# Further Results on the Effects of Suction on Boundary-Layer Separation

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### Nomenclature

$d^*$ = slot width
$\dot{m}$ = mass flow rate per unit span
$M$ = Mach number
$p$ = pressure
$Re$ = Reynolds number
$x$ = chordwise surface distance from model leading edge
$\delta^*$ = boundary layer displacement thickness
$\Delta$ = nondimensional mass suction
$\Theta$ = boundary layer momentum thickness
$\Theta_F$ = flap deflection angle

***Subscripts***

$e$ = local condition at edge of boundary layer
$HL$ = hinge line
$i$ = incipient condition
$s$ = separation, also suction
$w$ = wall
1 = beginning of interaction
3 = conditions behind reattachment

### Introduction

RESULTS of an experimental program to determine the quantitative effect of mass suction through a slot in a compression corner, formed by a plate-flap combination, on separation of a laminar boundary layer at one Mach number and Reynolds number were presented in Ref. 1. This note describes further results obtained in different Mach and Reynolds number regimes.

### Test Model and Facilities

The surface pressure test model was a symmetrical wedge of 12° half angle followed by a flap whose angle could be varied from 0° to 30° with respect to the upper surface of the wedge to form the compression corner. The span of the model was 8 in. and the flap chord length 1.5 in. Suction was obtained by means of a spanwise-contoured slot between the wedge and the flap allowing controlled natural flow from the upper high-pressure region of the corner to the relatively low-pressure region at the base of the wedge. Since the pressure ratio across the slot was always in excess of two, the suction quantity was controlled by varying the width of the spanwise slot.

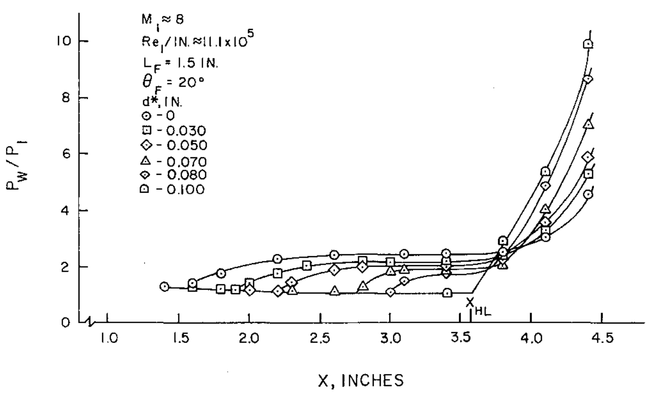


**Fig. 1 Typical streamwise pressure distributions for various mass transfer rates.**

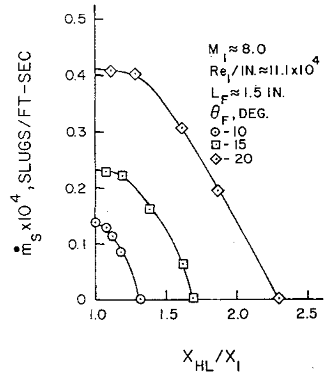


**Fig. 2 Typical effects of slot suction on extent of separation.**

The tests were performed at the Aerospace Research Labs., Wright-Patterson Air Force Base, Ohio in the 20-in. Hypersonic Wind Tunnel at a nominal freestream Mach number of 12.3 and a stagnation temperature of 1900°R. The facility is of the open jet, nonreturn type. The following local flow conditions were obtained on the wedge by pitching the model and also by changing the stagnation pressure:

a) $M_1 = 5.3$, $Re_{xHL} = 1.6 \times 10^5, 2.5 \times 10^5$

b) $M_1 = 6.7$, $Re_{xHL} = 3.3 \times 10^5$

c) $M_1 = 8.0$, $Re_{xHL} = 4.1 \times 10^5, 5.1 \times 10^5$

The wall to stagnation temperature ratio was about 0.56 for all tests.

### Results and Discussion

Initial tests, without suction, established that the flow was two-dimensional as a whole, laminar to reattachment, and that the flap length was sufficient to preclude introduction of chord effects. Slot suction effects are illustrated in Fig. 1 where it is seen that increasing the slot width, which will be related to mass flow in a moment, decreases the extent of separation. Typical results of the mass transfer tests at the three Mach numbers and various Reynolds numbers are given in Fig. 2 in terms of the mass flow removed per unit span versus the extent of separation, $x_{HL}/x_1$. The mass flow is calculated through a one-dimensional analysis for sonic conditions at the throat, $d^*$, of a convergent divergent channel assuming isentropic flow. The effective stagnation conditions are taken as the plateau pressure and the wall temperature so that

$$\dot{m}_s \backsim p_p d^* T_w^{-\frac{1}{2}}$$

the constant of proportionality being 0.01653 for air and $\dot{m}_s$ in slugs/ft-sec.

