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A GENERAL REVIEW OF CONCEPTS FOR REDUCING SKIN FRICTION, INCLUDING RECOMMENDATIONS FOR FUTURE STUDIES

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16. Abstract

A literature survey was conducted wherein concepts proposed for reducing aerodynamic skin friction were reviewed. Four main concepts which have significantly reduced skin friction in experimental studies are discussed; suction, gaseous injection, particle additives, and compliant wall. It is considered possible that each of these concepts could be developed and applied in viable skin-friction reduction systems for aircraft application. Problem areas with each concept are discussed and recommendations for future studies are made.

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SUMMARY

A literature survey was conducted to review concepts previously proposed for reducing aerodynamic skin friction, with an emphasis toward reviewing those with potential for aircraft application. The four main concepts discussed are suction, gaseous injection, particle additives, and compliant wall. Each of these concepts has significantly reduced skin friction in experimental studies. Laminar flow control by suction on full-scale aircraft may offer sizable potential rewards; however, no significant experimental-development effort is currently being pursued. Previous practical knowledge attained in laminar flow-control flight studies should be extended to a flight-experimental-development program utilizing a large subsonic transport. Gaseous tangential slot injection offers an attractive potential at hypersonic speeds, where both large reductions in skin-friction drag and surface temperatures have been measured. Continuing efforts are underway to determine the effect of swept and multiple slots. The simplicity of the compliant wall concept (no internal hardware) makes it particularly appealing. Preliminary guidelines have been presented for the selection of compliant materials to match the test conditions in future studies. Future efforts with particle additives should concentrate on defining the basic mechanisms involved, and therein allow for selection of optimum size, density, and concentration of particles for the largest drag reduction. Tangential slot injection of these optimum particles should be the most feasible method.

INTRODUCTION

Fluid dynamicists have expended considerable effort in attempts to minimize the skin-friction drag of aerodynamic vehicles. Various methods have been investigated, but associated and often frustrating performance penalties or hardware problems have prevented the development of any functional and economical system for full-scale aircraft application. Recently, interest in reducing skin friction has reintensified. This resurgence of emphasis is mainly due to the pressing need to conserve our fuel resources and is partially due to the level of sophistication reached in reducing form drag (thus,

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further significant drag reductions in that area are limited) and also to the magnitude of the skin-friction drag contribution to the total drag (about 45 percent of the total drag of a subsonic transport, 35 percent for a supersonic transport, and 25 percent for a hypersonic transport). The potential savings in fuel, or gain in payload or range from even moderate skin-friction drag reduction merits a reevaluation of methods for reducing skin-friction drag. A brief summary review of each method will be given and then a detailed discussion follows. The intent of this paper is to present an aerodynamic review of each concept, wherein the merits or disadvantages from a fluid mechanics point of view are discussed. Detailed discussion relating to the practicality from a systems-economic point of view is generally avoided, especially since this type of information is often questionable or unavailable. Each of the following skin-friction reduction methods is discussed in the order indicated:

(1) Suction

(2) Gaseous injection

(3) Compliant wall

(4) Particle additives

(5) Miscellaneous

Two classical methods for reducing skin friction in air boundary layers have received more attention in the literature than all the other techniques combined. The first of these is suction where mass is drawn away from the laminar boundary layer through porous walls or slots. If sufficient suction is applied and the boundary layer is not allowed to develop and grow normally, the boundary layer presumably will remain laminar; thus, the associated skin friction will be lower than that for turbulent flow. Another frequently investigated method is gaseous injection where a cool gas is forced into the turbulent boundary layer through a porous wall (transpiration) or through slots (which are generally tangential). The cool injected gas provides a protective inner layer and thickens the boundary layer, and thereby reduces both the skin friction and wall temperature for a considerable distance downstream of the slot and porous surface.

A third method (and perhaps from a practical standpoint the most intriguing) for reducing skin friction is to utilize a compliant wall where the flexible or compliant wall material responds to the fluctuations of the turbulent boundary layer and presumably produces a favorable reduction in the Reynolds stress $\left(\overline{u'v'}\right)$ correlation near the wall and thus reduces turbulent skin friction.

