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EXPLORATORY STUDY OF THE REDUCTION IN FRICTION DRAG DUE TO STREAMWISE INJECTION OF HELIUM

By Byron L. Swenson

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Moffett Field, Calif.

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EXPLORATORY STUDY OF THE REDUCTION IN FRICTION DRAG DUE TO STREAMWISE INJECTION OF HELIUM

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SUMMARY

A study has been made of the effect on skin friction of the streamwise injection of a light-gas film into a boundary layer. A simple analysis of the flow was made based on the assumption that the boundary layer was completely replaced with this light-gas film. From the analysis, reductions in skin friction of up to about 60 percent for laminar flows and equal or greater reductions for turbulent flows were indicated with helium used as the light gas. To test this concept, experiments were conducted with a 6° half-angle cone at Mach numbers from 3 to 5 and free-stream Reynolds number (based on cone length) of nominally 1.8 to 10 million. Reductions in the skin-friction drag of about 60 percent were measured at Mach number 5 with an injection of helium at a mass rate equal to about 0.2 percent of the mass rate of free-stream air swept out by the base of the model.

INTRODUCTION

At high supersonic speeds, skin friction is a major contributor to the drag of slender vehicles and thus it is of primary importance in their design. A substantial decrease in the friction drag of such vehicles can materially increase their lift-drag ratios and hence their range. Furthermore, a reduction in skin friction is normally accompanied by a corresponding reduction in heat transfer. Experimentally, Pappas (ref. 1) has shown that reductions in both skin friction and heat transfer can be obtained by transpiration or normal injection of helium through a porous wall. Several experimental studies (refs. 2, 3, and 4) in connection with heat-transfer reduction have shown that the streamwise injection of a film of a light gas into a boundary layer can produce substantial reductions in the heat-transfer rates to the wall. In the belief that this technique might well lead to a corresponding reduction in skin-friction drag, an exploratory study of the effect of helium film injection on a 6° half-angle cone was undertaken.

SYMBOLS

A	cross sectional area of injection port
a	speed of sound
C	viscosity-temperature proportionality constant
C_{A_f}	forebody axial-force coefficient referenced to base area, $\frac{\text{(axial force) - (base force)}}{qS}$
C_{D_f}	skin-friction drag coefficient, $\frac{\text{friction drag}}{qS}$
C_i	injection coefficient (see eq. (12))
C_p	surface pressure coefficient, $\frac{P_l - P}{q}$
C_T	injection thrust coefficient (see eq. (13))
c_f	local skin-friction coefficient
f	proportionality factor between c_f and Re
I_s	equivalent specific impulse of injection (see eq. (14))
M	Mach number
m	molecular weight
$\dot{m}_H$	mass rate of helium injection
P	pressure
Pr	Prandtl number
q	dynamic pressure
R	gas constant
$\bar{R}$	universal gas constant
Re	Reynolds number
Re'	Reynolds number per foot
S	base area

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T temperature

Th thrust force due to helium injection

u velocity

x distance along axis of cone

α angle of attack

γ ratio of specific heats

μ coefficient of viscosity

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ρ density

τ wall shear stress

ω temperature exponent of viscosity

Subscripts

a air

H helium

e condition just inside outer edge of boundary layer

Superscript

$*$ sonic conditions (i.e., conditions where the local speed is equal to the local speed of sound)

ANALYSIS

A first estimate of the effect on friction drag of injecting helium in a streamwise manner into a boundary layer can be made with the assumption that all the boundary layer is completely replaced by helium. With this assumption mixing of the free-stream air and the helium boundary layer is considered to be negligibly small and only on a molecular scale. Attention will be focused on flows over a flat plate, but with the use of simple transformations (see, e.g., ref. 5, pp. 262-264) the results are applicable to cones with the same local conditions external to the boundary layer as the flat plate.

Laminar

For laminar flow over an adiabatic wall with zero surface pressure gradient, the mean skin-friction coefficient for a flat plate may be written as (see ref. 5, pp. 211-214)

$$c_f = \frac{f}{\sqrt{Re}} \qquad (1)$$

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where f is, in general, a function of Mach number, Prandtl number, and a parameter ω. The parameter ω is defined by the viscosity approximation

$$\mu = CT^{\omega}$$

The Reynolds number, Re, is evaluated at conditions just inside the outer edge of the boundary layer.

As a first approximation ω may be taken as unity and in this case f is a constant independent of Mach number and Prandtl number. Therefore, by use of this approximation the ratio of the skin-friction coefficient of a helium boundary layer to that of an air boundary layer may be written as:

$$\frac{c_{f_H}}{c_{f_a}} = \sqrt{\frac{\rho_a}{\rho_H}\frac{u_a}{u_H}\frac{\mu_H}{\mu_a}} \qquad (2)$$

Physically the helium film must be at the same pressure as the air boundary layer it is replacing. Therefore, with the use of this fact and the equation of state

$$P = \frac{\overline{R}}{m}\rho T$$

(where $\overline{R}$ is the universal gas constant and m is the molecular weight of the gas) equation (2) reduces to:

$$\frac{c_{f_H}}{c_{f_a}} = \sqrt{\frac{m_a}{m_H}\frac{u_a}{u_H}\frac{T_H}{T_a}\frac{\mu_H}{\mu_a}} \qquad (3)$$

In order to simplify equation (3) attention is now directed to the viscosity ratio, μ_H/μ_a, and the viscosity data for helium and air presented in figure 1. It can be seen that approximately equal viscosities exist in helium and air at the same temperature. Then, inasmuch as μ has been assumed to be proportional to T, we may write the following:

$$\frac{\mu_H}{\mu_a} = \frac{C_H}{C_a}\frac{T_H}{T_a} \approx \frac{T_H}{T_a}$$

Thus the ratio of skin-friction coefficients then becomes:

$$\frac{c_{f_H}}{c_{f_a}} = \frac{T_H}{T_a}\sqrt{\frac{m_a}{m_H}\frac{u_a}{u_H}} \tag{4}$$

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The ratio of the wall shear stress (i.e., skin-friction drag force per unit area) of the helium layer to that of the air is given by:

$$\frac{\tau_H}{\tau_a} = \frac{q_H}{q_a}\frac{c_{f_H}}{c_{f_a}}$$

or

$$\frac{\tau_H}{\tau_a} = \frac{m_H}{m_a}\frac{T_a}{T_H}\frac{{u_H}^2}{{u_a}^2}\frac{c_{f_H}}{c_{f_a}} \tag{5}$$

Combining equations (4) and (5) yields

$$\frac{\tau_H}{\tau_a} = \left(\frac{m_H}{m_a}\right)^{1/2}\left(\frac{u_H}{u_a}\right)^{3/2} \tag{6}$$

Examination of equation (6) shows that in order to reduce the ratio τ_H/τ_a, the molecular weight of the injected gas should be low in comparison to that of the air, thus justifying the choice of helium as the injection gas. It also appears that to minimize τ_H/τ_a the value of the film velocity u_H should be small compared to that of the air it is replacing. However, it is felt that if the value of u_H/u_a deviates much from 1, the protective nature of film will be destroyed by large-scale mixing (i.e., increased effective molecular weight of the film).

For the case of matched velocities (i.e., $u_H/u_a = 1$) ratio of the wall shear stress with helium injection to that without becomes

$$\frac{\tau_H}{\tau_a} = 0.4$$

or there will be approximately a 60-percent reduction in skin-friction drag over the area which remains laminar after the injection of helium.

Turbulent

The mean skin-friction coefficient for turbulent flow is given by the following (see ref. 6)

$$c_f = \frac{f}{R_e^{1/5}} \tag{7}$$

Using the same arguments as in the laminar flow case, we obtain the ratio of turbulent skin-friction coefficients:

$$\frac{c_{f_H}}{c_{f_a}} = \frac{f_H}{f_a} \sqrt[5]{\frac{m_a}{m_H} \frac{u_a}{u_H} \left(\frac{T_H}{T_a}\right)^2} \tag{8}$$

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where the ratio f_H/f_a is, in general, not unity.

The value of f is primarily a function of Mach number. The approximate variation of f_a with Mach number has been calculated and the results are shown in figure 2. This variation was calculated with the aid of the results of Van Driest (ref. 7). Friction coefficients given in reference 7 for adiabatic wall conditions and various Mach numbers at a Reynolds number of 1.0×10^7 were employed in equation (7) to obtain f_a. It should be remembered that this variation is for air flowing over a flat plate and some modification is necessary to obtain the variation for helium. In reference 8 it is shown that turbulent boundary layers in the two gases will be similar if

$$M_a = M_H \sqrt{\frac{\gamma_H - 1}{\gamma_a - 1}} = 1.29 M_H$$

In effect, this result means that a turbulent helium boundary layer has the same friction coefficient as a turbulent boundary layer in air flowing at the same Reynolds number and a local Mach number 1.29 times the Mach number of the helium flow. Therefore it may be deduced that

$$\left. f_H \right]_{M_H} = \left. f_a \right]_{M = 1.29 M_H}$$

or that

$$\frac{f_H}{f_a} = \frac{\left. f_a \right]_{M = 1.29 M_H}}{\left. f_a \right]_{M = M_a}} \tag{9}$$

where f_a is determined from figure 2.

