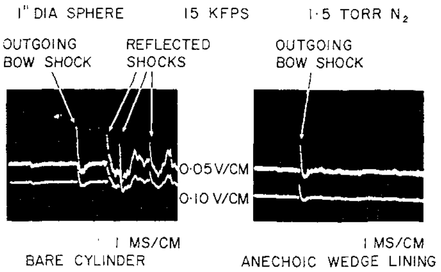

Fig. 5 Pressure transducer measurements in the anechoic wedge treatment compared to results in a bare cylinder; the reflected shocks are not detected in the treated cylinder.

using acoustic materials. Deflection schemes have not proved adequate because of diffraction effects, while normally highly absorbent acoustic materials appear very reflective at the low pressures to which the ranges are evacuated. However, a treatment based on smoothly tapered fiberglas wedges, installed as shown in Fig. 4, has been found to produce significant improvement. Figure 5 compares test results obtained in firings through untreated and treated cylinders using Atlantic Research Corporation LC-5 pressure transducers; the reflected shocks evident in the former case cannot be detected in the latter. Electrostatic probe results indicate a significant reduction in wake disturbance with the wedge treatment, provided the range geometry is symmetrical. Some residual effect does remain, probably due to the presence of a smeared pressure distribution persisting as a result of inefficient energy absorption by the treatment at low ambient pressures.

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Critical Height Phenomenon for Vertical Jets Mounted in Flat Surfaces

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Introduction

An investigation was made into the effects of the flow between two flat, parallel surfaces where the flow originated from a nozzle in one of the surfaces exhausting normal to the other surface. One surface, which we shall call the vehicle for convenience, was finite in area and cantilevered on the air supply line. The other surface, which we shall call the ground plane, was relatively infinite but adjustable for the purposes of the investigation. The configuration is that of an air-bearing type ground effect machine. The flow through the nozzle acted as a source of thrust for the vehicle portion of the test apparatus. At large distances between the two surfaces the presence of the ground plane had no effect on the thrust experienced by the vehicle. As the two surfaces were brought closer together and the flow became turned by the ground plane so that a velocity parallel to the surfaces was created, the amount of net thrust experienced by the vehicle decreased. At a certain distance, herein called the critical height, the net thrust acting on the vehicle was zero. For separation of the vehicle and ground plane by less than this distance the net thrust became negative, or toward the ground plane. It was found that, of the parameters tested, the value of the critical height depended only on the area of the vehicle surface. This study expands upon results obtained by Spreeman and Sherman[1] for similar configurations and by von Glahn[2] for nozzles with no surfaces around them. Different parameters were varied and some parameters were varied over wider ranges than in the previous studies. Data obtained in the experiment were nondimensionalized in a different manner resulting in the discovery of what we shall call the critical height phenomenon.

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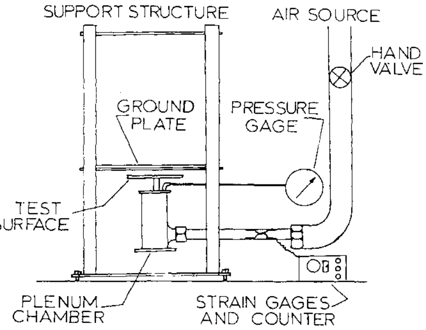

Fig. 1 Test apparatus.

Test Apparatus and Procedure

A simple cold-flow apparatus was used with air as the working fluid (Fig. 1). The apparatus was inverted with respect to the normal aircraft-ground orientation for convenience in taking the required data and making the necessary variations of physical parameters. The flow was provided from a high-pressure compressed air source at the Auburn University High Speed Wind Tunnel facility. The vehicle surfaces tested consisted of circular plates $2\frac{3}{8}$, 7, $9\frac{1}{4}$, and 11 in. in diameter and one elliptical planform approximately 5×10 in. The elliptical planform had the same area as the 7-in. circle and was used to determine the effect of small changes in the symmetry of the vehicle surface. The aspect ratio of the ellipse was less than three. Aspect ratio as used here is the length of the major axis squared divided by the area of the surface. In this respect the aspect ratio of the circular planforms was $4/\pi$. Three different nozzles were used: a 1-in. diam straight-walled nozzle; a $\frac{1}{2}$-in. diam straight-walled nozzle; and a $\frac{1}{2}$-in. diam nozzle which diverged to $\frac{5}{8}$ in. with a total angle of 24°. The ground plane was a heavy metal plate that was not moved by the flow. Deflection of the vehicle surface due to the net thrust acting upon it was not measurable. The separation between the two surfaces was varied by adjusting the height of the ground plane. The thrust experienced by the vehicle was measured using four electrical strain gages in a Wheatstone bridge arrangement. The strain gages were mounted on the air supply line which also served as the sole support for the vehicle portion of the apparatus.