Particle additives in liquid flows, such as polymers or other high-molecular-weight long chain molecules are believed to aline themselves in a unique manner and with only a few parts per million of additive can produce marked changes in the small-scale turbulent structure and thus Reynolds stress (skin friction). Boundary-layer additives in air flows, such as dust particles or glass beads can significantly reduce turbulent skin friction if the proper size, density, and mass concentrations are utilized.

Under the heading "Miscellaneous Approaches" are grouped skin-friction reduction concepts, some of which are feasible from a basic fluid mechanics standpoint, but which are difficult to implement in practice (such as control of pressure gradient or body contour to maintain nearly separated turbulent flow (low skin friction)).

NOMENCLATURE

A	area
C_D	total drag coefficient
$C_{D,f}$	total skin-friction drag coefficient
C_f	local skin-friction coefficient, τ_w/q_∞
C_L	lift coefficient, $L/q_\infty A$
ΔC_L	increment in lift coefficient, $\Delta L/q_\infty A$
C_Q	suction flow coefficient, $Q/u_\infty A$
c	airfoil chord
D	pipe diameter
d	wing thickness
E	Young's modulus, defined by equation (1)
F	mass-injection parameter, $\rho_w v_w/\rho_\infty u_\infty$ or $\rho_j v_j/\rho_\infty u_\infty$
f	pipe friction factor
L	lift

ΔL	increment in lift
M	Mach number
$\dot{m}$	mass flow rate
p	pressure
p'	root-mean-square pressure fluctuation
Q	volume air flow through suction slot or porous surface
q	dynamic pressure, $\frac{1}{2}\rho u^2$
R_c	Reynolds number based on wing chord, $\rho uc/\mu$
R_D	Reynolds number based on D, $\rho uD/\mu$
R_x	Reynolds number based on x, $\rho ux/\mu$
S	slot height
T	temperature
T_z	applied skin tension
t	material thickness
u	longitudinal velocity component
u^+	normalized velocity component, u/u_τ
u_τ	shear velocity, $\left(\tau_w/\rho_w\right)^{1/2}$
u_∞	free-stream velocity
v	normal velocity component
x	distance from leading edge or slot

y	height above surface
Δy	normal displacement of surface
y^+	normalized height, yu_τ/ν_w
α	angle of attack
δ	boundary-layer thickness
θ	momentum thickness
μ	dynamic viscosity
ν	kinematic viscosity, μ/ρ
ρ	density
τ_w	shearing stress, $C_f q_\infty$

Subscripts:

a	air
e	edge of boundary layer
j	slot
max	maximum
o	no mass injection or suction
p	particle
sl	sublayer
t	total conditions

w	wall conditions
∞	free-stream conditions

Primes denote fluctuations.

DISCUSSION

Suction

Laminar boundary-layer control through wall suction was visually observed by Prandtl as early as 1904 (as discussed by Schlichting (ref. 1)). Application of suction to an airfoil may produce two favorable effects: (1) a reduction in skin-friction drag by delaying or preventing boundary-layer transition and (2) an increase in the maximum lift coefficient by delaying or preventing boundary-layer separation. German scientists were very active in this field and by the late 1930's were conducting partially successful flight experiments utilizing laminar flow control on aircraft wings. (See Schlichting (ref. 1) for discussion.) Numerous wind-tunnel and flight investigations (refs. 2 to 15) have been conducted to determine the effects of such parameters as composition of suction surface (slots or porous region), configuration of slots, suction mass flow rates compared with boundary-layer mass flow rates, optimum location of suction region on airfoil, wing sweep, and minimum suction volume for prevention of separation. For a complete list of low-speed references, the reader is referred to Schlichting (ref. 1). Experimental wind-tunnel (refs. 1 to 13) and flight (refs. 14 to 15) data generally demonstrate the same result, that by properly shaping and positioning the suction slots or porous suction surface and by applying sufficient suction, separation and transition can be delayed or prevented. Considerable reductions in drag (maximum of about 66 percent) were measured on low-speed airfoils with suction by Pfenninger (ref. 8) as illustrated in figure 1 where reductions of 50 percent are evident (from Schlichting (ref. 1)), even when the suction pump power consumption is charged against the system. Figure 2, taken from Schlichting (ref. 1) after the work of Poppleton (ref. 2), indicates the importance of correct positioning of the suction porous zone or slits on increasing the lift of an airfoil at low speeds.

