AEDC-TDR-63-23

INVESTIGATION OF DRAG REDUCTION BY BOUNDARY-LAYER SUCTION ON A 36-DEG SWEPT WING AT M_∞ = 2.5 TO 4

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ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

NOTICES

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a subsidiary of Sverdrup and Parcel, Inc.

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ABSTRACT

Tests were conducted in the 40-Inch Supersonic Tunnel (A) of the von Kármán Gas Dynamics Facility to determine the effectiveness of boundary-layer suction for laminar flow control on a two-dimensional, biconvex, 36-deg swept wing. Test Mach numbers were 2.5, 3, 3.5, and 4 with a Reynolds number range based on wing chord from 10 to 25 million for angles of attack of 0 and -3.25 deg.

With suction, laminar flow was maintained at $\alpha = 0$ deg for $M_\infty = 2.5$, 3, and 3.5 up to length Reynolds numbers based on rake location of 18, 25, and 20×10^6, respectively, which resulted in drag reductions of 60 percent as compared to the no suction, fully turbulent drag data. At $M_\infty = 3$ and 3.5, no major difference existed between the minimum total drag coefficients obtained for zero angle of attack and -3.25 deg. Also presented for all test Mach numbers are the fully turbulent, wake drag coefficients obtained with the conditions of no suction.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

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DCS/Test

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Colonel, USAF
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NOMENCLATURE

A_n	Reference area based on n^{th} chamber average span and rake location $(A_n = b_n \cdot x)$, sq in.
b_n	Reference width (average span in n^{th} chamber), in.
C_{D_S}	Suction drag coefficient, $\sum_{n=1}^{x} C_{m_n} \left(1 + \frac{M_n^2 T_n}{M_\infty^2 T_\infty}\right)$
C_{D_T}	Total drag coefficient, $(C_{D_W} + C_{D_S})$
C_{D_W}	Wake drag coefficient, $(2\theta_\infty / x)$
C_{m_n}	Local suction coefficient, $(m_n/\rho_\infty U_\infty A_n)$
C_{m_t}	Total suction coefficient, $\sum_{n=1}^{x} C_{m_n}$
c	Model chord length, measured parallel to free stream, in.
LE	Leading edge
M_n	Suction chamber Mach number
M_r	Mach number outside the boundary layer
M_∞	Free-stream Mach number
m_n	Local mass rate of suction, lb-sec/in.
q_∞	Free-stream dynamic pressure, psia
Re_c	Reynolds number based on wing chord length
Re_x	Reynolds number based on rake location
T_n	Suction chamber temperature, °R
T_∞	Free-stream static temperature, °R
U_r	Velocity outside boundary layer, in./sec
U_∞	Free-stream velocity, in./sec
u	Local velocity in boundary layer, in./sec
x	Model surface coordinate or boundary-layer rake location, measured from model leading edge, in.
y	Model surface coordinate or distance normal to model surface, in.
α	Wing angle of attack, deg
δ	Boundary-layer total thickness, in.

θ_r	Boundary-layer momentum thickness at rake location, in. $\int_0^\delta \frac{\rho u}{\rho_r U_r}\left(1 - \frac{u}{U_r}\right) dy$
θ_∞	Boundary-layer momentum thickness for free-stream conditions, in.
ρ	Local density in the boundary layer, $\frac{\text{lb - sec}^2}{\text{in.}^4}$
ρ_r	Density outside boundary layer, $\frac{\text{lb-sec}^2}{\text{in.}^4}$
ρ_∞	Free-stream density, $\frac{\text{lb - sec}^2}{\text{in.}^4}$

SUBSCRIPTS

n	The n^{th} suction chamber
r	Conditions outside the boundary layer
∞	Free-stream conditions

1.0 INTRODUCTION

Under the sponsorship of the Aeronautical Systems Division (ASD), Air Force Systems Command (AFSC), a second experimental boundary-layer control test was conducted on a 36-deg two-dimensional swept wing for the NORAIR Division of the Northrop Corporation. Tests were made in the 40-Inch Supersonic Tunnel (A) of the von Kármán Gas Dynamics Facility (VKF), Arnold Engineering Development Center (AEDC), AFSC, during the period October 10 to 17, 1962. Test Mach numbers were 2.5, 3, 3.5, and 4 over a Reynolds number range based on wing chord from 10 to 25 million at angles of attack at 0 and -3.25 deg.

The purpose of the test was to determine the effect of boundary-layer suction in establishing extensive lengths of laminar flow when the boundary layer was subjected to the destabilizing effects of cross-flow. The first test (Ref. 1), also conducted in the 40-Inch Supersonic Tunnel (A), was successful in establishing full chord laminar flow up to a Reynolds number of 11 million at $M_\infty = 3$, $\alpha = 0$, but at higher Reynolds numbers the flow became turbulent. For the present investigation, NORAIR modified the existing model by increasing the slot widths and placing two additional suction suction slots in the leading edge region.

2.0 APPARATUS

2.1 WIND TUNNEL

The 40-Inch Supersonic Tunnel (A) in Fig. 1 is a continuous, closed circuit, variable density wind tunnel with an automatically driven flexible-plate-type nozzle. The tunnel operates at Mach numbers from 1.5 to 6 at maximum stagnation pressures from 29 to 200 psia, respectively, and stagnation temperatures up to 300°F ($M_\infty = 6$). Minimum operating pressures are about one-tenth of the maximum at each Mach number. A complete description of the tunnel and airflow calibration information is given in Ref. 2.

2.2 MODEL

The 36-deg NORAIR swept wing (Fig. 2) spanned the tunnel test section and was supported by the tunnel sidewalls. The wing (Fig. 3)

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had a three percent thick, biconvex, circular-arc profile section (measured perpendicular to the leading edge (LE) with a LE thickness of 0.008 in. Coordinates for the surface are presented in Fig. 4. A section of the top surface was vented with 68 suction slots that were parallel to the LE and varied in widths of 0.005 to 0.014 in. from the first to the last slot (see Fig. 4). For the present investigation, NORAIR added two slots to the LE region, changing the perpendicular distance of the first slot from 1.6 to 0.78 in. aft of the LE. The suction slot widths were also increased an additional 0.001 to 0.002 in. By increasing the slot widths, the wing suction system design Mach number changed from Mach number 3 to 3.5.

Eight separate suction chambers were contained within the model and connected separately to an individual metering box; thus variable suction was provided over the model surface. The model was instrumented to measure the surface pressure at six chord stations and in each suction chamber. Temperatures were measured in three of the eight suction chambers.

2.3 BOUNDARY-LAYER RAKE

The rake (Fig. 5) was composed of 16 probes ranging in height (distance from the probe centerline to the model surface) from 0.012 to 0.490 in. Each probe had an ID of 0.010 in. and an OD of 0.012 in. at the tip and was located in a plane parallel to the wing leading edge. Two probes (15 and 16) were located outboard of the main rake assembly to determine if any contamination of the laminar flow in the suction area resulted from the adjacent turbulent flow. The probes could be automatically driven to traverse a distance of 10 in. (from the trailing edge) along the suction area centerline. A magnet was located in the probe head to assure continuous contact with the curved surface.

2.4 SUCTION SYSTEM

Suction (operating range from 0.04 to 0.10 psia) was provided by a 12-in. vacuum line, which was connected separately by 2-in. ID rubber pipe to each of the eight metering boxes (Figs. 2c and 6). Flow regulation to each suction chamber was maintained by a throttling valve on each metering box. Separately interchangeable nozzles facilitated measurement of the different levels of mass flow from each of the eight suction chambers.

2.5 INSTRUMENTATION

Model data recorded during the test were boundary-layer pitot pressures, model surface static pressures, suction chamber pressures and temperatures, metering chamber total pressures and temperatures, and metering nozzle static pressures. Pressures were measured with differential transducers, and data were processed with the VKF data handling system and computer to provide reduced data while the test was in progress.

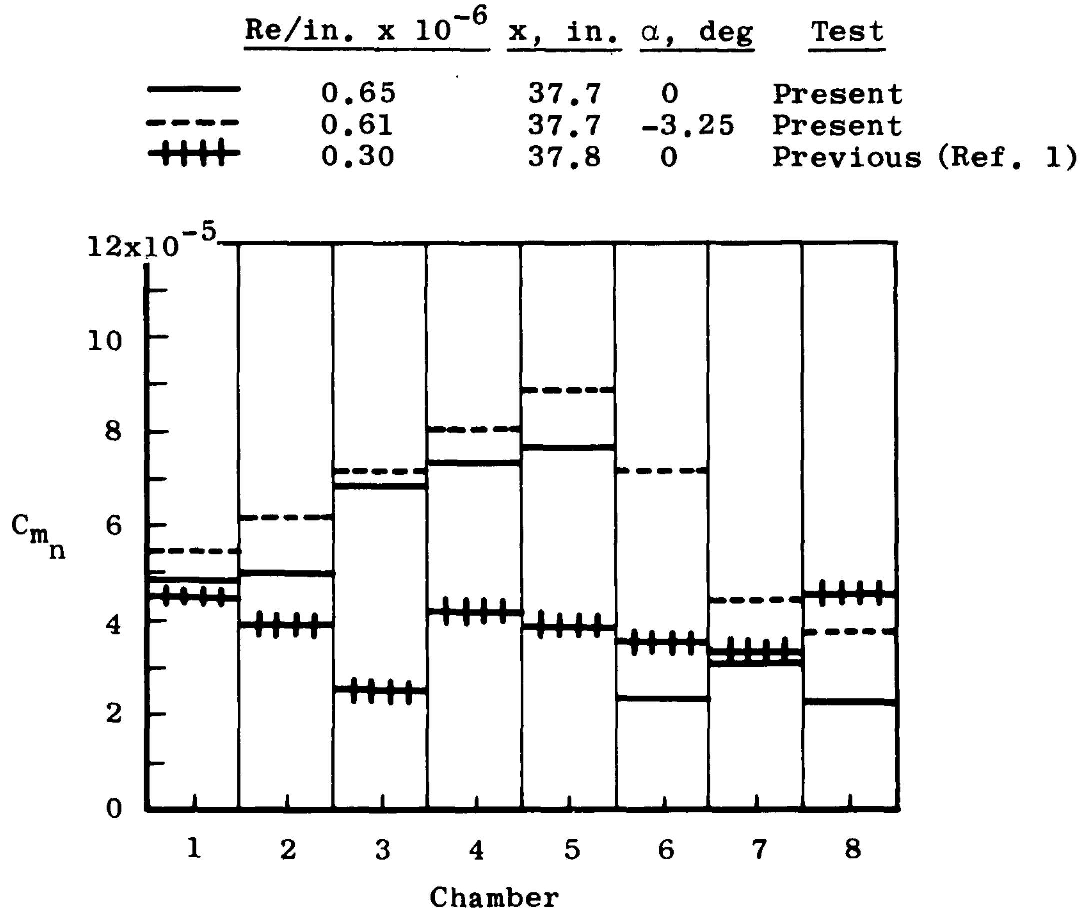
3.0 PROCEDURE

Testing was conducted with variable suction and no suction at each of the following conditions:

Nominal Mach No.	Maximum Re/in. x 10^{-6}	Minimum Re/in. x 10^{-6}	Rake Location, in.	α, deg
2.5	0.54	0.26	32.9 to 37.7	0
3.0	0.66	0.33	27.7 to 37.9	0
3.0	0.66	0.32	33.0 to 37.8	-3.25
3.5	0.52	0.34	27.8 to 37.8	0
3.5	0.52	0.33	33.0 to 37.8	-3.25
4.0	0.53	0.29	27.7	0
4.0	0.53	0.36	27.8 to 37.8	-3.25

Boundary-layer profiles were measured for the above-listed Reynolds number ranges, angles of attack, and chordwise rake locations. The condition of no suction was obtained by closing the metering chamber valves and leaving the slots unsealed. The effect of varying the suction quantities through the eight chambers was observed by noting the changes in the boundary-layer profile at a particular station.