A large number of tests were made using all possible combinations of planforms and nozzles at various mass flows and heights. The pressure in the plenum chamber upstream of the nozzle was varied to provide both choked and unchoked flow to the nozzle. In all cases, the thrust produced in the

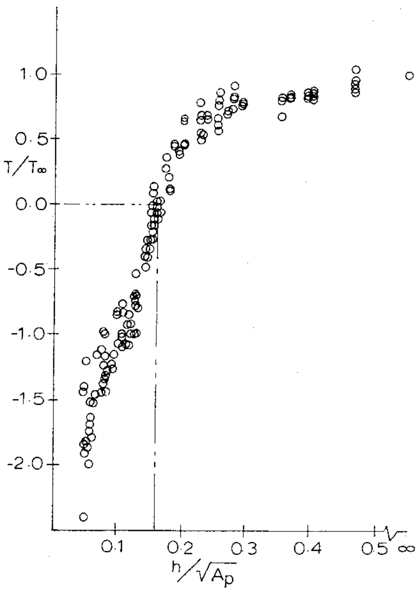

Fig. 2 Nondimensionalized thrust vs height.

ground effect region was less than that out of ground effect as is expected with this configuration. The loss in this net positive thrust was due to the high-velocity flow parallel to the surfaces. This flow creates a low static pressure on the lower vehicle surface. Since ambient pressure is acting on the upper vehicle surface a pressure differential exists across the vehicle surface. The integral of this pressure differential across the entire surface was the ground effect force and of course acted in a direction opposite to the thrust produced by the flow through the nozzle. When the two forces are equal and opposite the vehicle experiences no net force. The height at which this occurs has been called the critical height. For separation less than this, the ground effect force is greater than the thrust due to mass flow and the net force on the vehicle is toward the ground plane. The ground effect force actually became several times the magnitude of the original thrust out of ground effect for separations smaller than the critical height. It was found that, of all the parameters tested, only the planform area (which included the nozzle area) had an effect on the value of the critical height. Once at the critical height for a certain planform, a change in mass flow, nozzle size, nozzle geometry, or aspect ratio (less than three) had no effect in changing the net thrust from its zero value. For a given planform area, at any pressure ratio the flow created a ground effect force exactly equal to the thrust due to mass flow at the same height. This is the critical height phenomenon. Plots were made of the ratio of thrust at any height divided by the thrust out of ground effect, T/T_∞, vs the height divided by the square root of the planform area (Fig. 2). In each case the critical value of $h/(A_p)^{1/2}$ where T/T_∞ was zero was about 0.16. This is very close to $\frac{1}{2\pi}$. Since only circular and elliptical shapes were used for the vehicle surface, a comparison of the data obtained by Spreeman and Sherman[1] for square and rectangular shapes was made. Again the critical height had the same value when nondimensionalized with respect to the square root of the planform area.

The range of values tested included: plenum chamber pressures of from 5 to 20 psi above ambient; planform areas of from 4.43 to 95.1 in.^{2}; planform-to-nozzle area ratios of from 21.6 to 485; aspect ratios less than three; nozzle minimum areas of 0.106 and 0.785 in.^{2}; and nozzle divergence of 0 and 24° total angle.

Concluding Remarks

An experimental investigation has led to the discovery of the critical height phenomenon. A cold-flow test procedure found that, of the parameters tested and within the limits tested, only the vehicle surface area had an effect on the value of the critical height, and therefore that nondimensionalizing the critical height with respect to the area gave the same value for all configurations. This value was found to be given very closely by $\frac{1}{2\pi}$.

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Skin-Friction Measurement at Supersonic Speeds

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Nomenclature

i = hot film current
k = thermal conductivity
L = streamwise length of heated film
q = mean heat transfer per unit area
R = hot film operating resistance
ΔT = temperature difference between hot film and local recovery temperature
μ = viscosity
ρ = density
σ = Prandtl number
τ = shear stress

Subscript

w = wall condition

Theoretical Considerations

It has been shown that the wall shearing stress of a laminar or turbulent boundary layer in incompressible flow can be determined from heat-transfer measurements at the surface (Ref. 1). In this case, it is possible to restrict the temperature difference ΔT to values small enough to neglect variations of μ, ρ, and k. However, in order to extend the previous equations to high-speed flow, variations of fluid properties due to temperature variations in the boundary layer must be considered.

For a small heated element the thermal boundary-layer thickness is much less than the velocity boundary-layer thickness, so when solving the energy integral equation the velocity may be approximated by

$$u = (\tau_w/\mu)y + (1/2\mu)(dp/dx)y^2 \quad (1)$$

Thus, it has been shown in Refs. 1 and 2 that in zero-pressure-gradient, incompressible, laminar flow the heat transfer from a hot film is related to the mass flow-rate near the surface by the equation

$$Nu = (q_w L/k\Delta T)\alpha(\rho\tau/\mu^2)^{1/3}(\sigma L^2)^{1/3} \quad (2)$$

Liepmann and Skinner[2] extended this analysis to turbulent boundary layers under the assumption that the temperature field due to the heated film constituted a thermal boundary layer that was contained entirely within the laminar sub-

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