A summary of some successful experimental wind-tunnel and flight studies where suction was utilized to maintain laminar flow is presented in table I. For low speeds in wind tunnels, laminar flow was maintained by suction on a 0° swept wing for Reynolds numbers based on chord up to 17×10^{6}. (See ref. 12.) Wind-tunnel laminar flow control studies on a 30° swept wing (refs. 9 and 10) were successful in maintaining laminar flow up to Reynolds numbers based on chord of 29×10^{6}. Wind-tunnel turbulence was believed

TABLE I.- SUMMARY OF SOME SUCCESSFUL WIND-TUNNEL AND FLIGHT EXPERIMENTS USING LAMINAR FLOW CONTROL

Reference	Laminar controlled surface	Airfoil thickness ratio	Mach number	Reynolds number based on maximum chord or length for laminar flow	Type of experiment
8	Airfoil, 0° sweep	0.105	≈ 0	2.5×10^6	Wind tunnel
12	Airfoil, 0° sweep	.15	≈ 0	17	Wind tunnel
9,10	Airfoil, 30° sweep	.12	≈ 0	29	Wind tunnel
2	Airfoil, 40° sweep	.10	≈ 0	2.6	Wind tunnel
14	Airfoil, 0° sweep	.13	.7	36	Flight (F-94)
15	Airfoil, 30° sweep	.10	.7	46	Flight (X-21A)
13	Airfoil, 36° sweep	.03	2.5	17	Wind tunnel
13	Airfoil, 36° sweep	.03	3.0	25	Wind tunnel
13	Airfoil, 36° sweep	.03	3.5	20	Wind tunnel
13	Airfoil, 72.5° sweep and camber	----	2.0	9	Wind tunnel
13		----	2.25	6.5	Wind tunnel
13	Ogive-cylinder	----	2.5	16	Wind tunnel
13	Ogive-cylinder	----	3.0	12	Wind tunnel
13	Flat plate, $\alpha = 0^{\circ}$	----	3.0	26.4	Wind tunnel

to be the source which limited reaching higher laminar flow Reynolds numbers. In flight, suction slots were used on the wing glove of an F-94 aircraft (ref. 14), and full-chord laminar flow up to a Reynolds number of 36×10^6 was achieved.

The largest scale flight experiment conducted to date with laminar flow control on wings by suction was with the X-21A aircraft (ref. 15). The X-21A wings were swept 30° (wing area 1250 ft^2) and were constructed with narrowly spaced fine laminar-flow-control suction slots. Various configuration difficulties were encountered, as well as spanwise turbulent contamination of the inboard two-thirds of the wing from the turbulent boundary layer at the wing-fuselage intersection. Various modifications were made to the wing-suction design and full chord laminar flow was achieved up to Reynolds numbers of 46×10^6. The X-21A flight program demonstrated the feasibility of laminar flow control on the wing of large aircraft, but also demonstrated that much experimental development work needs to be conducted. Based on the results of the X-21A flight tests, Kosin (ref. 15) estimated that laminar flow control on the wing of a large present-day transport could increase the range by 35 percent for the same payload.

Examples of laminar flow control in supersonic wind tunnels by suction on airfoils, an ogive-cylinder, and a flat plate are given in table I. Full-chord laminar flow on a 36° swept airfoil at Mach 3 was maintained up to a Reynolds number of 25×10^6 and on a flat plate up to 26.4×10^6. (See ref. 13.) For these tests (ref. 13), wind-tunnel noise was believed to cause premature transition and thus the maximum laminar flow Reynolds number attainable was limited.

To determine the gains possible with laminar flow control on the wings of a large present-day transport, a study (ref. 16) was conducted by assuming laminar flow over 90 percent of the chord of a 200-passenger, 5700-nautical-mile range, Mach 0.815 transport. Quiet turbofan engines with a bypass ratio of 5 were assumed to be available, and special exhaust duct design was envisioned to reduce the jet and exhaust noise which could induce premature transition. A laminar-flow-control system weight penalty of 1.5 lb/ft^2, based on the laminar-controlled surface area was assumed. For the same payload and range, the aircraft with laminar flow control on the wings had a take-off gross weight reduction of about 18 percent, the required wing area was reduced about 5 percent, and the engine size (thrust) was reduced about 25 percent. In terms of direct operating costs, the transport with laminar flow control on the wings registered a 7.5-percent reduction (ref. 16) even though a 10-percent penalty for manufacturing and maintenance costs was included. Obviously, if large segments of the fuselage were laminarized, further significant reductions in skin-friction drag and corresponding gains would be realized.