The following chart shows the typical suction coefficient distribution for the cases of optimum suction (lowest total drag) at two Reynolds numbers and at angles of attack of 0 and -3.25 deg for Mach number 3.



4.0 DATA ANALYSIS

Reduction of the boundary-layer data consisted of determining the momentum thickness from a graphical integration of the momentum parameter. The momentum parameter was normalized with respect to the local free-stream conditions ($\rho_r U_r$), which were determined from the measured local static pressure on the model surface and the tunnel stagnation conditions. The loss in total pressure attributable to the model leading edge shock and the suction slot shocks was considered to be negligible.

For a surface with zero pressure gradient ($U_r = U_\infty$) the wake drag coefficient, which is the skin friction coefficient per unit span, is determined from

$$C_{D_W} = \frac{2\,\theta_\infty}{x} = \frac{2\,\theta_r}{x} \tag{1}$$

where x is the distance of the boundary-layer rake from the model leading edge. If the conditions outside the boundary layer at the rake location differ from free stream ($U_r \neq U_\infty$) and the momentum equation of the wake is solved, then the wake drag coefficient (composed of skin friction and form drag) can be expressed as shown in Ref. 3 by

$$C_{D_W} = \left(\frac{2\theta_r}{x}\right)\left(\frac{U_r}{U_\infty}\right)^{(3.145-0.28\,M_r^2-0.30\,M_\infty^2)} \tag{2}$$

In the following table are given the wake drag coefficients as determined by the two methods, Eqs. (1) and (2):

M_∞	α, deg	x, in.	$Re_x \times 10^{-6}$	$\theta_r \times 10^3$	Eq. (1) $C_{D_W} = \frac{2\theta_r}{x} \times 10^4$	Eq. (2) $C_{D_W} = \left(\frac{2\theta_r}{x}\right)\left(\frac{U_r}{U_\infty}\right)^{(3.145-0.28\,M_r^2-0.30\,M_\infty^2)} \times 10^4$
2.5	0	37.7	12.8	4.800	2.544	2.507
2.5	0	32.9	11.1	4.364	2.646	2.631
3.0	0	37.7	24.7	3.540	1.875	1.799
3.0	0	27.7	18.2	2.824	2.035	2.009
3.0	-3.25	37.7	23.2	4.320	2.291	2.323
3.0	-3.25	33.0	20.2	3.420	2.073	2.104
3.5	0	37.8	19.7	4.780	2.530	2.371
3.5	0	27.8	14.4	3.240	2.335	2.234
3.5	-3.25	37.8	19.4	4.732	2.502	2.615

Differences up to approximately six percent existed, and therefore all data presented in this report were determined by Eq. (2).

The suction coefficient per unit span is defined by

$$C_{m_t} = \sum_{n=1}^{x} C_{m_n} = \sum_{n=1}^{x} \frac{M_n}{\rho_\infty U_\infty A_n} \tag{3}$$

Consideration of the reduction in skin friction drag by using suction must necessarily include an evaluation of the penalties in drag caused by suction. The total drag coefficient then consists of a summation of the wake drag and suction drag coefficients ($C_{D_W} + C_{D_S}$).

The suction drag coefficient is determined by the power required to accelerate the air removed from the boundary layer to free-stream conditions and is based on the assumption that the flow is isentropic and the efficiency of the suction compressor is equal to the propulsive efficiency of the propulsion system. The suction drag coefficient can then be expressed as shown in Ref. 3 by

$$C_{D_S} = \sum_{n=1}^{x}\left(C_{D_S}\right)_n = \sum_{n=1}^{x} C_{m_n}\left(1 + \frac{M_n^2\, T_n}{M_\infty^2\, T_\infty}\right). \tag{4}$$

where C_{D_S} is the suction drag coefficient.

When the wing is at a negative angle of attack with the corresponding pressure rise on the windward surface as compared to the zero angle of attack condition, the suction drag requirements, as computed by Eq. (4) must be corrected by the ratio $\frac{\rho_\infty U_\infty}{\rho_r\ U_r}$, where $\rho_r\ U_r$ are the conditions at the 50 percent chord.

Then for angle of attack

$$C_{D_S} = \sum_{n=1}^{x} \left(C_{D_S}\right)_n \left(\frac{\rho_\infty U_\infty}{\rho_r\ U_r}\right)_{50\%\ c} = \sum_{n=1}^{x} C_{m_n} \left(\frac{\rho_\infty U_\infty}{\rho_r\ U_r}\right)\left(1 + \frac{M_n^2\ T_n}{M_\infty^2\ T_\infty}\right) \tag{5}$$

The suction coefficient at angle of attack are also presented as

$$\underset{\alpha = 3.25^\circ}{C_{m_t}} = \sum_{n=1}^{x} C_{m_n} \left(\frac{\rho_\infty U_\infty}{\rho_r\ U_r}\right) = \sum_{n=1}^{x} \frac{M_n}{\rho_r\ U_r\ A_n} \tag{6}$$

where $\rho_r U_r$ are values at the 50 percent chord.

At Mach numbers 3 and 3.5, the ratios $\frac{\rho_\infty U_\infty}{\rho_r U_r}$ for α = -3.25 deg are 0.85 and 0.83 percent, respectively.

An alternate procedure often used for evaluating the suction drag consists of assuming that all the momentum removed from the boundary layer is lost, and the drag coefficient thus determined is

$$C_{D_S} = \sum_{n=1}^{x} \frac{\text{suction drag}}{q_\infty\ A_n} = \sum_{n=1}^{x} \frac{m_n\ U_\infty}{\frac{1}{2}\rho_\infty\ U_\infty^2\ A_n} = 2\sum_{n=1}^{x} C_{m_n} \tag{7}$$

These two methods determine the limits on suction drag. Shown below are the suction drag coefficients applied to typical data and the total drag coefficients for the two methods of evaluating suction drag:

M_∞	α	$Re_x \times 10^{-6}$	$C_{D_W} \times 10^4$	$C_{D_S} \times 10^4$	$C_{D_T} = (C_{D_W} + C_{D_S}) \times 10^4$
3.0	0	24.7	1.799	Eq. 4: 4.475	6.274
3.0	0	24.7	1.799	Eq. 7: 7.876	9.675

All suction drag coefficients used in this report were determined from the relationships expressed by Eqs. (4) and (5).

5.0 RESULTS AND DISCUSSION

The model used in the present test was tested previously in the 40-Inch Supersonic Tunnel (A) on March 26-30, 1962 (Ref. 1) to determine the effectiveness of boundary-layer suction for laminar flow control on a swept wing. During the test, full chord laminar flow was established up to a Reynolds number of 11 million at $M_\infty = 3$, $\alpha = 0$, but at higher Reynolds numbers, the flow became turbulent and the thickness of the turbulent boundary layer, even with maximum suction, approached the value of the fully turbulent profile that existed when there was no suction. This suggested that natural transition probably occurred before the first slot, and consequently, the applied suction was then ineffective in establishing laminar flow. At Mach number 3.5, laminar flow was not established.

For the present investigation, NORAIR modified the existing model by increasing the suction slot widths an additional 0.001 to 0.002 in. and adding two slots in the leading edge region. Increasing the slot widths changed the suction system design from primarily the conditions at $M_\infty = 3$ to those for $M_\infty = 3.5$. Modifications were also made in the model support equipment so that the model could be tested at zero and -3.25-deg angle of attack. The negative angle of attack gave an effective leading edge angle (measured perpendicular to LE) of approximately 7.6 deg for both the upper and lower surface. This eliminated the possibility of any airflow around the LE from the high pressure lower surface to the top surface that might otherwise have occurred at $\alpha = 0$.

Presented in Fig. 7 are typical boundary-layer profiles for Mach numbers 2.5, 3, 3.5, and 4 at $\alpha = 0$ for three rake stations and with the conditions of suction and no suction. As seen from the figures, suction was adequate to establish laminar flow at all test Mach numbers except Mach number 4. The laminar profiles are for the optimum suction condition (lowest total drag) and the turbulent profiles, for the conditions of no suction and the slots unsealed. The two outboard probes (15 and 16) gave no indication of contamination of the laminar region by the adjacent turbulent flow.

Presented in Fig. 8 are the velocity profiles, momentum profiles, and suction distribution obtained with the two additional slots open and with the two slots sealed for Mach number 3, $Re_x = 24.5 \times 10^6$, and rake station 37.7 in. The suction distribution was identical for the two cases (Fig. 8c) except for the number one chamber that was necessarily low when the slots were sealed. These data show explicitly the effect of the two additional slots in establishing laminar flow. With the slots open, laminar flow was readily obtained. With the two slots closed, the flow was turbulent and approached the value of the fully turbulent, no suction profile. This confirms the assumption that laminar flow was not obtained at the higher Reynolds number ($Re_x > 11 \times 10^6$) for $M_\infty = 3$, $\alpha = 0$ on the previous test because of natural transition occurring before the i rst suction slot.

The variations in wake drag, suction drag, and total drag coefficients for various total suction coefficients are presented in Fig. 9 for Mach number 2.5, $\alpha = 0$ and Figs. 10 and 11 for Mach numbers 3 and 3.5 for $\alpha = 0$ and -3.25 deg. With increased suction the wake drag will decrease, but the suction drag increases, and therefore a minimum value will exist for the total drag coefficient $\left(C_{D_T} = C_{D_W} + C_{D_S}\right)$. This point represents the minimum total drag coefficient and defines the optimum suction coefficient. These data show that at the negative angle of attack for $M_\infty = 3$ and 3.5 (Figs. 10b and 11b) higher suction quantities were required. This resulted in higher optimum suction values and higher minimum total drag values for the wing at $\alpha = -3.25$ deg.

