Influence of Finite Slot Size on Boundary Layer with Suction or Injection

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Introduction

SUCTION and injection are two widely used methods for boundary-layer control. In practice, the mass transfer at the wall is accomplished through a number of finite-size holes or slots. Most analytical models dealing with boundary layers subjected to mass transfer at the wall (see, for example, Refs. 1 and 2) make the following assumptions: first, the tangential velocity component at the wall is zero ($u=0$) and, second, the normal velocity component at the wall v may be specified arbitrarily. These two statements are tantamount to assuming that the surface is porous in the normal direction, and that these pores are infinite in number and infinitesimal in size. A study[3] is also reported in which the first assumption was relaxed by allowing slip ($u \neq 0$) in addition to the normal velocity. This in effect modifies the more restrictive model by allowing the wall porosity to be aligned at any angle depending on the magnitude of the velocity components u and v.

It is the objective of this Note to examine numerically the flowfield within a finite, two-dimensional slot through which fluid can either be added or subtracted from the boundary layer. The results obtained provide a more realistic and accurate description of the velocity distribution at the outlet of a slot. The effects of the size of the slot on the flowfield are noted.

Model for the Slot

The rectangular, two-dimensional slot model used in this study is shown in Fig. 1. The span of the slot L_s will be approximately equal to the displacement thickness of the boundary layer at this point. Suction or injection is activated by specifying the vertical velocity component at the bottom of the slot (Fig. 1 shows the velocity prescribed for suction). The slot height is chosen large enough so that the effect of arbitrarily specifying v will not be felt in the upper part of the slot. For the purpose of this example, the flowfield is assumed laminar and the outer stream is supersonic, with the freestream Mach number of 2.25 and the Reynolds number (based on L_{BL}, the characteristic boundary-layer length) of 10^5. The numerical solution to the problem is obtained by using the compressible boundary-layer equations in the viscous region above the slot, while the incompressible Navier-Stokes model is applied within the slot. The two regions are solved and matched interactively using the method developed in Ref. 4. This method overlaps the two computational regions for continuity of solution. The width of this overlap is limited by the incompressibility assumption inherent in the Navier-Stokes model of the slot flow. Otherwise, the numerical solution is less sensitive to the width of the region than it is to the grid spacing used (see Ref. 6 for further discussion of this point). The virtue of the present approach is that it allows the flow at the interface between slot and boundary layer to develop naturally while retaining computational efficiency lacking in the use of the exact flow equations over the whole region. It has been successfully applied to cavities driven by the shear layer.[5,6]

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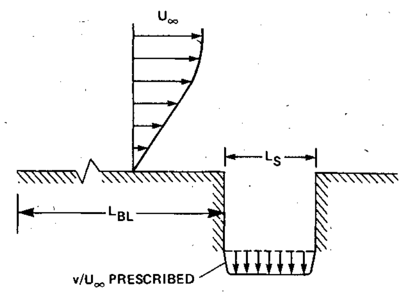

Fig. 1 Slot geometry (shown in the suction mode).

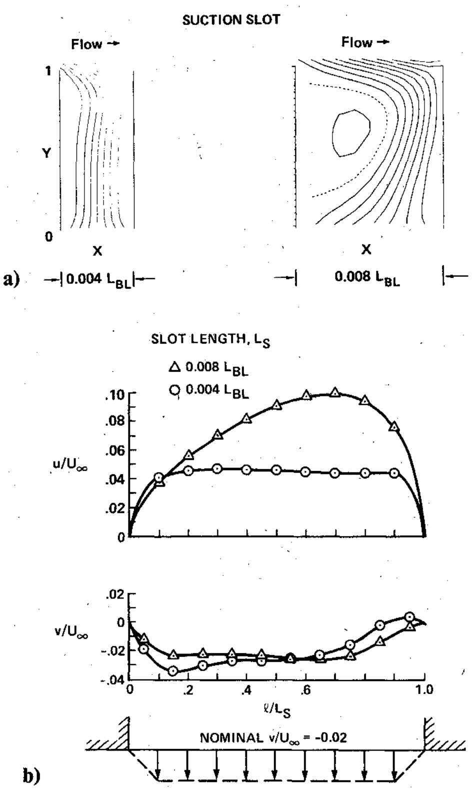

Fig. 2 Suction applied through the bottom of the slot: a) streamline plots for fluid entering the slot from the boundary layer; b) distributions of the two velocity components along the top of the slot for the two slot sizes.