The results of this study are significant and attractive, but, unfortunately, the practical problems have prevented the development of a laminar flow control system on a full-scale aircraft. Extensive research is needed to optimize the suction system consisting of turbines, compressors, ducts, elbows, bleed pipes, suction pods, suction slots, suction rates, etc. For a laminar flow suction system to be effective, the surface should be free of roughness elements (panel seams, rivet heads, and other irregularities) which would normally be permissible. Residue left from insect impacts produced unwanted boundary-layer trips on the X-21A laminar flow wing (ref. 15). At supersonic speeds, roughness should not be as critical. However, at supersonic and hypersonic speeds, the low form drag airframe design produces severe volume constraints for a laminar flow suction system. Stability and control problems may develop if turbulent flow occurs on large sections of one wing while the other remains laminar. Other unanswered questions include the effect of water (rain and salt), dirt, ice, and other particles on the reliability and maintainability of the suction system (ref. 16) as well as the level of performance expected under normal operating conditions. Atmospheric turbulence normally encountered in flight may cause intermittent transitional-turbulent flow to occur on the suction-controlled surface. Noise sources associated with the engine (compressor, turbine, and jet), the turbulent boundary layer on the fuselage, separated flow areas, and the suction flow through piping ducts and valves may have a detrimental effect on maintaining laminar flow. As a rough indicator for subsonic flow, a noise level of 110 dB is acceptable while maintaining laminar flow for a Reynolds number based on chord of 30×10^6. (See ref. 15.)

In conjunction with the noise control problem, an attractive feature of maintaining a laminar boundary layer over large segments of an aircraft, especially the fuselage, is the corresponding reduction (or elimination) of wall pressure fluctations associated with conventional turbulent boundary layers. A considerable savings in weight and expense of insulative materials for passenger comfort may be realized, although shielding against jet noise is still necessary. Furthermore, fatigue of structural components due to boundary-layer noise should be lowered considerably. Unfortunately, the thick boundary layer associated with the fuselage (high R_x) combined with the unfavorable surface contours (such as cockpit, passenger windows) may limit the feasibility of laminar flow control on the fuselage.

Gaseous Injection

The injection of a cooled secondary fluid into a turbulent boundary layer through slots and porous surfaces has been studied extensively both theoretically and experimentally. (See for example, refs. 17 to 45.) Most of these studies were primarily concerned with the effectiveness of the film coolant in reducing surface temperatures. However, the twofold advantage of an effective gaseous injection system is that both surface temperatures and skin friction may be reduced. Injection of a cooled low-molecular-weight gas, such as helium, produces greater reductions in skin friction than injection of air. (See ref. 23.) The weight penalty for carrying these low-molecular-weight gases onboard initially are much greater than the ram drag penalty for bringing air onboard in flight to be used as the film coolant (ref. 22). Use of low-molecular-weight gases may be feasible in short-duration bursts for evasive action by military aircraft. Representative examples of two-dimensional film cooling geometries are illustrated in figure 3 (from Goldstein, ref. 40). In transpiration cooling (fig. 3(a)), the coolant fluid is introduced through a porous surface across the width of the test surface. For slot cooling, tangential slot injection of the coolant is the most efficient (low mixing of injected and free-stream gas) as shown in figure 3(b), but some studies alined the slot at an angle to the free stream. (See fig. 3(c).)

Injection of a cool secondary fluid into a turbulent boundary layer thickens the boundary layer and can reduce the velocity gradient at the wall (thus, C_f is reduced); if, however, the momentum of the injected gas is greater than the free-stream flow, the injected gas behaves as a wall jet and an increase in C_f occurs. (See ref. 32.) This increase in C_f may be offset by the gain in net thrust due to injecting gas into the boundary layer. The beneficial thrust gain is always realized with injection; however, at large injection mass flow rates (high momentum), the injection process is not practical. The cooler injected fluid provides a protective inner layer against the high aerodynamic heating which is usually present. A slow mixing rate between the boundary-layer gas flow and the injected gas flow is therefore desirable and increases the effectiveness of the injected gas in cooling the surface.