The ratio of wall shear stress of the helium layer to that of the air may now be determined by combination of equations (8) and (9) with equation (5), thus

$$\frac{\tau_H}{\tau_a} = \frac{f_a\Big]_{M = 1.29M_H}}{f_a\Big]_{M = M_a}} \left(\frac{m_H}{m_a}\right)^{4/5} \left(\frac{u_H}{u_a}\right)^{9/5} \left(\frac{T_a}{T_H}\right)^{3/5} \tag{10}$$

Rewriting the temperature ratio, T_a/T_H, as a function of the Mach number and velocity ratios yields:

$$\frac{T_a}{T_H} = \frac{\gamma_H}{\gamma_a} \frac{m_a}{M_H} \frac{M_H{}^2}{M_a{}^2} \frac{u_a{}^2}{u_H{}^2}$$

Thus substitution of the above relation into equation (10) yields

$$\frac{\tau_H}{\tau_a} = \frac{f_a\Big]_{M = 1.29M_H}}{f_a\Big]_{M = M_a}} \left(\frac{\gamma_H}{\gamma_a}\right)^{3/5} \left(\frac{m_H}{m_a}\right)^{1/5} \left(\frac{M_H}{M_a}\right)^{6/5} \left(\frac{u_H}{u_a}\right)^{3/5} \tag{11}$$

For the case of matched velocities the ratio of wall shear stress with helium injection to that without becomes:

$$\frac{\tau_H}{\tau_a} = 0.747 \frac{f_a\Big]_{M = 1.29M_H}}{f_a\Big]_{M = M_a}} \left(\frac{M_H}{M_a}\right)^{6/5}$$

or, for example, if $M_a = 5$ and $M_H = 1$ there will be approximately an 80-percent reduction in skin-friction drag over the area where the film flow is turbulent. In connection with this amount of reduction, it must be remembered that this is in comparison with a turbulent air boundary layer covering the same area. Now since film injection will probably be destabilizing to the boundary layer, the point of transition will probably move forward of the no injection point. Thus the actual reduction in skin-friction drag from the no injection value will probably be somewhat less than 80 percent.

In order to determine experimentally whether the reduction in skin-friction drag indicated by this simple analysis can be realized by helium injection, the following experiment was made.

EXPERIMENT

The study of the effect of streamwise helium injection on drag was made by use of a model tested in the Ames 10- by 14-inch supersonic wind tunnel at Mach numbers of 3.0, 3.5, 4.0, and 5.0. The 10- by 14-inch supersonic wind tunnel is described in detail in reference 9.

The model used in this investigation was a 6° half-angle cone as shown schematically in figure 3. The total length of the cone was 10.85 inches and the base diameter was 2.25 inches. The forward 2.85 inches of the cone formed a conical cap which served to aline the helium flow from the interior supply tube so that it was injected aft from a circular annulus along the cone surface. The width of the annular gap was nominally 0.02 inch.

Axial forces were measured with a strain-gage balance mounted aft of the model and sting connected to the base of the model. Pressures were determined from measurements on standard U-tube manometers. For pressures of less than 4 inches of mercury absolute, dibutylphthalate was used as the manometer fluid, and for greater pressures, mercury was used.

The model was equipped with four static-pressure orifices on the cone as shown in figure 3. In addition there was a static-pressure orifice on the interior helium supply tube. One of the cone pressure orifices was located on the cone at the point of injection. Base pressures on the model were also measured.

In all cases, helium was used for the injected gas. The helium was throttled from a high-pressure supply to the desired injection pressure by a pressure regulator and was injected from the model at a total temperature of 520° R (i.e., approximately room temperature). Mass-flow rates were measured by means of a tapered tube flowmeter calibrated for helium.

The conditions at which the model was tested are shown in the table below.

Free-stream Mach number	Free-stream Reynolds number per ft	Angle of attack, deg
3	2.5×10^{6}	0 to 4
3	5.7×10^{6}	0 to 3
3	8.8×10^{6}	0 to 2
3.5	10.6×10^{6}	0, 1
4.0	8.7×10^{6}	0 to 2
5.0	3.9×10^{6}	0, 1

RESULTS AND DISCUSSION

The objective of the experiments is to evaluate the influence on skin-friction drag of replacing the high-energy air boundary layer with a film of low-energy helium. In order to study this effect, measurements were made of total axial force on the conical model. The skin-friction drag was arrived at by the subtraction of the base drag and pressure drag and the addition of the thrust due to the momentum of the injected gas to the total axial force. First, let us focus attention on the influence of injection on pressure drag.

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Pressure distributions over the cone for each of the test conditions are shown in figure 4 for zero angle of attack only and for some representative values of the amount of injection. Note that the amount of injection is given in coefficient form, C_i, which is defined as the ratio of the mass rate of helium injection to the mass rate of free-stream air swept out by the base area of the model, or

$$C_i = \frac{\dot{m}_H}{\rho u S} \tag{12}$$

The data in figure 4 do not include the pressure coefficients measured at the point of injection. The pressure coefficients at this point vary from negative values with no injection to high positive values with the largest amounts of injection.

Examination of the results presented in figure 4 shows that the pressures were not affected appreciably by the injection so that the pressure drag of the cone remained essentially constant with injection.

The forebody axial-force coefficients (i.e., with base drag removed but forebody pressure drag retained) for each of the test conditions listed in the above table are shown in figures 5(a) to 5(f). Again the amount of injection is represented in coefficient form. It should be noted that these data show the entire effect of injection (i.e., streamwise) and part of the decrease in axial-force coefficient is due to the thrust obtained from the momentum of the injected gas. The lines labeled "sonic thrust decrement" on figures 5 show the amount of decrease in axial-force coefficient from the zero injection axial-force coefficient that is due to this thrust. This decrement was obtained from the analysis of appendix A which is based on the assumption that the helium flow in the injection port is sonic. This assumption was borne out by comparison of the measured pressure in the injection port and the pressure in the interior helium supply tube. The thrust coefficient is derived as:

$$C_T = \frac{Th}{(1/2)\rho u^2 S} = \frac{2(\gamma_H+1)}{\gamma_H} \frac{a_H^*}{u} C_i \tag{13}$$

From the results in figures 4 and 5 the skin-friction drag coefficients may now be obtained by subtraction of the forebody pressure-drag coefficient and addition of the thrust coefficient to the forebody axial-force coefficient. Results obtained in this manner are shown in figure 6 as the ratio of the skin-friction drag coefficient with injection to that with no injection. The drag-coefficient ratios, which are for $C_i = 2\times10^{-3}$ and $\alpha = 0^{\circ}$, are shown as a function of the air to helium velocity ratio. Also shown are the results of the simple analysis of the previous section for both laminar air to laminar helium flows and turbulent air to turbulent helium flows. Included in the turbulent curve are both the effects of velocity ratio and Mach number of the experimental data presented. Note first that the data indicate that large reductions in skin-friction drag can be accomplished by the film injection technique. Reductions as large as 60 percent were found when the velocity ratio approached unity. It is felt that at least part of the difference between the results of the analysis and the other data is attributable to mixing. As noted before, increased mixing between the air and the helium film is to be expected when the velocities of helium and exterior air flows are mismatched. The analysis also indicates a continued downtrend of skin-friction drag as the helium velocity is reduced; however, it seems reasonable to expect that mixing will eventually occur, modifying this trend.

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Visual comparison of the film flows at the extremes of the velocity ratios shown in figure 6 (i.e., $M = 3$ and $M = 5$) can be made by examination of the spark shadowgraphs shown in figures 7 and 8. Also, for comparison, a spark shadowgraph taken at $M = 5$ and no helium injection is shown in figure 9.

It is apparent from the data that large reductions in skin-friction drag can be accomplished by a streamwise film injection technique if some care is exercised in the manner of injection. Consider now the effect on skin friction of the rate of injection.

In figure 10 is shown the skin-friction drag coefficient for the $M = 5$ test condition versus the injection coefficient C_i. We have seen that it appears that the assumptions of the analysis presented in this paper tend to be satisfied best at the test condition photographed in figure 8. Therefore, it was at this point that the simplified analysis was applied to obtain an estimate of the amount of skin-friction reduction. From the photograph, transition of the film flow was determined to occur 3.85 inches aft of the cone tip. The theory of Van Driest (ref. 7) was used to determine the air friction drag which was corrected to conical flow, and equations (6) and (11) were used to adjust the result for the effects of film injection. The result of these calculations is shown as the filled symbol at $C_i = 1.35\times10^{-3}$ in figure 10. Also shown in figure 10 is an estimate of the no-injection friction drag coefficient (i.e., filled symbol at $C_i = 0$). Transition was determined to occur 8.8 inches aft of the cone tip with no injection (see fig. 9). The theory of Van Driest was used to determine the air friction drag which was corrected to conical flow.