The minimum total drag coefficients and optimum suction coefficients for $M_\infty = 2.5$, $\alpha = 0$ and $M_\infty = 3$ and 3.5 for $\alpha = 0$ and -3.25 deg are presented in Fig. 12. Laminar flow was maintained for $M_\infty = 2.5$, 3, and 3.5, $\alpha = 0$ (Figs. 12a, b, and d) up to the length Reynolds numbers (Re_x) of 18, 25, and 20 million, respectively, Figure 12b shows that suction at $M_\infty = 3$ in the previous test of Ref. 1 could only maintain laminar flow up to a length Reynolds number of about 11 million. Above a Reynolds number of 11×10^6, the total drag coefficient rapidly approached the no suction, fully turbulent value. As shown in Fig. 12b there was no disagreement between the minimum total drag coefficient obtained for laminar flow conditions in the previous test at $Re_x = 11 \times 10^6$ and the present investigation at $Re_x = 12 \times 10^6$. As the Reynolds number was increased in this investigation, a sharp rise in suction with a corresponding rise in total drag was necessary to maintain laminar flow at $M_\infty = 2.5$ and 3, $\alpha = 0$. Figures 12a and b also show that there was no appreciable difference between the minimum total drag coefficients and optimum suction coefficients obtained for $M_\infty = 2.5$ and 3, $\alpha = 0$ at the different rake locations.

Shown in Fig. 12c are the minimum total drag coefficients and optimum suction coefficients for $M_\infty = 3$ and $\alpha = -3.25$ deg. Higher suction coefficients were required, which resulted in slightly higher total drag coefficients than for the $\alpha = 0$ condition, but otherwise there were no appreciable differences.

Illustrated in Fig. 12d are the minimum total drag and optimum suction coefficients for α = 0 and -3.25 deg for M_∞ = 3.5. There was no abrupt rise in suction coefficient values as exhibited by the M_∞ = 2.5 and 3 data, and the suction coefficients and the minimum total drag coefficients were lower than the M_∞ = 2.5 and 3 results, α = 0. Compared to the results at α = 0, the minimum total drag coefficients and optimum suction coefficients were slightly higher at α = -3.25 deg.

At Mach number 4 (Fig. 13a) laminar flow could not be established with maximum suction applied. Suction, in fact, had little effect as shown in the comparison between the total drag coefficients obtained with maximum suction and the no-suction values.

Turbulent wake drag coefficients obtained with no suction and the slots unsealed for M_∞ = 2.5, 3, 3.5, and 4 are presented in Fig. 13b for various rake locations. These data are noticeably lower than the theoretical, adiabatic, flat plate estimates (Ref. 4). This difference is attributed to the favorable pressure gradient that existed on the wing.

Data from Figs. 12a, b, d, and 13a are re-plotted in Fig. 14 as the percent reduction in wake drag obtained by applying suction. The maximum drag reduction would be from measured values for a turbulent profile (no suction) to drag values for a theoretical laminar profile. By applying suction, reductions of 70 percent were obtained at M_∞ = 2.5, x = 37.7 in. for a Reynolds number of 10 x 10^6 (Fig. 14a). As mentioned previously, a rise occurred in the drag data between Re_x = 10 and 13 x 10^6, and accordingly the reduction in total drag decreased from 70 to 60 percent for the higher Reynolds numbers. There was no noticeable difference between results for various rake stations.

Illustrated in Fig. 14b are the percent reductions in total drag by applying suction for M_∞ = 3, x = 37.7, 32.7, and 27.7 in. The percent drag reduction decrease occurring between Re_x = 12 and 17 x 10^6 from 65 to 55 percent) is similar to the M_∞ = 2.5 results. Drag reductions of 60 percent resulted at the higher Reynolds number without any significant difference existing between rake stations.

Presented in Fig. 14c are the percent reductions in total drag for M_∞ = 3.5 and 4. There was a difference between results obtained at the different rake stations for M_∞ = 3.5. At M_∞ = 4, x = 27.7, there was no significant reduction in drag, even though maximum suction was applied.

6.0 CONCLUDING REMARKS

Tests were conducted at Mach numbers 2.5, 3, 3.5, and 4 to determine the effectiveness of boundary-layer suction for laminar flow control on a 36-deg swept wing. On the basis of these tests the following conclusions are made:

1. In the previous investigation laminar flow was maintained up to a Reynolds number (Re_x) of 11×10^6 at $M_\infty = 3$, $\alpha = 0$, but for the higher Reynolds numbers the flow became turbulent because of natural transition occurring before the first suction slot, and the total drag approached the no-suction, fully turbulent value.
2. The addition of two suction slots in the leading edge region and an increase in suction slot widths resulted in laminar flow being established at $M_\infty = 2.5$, 3, and 3.5 for $\alpha = 0$ up to length Reynolds numbers based on rake location of 18, 25, and 20×10^6, respectively, with total drag reductions of 60 percent, as compared to the no-suction, fully turbulent wake drag.
3. Slightly higher total drag coefficients and suction coefficients occurred at $M_\infty = 3$ and 3.5 for $\alpha = -3.25$ than for $\alpha = 0$, but otherwise no unusual results were obtained.
4. Laminar flow was not established at $M_\infty = 4$.

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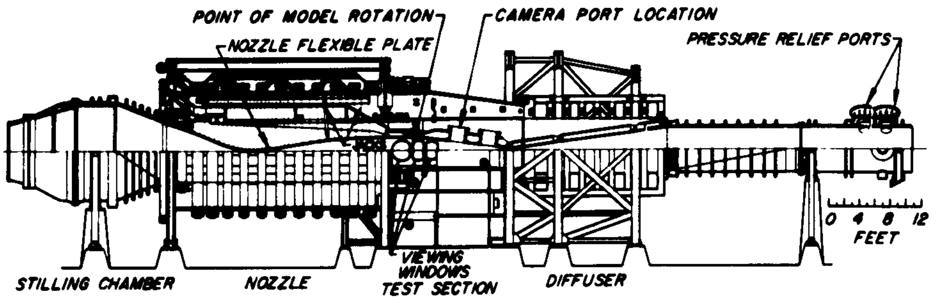
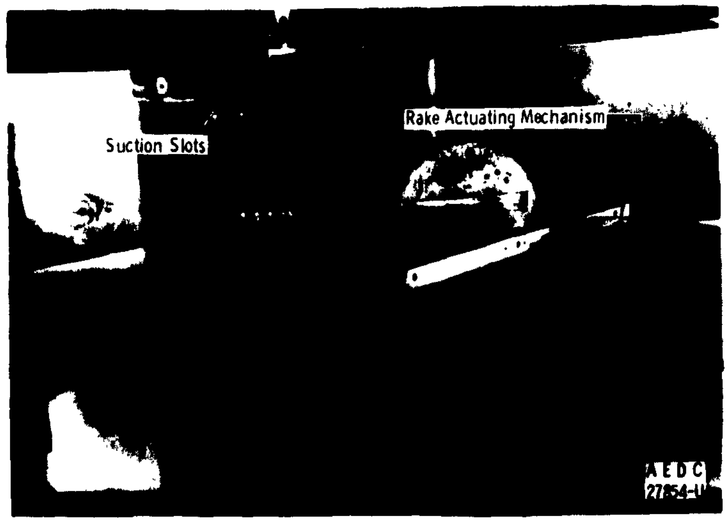


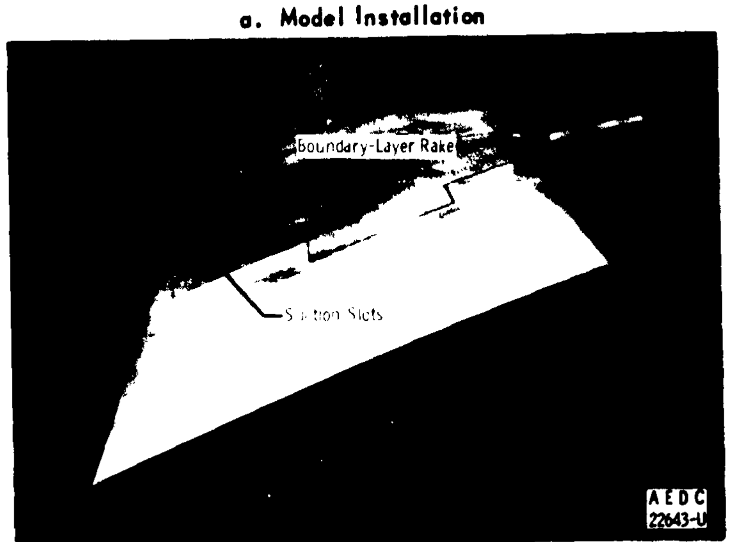
Assembly

Nozzle and Test Section

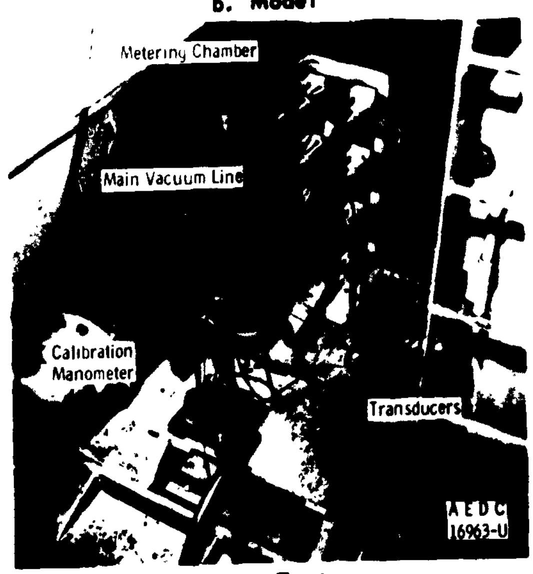
Fig. 1 The 40-Inch Supersonic Tunnel (A)