The effectiveness of reducing turbulent skin friction for both cones and flat plates by injecting gas through a porous surface is illustrated in figure 4 (taken from ref. 20). As shown in figure 4, significant reductions in turbulent C_f can be achieved, depending on the blowing rate parameter F. A major disadvantage with transpiration cooling systems is that porous materials have low structural and thermal rigidity and can be easily clogged up, so that their application to high-speed vehicles, where loading and heating is severe, may be limited. In fact, systems studies (refs. 46 and 47) which evaluated transpiration and convective (internal) cooling systems for flight application found convective cooling to be superior to transpiration cooling.

A slot injection system does not have many of the inherent physical deficiencies of a transpiration cooling system. The film cooling effectiveness of a slot injection system will be mentioned first, followed by a discussion of skin-friction reduction due to slot injection. Examples of subsonic studies dealing with two-dimensional tangential slot injection into a turbulent boundary layer are given in references 41 to 45. See Goldstein (ref. 40) for an excellent review of film-cooling studies, especially at subsonic speeds. At supersonic speeds, an example of two-dimensional tangential slot injection of both air and helium into air is given in reference 37. Tangential slot injection results with a three-dimensional wing at Mach 2.01 are discussed in reference 22. For hypersonic flow, a limited number of experimental results are available for two-dimensional tangential slot injection film cooling. (See refs. 34 to 36.) These recent studies (refs. 34 to 36) illustrate that the effectiveness of film cooling at hypersonic speeds in reducing the surface temperature is considerably greater than that for low-speed flows or than that previously estimated by extrapolation of low-speed data to hypersonic conditions. However, realistic comparisons of the hypersonic results with subsonic and supersonic results are limited since the boundary-layer thicknesses in the low-speed cases were small compared with the slot height and may have reduced the effectiveness of film cooling. Available subsonic and supersonic slot injection results have maximum ratios of δ/S of about 5 (ref. 43) and 0.25 (ref. 37), respectively, compared with 32 (ref. 34) for hypersonic tests. Evaluation studies (refs. 48 and 49) which concluded that transpiration cooling was superior to film cooling for high-speed application are probably incorrect, since the film cooling effectiveness was extrapolated from lower speed results. Consequently, current complete mission evaluation studies with full-scale supersonic and hypersonic vehicle concepts (similar to those of refs. 48 and 49) should be conducted based on the recent findings of references 34 to 36.

The dramatic reduction in C_f due to slot film cooling at Mach 6 is illustrated in figure 5 (from ref. 34). The largest reduction in C_f occurs just downstream of the slot. Note that the total temperature of the injected air has an insignificant effect on C_f for the range of $T_{t,j}/T_{t,\infty}$ considered and that the theoretical finite-difference prediction of reference 32 gives excellent agreement with the data. Cary and Hefner (ref. 34) integrated local skin-friction distributions similar to those of figure 5 and found total skin-friction drag reductions of approximately 60, 45, and 30 percent over distances of 25, 50 and 100 slot heights downstream of the slot, respectively. (See fig. 6.) Theoretical predictions from reference 32 indicate that multiple slots (spaced at about $x/S = 100$) would produce an accumulative effect with additional reductions in skin-friction drag.

The reduction in overall drag due to slot injection, as well as the positive net thrust gained by injecting the coolant through the slots, will only partially offset the ram drag penalty charged to the system for bringing on air to be used as the film coolant. (See refs. 50 and 51.) For hydrogen-fueled vehicles, the fuel heat sink could be used for cooling the air prior to slot injection. A source of "low cost" air coolant may be the "turbocooler" suggested by Ferri et al. (See ref. 52.) This turbine-compressor device brings on air, reduces its temperature by passing it through a supersonic impulse turbine, and delivers this cooled air to the slot injection system. Excess captured air is cycled through a compressor and exhausted through a nozzle to produce thrust. The net drag penalty is reduced considerably for this arrangement. A cursory systems study by Frank S. Kirkham at Langley Research Center (unpublished) utilizing both the beneficial effects of multiple slots as predicted from reference 32 and the turbocooler concept from Ferri et al. (ref. 52) on a proposed Mach 6 transport concept has shown that cooling the surface to temperatures suitable for titanium is possible with a 5-percent net drag penalty. As suggested by Becker (ref. 50), the ultimate design for supplying low cost coolant air may be to integrate the turbocooler concept in the normal propulsion system.

