Engineering Notes

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Boundary-Layer Separation: Effect of Low-Speed Wall Jets

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TANGENTIAL wall jets are used, in practice, to control turbulent boundary-layer separation on airfoils with good success. These applications employ a jet velocity several times larger than the mainstream velocity, to provide kinetic energy to the fluid layers near the wall.

Thomas[1] gives an empirical method for calculation of separation control on airfoils by wall jets, where the wall jet velocity u_w is at least twice that of mainstream u_m. This Note comments on the effects of lower-speed wall jets. The latter condition finds applications in separation control in supersonic engines, where jets speeds much above the mainstream speed are impractical.

Thomas says that a wall jet corresponds to a change in momentum thickness, by the amount

$$\Delta\theta = MS(1 - V) \tag{1}$$

where M = the mass velocity ratio $(\rho_w u_w)/(\rho_m u_m)$; S = the slot height or the initial jet thickness; V = the velocity ratio u_w/u_m.

This can be derived from first principles, with the assumption that the initial jet velocity is uniform. Based on experiments, Thomas finds that $\Delta\theta$ changes rapidly near the injection slot, such that the useful change in the momentum thickness, $\Delta\theta_{use}$ is

$$\Delta\theta_{use} = 0.85(1 - 1/V)\Delta\theta \tag{2}$$

for $V > 2$. Next the variation of momentum thickness along the surface is calculated, using the potential velocity distribution, and oblivious to the actual separation and the jet. One can find this variation in momentum thickness by any one of several empirical methods, such as expounded in Ref. 2. The calculated change in this artificial momentum thickness $\Delta\theta_{nosep}$ from the real no-injection separation point equals, at some point on the wall, the negative of $\Delta\theta_{use}$, and separation shifts to this point. Figure 1 shows the process schematically.

This empirical method has met with success in predicting separation control on trailing flaps of airfoils, although there are problems regarding its precision. The problems associated with applying it to lower velocity jets are basically two: 1) the relation between $\Delta\theta$ and $\Delta\theta_{use}$, and 2) nearness to the slot. (Thomas states that the momentum thickness increment due to the wall jet changes, $\Delta\theta$ to $\Delta\theta_{use}$, within 150 slot heights of the slot. At $V < 2$, separation will often occur in this near-slot region.)

Problem 1 has an approximate solution as follows. Experimental velocity profiles in Refs. 3 to 5 indicate a fair fit to an equation,

$$\Delta\theta_{use} = 2(1 - V)\Delta\theta \tag{3}$$

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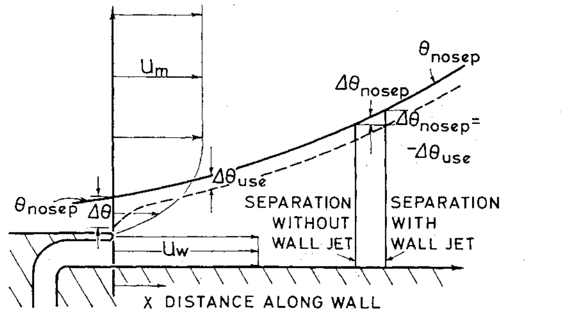

Fig. 1 A schematic of Thomas' method for calculating wall jet effects on boundary-layer separation.

for $V < 1$. These data do not concern rising pressure, and there are slight temperature differences between the streams, but they represent what is available in the literature. No data were found for $1 < V < 2$; however, as Eqs. (2) and (3) agree at $V = 1$, Eq. (2) is taken as provisionally correct in this region. We will discuss the second problem in light of the experiments of this Note.

A series of experiments was done, wherein separation was induced on a flat wall of a two-dimensional diffuser. This wall contained a wall jet injection slot. The variation of the separation location with wall jet speed was noted. The injection slot was then moved to different locations, in the wall and relative to the separation, and the wall-jet-speed-to-separation relationships were again recorded. Sufficient data were taken to determine the theoretical shift in the separation point (considering problem 1 above), and to compare it to the actual. The range of V was 0.3 to 1.1. Details of the experiments and calculation may be found in Ref. 6. Some results are shown in Fig. 2. We see that 1) theory predicts, and experiments show, low wall jet velocities cause the separation to move upstream; 2) theory is steadily pessimistic, it predicts separation upstream of where it actually occurs; and 3) theory is reasonably accurate where distance is relatively large *and* jet velocity is relatively low