a. Model Installation

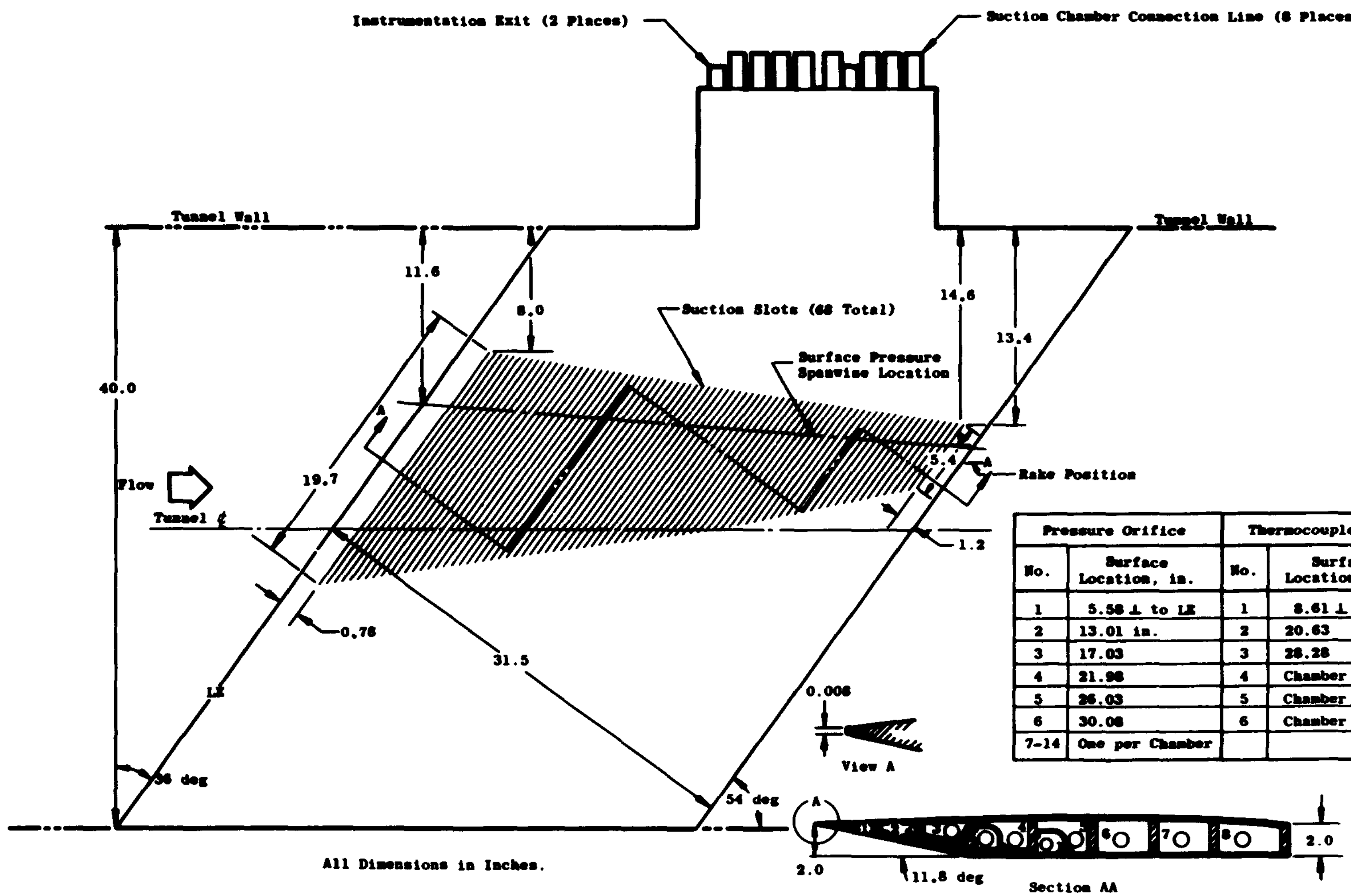


b. Model



c. Suction Equipment

Fig. 2 Model Installation and Suction Equipment



Pressure Orifice		Thermocouples	
No.	Surface Location, in.	No.	Surface Location, in.
1	5.58 ⊥ to LE	1	8.61 ⊥ to LE
2	13.01 in.	2	20.63
3	17.03	3	28.28
4	21.98	4	Chamber No. 3
5	26.03	5	Chamber No. 6
6	30.08	6	Chamber No. 8
7-14	One per Chamber		

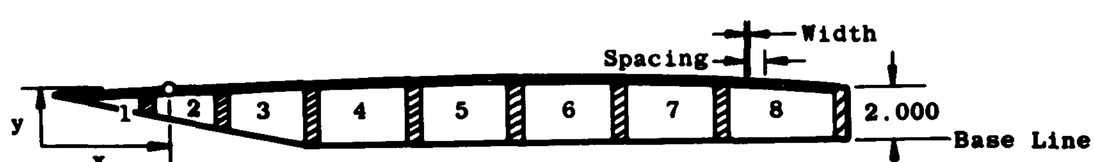
Fig. 3 Model Geometry

Model Profile Dimensions

x, in. ⊥ to L.E.	y, in. Upper Mold Line
00	2.000
0.315	2.019
0.630	2.037
0.945	2.055
1.260	2.073
1.575	2.090
2.363	2.131
3.150	2.170
4.725	2.241
6.300	2.302
7.875	2.354
9.450	2.397
11.025	2.430
12.600	2.454
14.175	2.468
15.750	2.473
17.325	2.468
18.900	2.454
20.475	2.430
22.050	2.397
23.625	2.354
25.200	2.302
26.775	2.241
28.350	2.170
29.138	2.131
29.925	2.090
30.240	2.073
30.555	2.055
30.870	2.037
31.185	2.019
31.500	2.000

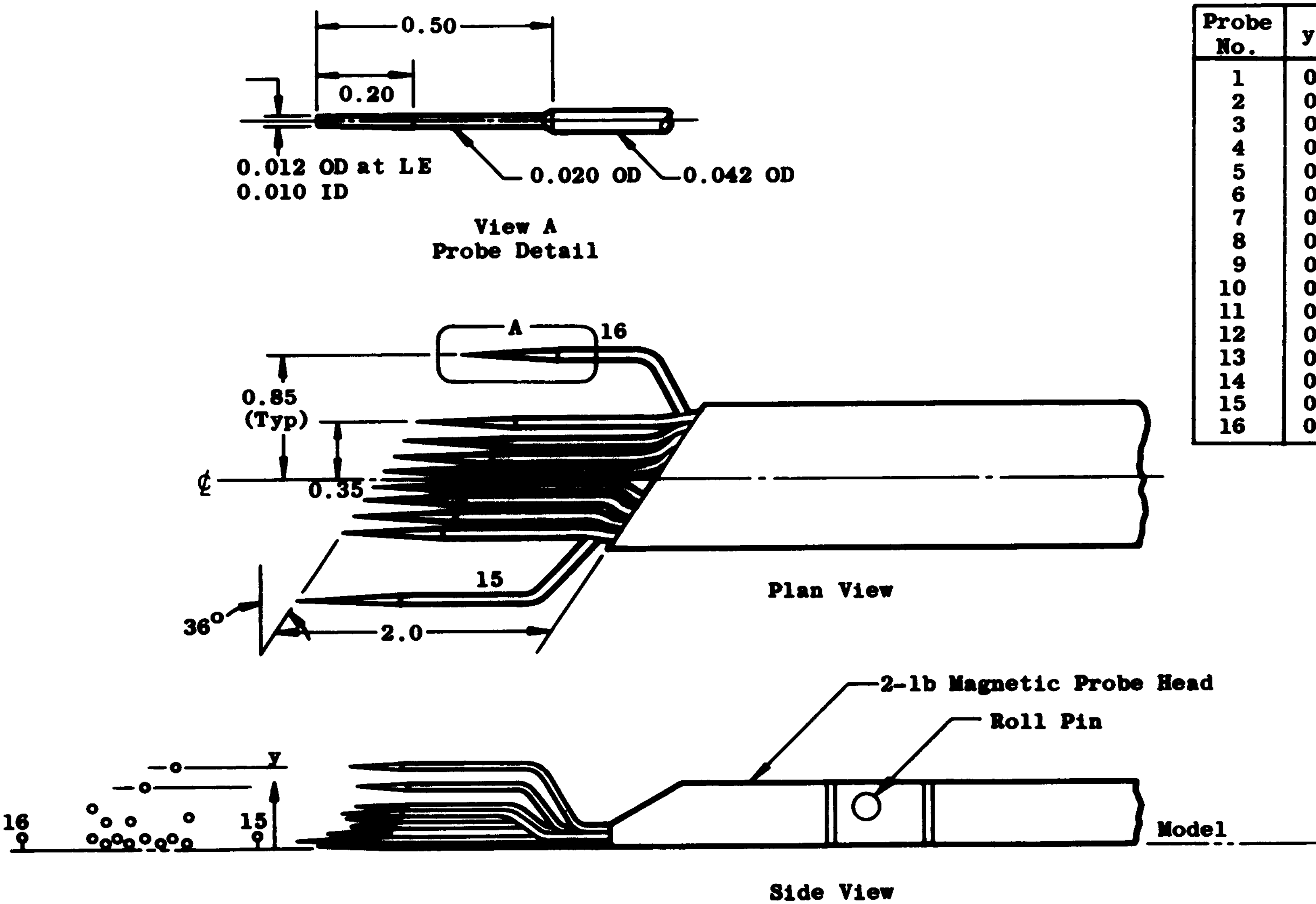
Suction Slot Locations and Dimensions

Chamber	No.	Spacing, in.	Width, in.
1	1,2	0.41	0.005
	3,4	0.42	0.006
	5,6	0.42	0.007
	7	0.42	0.008
2	8-15	0.42	0.008
3	16-23	0.44	0.009
4	24-32	0.44	0.009
5	33-35	0.45	0.009
	36-41	0.45	0.010
6	42-47	0.45	0.010
	48-50	0.45	0.011
7	51-56	0.45	0.011
	57-59	0.45	0.012
8	60-65	0.45	0.012
	66-68	0.45	0.014



Model Profile

Fig. 4 Model Profile and Suction Slot Dimensions



Probe No.	y, in.
1	0.012
2	0.025
3	0.030
4	0.040
5	0.065
6	0.080
7	0.110
8	0.135
9	0.155
10	0.210
11	0.235
12	0.310
13	0.400
14	0.490
15	0.090
16	0.090