For supersonic and hypersonic vehicles, film cooling is particularly attractive since film cooling can protect the surface from the high aerodynamic heat loads, and thus allow the use of lighter, less expensive materials, and can also reduce the skin-friction drag of the vehicle. Subsonic slot injection studies (refs. 40 to 45) were mainly concerned with film-cooling effectiveness rather than with C_f reduction, so that the effect of slot cooling on skin friction is uncertain for subsonic speeds. However, if subsonic vehicles have their engines oversized to reduce compressor noise and comply with Federal Aviation Administration noise requirements in the vicinity of the airport (ref. 53), any available excess air could be used for film cooling. Furthermore, the use of film cooling may reduce the intensity of the turbulent wall pressure fluctuations which, as mentioned with the laminar flow control concept, may result in a considerable savings in weight and expense of acoustic insulative material presently used for passenger comfort as well as reduce structural fatigue.

Compliant Wall

Skin-friction reduction using compliant surfaces is a concept unique from the other techniques discussed herein and offers distinct advantages. The main advantage is simplicity; no slots, ducts, or internal equipment of any nature. Furthermore, there is no requirement for air to be captured (no ram drag). Kramer (refs. 54 and 55) is credited with the original idea of drag reduction by compliant surfaces, based on his observation of dolphins swimming in water. His early experiments showed a drag reduction of approximately 50 percent for a towed compliant coated cylinder. He attributed this drag reduction to delayed transition from a laminar to a turbulent boundary layer. However, his experiment was not closely controlled (the cylinder was towed behind an outboard motor boat in Long Beach Harbor, California) and it has since been theorized that his drag reduction was due either to an alteration of the shape of his cylinder or a favorable interaction of the compliant coating with a turbulent wall flow to reduce skin-friction drag.

Theoretical studies by Benjamin (refs. 56 to 58), Kaplan (ref. 59), Landahl (ref. 60), Nonweiler (ref. 61), and Gyorgyfalvy (ref. 62) have shown that certain types of compliant surfaces should reduce the drag force by delaying the end of transition. Their work was based on linear stability theory as developed by Lin. (See ref. 63.) Essentially, by defining wall compliance parameters they were able to show that although compliant walls did not necessarily stabilize laminar boundary layers, they did tend to retard the rate of growth at which disturbances propagated into the boundary layer, and thereby delayed the transition to a purely turbulent boundary layer. However, the applicability of a linear stability analysis for predicting the growth or decay of finite disturbances in a transitional boundary layer is questionable since the proper governing equations can no longer be linearized. Many attempts have been made to verify experimentally this transition delay predicted by theory (see, for example, Laufer and Maestrello (ref. 64), Ritter and Porteous (ref. 65), or Dinkelacker (ref. 66); unfortunately, these results can at best be described as inconclusive, although Karplus (ref. 67) did observe early transition and concurrent retardation in the development of fully turbulent flow.

The most promising approach to drag reduction using compliant walls appears to be in the alteration of a fully turbulent boundary layer. Theoretical analyses of this area are even more sparse than the transition work, although attempts have been made by Ffowcs Williams (ref. 68), Blick (ref. 69), and Semenov (ref. 70). On the other hand, the experimental results in this area have been considerably more promising than the previously mentioned transition work. Total skin-friction drag reductions of up to 50 percent have been reported by Blick and his co-workers (refs. 71 to 79) in their studies of low-speed turbulent boundary-layer flow over compliant surfaces. Skin-friction drag measured on polyvinyl chloride (PVC) – water saturated polyurethane foam compliant walls by