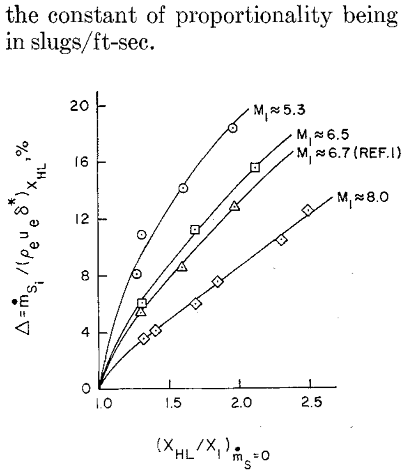


**Fig. 3 Nondimensionalized mass transfer required to achieve incipient separation for given extent of separation without suction.**

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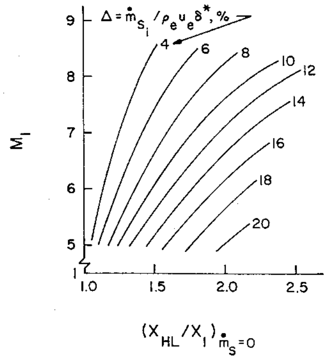


**Fig. 4 Generalized mass transfer required to achieve incipient separation for given Mach number and extent of separation.**

The mass flow for which $x_{HL} = x_1$ is obtained in Fig. 2 is defined as the incipient condition, $\dot{m}_{si}$. The incipient mass flow is nondimensionalized by the boundary-layer mass defect at $x = x_{HL}$ without separation, i.e., $[\rho_e u_e \delta^*]_{xHL}$, and presented versus the extent of separation without mass removal, i.e., $\dot{m}_s = 0$, in Fig. 3. The utility of the results of Fig. 3 is improved by a cross-plot as shown in Fig. 4 and may be interpreted as follows for the range of conditions investigated. 1) $M_1$, $x_1$, $x_{HL}$ and $Re_1$ are assumed known. 2) For these conditions, the percent of boundary-layer mass defect that is required to be removed by slot suction for incipient separation is obtained by entering Fig. 4 at $M_1$ and $x_{HL}/x_1$.

As might be expected for constant $M_1$, $\Delta$, the nondimensional mass suction, increases as the extent of separation increases. For a constant extent of separation $\Delta$ decreases as the Mach number increases.

An analysis for incipient mass flow required for laminar separated boundary layers, similar to that of Ref. 2 and to that of Ref. 3 for turbulent flows, was performed. The first momentum integral equation is integrated assuming constant momentum thickness and a constant transformed form factor at incipient separation, i.e., zero wall shear stress.

The results of such an analysis are shown in Fig. 5 in terms of the inviscid pressure ratio across the hinge line. Considering the simplifying assumptions involved in the analysis, the over-all agreement is much better than expected. The agreement is good for a pressure ratio on the order of 10. For very large mass flows an unrealistic asymptote is obtained for the pressure ratio. The analysis also does not predict a pressure ratio, i.e., a flap deflection angle, that the boundary layer can negotiate without separating.

### Conclusions

The effects of slot suction on two-dimensional separated laminar boundary layers have been studied over a Mach number range at the beginning of the interaction of 5.3 to 8 and a Reynolds number per inch range of $0.45 \times 10^5$ to $1.45 \times 10^5$ at a wall to stagnation temperature ratio of 0.56. For this range of test parameters it is concluded that:

1) The separated laminar boundary layer is very sensitive to slot suction. Removal of a small percentage of the boundary-layer mass defect is sufficient to collapse the separated flow region.

2) By integration of the first momentum integral equation for a compressible laminar boundary layer with the assumption of constant momentum thickness, an expression is obtained for the mass suction required to maintain incipient separation. The results are in fair agreement with experimental results.

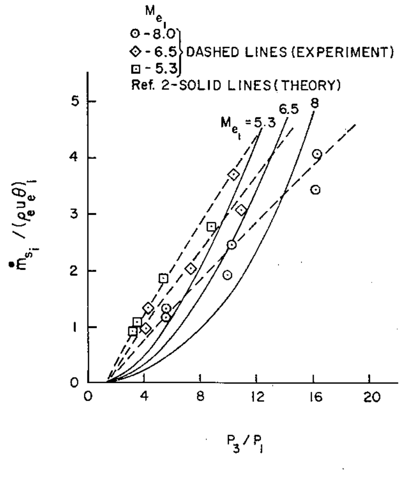


**Fig. 5 Comparison of theory with experiment for the mass suction required for incipient separation.**


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[2] Ball, K. O. W., "Elimination of Boundary Layer Separation by Slot Suction," *Office of Aerospace Research Review*, Vol. III, No. 2, Feb. 1968.

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# Electron Density Reduction in Re-Entry Plasma due to Nitrogen Atom Removal


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In the past few years emphasis has been placed on fluid injection methods for reducing electron concentration in the plasma surrounding a re-entry vehicle in order to alleviate the radio blackout. One method, such as the one advanced by Evans of the Langley Research Center, is to use liquid droplets as sites to achieve recombination of electrons and

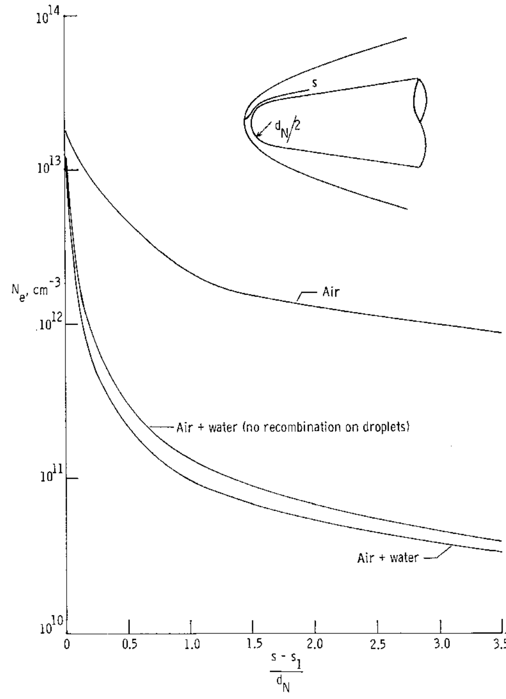


**Fig. 1 Reduction in electron concentration due to water injection.**


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