Also shown in figure 10 is the value of the injection coefficient when the static pressure of the helium film, as it issued from the sonic port, is exactly matched to the air static pressure on the cone (i.e., $P_H^* = P_e$). It can be seen from figure 10 that for injection rates greater than about $C_i = 2\times10^{-3}$, the skin-friction drag coefficient tends to return to the level of the no-injection value. This behavior is understandable if one examines a spark shadowgraph of the flow over the cone at $M = 5$ and $C_i = 4.5\times10^{-3}$ as shown in figure 11. It can be seen that at these relatively high mass flows the film as it is injected over the cone is overpressurized with respect to the air flowing next to the cone. The film immediately expands to alleviate this condition and it appears that intense mixing results. However, in spite of this mixing it appears that the helium film must still be quite effective since it counteracts the effect of transition moving forward to the injection port. Again it is evident that some care must be taken in the manner of injection to obtain the large reductions in skin-friction drag. It appears also that the static pressure of the film at the injection port should be approximately equal to the static pressure of the air at the point of injection.

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The data have shown that streamwise injection of helium into the boundary layer of slender bodies can provide sizable reductions in skin-friction drag as well as a slight thrust. It is interesting to evaluate these gains in terms of an equivalent specific impulse. The equivalent specific impulse is defined as:

$$I_s = \frac{\text{drag reduction (including injection thrust), lb}}{\text{weight flow of helium, lb/sec}}$$

or

$$I_s = \frac{\Delta C_{A_f}(1/2)\rho u^2 S}{g C_i \rho u S} = \frac{\Delta C_{A_f} u}{2 g C_i} \tag{14}$$

where

$$\Delta C_{A_f} = \Delta C_{D_f} + C_T$$

If equation (13) is used for the thrust coefficient, the equivalent specific impulse can then be written as:

$$I_s = \frac{\Delta C_{D_f} u}{2 g C_i} + \frac{\gamma_H + 1}{\gamma_H} \cdot \frac{a_H^*}{g}$$

Performing the calculation for the best point at $M = 5$ (i.e., $C_i = 1.35\times10^{-3}$, see fig. 10) we obtain a specific impulse due to friction drag reduction of 410 seconds and a specific impulse due to thrust of 140 seconds, or a total of 550 seconds. This is not meant to imply that the film injection technique may be used as an efficient means of propulsion. On the other hand, it is indicated, for example, that the helium film injection technique is more efficient in reducing axial friction force than chemical rocket motors are in overcoming that force.

The model was tested at only small angles of attack and it appeared that at small angles of attack no appreciable washout of the film occurred; however, it seems reasonable to expect that at least some washout will occur at high angles of attack.

CONCLUDING REMARKS

It has been shown experimentally that a reduction in skin-friction drag of a slender vehicle traveling at hypersonic speeds can be obtained by the injection of a light gas into the boundary layer near the nose. At a Mach number of 5 a 60-percent reduction in the skin-friction drag of a 6° half-angle cone was found with the injection of a comparatively small mass rate of helium (0.15 to 0.2 percent of the mass rate of free-stream air swept out by the base of the cone).

It was also indicated that care must be exercised in the manner of injection so as to minimize the amount of large-scale turbulent mixing of air into the helium film.

Very little effect of the helium injection on pressure distribution of the cone was noted. At small angles of attack essentially no washout of the helium film was observed.

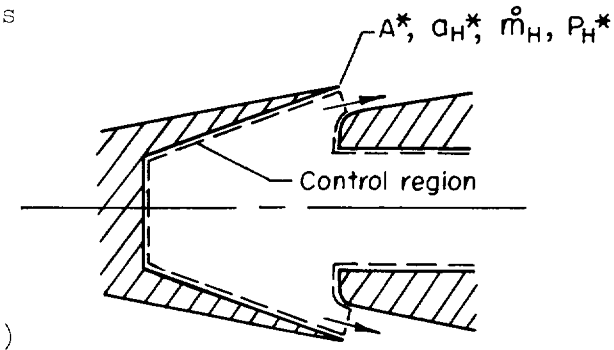
Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., July 26, 1960

APPENDIX A

THRUST CORRECTION

Because of the manner of injection (i.e., streamwise) some thrust is realized from the momentum of the injected gas. To determine the effect of injection upon the skin-friction drag of the cone it is necessary to correct the measured data for this thrust.

Comparison of the measured pressure at the injection port and that measured in the interior helium supply tube shows that sonic flow was attained by the helium in the injection port. Therefore in the analysis of the thrust correction it will be assumed that the injection is always sonic. A diagram of the control region of the analysis is shown in the sketch below. The thrust (acting on the model) is defined as the sum of pressure forces in the axial direction on the interior metal surfaces of the model (positive forward). The forces of the metal walls on the control region are therefore equal and opposite in direction. The momentum theorem written for the control region is then (neglecting the slight inclination of the flow)



$$Th - P_H^*A^* = \dot{m}_H a_H^* \qquad \text{(A1)}$$

where it is assumed that no momentum is added through the right-hand side of the control region. Note that since sonic flow is assumed in the injection gap, we may write the following.

$$P_H^*A^* = \rho_H^*A^*a_H^* \frac{R_H T_H^*}{a_H^*} = \dot{m}_H \frac{a_H^*}{\gamma_H} \qquad \text{(A2)}$$

Therefore the thrust may be written:

$$Th = \dot{m}_H a_H^* \frac{\gamma_H + 1}{\gamma_H}$$

Defining a thrust coefficient, we finally obtain the following relation for the thrust correction.

$$C_T = \frac{Th}{(1/2)\rho u^2 S} = \frac{2(\gamma_H + 1)}{\gamma_H} \frac{a_H^*}{u} C_i \qquad \text{(A3)}$$

where

$$C_i = \frac{\dot{m}_H}{\rho u S}$$

In the more general case of either subsonic or supersonic flow in the injection port, equation (A1) becomes,

$$Th - P_H A = \dot{m}_H u_H$$

We may write the pressure force term in the following form.

$$P_H A = \rho_H A u_H \frac{R_H T_H}{u_H} = \dot{m}_H \frac{u_H}{\gamma_H {M_H}^2}$$

Thus the thrust may be written as:

$$Th = \dot{m}_H u_H \frac{\gamma_H {M_H}^2 + 1}{\gamma_H {M_H}^2}$$

Again defining the thrust coefficient, we obtain the following relation:

$$C_T = \frac{Th}{(1/2)\rho u^2 S} = \frac{2(\gamma_H {M_H}^2 + 1)}{\gamma_H {M_H}^2} \frac{u_H}{u} C_i \qquad (A4)$$

where

$$C_i = \frac{\dot{m}_H}{\rho u S}$$

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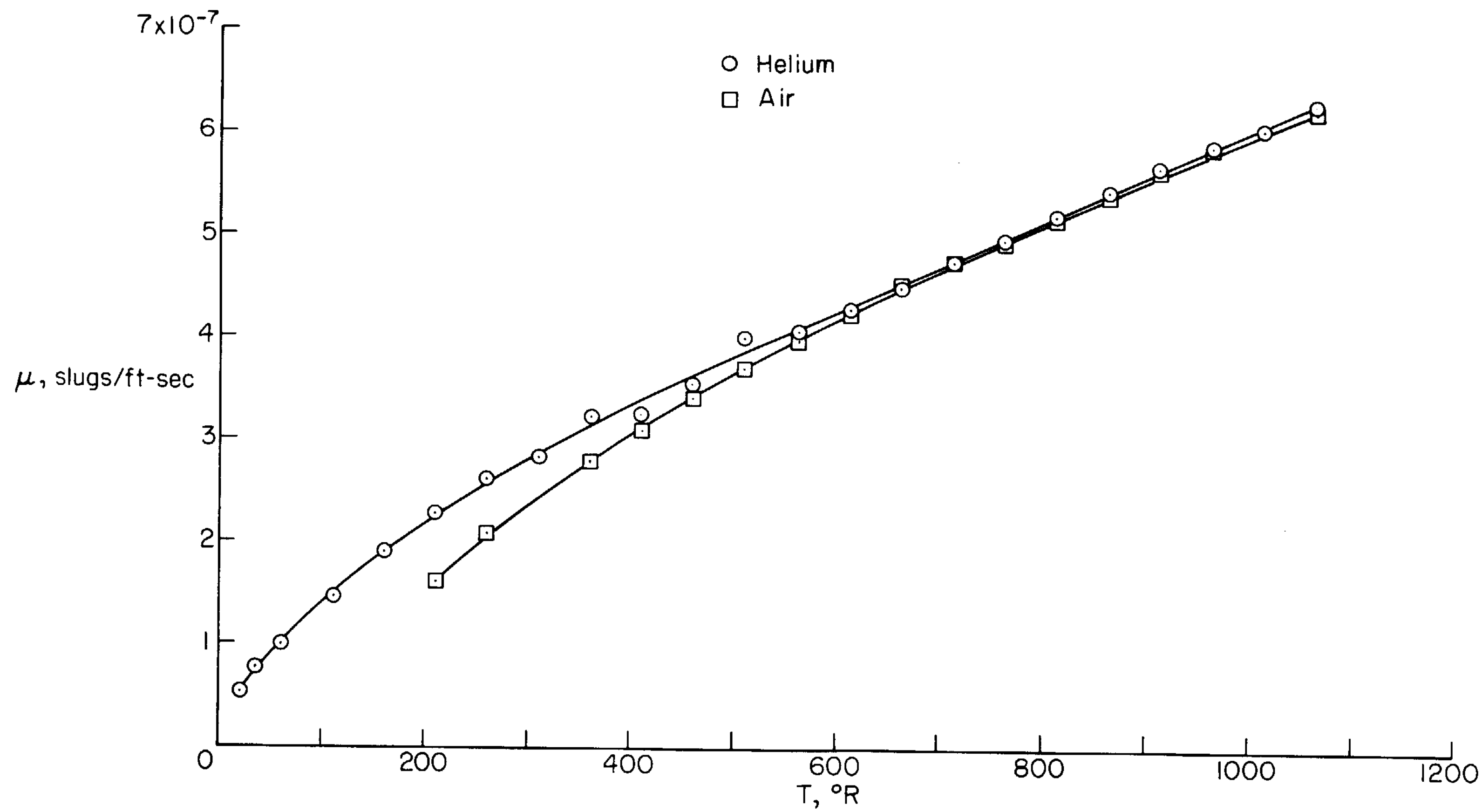

Figure 1.- Comparison of air and helium viscosity data.

