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Extension of Reaction Control Effectiveness Criteria to Mach 10: Experiment and Theory

Paul W. Vinson*

Martin Company, Orlando, Fla.

Reaction control experiments at supersonic speeds have shown that control forces significantly greater than the jet reaction force can be generated in atmospheric flight.[1–7] Data of Ref. 2 indicate that two-dimensional reaction control effectiveness can be obtained on bodies of revolution by employing fixed, low-aspect-ratio fins to retard circumferential propagation of the upstream separated flow. Theories have been advanced by several investigators[1–5] which indicate the beneficial effects of increased flight Mach numbers. However, available experimental data have not covered a wide enough Mach number range to establish conclusively the Mach number influence.

The purpose of this note is to present experimental data on reaction control effectiveness at Mach 6 and 10. Tests were conducted at the Naval Ordnance Laboratory, Silver Spring, Md., in tunnel no. 8 and employed a body-of-revolution model with fins as shown in Fig. 1. A cold air jet, consisting of a sonic slot spanning the body circumference between adjacent fins, was utilized. Slot width was 0.015 in. and the slot was located 0.25 in. from the model base. Force balance as well as body pressure data were obtained at all test points, and a turbulent boundary layer was obtained by mounting a 0.015-in.-diam wire on the model nose.

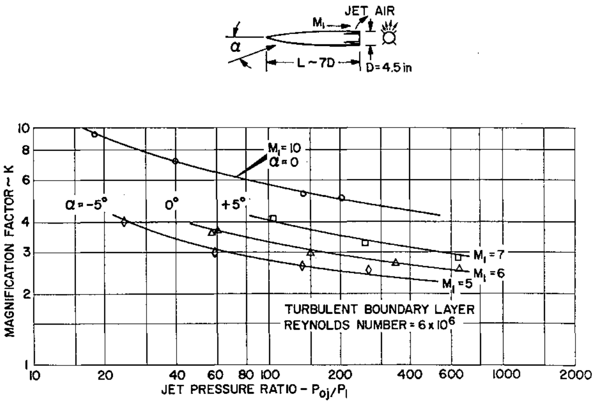

Fig. 1 Experimental magnification factors at hypersonic Mach numbers.

Experimental Data

Figure 1 indicates the influence of Mach number and jet pressure ratio on the jet magnification factor where the magnification factor is defined as the ratio of body plus reaction force to reaction force. Model angle of attack was varied to ±5° at Mach 6 providing local Mach numbers of 5 and 7. These data clearly show the improved effectiveness at hypersonic Mach numbers.

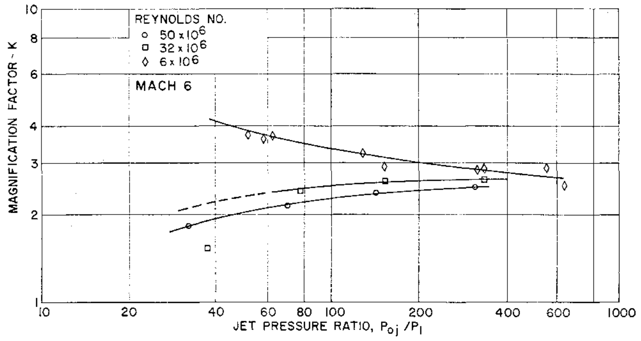

Fig. 2 Effect of Reynolds number on magnification factor.

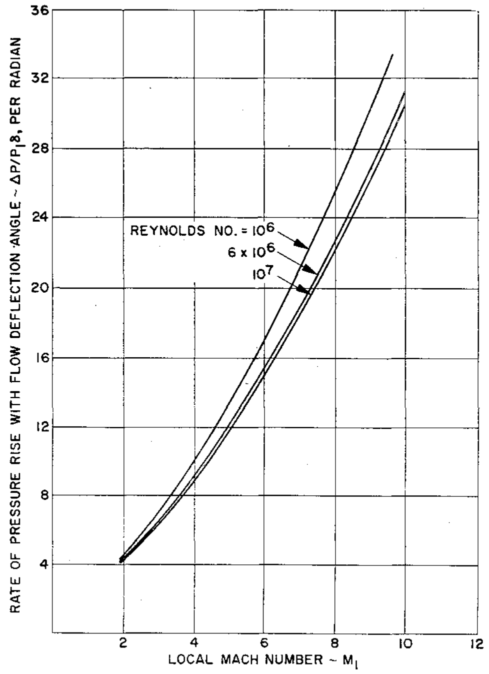

Fig. 3 Turbulent boundary-layer separation.

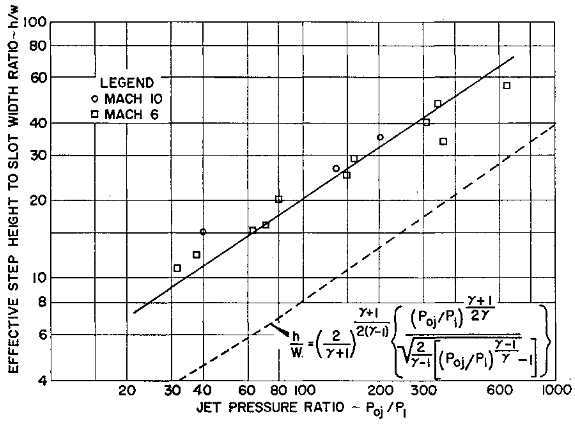

Fig. 4 Correlation of jet penetration data.