Fig. 5 Sketch of Boundary-Layer Rake

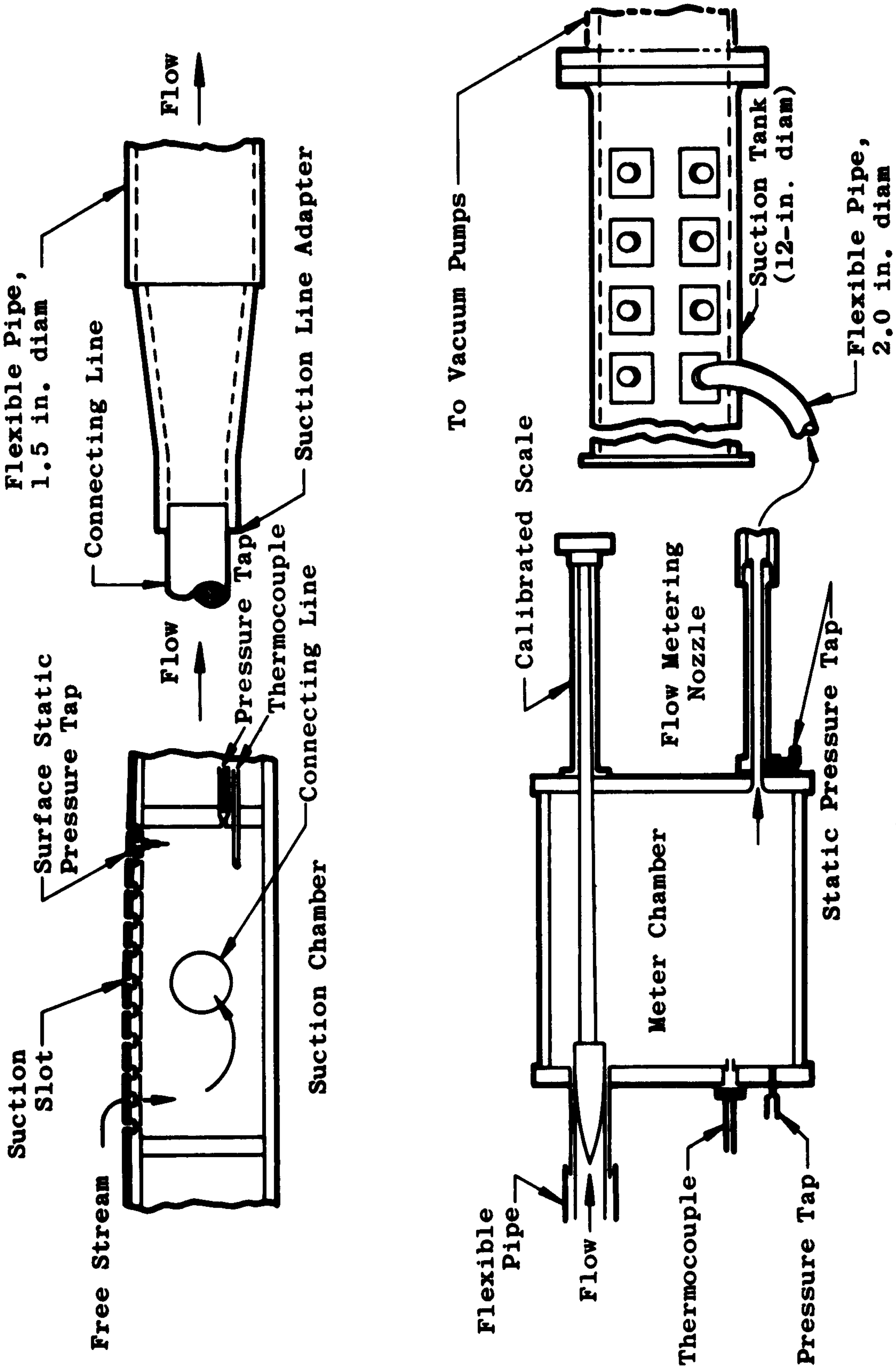
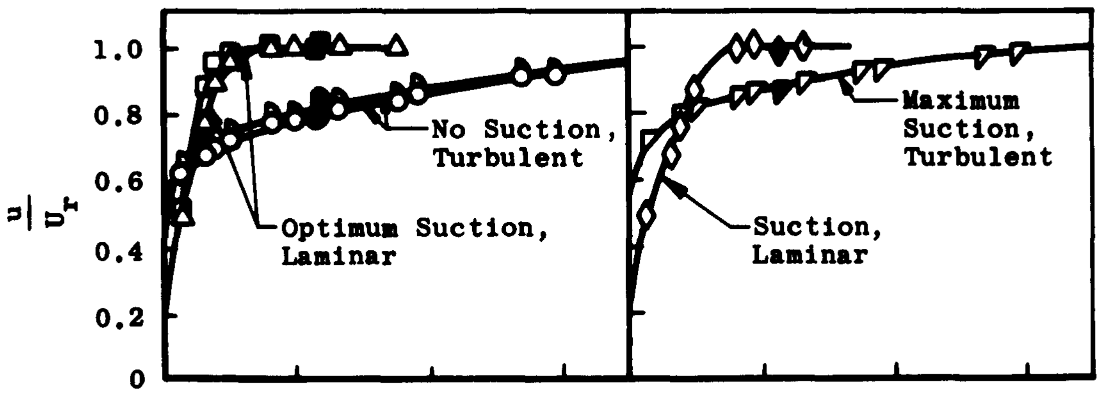
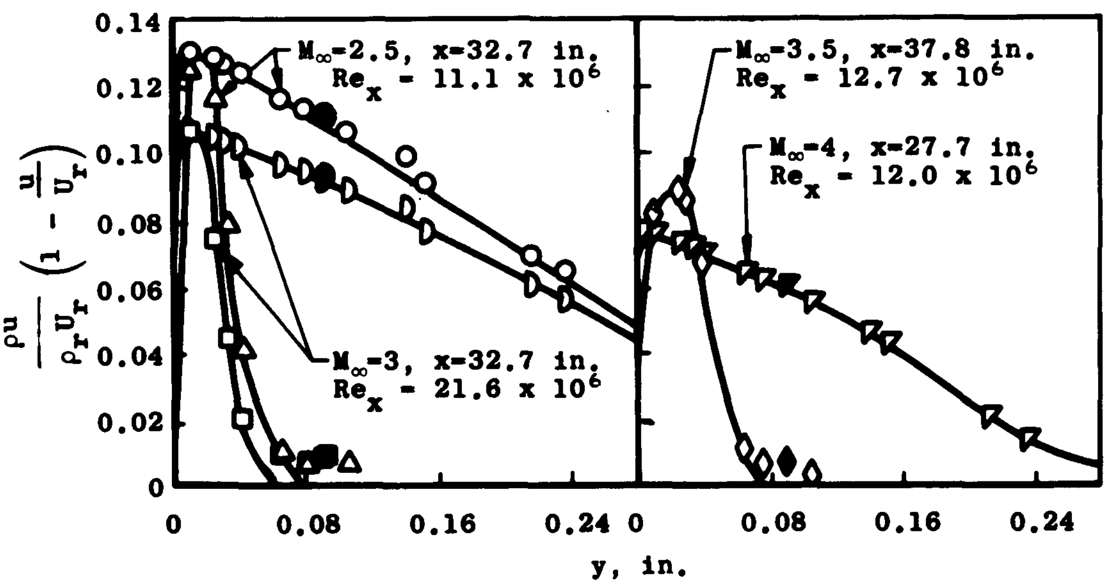


Fig. 6 Schematic Drawing of Suction System

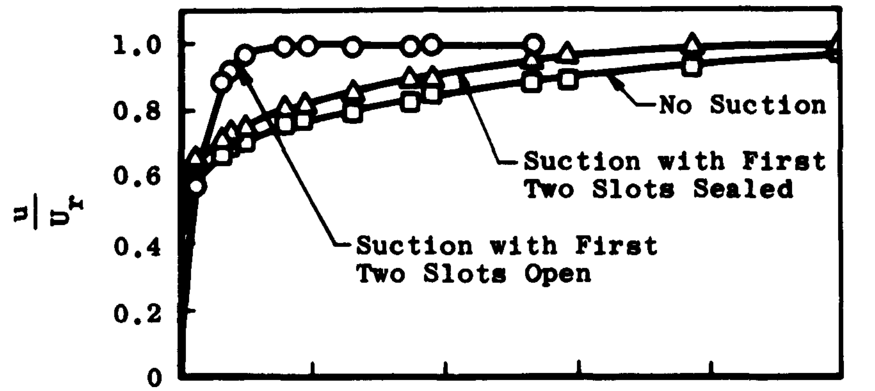


a. Velocity Profiles

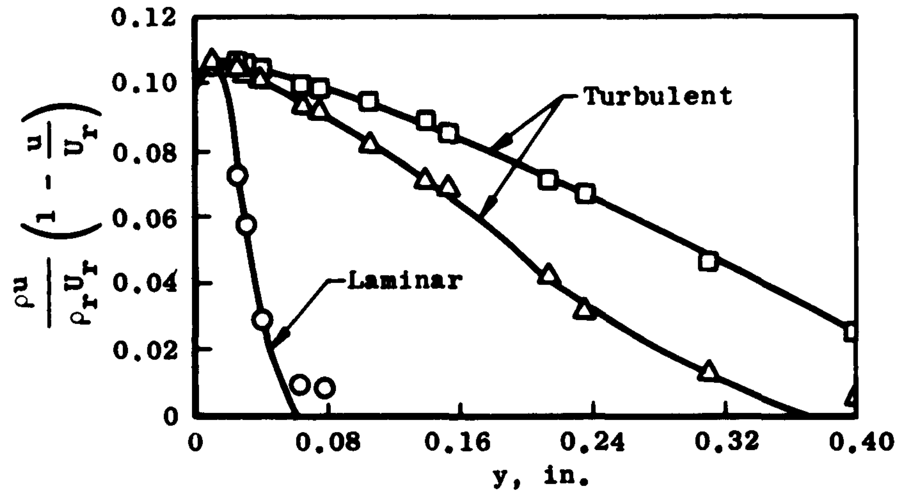


b. Momentum Profiles

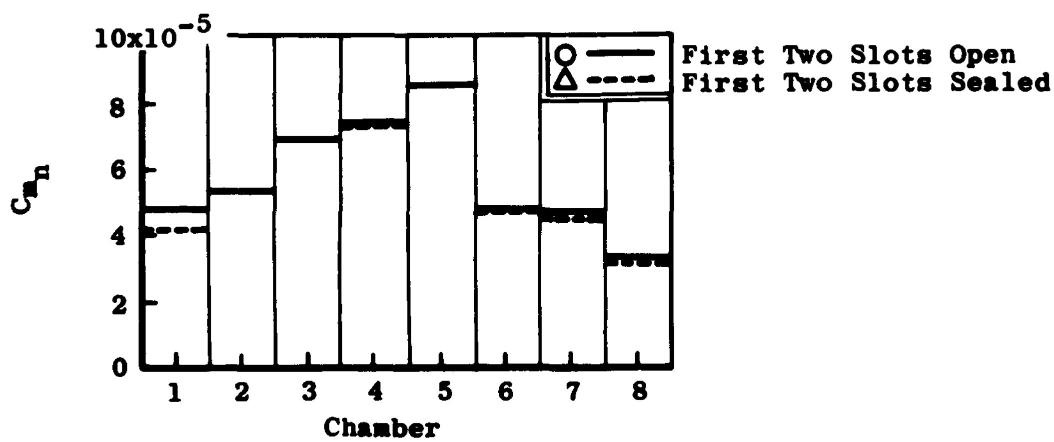
Fig. 7 Boundary-Layer Profiles at $\alpha = 0$ with and without Suction