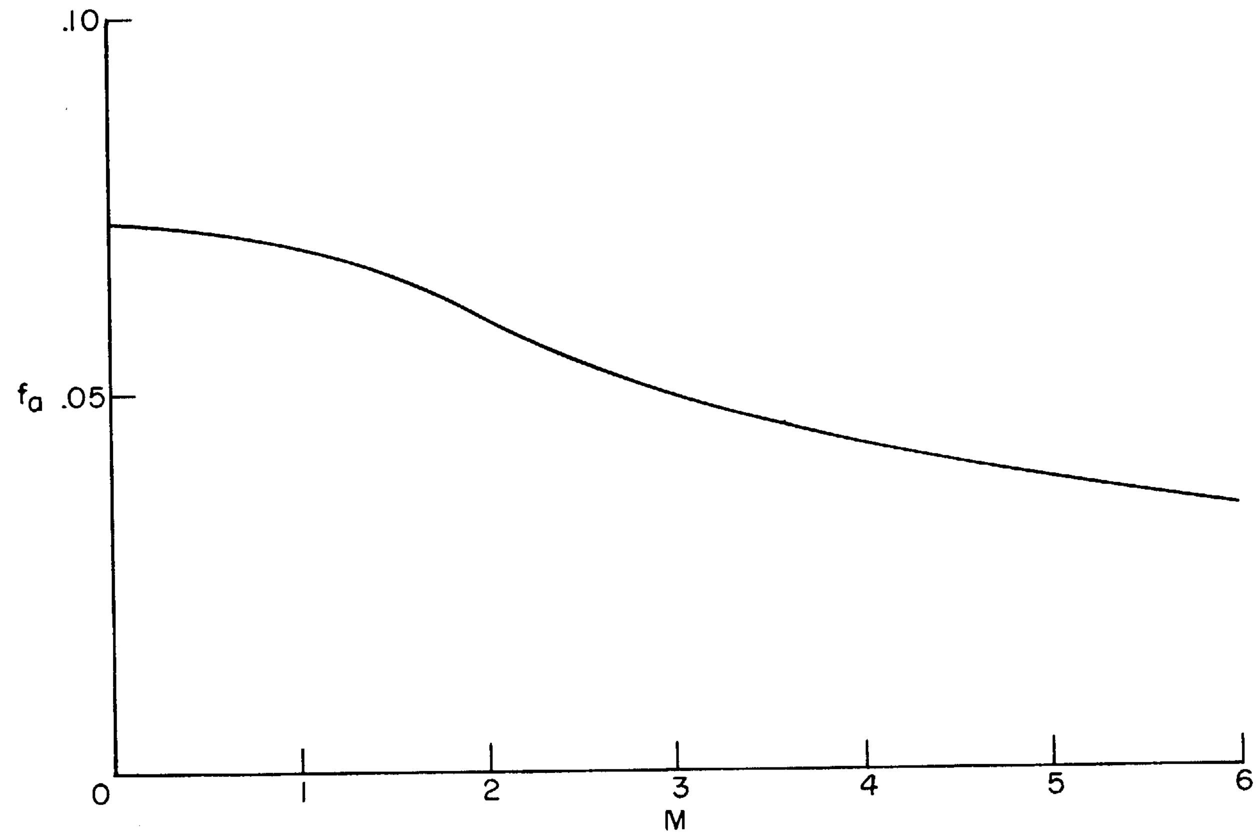

Figure 2.- Turbulent mean skin-friction proportionality constant as a function of Mach number for an adiabatic wall.

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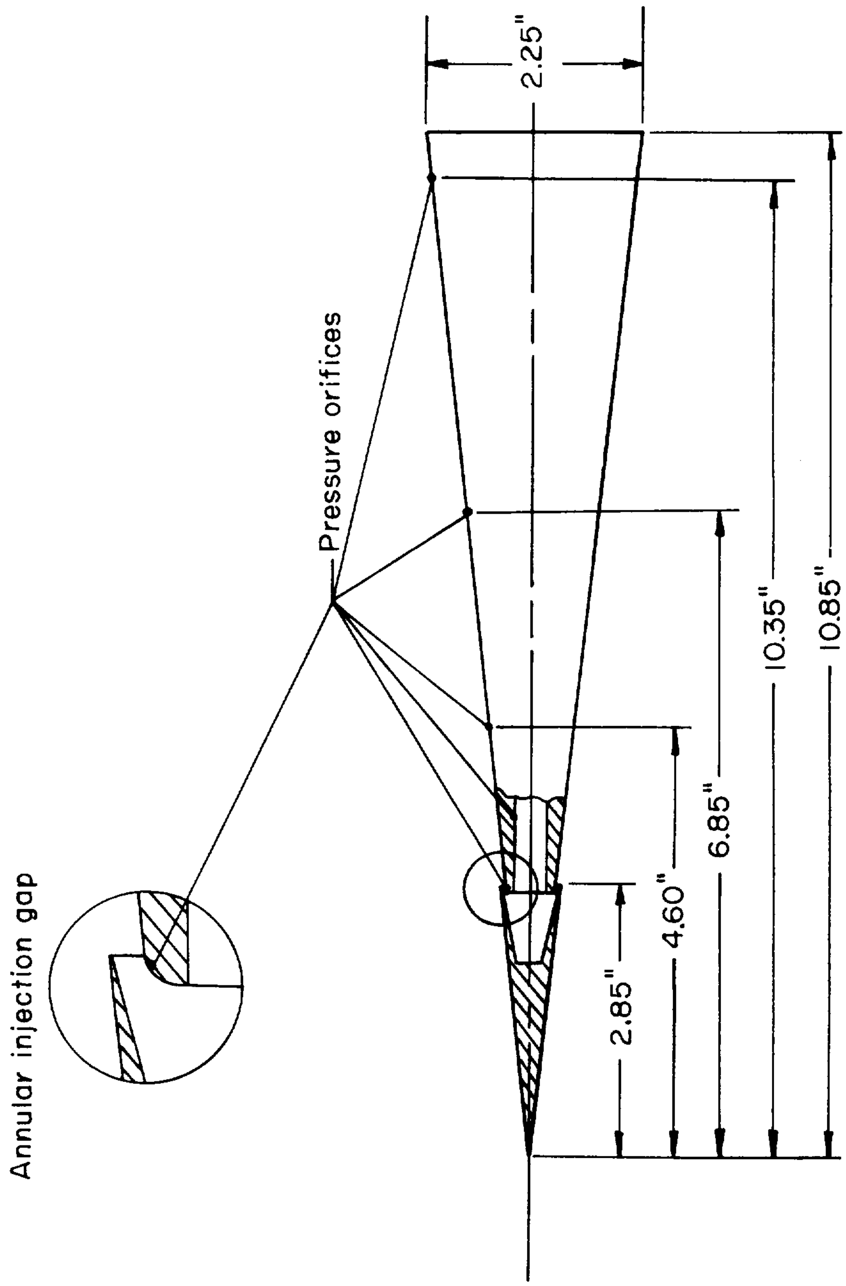

Figure 3.- Schematic diagram of model.

