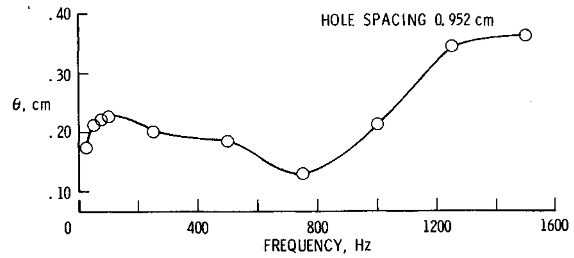

Fig. 3 Momentum thickness as a function of frequency.

along with the vertical and horizontal smoke wire pictures, indicate that the area-averaged drag reductions are not just a result of a shift in the transition region location (e.g., thicker boundary layer), but are most probably a result of the production of smaller turbulence scales.

As stated earlier, the purpose of this investigation was to attempt to produce local skin-friction reduction through alteration of the Emmons spot structures. Having produced such a drag reduction, it is of interest to examine the overall efficiency of such an approach. The expected longitudinal extent of the skin-friction reduction is of $\mathcal{O}(120\delta)$.[10] Based on this length, the power saved is of $\mathcal{O}(5.27\times10^{-3}$ W). The power required to run the acoustic horn driver trigger is of $\mathcal{O}$(3.16 W). Obviously, the present trigger system does not allow a net reduction; however, other, perhaps passive, trigger approaches may do so.

Conclusions

In summary, an Emmons spot generation system was designed to trigger closely spaced Emmons spots in the spanwise and longitudinal directions. For certain combinations of generator frequencies and amplitude, hole size, and hole spacing, quantitative and qualitative results indicate smaller turbulence scales and a reduction in skin friction [of $\mathcal{O}$(15%)]. This reduction in local drag does not appear to be a result of simply shifting the transition region location. The efficiency of the present trigger system does not allow a net drag reduction. However, other, perhaps passive, trigger approaches may do so.

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Boundary-Layer Blowing

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Introduction

HAVING worked on external flow problems[1,2] the author has applied the method developed previously to investigate two-dimensional boundary-layer separation and attachment due to small blowing through a transverse porous slot. Steady-state Navier-Stokes equations are taken as the governing equations for the fluid motion, and appropriate boundary conditions are used. The flow is assumed to be incompressible and laminar to simplify the problem.

The geometrical representation of the flow problem is shown in Fig. 1. Flat plate 4 is assumed to be placed parallel to the flow stream. The flow takes place from left to right. At point 5 there is a porous slot through which small blowing occurs. The flow on the upstream side (1) of the flat plate is a similarity solution of Blasius[3] and it is assumed that blowing does not influence the upstream boundary condition. At the top of the plate, i.e., boundary 2, the normal derivative of stream function ψ gives freestream velocity U, and the normal derivative of vorticity is taken as zero. On the downstream boundary 3, the values of vorticity and stream function are extrapolated according to Adam's predictor-corrector scheme.[4] On the surface of the flat plate, i.e., boundary 4, no-slip conditions exist and the normal component of velocity is zero. At the porous slot, i.e., boundary 5, uniform upward velocity exists and the component of velocity along the plate is zero.

Governing Equations

The Navier-Stokes equations governing the steady, incompressible viscous motion of fluid without body force can be written as

$$\nabla^2\psi+\zeta=0 \tag{1}$$

$$\nabla^2\zeta+Re\left(\frac{\partial\psi}{\partial y}\frac{\partial\zeta}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial\zeta}{\partial y}\right)=0 \tag{2}$$

Equation (1) is known as the stream function equation and Eq. (2) as the vorticity equation. The coordinates x and y are stretched using a simple transformation and the resulting equations are written in finite difference form. The finite difference equations are solved by a modified version of the extrapolated Liebmann method.[1,2]

Results and Discussion

Before attempting to solve the problem of boundary-layer blowing, a simple problem of laminar steady flow over a flat plate is examined at a plate Reynolds number of order 10^4. The reason for solving flow over a flat plate is to establish the validity of technique and compare the results with well-known and established results; as follows.

The no-slip and zero normal velocity boundary condition is applied along the entire flat plate for this case with the other boundary conditions described previously. After some numerical experimentation a grid of 64×32 was chosen. The results obtained compared to within 3% with Blasius

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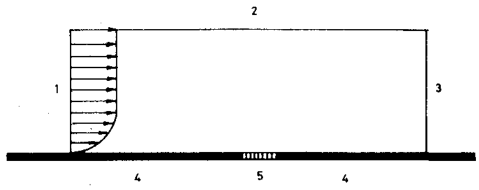

Fig. 1 Transverse blowing through a porous slot.