a. Velocity Profiles

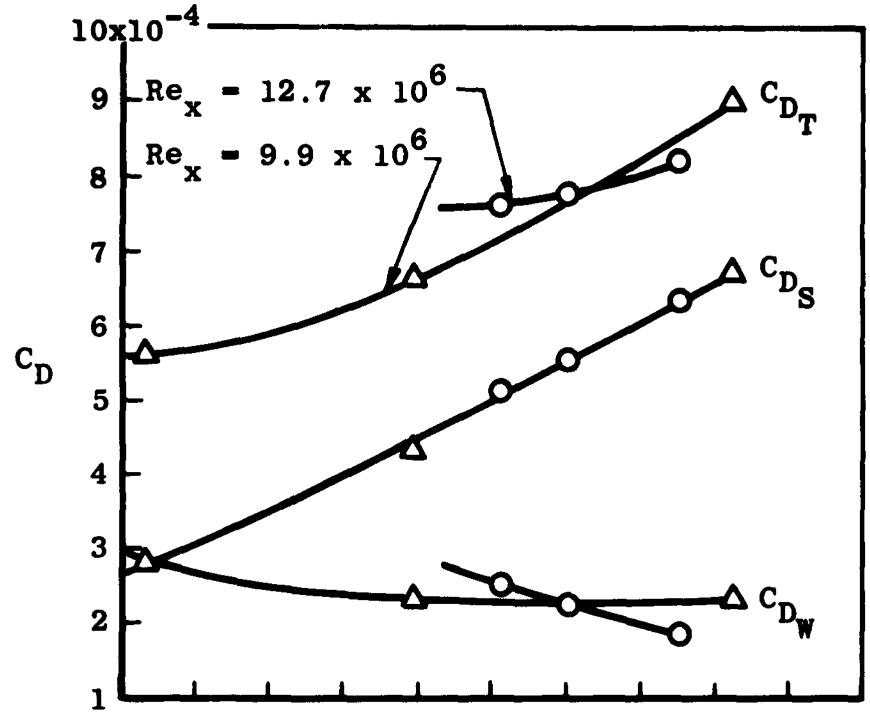


b. Momentum Profiles

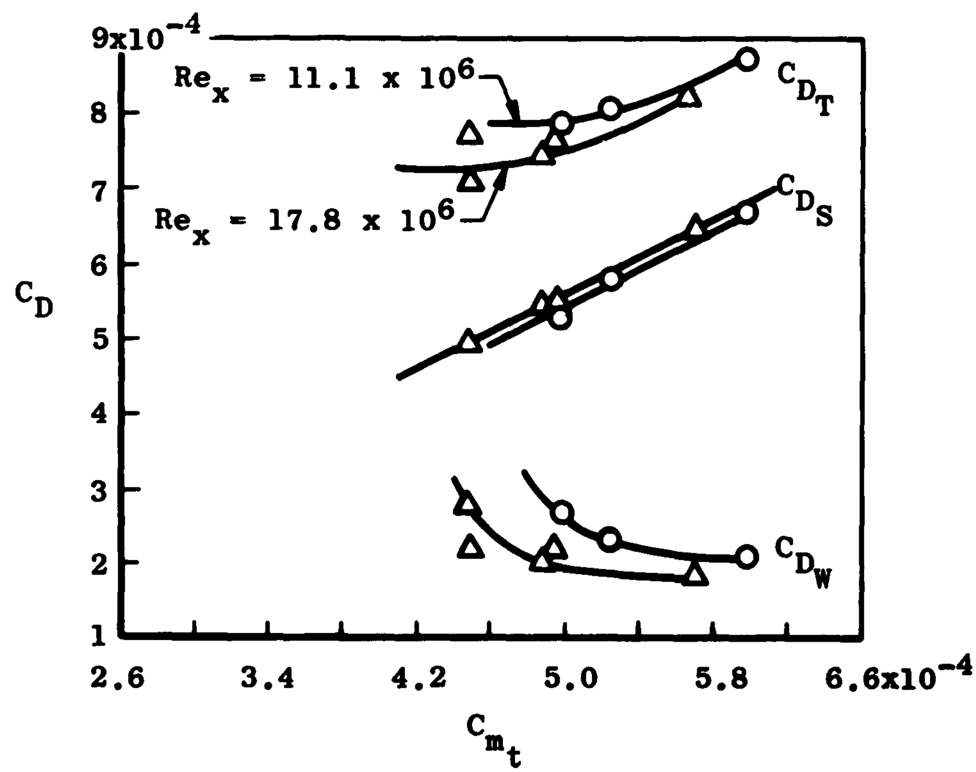


c. Suction Distribution

Fig. 8 Effect of Two Additional Slots on Boundary-Layer Profiles and Suction Distributions at $M_\infty = 3$, $Re_x \approx 24.5 \times 10^6$, $x = 37.7$ in., and $C_{m_t} \approx 4.5 \times 10^{-4}$

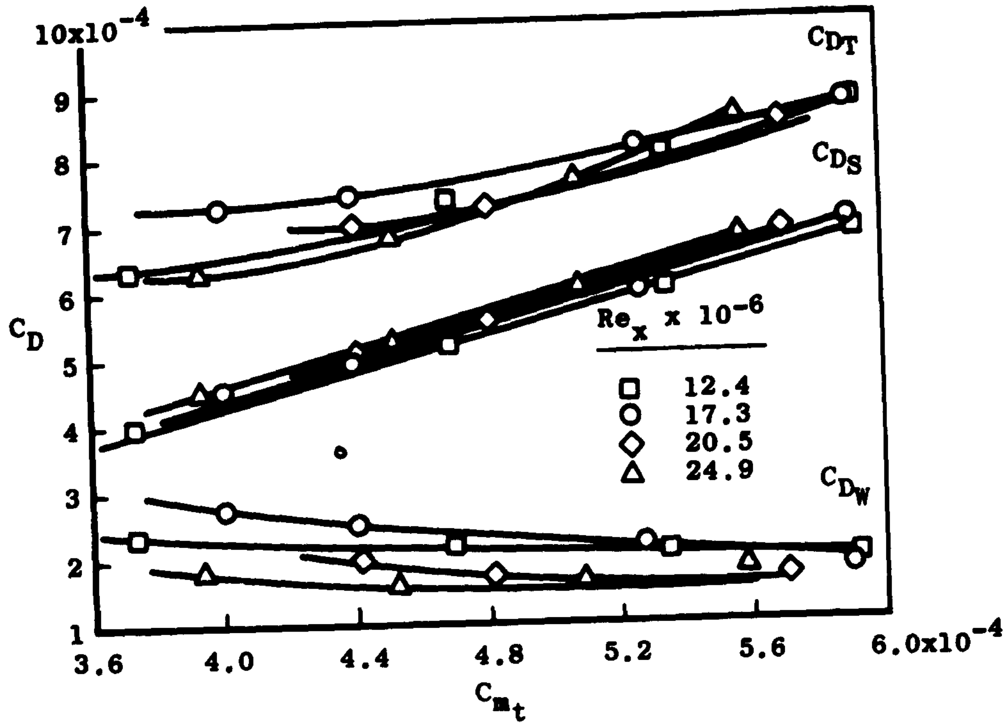


a. x = 37.7 in.

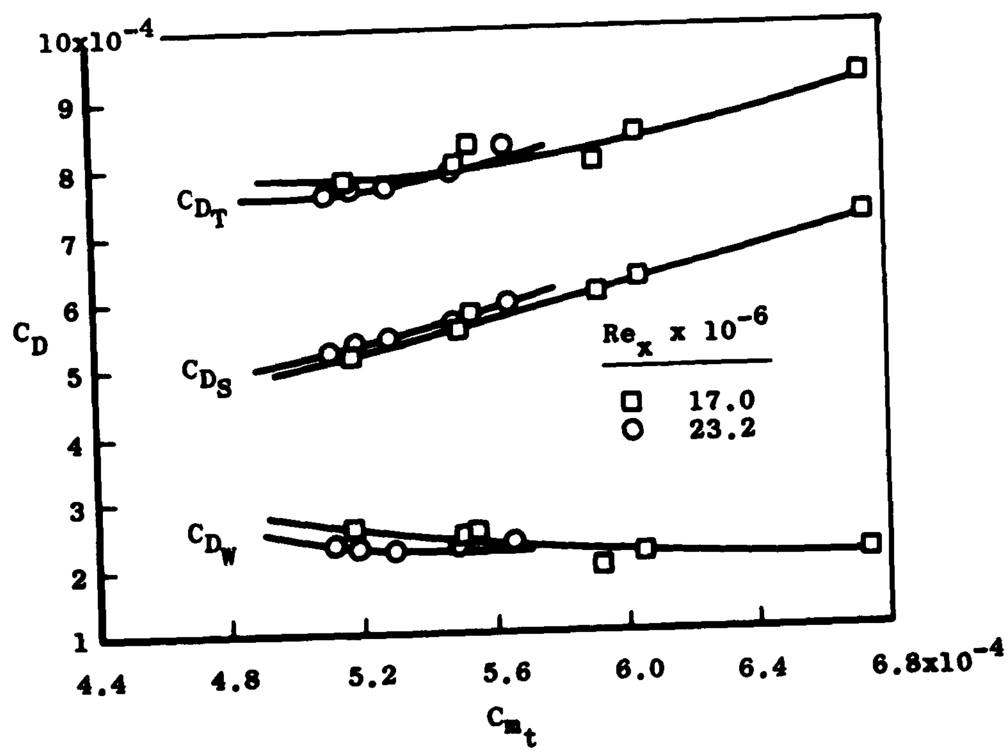


b. x = 32.8 in.

Fig. 9 Variation of Drag Coefficients with Suction Coefficients at $M_\infty = 2.5$, $\alpha = 0$



a. $\alpha = 0$



b. $\alpha = -3.25$ deg

Fig. 10 Variation of Drag Coefficients with Suction Coefficients at $M_\infty = 3$, $\alpha = 0$ and -3.25 deg, and $x = 37.7$ in.