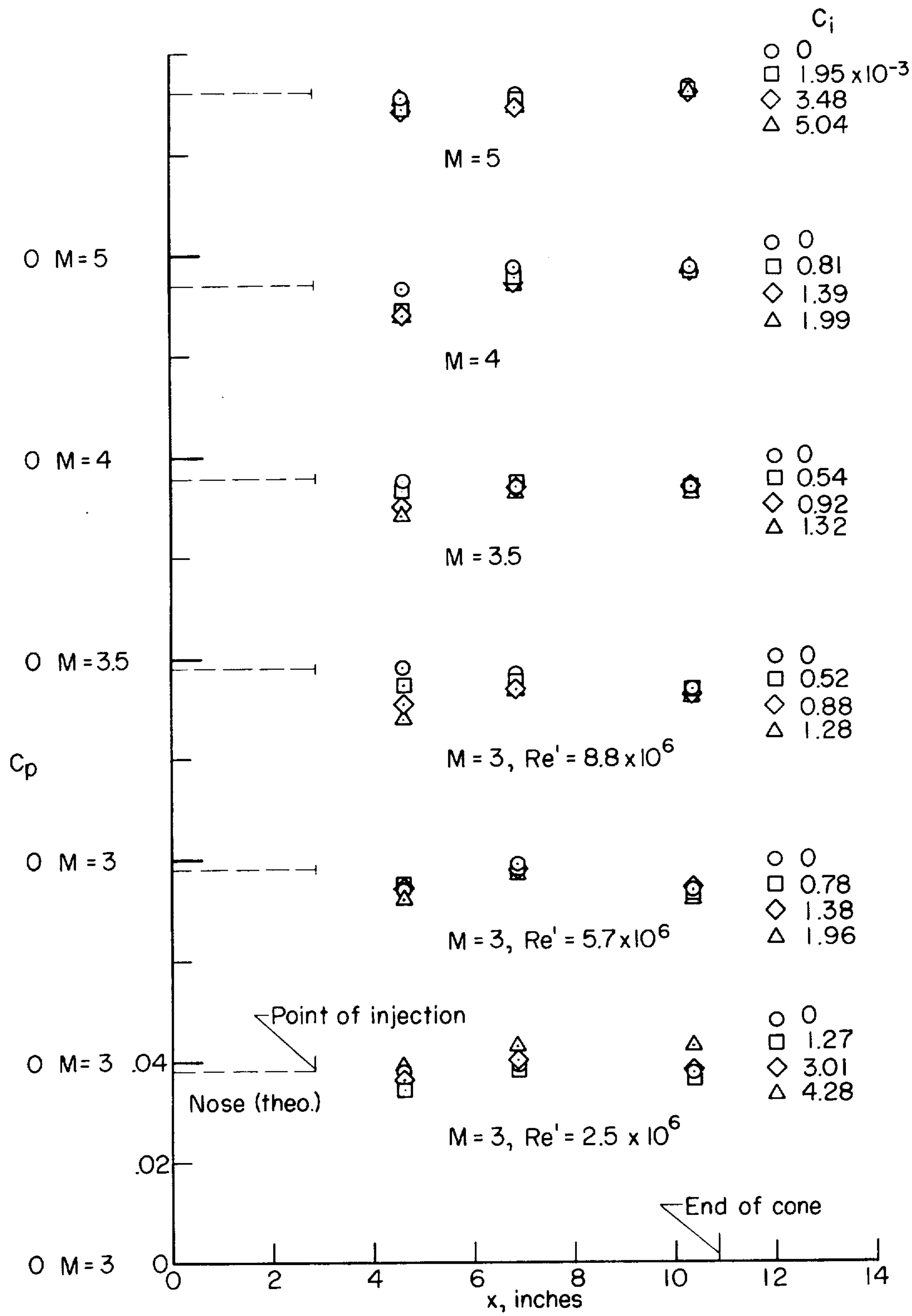

Figure 4.- Basic data; pressure distribution.

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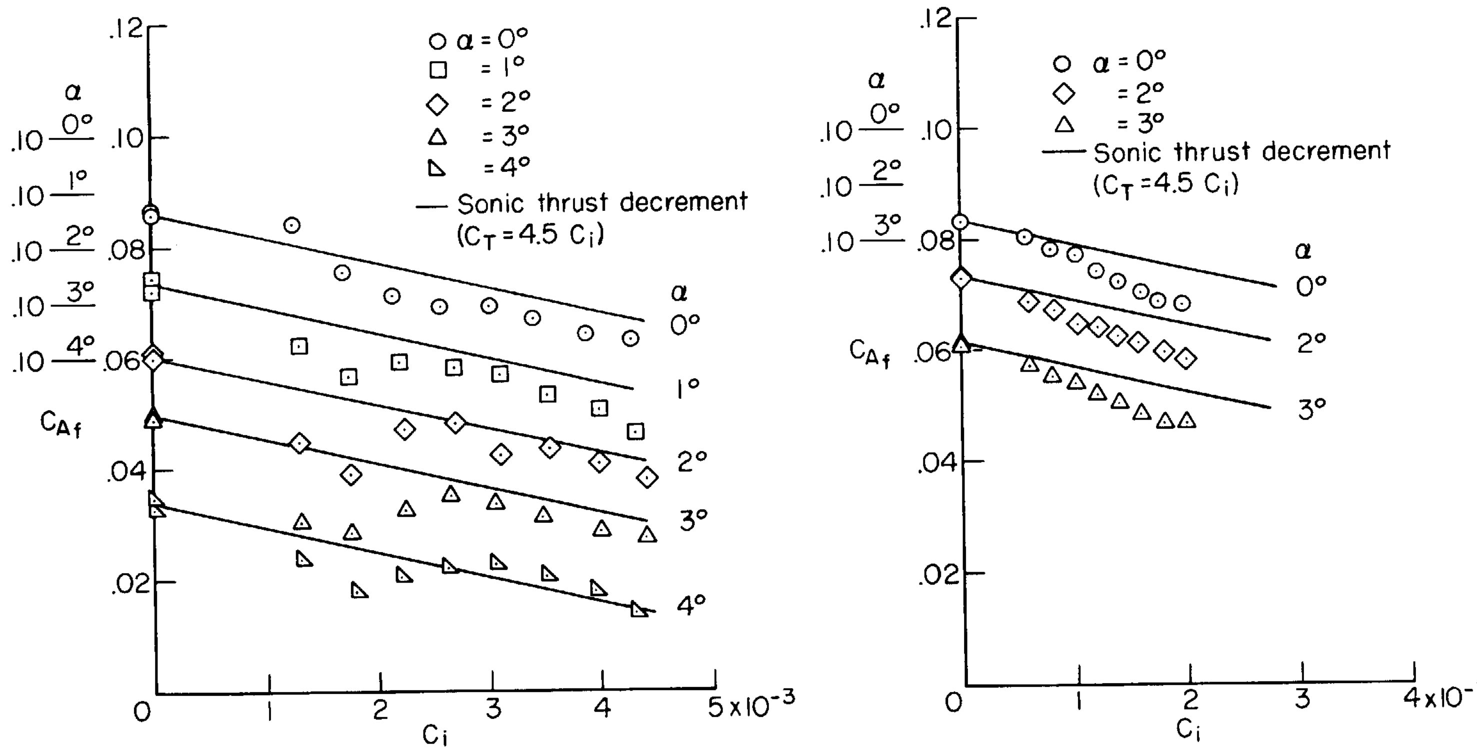
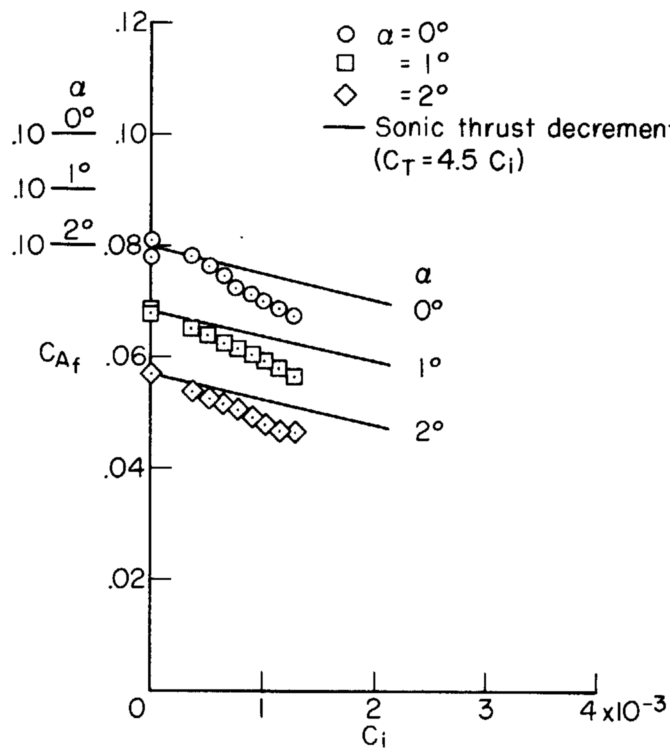


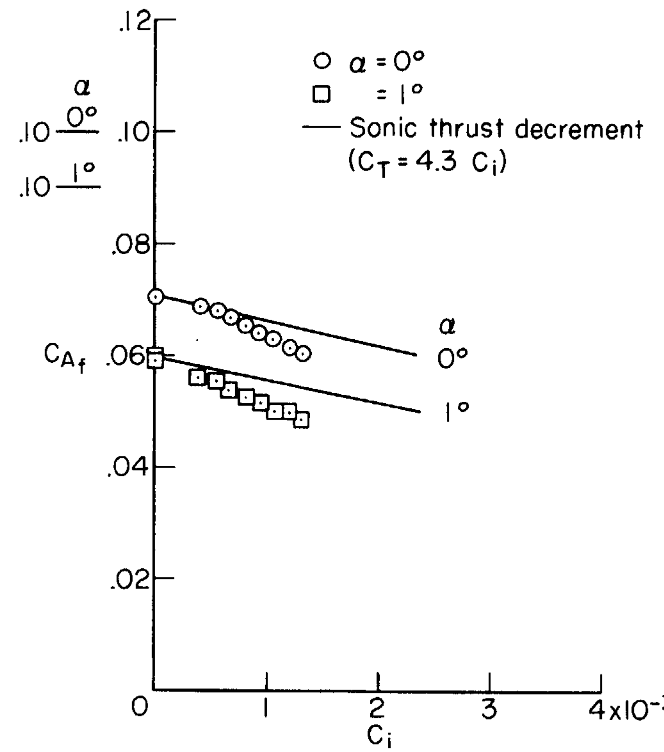
(a) M = 3, Re' = 2.5 x 10^6/ft

(b) M = 3, Re' = 5.7 x 10^6/ft

Figure 5.- Basic data; forebody axial-force coefficient.

