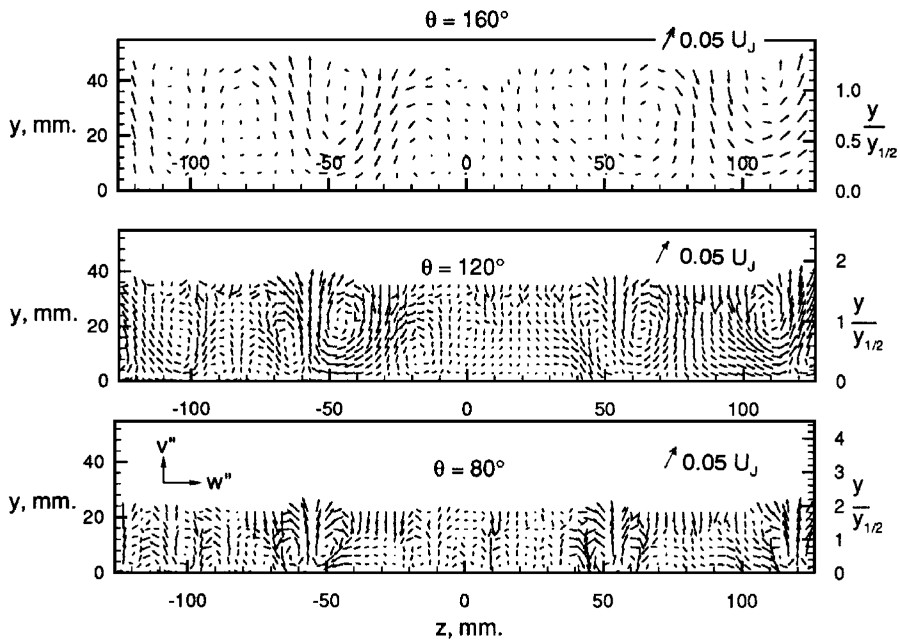

Fig. 3 Measured crossflow velocity vectors in three radial planes on the circular cylinder (still air, $R = 63.5$ mm, $b = 0.95$ mm, $U_J b/\nu = 4700$).

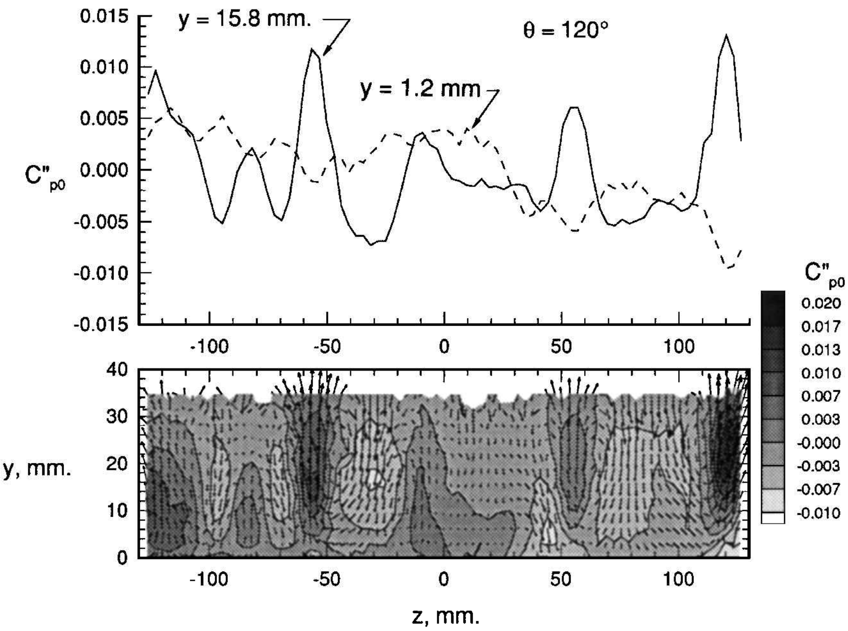

Fig. 4 Measured crossflow velocity vectors and total pressure in the $\theta = 120$ deg plane on the circular cylinder [conditions as in Fig. 3; $C_{P0} = (P_0 - p_\infty)/0.5\rho U_J^2$; $''$ denotes the difference between local and spanwise ensemble-average values].

vortices whose size and strength were nevertheless comparable to those with the original dirty slot lip.

The evidence indicates that streamwise vortices develop as a result of rapid amplification of small initial distortions introduced into the thin, centrifugally unstable, free shear layer that forms the upper boundary of the flow leaving the slot. Furthermore, the sensitivity to distortions appears to be such that streamwise vortices would most probably be present in any practical realization of tangential blowing over surfaces with substantial convex curvature. Values of $U_J b/\nu$ in the present and earlier[3,4] experiments are as much as an order of magnitude lower than in practical applications. However, the experimental flows were fully turbulent, with longitudinal turbulence intensities of about 12% at $y = y_{1/2}$ (Ref. 3). The observed flow behavior is thus expected to be representative of that of turbulent convex wall jets regardless of the value of the Reynolds number.

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Two-Layer Approach Combining Reynolds Stress and Low-Reynolds-Number k–ε Models

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I. Introduction

THE modeling of low-Reynolds-number (LRN) turbulence in the immediate vicinity of a wall has become one of the most important issues in turbulence modeling work. A number of LRN versions of the Reynolds stress models (RSM) have been developed recently.[1–3] Each new LRN RSM is more complex mathematically than the original RSM version. Furthermore, these LRN RSM have mostly been tested with simple isothermal flows. The generality of these models to the simulation of complex flows with/without wall heat/mass transfer is questionable. An alternative approach that was widely adopted in the past decade is the two-layer model, which depicts the overall turbulent flowfield by dividing it into the near-wall and fully turbulent flow zones. The basic idea of this alternative approach is that even a complex (more anisotropic) flow would become a simple (less anisotropic) type while being located within the near-wall region. This kind of turbulent model includes the k–ε/one-equation model (OEM),[4–7] algebraic stress models (ASM)/OEM,[8] RSM/OEM,[1] and ASM/LRN k–ε model.[8,9] Although two-layer models have been applied to many kinds of turbulent flows including nonisothermal cases, their performances were not always plausible. The reasons are as follows: The two-layer models are a combination of two turbulence models applicable individually to the high- and low-Reynolds-number flow regimes. The shortcomings of the k–ε models and the ASM in applications on complex flows are well known.[2] The incapability of the one-equation turbulence model to

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