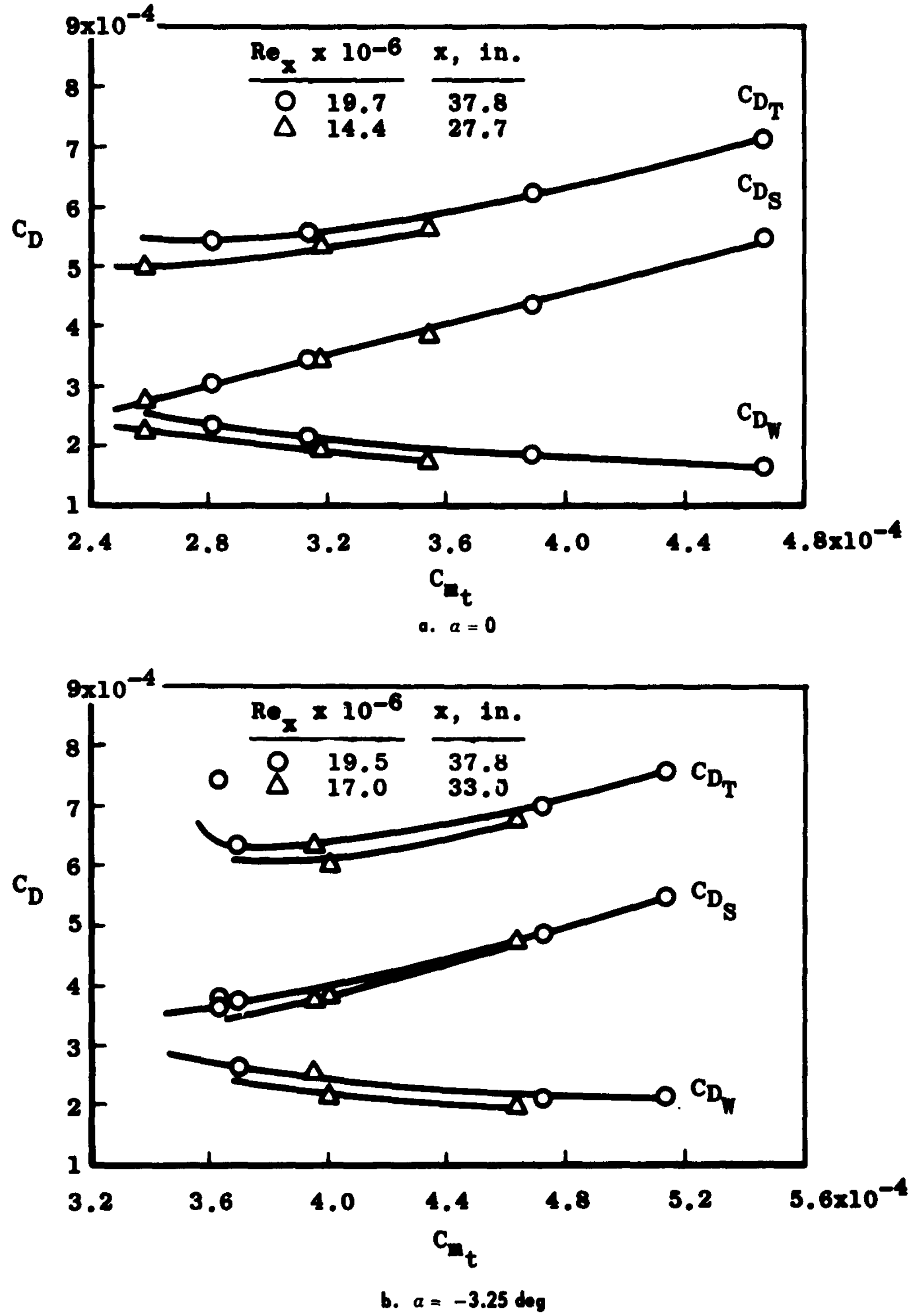
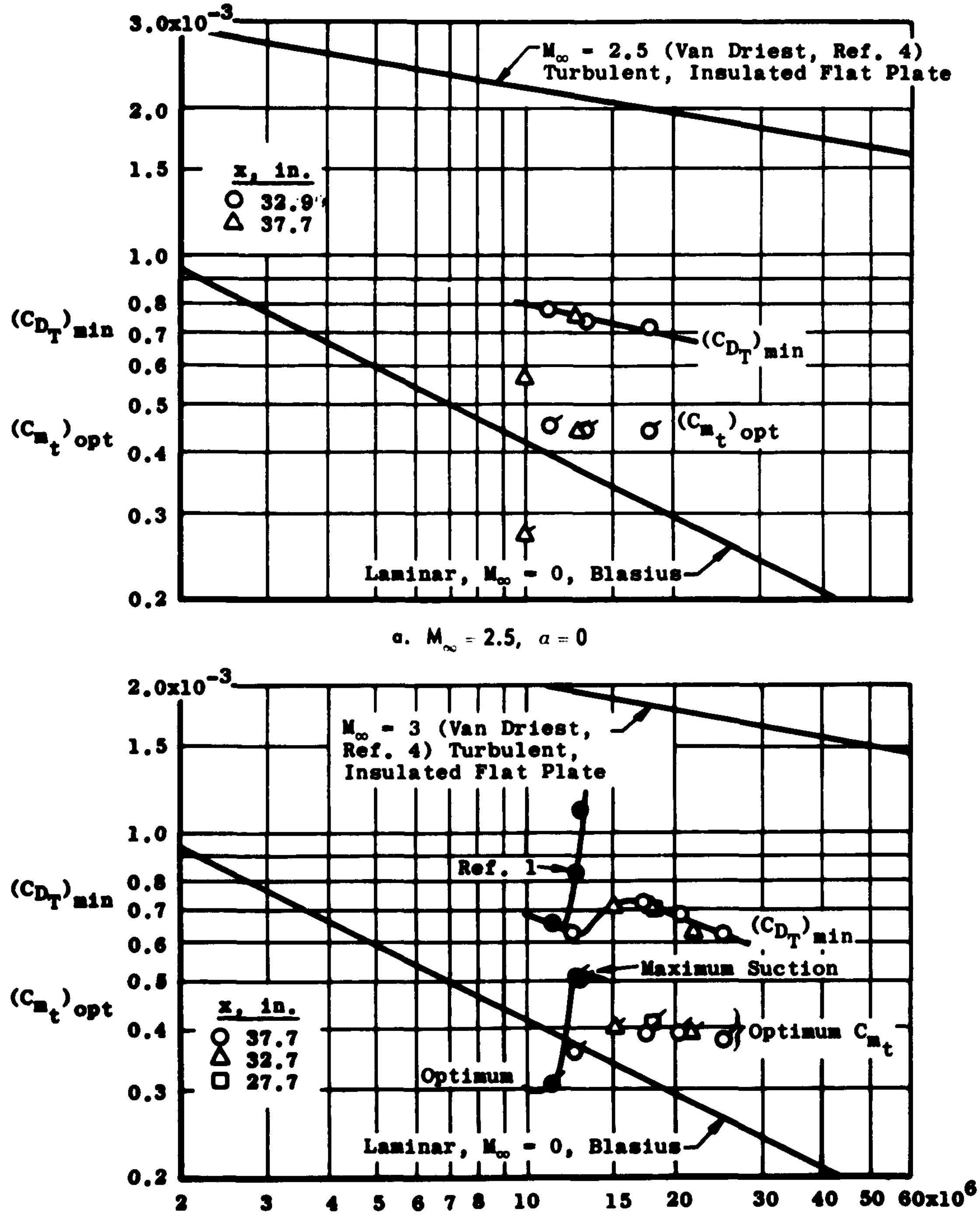


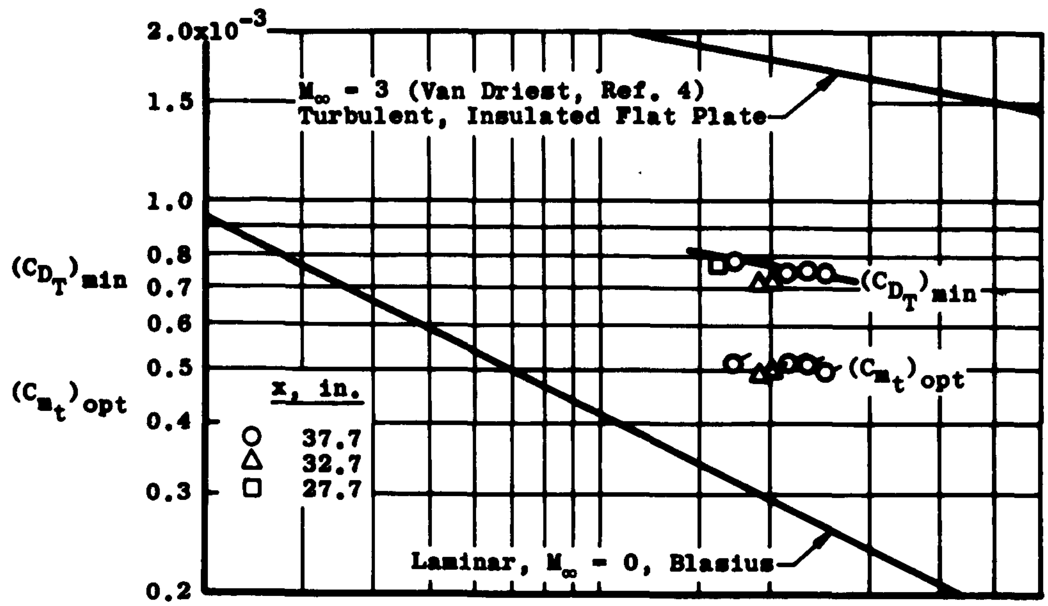
Fig. 11 Variation of Drag Coefficients with Suction Coefficients at $M_\infty = 3.5$ and $\alpha = 0$ and -3.25 deg



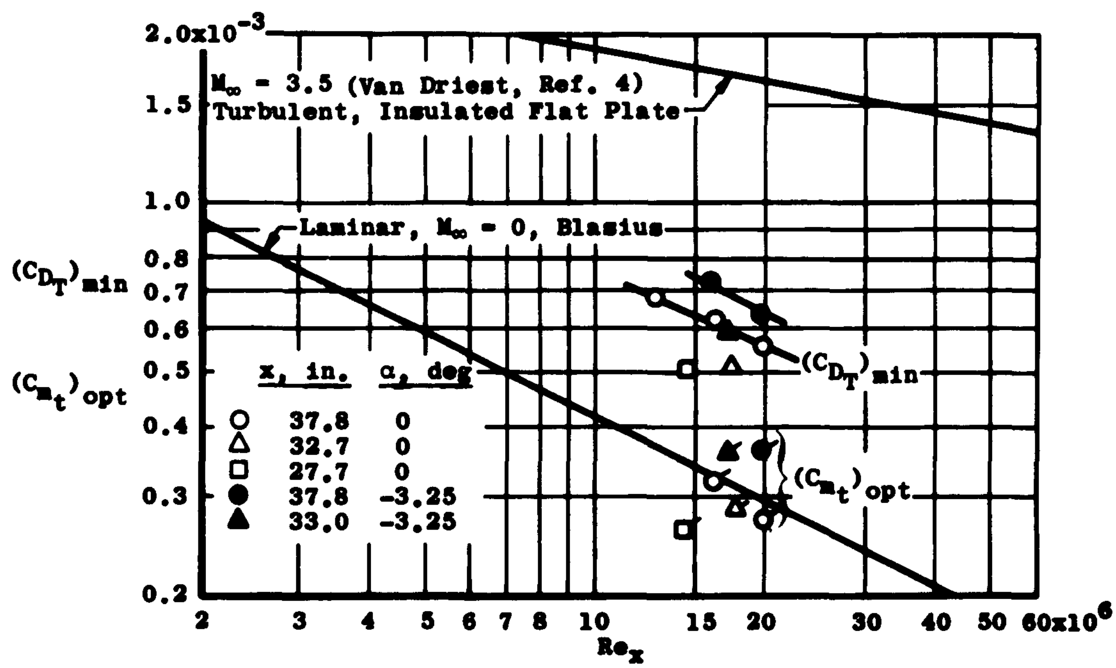
a. $M_\infty = 2.5$, $\alpha = 0$

b. $M_\infty = 3$, $\alpha = 0$

Fig. 12 Minimum Total Drag and Optimum Total Suction Coefficients versus Reynolds Number