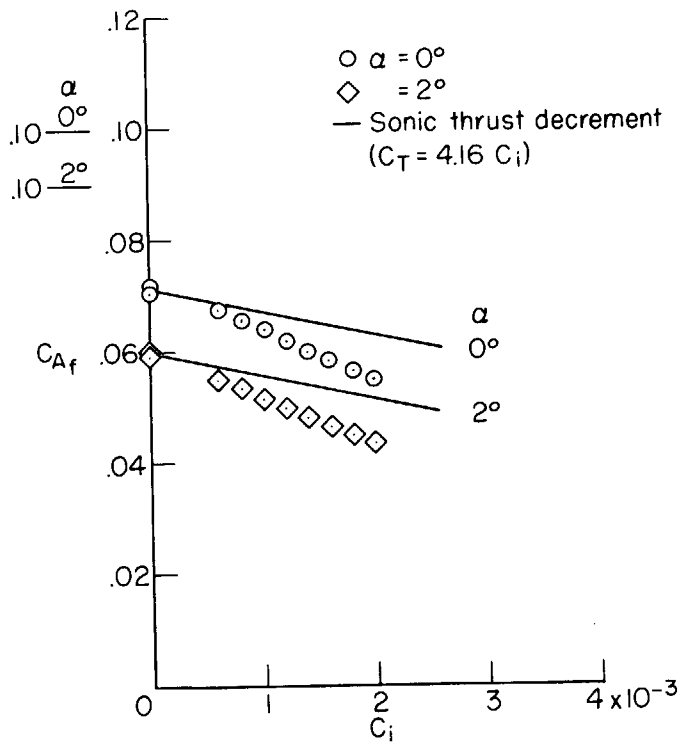


(c) M = 3, Re' = 8.8 x 10⁶/ft

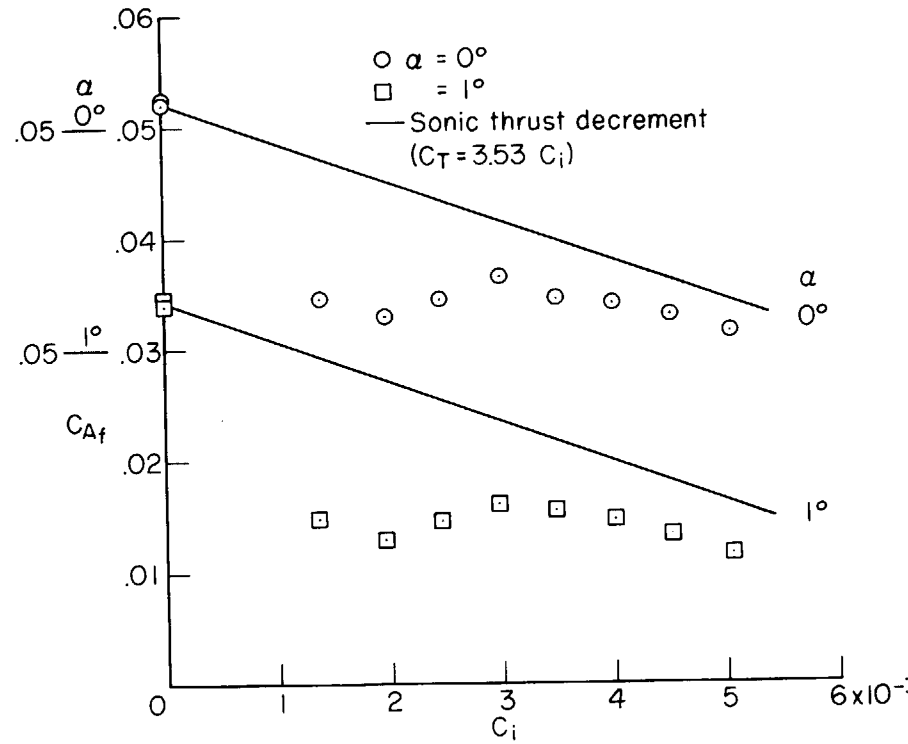


(d) M = 3.5, Re' = 10.6 x 10⁶/ft

Figure 5.- Continued.



(e) M = 4, Re' = 8.7 x 10^6/ft



(f) M = 5, Re' = 3.9 x 10^6/ft

Figure 5.- Concluded

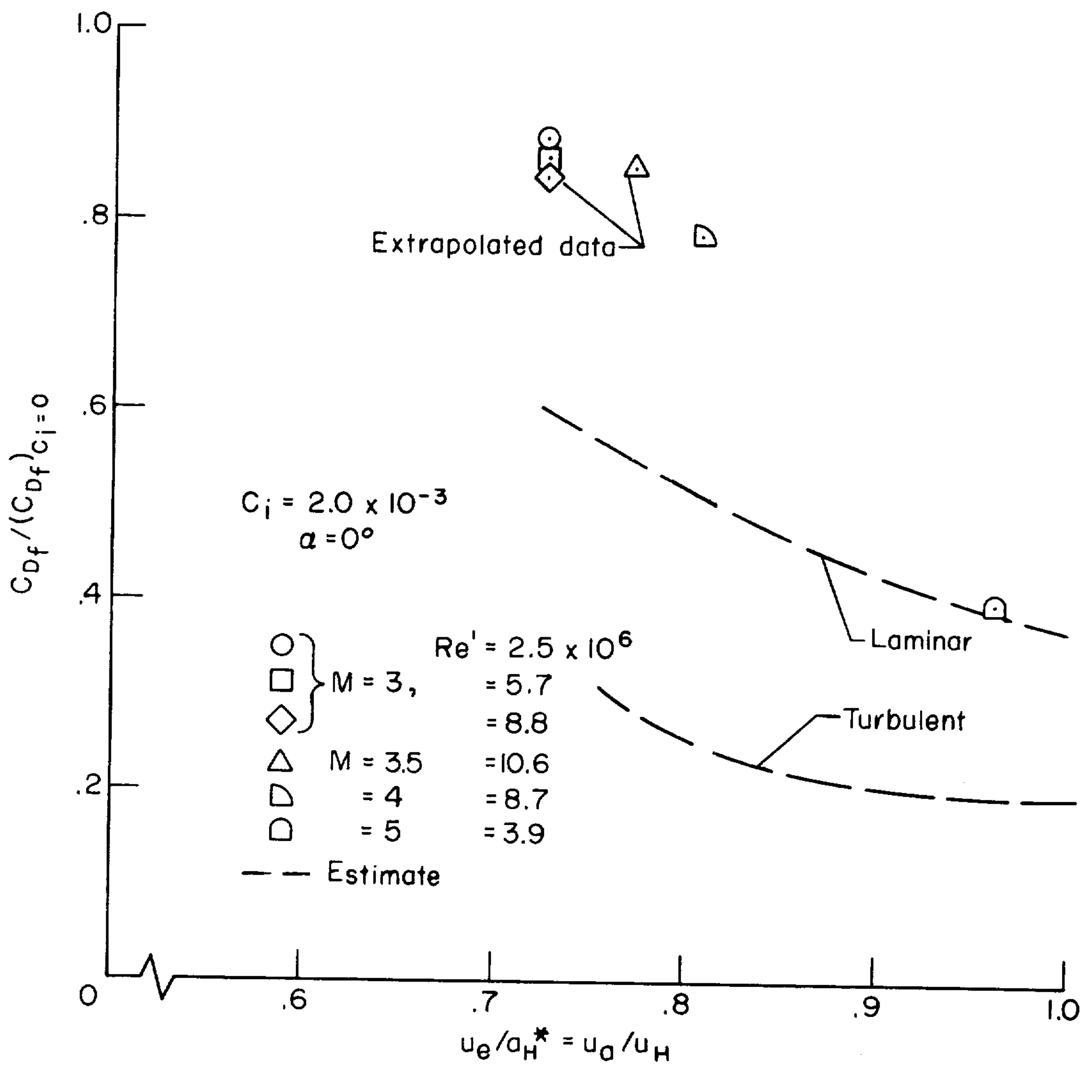


Figure 6.- Friction-drag reduction as a function of injection velocity ratio.