Blick, et al. (ref. 78) is shown in figure 7 as a function of velocity and skin tension; drag reductions of as much as 40 percent are obvious. Chu (ref. 79) fabricated compliant (PVC-polyurethane foam) and rigid NACA 0009 airfoils with both 40.7-cm and 102-cm chords. Total skin-friction drag reductions (parasite drag due to end effects was subtracted) for the compliant airfoils, as compared with the rigid airfoil results, are presented in figure 8 as a function of chord Reynolds number. Unfortunately, the boundary-layer transition location was not fixed so that variations in natural transition location may have produced irregularities in the data (although a drag reduction apparently was observed). Two interesting features are observed: first, the airfoil with the largest chord displays a higher drag reduction which suggests that a certain developing length (high x/δ ratio) may be necessary to achieve optimum surface—boundary-layer interaction. Secondly, there is a significant effect due to PVC skin thickness. The present authors believe this effect is due to variations in skin tension and associated membrane flutter; unfortunately, airfoil skin tension was not measured in these tests. Furthermore, the present authors believe that the skin-friction reductions measured by Blick and his co-workers (refs. 71 to 79) were due to membrane flutter rather than displacement of the polyurethane foam substrate. This conclusion is based in part on knowledge of the model construction details. Therefore, the function of the foam was to damp the amplitude of the flutter oscillation and possibly to influence the membrane frequency response. Lissaman and Harris (ref. 80) have studied similar compliant-wall boundary-layer flows and also found reduced skin-friction drag (although only a 10-percent reduction). They also showed a reduced pressure drop for compressible flow through a flexible aluminum foil pipe. Pelt (ref. 81) also investigated pipe flows and found that flexible walls can reduce the overall pressure drop. However, there is some question about Pelt's pipe flow data because the laminar flow data also show a drag reduction which is unexplained.

It should be mentioned that there is an abundance of experimental data with air and water flows which contradicts the previously cited work on fully turbulent flows. (See refs. 64 to 66, for example.) Much of the disagreement is probably caused by the approach employed by many experimenters. Rather than attempt to identify the parameters which contributed to compliant drag reduction and isolate them, the typical approach has been to try something and see whether it works. Naturally, this technique leads to a great deal of inconclusive data. Aside from the difficulty in selecting an appropriate material, additional considerations such as length, thickness, skin tension, backing materials, mountings, boundary-layer thickness, roughness, and the presence of panel flutter must be included. Needless to say, the probability of randomly hitting the right set of experimental conditions is low.

The first systematic investigation on governing parameters is probably that of Grosskreutz (ref. 82). He theorized that in order to produce a drag reduction, it was necessary to cause the fluctuation velocities u' and v' to be related in such a way that the turbulent Reynolds stress would be negative at the wall rather than positive. He proposed manufacturing such a boundary by attaching a smooth surface to a brush-like substrate whose bristles sloped against the direction of flow. In that way, a positive u' fluctuation would tend to move the skin back which would rotate the bristles upward, elevating the surface locally and producing an upward motion; thus, a positive v' fluctuation was created. Then $u'v'$ would be a positive number and the Reynolds stress which is related to $-u'v'$ would be negative. Grosskreutz manufactured and tested such a material. His measured drag reduction was found to be rather small (about 5 percent), and some of his experimental conclusions were contradictory. However, it would appear that his test material was not appropriate because its modulus of elasticity was too large when examined in terms of anticipated turbulent pressure fluctuations.

Future compliant wall experimental studies (in air) should be concentrated in the higher speed regime, say $M \geqq 0.85$, where the higher dynamic pressures will allow the utilization of more suitable materials (other than membranes). Skin friction can be measured by mounting the compliant surface on a drag balance, or by obtaining boundary-layer pitot surveys at various lengthwise stations on the rigid (noncompliant) surface and each of the compliant surfaces tested. With the latter technique, skin friction can then be determined both from the momentum integral equation for a flat plate with $dp/dx = 0$, $C_f/2 = d\theta/dx$, and by transforming the measured velocity data to "law of the wall" coordinates, u^+ and y^+. Walters (ref. 77) and Blick et al. (ref. 78) have shown that velocity profile measurements obtained in turbulent flow over a compliant surface display the conventional logarithmic "law of the wall" behavior, but are displaced upward because of a decrease in skin friction. (See fig. 9.)