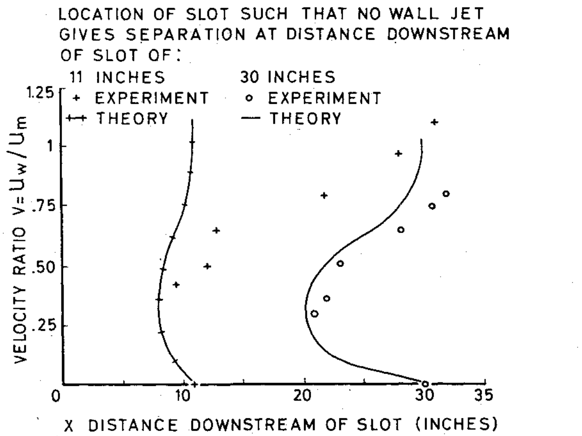

Fig. 2 Location of separation point for two slot positions as a function of wall jet speed.

The major conclusion is that Thomas' method, with minor variations for $V < 1$, gives a limit, on the upstream side, to the separation point, and that, under conditions for relative remoteness from near-slot effects, is reasonably accurate. Much more cannot be said, due to the limitations of this data. Slot heights other than the one used may have an effect. There was a slight difference in temperature between the mainstream and jet; a density effect may appear. Finally, the data imply that separation control when $1 < V < 2$ is good. The apparatus was not long enough to determine the separation point in this range. More data would be very valuable.

References

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Simplification of the Wing-Body Interference Problem

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Nomenclature

C_{L_α} = lift-curve slope coefficient
K = interference factor
r = radius of body
S = area
s = wing maximum semispan in combination with body

Subscripts

B = body
e = exposed wing
N = nose
REF = reference upon which coefficient is based
W = wing

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Discussion

A FREQUENTLY recurring problem in aerodynamic design is the determination of the lift-curve slope of a wing-body combination. A well-known technique for solving this problem is used in Ref. 1 and is taken from the original work reported in Ref. 2. The technique is derived from slender-body theory and may be expressed as

$$(C_{L_\alpha})_{WB} = (C_{L_\alpha})_N S_{N\text{REF}}/S_{\text{REF}} + (C_{L_\alpha})_e (S_e/S_{\text{REF}})[K_{W(B)} + K_{B(W)}] \quad (1)$$

where the first term represents the body nose lift-curve slope, and the second term represents the wing lift-curve slope in the presence of the body and of the body caused by the wing. The interference factors were expressed in Ref. 2 [Eqs. (14) and (21), respectively], as follows:

$$K_{W(B)} = \frac{2}{\pi}\left\{\left(1+\frac{r^4}{s^4}\right)\left[\frac{1}{2}\tan^{-1}\frac{1}{2}\left(\frac{s}{r}-\frac{r}{s}\right)+\frac{\pi}{4}\right] - \frac{r^2}{s^2}\left[\frac{s}{r}-\frac{r}{s}+2\tan^{-1}\frac{r}{s}\right]\right\}\Big/\left(1-\frac{r}{s}\right)^2 \quad (2)$$

$$K_{B(W)} = \left(1-\frac{r^2}{s^2}\right)^2 - \frac{2}{\pi}\left\{\left(1+\frac{r^4}{s^4}\right)\left[\frac{1}{2}\tan^{-1}\frac{1}{2}\left(\frac{s}{r}-\frac{r}{s}\right)+\frac{\pi}{4}\right] - \frac{r^2}{s^2}\left[\left(\frac{s}{r}-\frac{r}{s}\right)+2\tan^{-1}\frac{r}{s}\right]\right\}\Big/\left(1-\frac{r}{s}\right)^2 \quad (3)$$

where r is the body radius, and s is the wing semispan. Equations (2) and (3) may be combined to yield

$$K_{B(W)} + K_{W(B)} = [(r/s) + 1]^2 \quad (4)$$

The combined interference factors thus are expressed in a simple, easily remembered form that makes it unnecessary for the designer to refer to the graphs of each factor (presented in Ref. 2, p. 48).

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