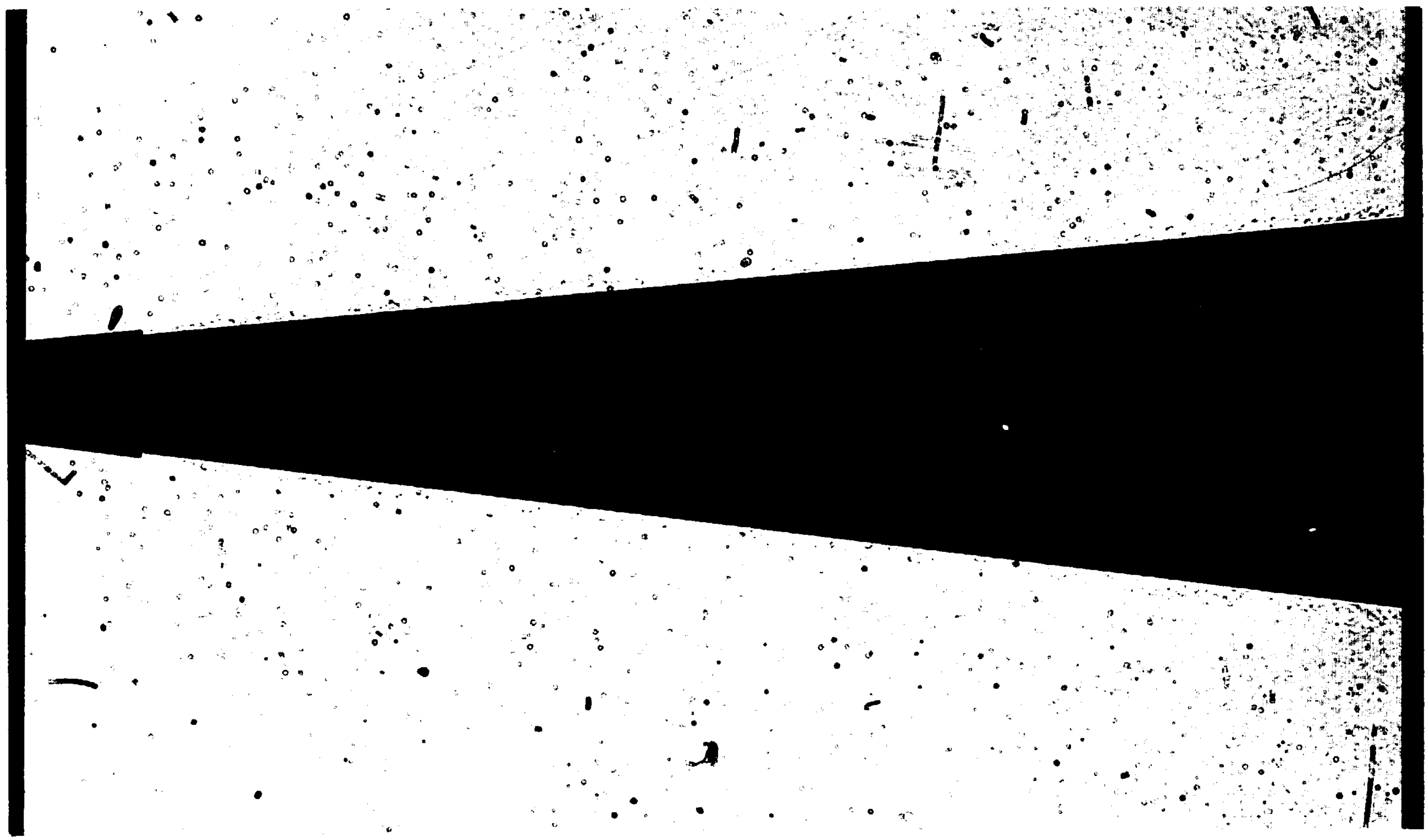


Figure 7.- Shadowgraph: $M = 3$, $Re' = 2.5 \times 10^6/ft$, $C_i = 2.57 \times 10^{-3}$.

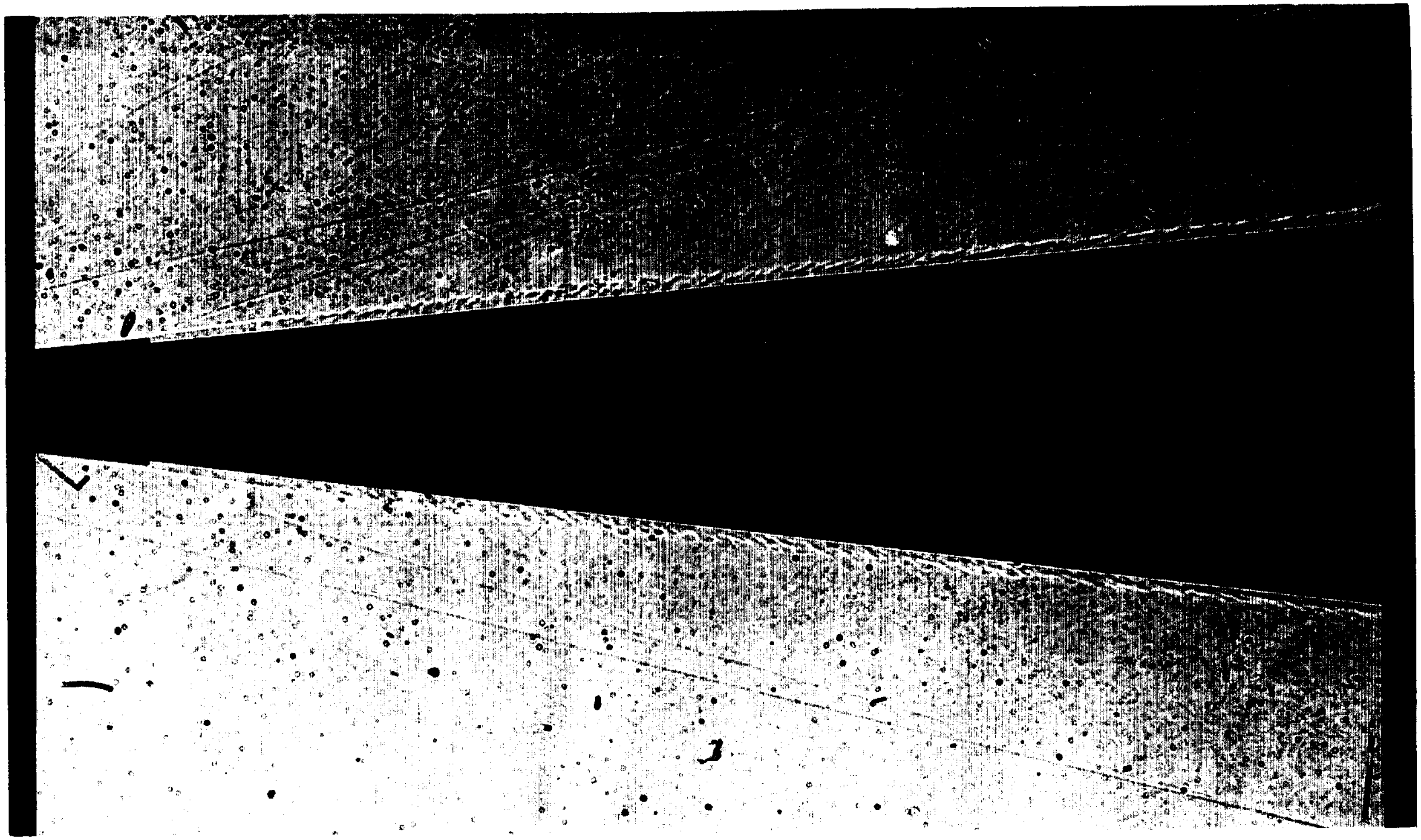


Figure 8.- Shadowgraph: $M = 5$, $Re' = 3.9 \times 10^6/ft$, $C_i = 1.36 \times 10^{-3}$.