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* Design Engineer. Member AIAA.

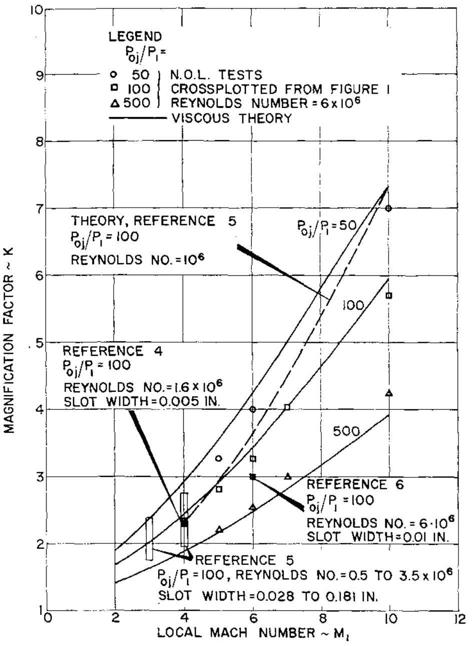

Fig. 5 Comparison of theoretical and experimental magnification factors (turbulent boundary layer).

An investigation of Reynolds number effects at Mach 6 was conducted, and these results are shown in Fig. 2. Although, as will be shown later, increased Reynolds number is expected to slightly reduce effectiveness, the peaking of the high Reynolds number data was not anticipated, and no theoretical explanation of this effect is known to the author.

Theoretical Analysis

An analytical expression for the sonic slot magnification factor, taken from Ref. 1, is

$$K = 1 + \frac{(\Delta P/p_1\delta)(h/w)}{2[2/(\gamma + 1)]^{i/(\gamma - i)}(P_{0j}/P_1) - 1} \tag{1}$$

Utilizing the turbulent boundary-layer plateau pressure rise correlation presented in Ref. 4, together with an equivalent wedge angle δ required to produce the pressure rise, the term $\Delta P/P_1\delta$ becomes

$$\frac{\Delta P}{P_1\delta} = 2.6\,\frac{(M_1{}^2 - 1^{1/2})}{(R_1)^{1/10}\delta}\ \ \mathrm{rad}^{-1} \tag{2}$$

This expression is plotted in Fig. 3.

It was assumed in Ref. 1 that the jet penetration height h was equivalent to the area ratio required to isentropically expand the jet flow to ambient pressure. However, schlieren observations of this study and of Ref. 5 have shown the actual penetration heights to be approximately twice as great for a given jet pressure ratio. These data are shown in Fig. 4 and provide the basis for evaluation of the h/w term in Eq. (1).

Figure 5 compares this theoretical prediction and the theory of Ref. 5 with the experimental data shown in Fig. 1 and data of Refs. 4–6. Apparently the linear addition of viscous and inviscid effects, as proposed in Ref. 5, is overly optimistic at hypersonic Mach numbers, whereas the viscous theory originally proposed in Ref. 1 appears to properly indicate Mach number and jet pressure ratio effects. Further experimental investigation of Reynolds number effects on reaction control performance is required.

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Convection from Heated Wires at Moderate and Low Reynolds Numbers

Peter D. Richardson*
Brown University, Providence, R. I.

Two-dimensional convection from heated wires placed transverse to a stream is of interest in hot-wire anemometry. The correlations that have been presented by King,[1] Hilpert,[2] McAdams,[3] and Collis and Williams[4] are particularly well known. Each of the correlations given by these authors is chosen because it is found empirically to fit the relevant measurements for a limited range of Reynolds number. None of the correlation equations has been chosen because it explicitly represents detailed knowledge of the local flow around the surface of a cylinder and the consequent local distribution of heat-transfer coefficient. Recently, correlations have been proposed[5] for convection from cylinders at high Reynolds numbers which do attempt to take explicit account of the local variation of heat transfer around the cylinder. The purpose of this short paper is to show that the latter correlation can be used to represent heat transfer from wires at moderate and low Reynolds numbers down to a Reynolds number of about 1.0 when certain slight adaptations are made to it to represent some of the physical changes in the flow pattern as the Reynolds number becomes smaller. The availability of a single correlation, covering a large range of Reynolds number, can make the interpretation of hot-wire measurements an easier and more straightforward process.

At moderate and low Reynolds numbers it is apparent that freestream turbulence does not have a strong influence upon the heat transfer on the forward portion of a cylinder, in contrast with the findings at high Reynolds numbers. For this reason the discussion here will be centered upon the correlation given[5] for heat transfer at high Reynolds number but low turbulence intensities:

$$Nu = 0.37\,Re^{1/2} + 0.057\,Re^{2/3} \tag{1}$$

In this equation, the first term represents the heat transfer from the forward portion of the cylinder (which is covered by a laminar boundary layer), while the second term represents

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* Assistant Professor of Engineering.