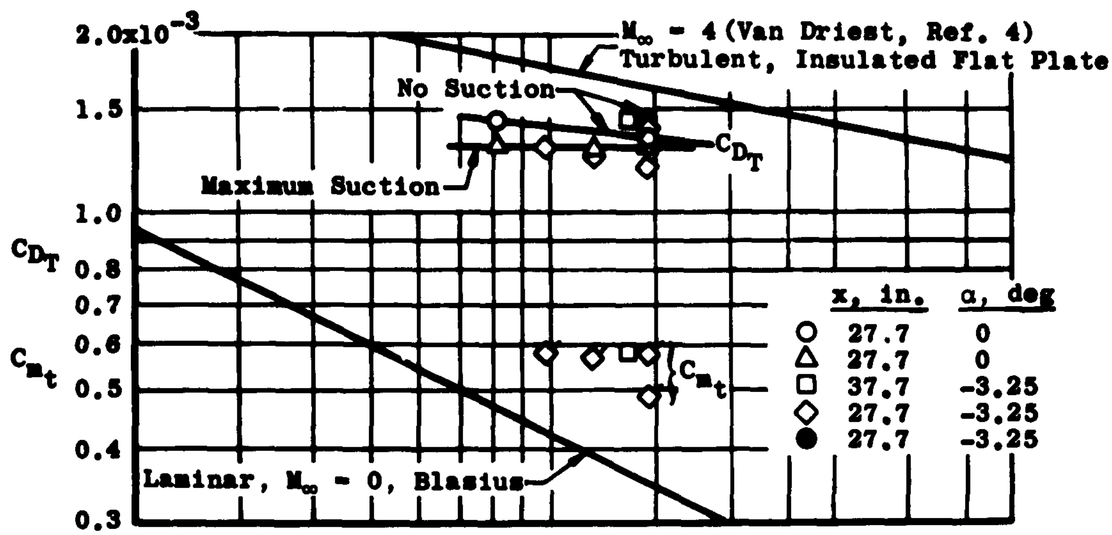


c. $M_\infty = 3$, $\alpha = -3.25$ deg

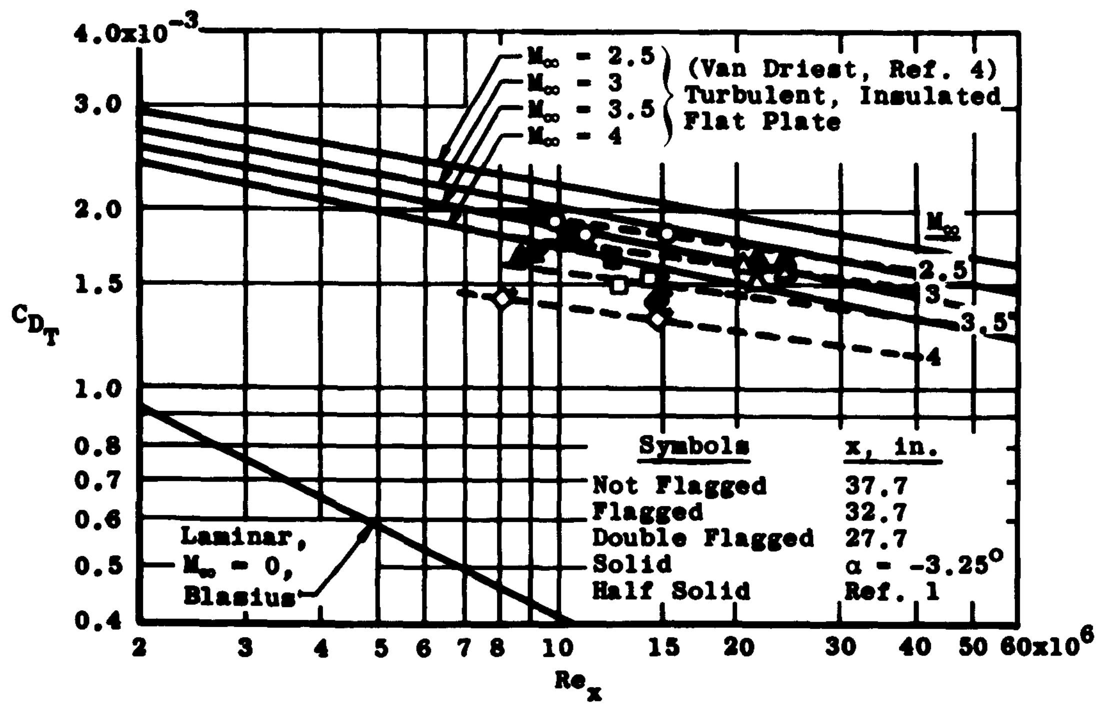


d. $M_\infty = 3.5$, $\alpha = 0$ and -3.25 deg

Fig. 12 Concluded

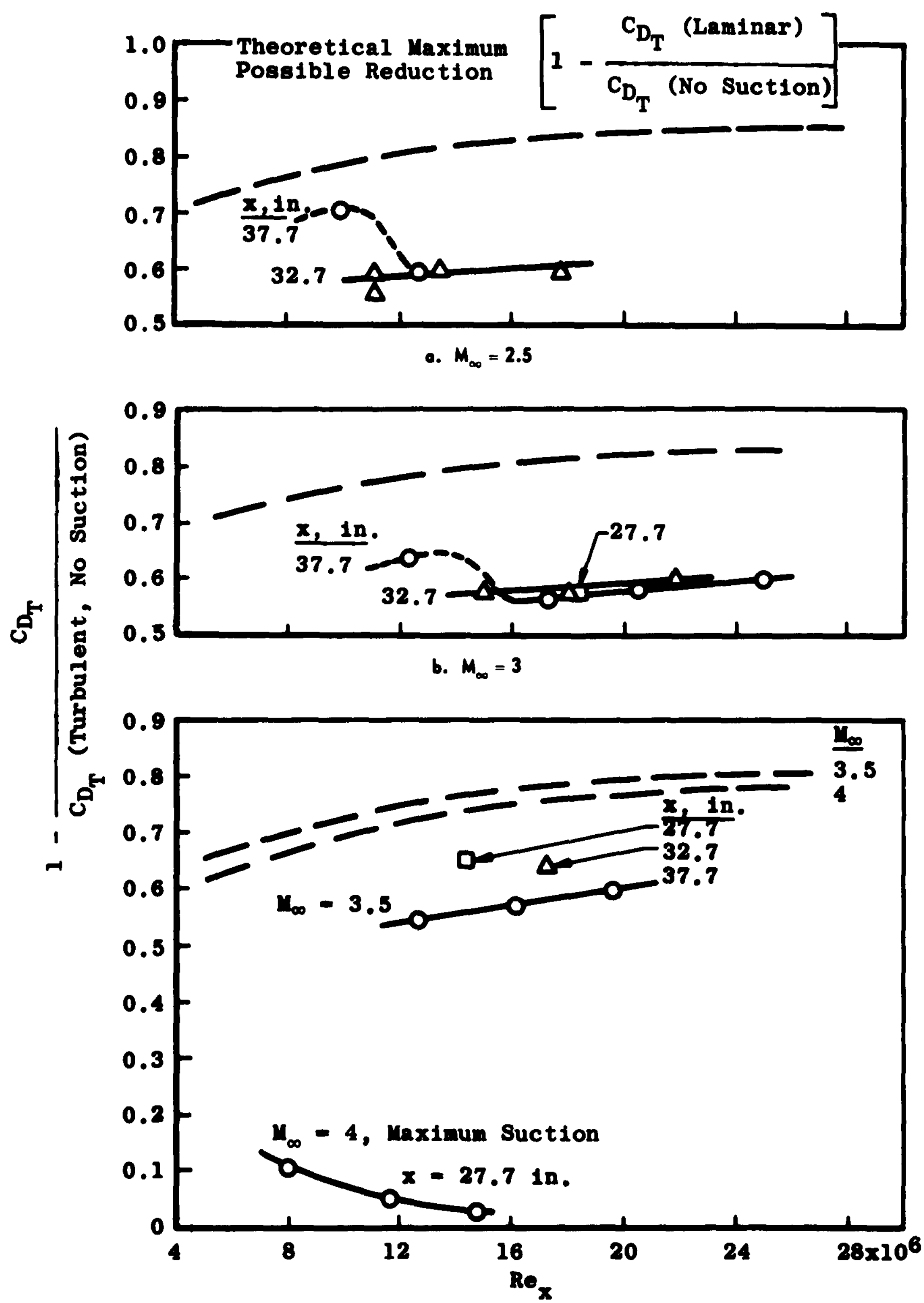


a, $M_\infty = 4$, Maximum Suction and No Suction



b. $M_\infty = 2.5$, 3, 3.5, and 4, No Suction

Fig. 13 Total Drag Coefficients versus Reynolds Number with and without Suction, $\alpha = 0$, and -3.25 deg



c. $M_\infty = 3.5$ and 4

Fig. 14 Variations of Minimum Total Drag Reductions with Reynolds Number at $M_\infty = 2.5$, 3, 3.5, and 4 for $\alpha = 0$

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Rpt. No. AEDC-TDR-63-23 INVESTIGATION OF DRAG REDUCTION BY BOUNDARY-LAYER SUCTION ON A 36-DEG SWEPT WING AT $M_\infty = 2.5$ TO 4. February 1963, 33 p. incl 4 refs., illus.
Unclassified Report

Tests were conducted in the 40-Inch Supersonic Tunnel (A) of the von Kármán Gas Dynamics Facility to determine the effectiveness of boundary-layer suction for laminar flow control on a two-dimensional, biconvex, 36-deg swept wing. Test Mach numbers were 2.5, 3, 3.5, and 4 with a Reynolds number range based on wing chord from 10 to 25 million for angles of attack of 0 and -3.25 deg. With suction, laminar flow was maintained at $\alpha = 0$ deg for $M_\infty = 2.5$, 3, and 3.5 up to length Reynolds numbers based on rake location of 18, 25, and 20 x 10^6, respectively, which resulted in drag reductions of 60 percent as compared to the no suction, fully turbulent drag data. At $M_\infty = 3$ and 3.5, no major difference existed between the minimum total drag coefficients obtained for zero angle of attack and -3.25 deg. Also presented for all test Mach numbers are the fully turbulent, wake drag coefficients obtained with the conditions of no suction.

1. Drag
2. Reduction
3. Boundary layer control
4. Suction slots
5. Swept wings
6. Supersonic characteristics

I. AFSC Program Area 750A, Project 1366, Task 136612
II. Contract AF 40(600)-1000
III. ARO, Inc., Arnold AF Sta., Tenn.
IV. S. R. Pate and J. S. Deitering
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