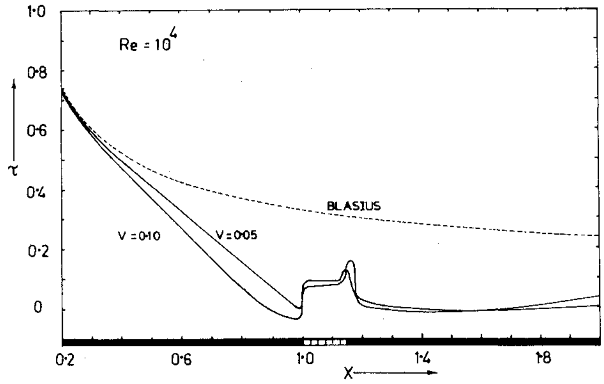

Fig. 2 Wall shear due to transverse blowing.

similarity solutions in terms of velocities and surface shear. Uniqueness and existence of solution is also established.

Then blowing is introduced through a porous slot and boundary conditions on the surface of flat plate are appropriately modified. The Reynolds number Re in the problem is 1×10^4. Where $Re=UL/\nu$ and L is the length of the plate from leading edge to the beginning of the slot, U the freestream velocity, and ν kinematic viscosity. The boundaries in the problem were shifted further away from the porous slot, thus decreasing the influence of blowing on the boundaries and the results were not altered significantly. Thus, it was felt that boundary conditions have been placed at appropriate distances for the blowing parameters considered.

In Fig. 2 wall shear $\tau=-(\omega L/U\sqrt{Re})$ as obtained in the present research is compared with the Blasius similarity solution. There is a continuous decrease in the wall shear due to blowing upstream of the slot. The rate of decrease in wall shear is higher for boundary-layer blowing than for the Blasius similarity solution. This indicates that there is a tendency for boundary-layer flow to separate upstream of the slot. For smaller rates of blowing, i.e., $v=0.05$, there is no separation ahead of the slot but for higher rates of blowing, i.e., $v=0.10$, there is separation of boundary layer ahead of the slot. Downstream of the slot the jet has a tendency to stick to the plate for some distance and then it separates; further downstream it reattaches to the plate. Thus, a recirculatory region is formed at a certain distance downstream of the slot. The size and position of the recirculatory region is influenced by the velocity of blowing of the transverse jet. In the range of blowing parameters investigated the surface shear downstream of the slot is not altered appreciably due to the jets, though it differs greatly from values of shear due to no blowing (i.e., Blasius similarity solution).

In Figs. 3 and 4 streamlines have been plotted for blowing paramters $v=0.05$ and 0.10. For smaller blowing, i.e., $v=0.05$, there is no separation upstream of the jet. For higher rates of blowing, i.e., $v=0.10$, the flow separates upstream of the jet and a recirculatory region is thus formed. In this recirculatory region there are two cells, each having a rotation

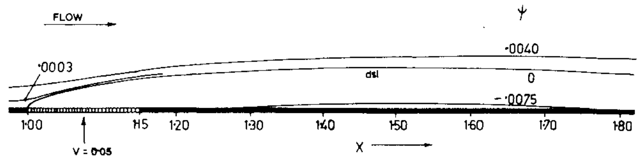

Fig. 3 Streamlines for transverse blowing, $Re=10^4$

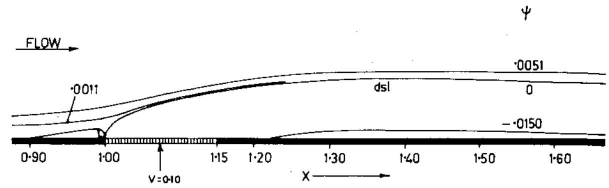

Fig. 4 Streamlines for transverse blowing, $Re=10^4$.

in the opposite direction. The cell next to the jet is a smaller cell and has counterclockwise rotation, while the second one further on the upstream side is a longer cell and has clockwise rotation.

In both cases on the downstream side, the jet is initially attached to the flat plate and then separates; after some distance downstream it reattaches to the plate. Thus, a recirculatory region is formed downstream of the jet. This region is very thin and long. The size of the recirculatory region increases with increase in velocity of blowing.

In these diagrams, the dividing streamline (dsl) is also shown and it may be observed that the dsl is roughly a parabola-shaped curve. The shape of this parabola depends upon the blowing velocity. In the boundary-layer solutions of jet interaction this curve has been assumed to be a straight line in some research work.

Conclusion

In this analysis a simple problem has been dealt with in which the density of a transverse jet is assumed to be the same as that of main flow and, thus, no diffusion is present. The flow is of nonreacting fluids with no combustion and no particulate matter. Results highlight certain very interesting phenomena. For blowing velocity of a jet of order 10^{-2} as compared to the mainstream velocity (for small blowing) there is no separation upstream of the transverse jet, but for a larger blowing velocity the flow separates upstream of the jet and a recirculatory region is formed having two recirculating cells. On the downstream side, a very thin and long recirculatory region is formed at some distance downstream of the jet depending upon the transverse jet velocity. The size of the downstream recirculatory region increases with an increase in the transverse velocity of the jet. The dividing streamline is approximately a parabola and the shape depends upon the transverse jet velocity.

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