Results

Solutions for the flowfield around slots through which suction or injection is applied are presented in Figs. 2 and 3 for two slot sizes expressed as a fraction of the characteristic boundary-layer length (L_{BL}): $L_s = 0.008\ L_{BL}$ and $0.004\ L_{BL}$. Air is withdrawn or injected through the bottom of the slot with the uniform velocity $0.02U_\infty$ (U_∞ is the freestream velocity) for all cases considered. The streamline plots for the two slot sizes in the suction mode appear in Fig. 2a. It is clearly seen that in both cases the streamlines are entering the slot at an angle with the horizontal different from zero, indicating that both velocity components are present at the interface between the boundary layer and the slot. For the wider slot the existence of a large recirculation bubble attached to the upstream wall is seen. (A recent paper by Thomas and Cornelius[7] presents fluorescent dye line visualization of flows into a suction slot, showing a separation bubble of same shape and location.) At its widest point this bubble reduces the area through which the withdrawn fluid must flow by more than 50%, thus increasing its speed. Its second, less obvious effect is to decrease the angle through which the layers of inflowing fluid adjacent to the wall must turn upon entering the slot. Figure 2b shows the

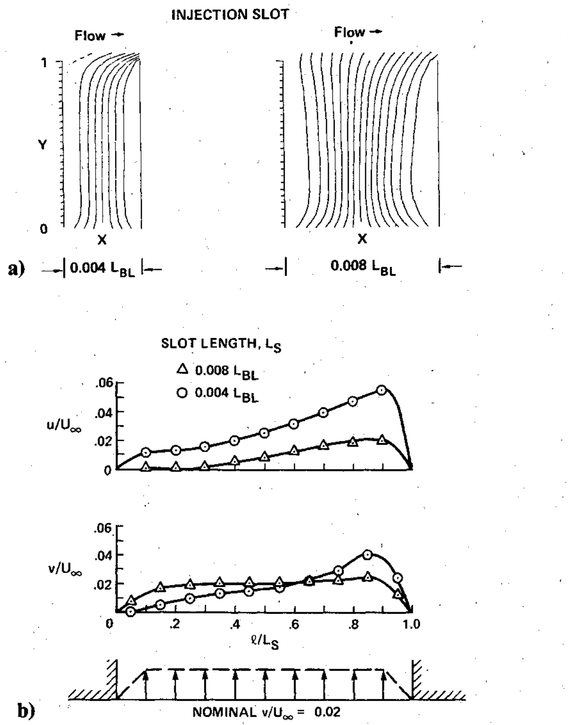

Fig. 3 Injection applied through the bottom of the slot: a) streamline plots for fluid injected into the boundary layer; b) distributions of the two velocity components along the top of the slot for the two slot sizes.

tangential and normal velocity distributions along the open top for the two slots in Fig. 2a. For the shorter slot, the u distribution is flat, while the v distribution shows the largest (negative) velocity close to the upstream corner, which then decreases in the downstream direction. For the larger slot, the u distribution is curved and the maximum value is 2.5 times greater than for the previous case, since the shear layer has more distance over which to develop. For comparison, the maximum values of u indicated in Fig. 2b are twice as large as the corresponding values for the case of the slot closed off at the bottom (the shear-layer-driven cavity).[6] This increase, then, represents the net streamwise acceleration of the lower part of the shear layer due to the fluid withdrawn at the bottom of the slot.

Figure 3 addresses the problem of injecting air through the slot into the boundary layer. The streamline plots (Fig. 3a) show that the injected fluid turns much more severely upon merging with the boundary layer for the case of the smaller slot. Examination of the velocity component distributions at the interface (Fig. 3b) lends further support for that statement. For the larger slot, u is practically zero over a third of the span, and substantially less over the whole span than the corresponding values for the smaller slot. Again, comparing these results with those for slots closed off at the bottom,[6] it is found that injecting through the larger slot substantially retards the bottom portion of the shear layer, while injecting through the smaller slot initially retards it but substantially accelerates it over the downstream third of the span. It is appropriate to note that (as in the case of suction) the rate of mass transfer per unit span of the slot is the same for the two slot sizes. The distributions of v velocity in Fig. 3b again show near uniformity for the larger slot, while for the shorter slot v increases in the downstream direction and peaks close to the downstream corner.

Discussion and Conclusion

The results presented in the previous section indicate that the influence of the injected (or withdrawn) fluid on the shear layer development in the vicinity of a slot is significant. Both u and v velocity components are present at the interface. The presence of the u velocity component (usually neglected in analysis of boundary layers with mass transfer at the wall) can have a significant influence on the development of the boundary layer, affecting the ability of the boundary layer to separate or stay attached. It also affects the displacement thickness, thus influencing the interaction of the boundary layer with the (inviscid) freestream.

The flowfield in the interface region was seen to be affected by the slot size. The larger slot was more effective in accelerating the bottom portion of the shear layer when in the suction mode and in blowing off the shear layer when in the injection mode. The slot efficiency could be improved by rounding off the corners and by appropriately inclining the slot with respect to the flow.[8] Thus recirculation bubbles such as the one shown in Fig. 2a could be suppressed.

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Sensitivity of Chamber Turbulence to Intake Flows in Axisymmetric Reciprocating Engines

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Introduction

In reciprocating internal-combustion engines, combustion controls efficiency and emissions and turbulence controls combustion. Turbulence is generated during intake but there are sources and sinks of it during compression. Since com-

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