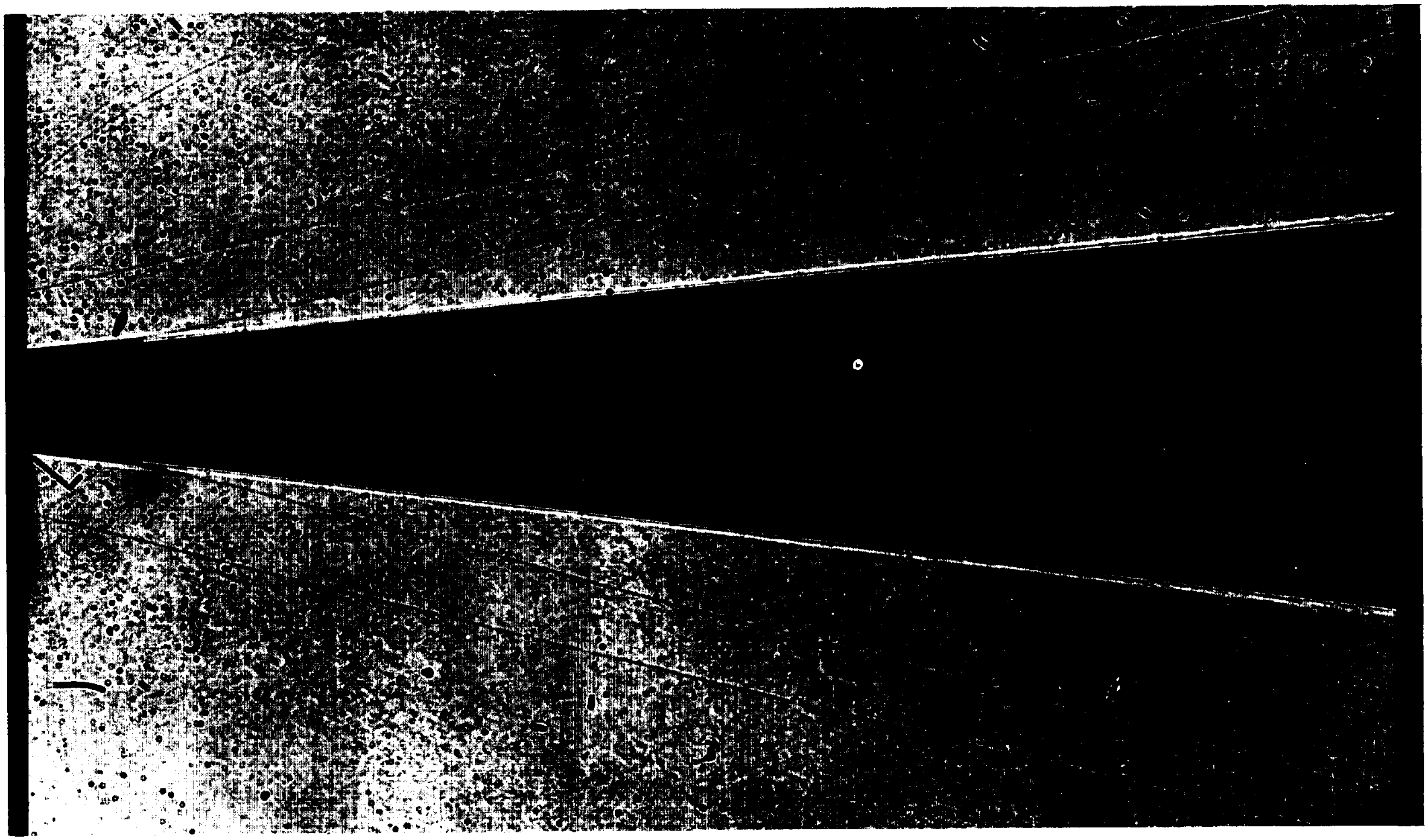


Figure 9.- Shadowgraph: $M = 5$, $Re' = 3.9 \times 10^6/ft$, $C_i = 0$.

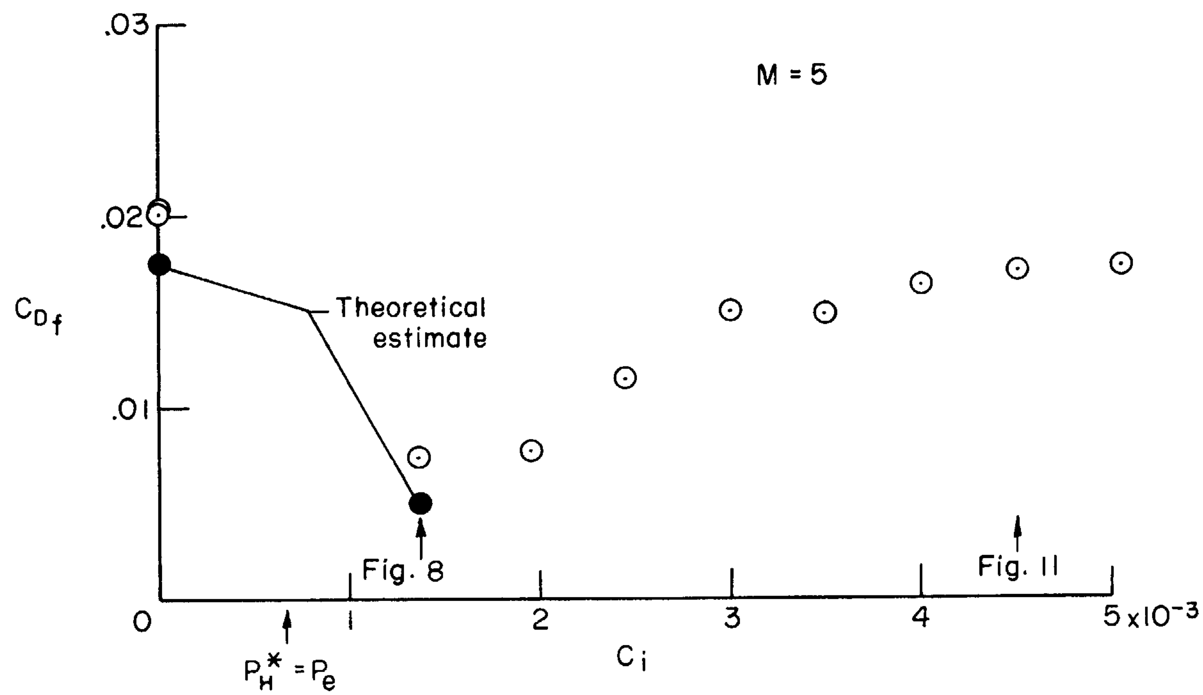


Figure 10.- Skin-friction drag coefficient as a function of injection coefficient.

A
4
1
4

A
4
1
4

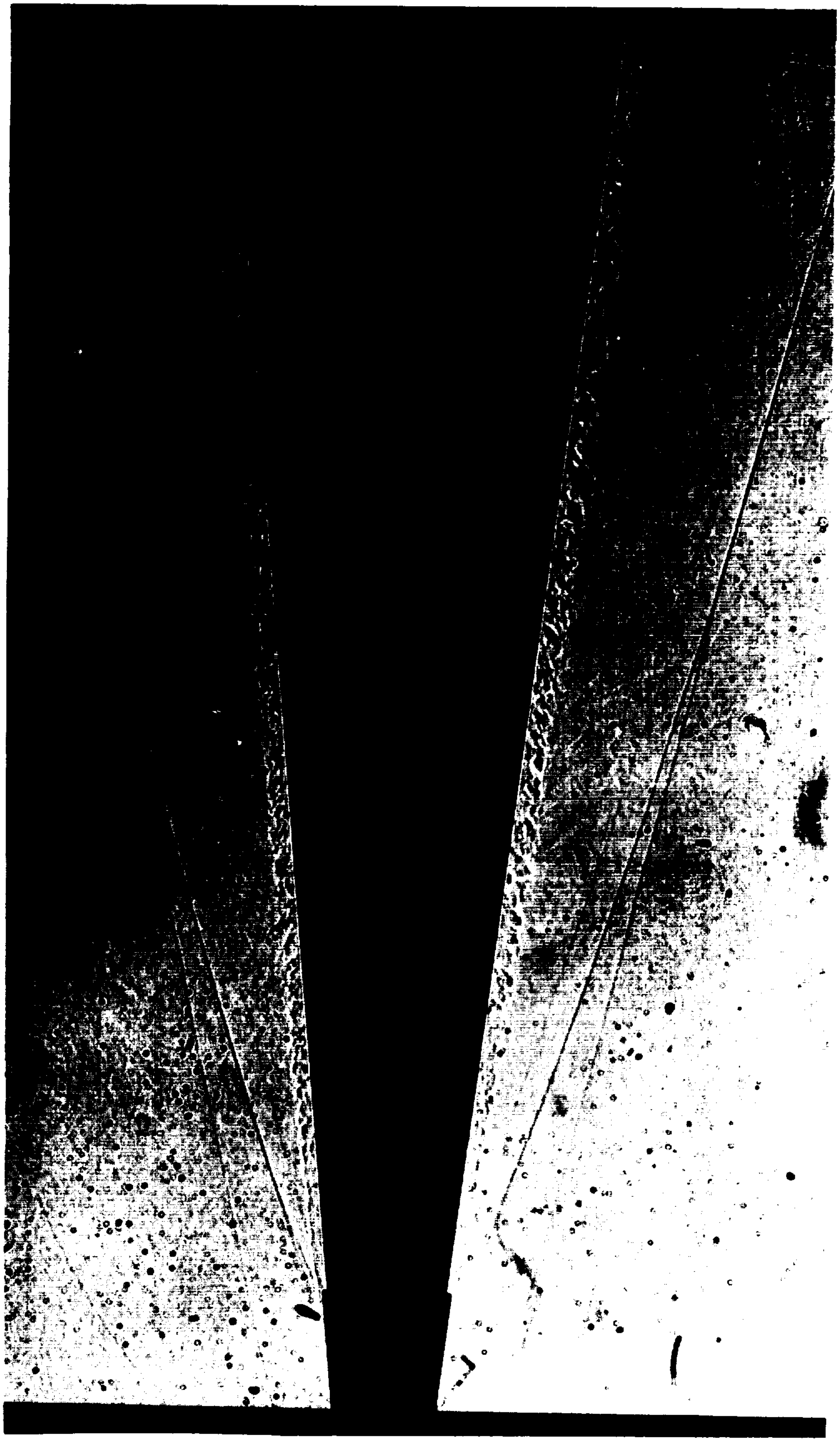


Figure 11.- Shadowgraph: $M = 5$, $Re' = 3.9 \times 10^6$/ft, $C_i = 4.50 \times 10^{-3}$.

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(NASA TECHNICAL NOTE D-342)

The effects on average skin-friction drag and pressure drag of the streamwise injection of helium into the boundary layer near the nose of a 6° half-angle cone at Mach numbers of 3 to 5 are presented. Large reductions in skin friction are shown to be possible with relatively small amounts of helium injection.

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