Currently, a compliant wall experimental study is under way at Langley utilizing a 1.525-meter-long flat plate with interchangeable compliant surfaces. These tests are being conducted in the Langley 4-ft supersonic pressure tunnel at $M_\infty = 2.2$. Boundary-layer pitot surveys are being obtained along the surface, and the entire compliant model will be mounted on a force balance to determine whether an overall drag decrease occurs. For these tests, a guideline for the selection of compliant elastic slab materials has been employed which assumes that surface displacements should be less than the laminar sublayer thickness. The authors believe that displacements greater than the sublayer thickness will produce unwanted roughness drag. Since the compliant material responds to (and is displaced by) the turbulent wall pressure fluctuations, the level of anticipated wall pressure fluctuations should be calculated from correlations such as are found in reference 83 for a particular Mach number and dynamic pressure. By assuming the magnitude of the calculated wall pressure fluctuation is p_w' and the desired surface displacement is Δy (which is less than the sublayer thickness), the compliant wall modulus of elasticity (E) and thickness (t) should be related by

$$E = \frac{p'_w}{(\Delta y/t)} \tag{1}$$

The authors acknowledge that this is a crude first-order guideline for selection of a desirable compliant wall material. The power spectrum of the turbulent pressure field must certainly determine the frequency response characteristics required for a compliant wall drag reduction, and the turbulent eddy scale will influence the magnitude of the local force experienced by the wall. However, at this time neither a desirable frequency response range nor an eddy size parameter have been developed which can be used in the design process. Consequently, only the steady–state displacement criterion discussed has been used in the preliminary design and development stages.

By using equation (1) in a generalized manner, estimates of the required compliant material modulus can be determined for subsonic, supersonic, and hypersonic flight conditions. Figure 10 illustrates the manner in which these estimations were accomplished. Curve (1) in the lower part of the figure represents the estimated wall pressure fluctuations normalized by dynamic pressure (ref. 83). The cruise dynamic pressure for typical flight vehicles is illustrated by curve (2). Multiplication of curves (1) and (2) produces curve (3), the estimated wall pressure fluctuations. Calculations were then made of the turbulent boundary-layer thickness on the fuselage (at the half-length station) of typical subsonic (length of 61 m) and proposed supersonic (length of 61 m) and hypersonic (length of 91.5 m) vehicles at cruise conditions. These calculations assumed fully turbulent flow over the entire fuselage. By estimating the laminar sublayer thickness from a correlation found in reference 84, with $R_\theta = 10\ 000$, and assuming surface displacements to be some reasonable fraction of the sublayer thickness ($\Delta y = 0.1\delta_{sl}$ and $0.5\delta_{sl}$), calculations of the compliant material modulus were made. The variation of the compliant material modulus with Mach number, an initial compliant wall thickness of 5.08 cm being assumed, is presented in the upper part of figure 10. From this crude analysis, it appears that materials with the desired response to turbulent pressure fluctuations would be available for subsonic and supersonic vehicles.

A corresponding Langley Research Center theoretical investigation by the present authors dealing with compliant surfaces has focused on two problems: (1) developing estimates of local surface displacements produced by turbulent fluctuations so that a Glushko (ref. 85) type mixing length analysis can be used, and (2) studying the interaction between a turbulent boundary layer and an elastic boundary. The displacement estimates are being generated by attempting to simulate a fluctuating pressure field over an elastic or membrane surface. Then, hopefully, the experimental data of Blick and others can be correlated to show that there is some optimum wall motion. In addition, an attempt has been made to combine panel flutter theory with fluid mechanics to ultimately allow simultaneous analysis of the fluid-elastic system. The source of most of the panel flutter information was the survey paper by Dowell. (See ref. 86.)

The mixing length study (for use with a flexible skin or membrane surface) is fairly well developed at this point, although no solutions have been generated. An exact solution has been developed for the response of a nonuniformly loaded membrane to an instantaneous point pressure pulse. This solution can be used to develop the membrane response due to any unsteady pressure distribution. The data presented by Deardorff (ref. 87) can be used to generate an instantaneous pressure field which can then be used to analyze the local displacements of the membrane. From this analysis, a characteristic wall displacement length can be calculated and used in the analysis of Blick's membrane data. Hopefully, these data will show an optimum wall motion and provide some insight into the fundamental fluid mechanisms involved.

A finite-thickness elastic layer is far more desirable from a structural point of view (as compared with a flexible membrane), but it is much more complicated to analyze. The difficulties are twofold. First, no consistent experimental data are available (probably because of the low modulus of elasticity required to produce appropriate wall motions at low subsonic speeds). Second, an analytical solution to the three-dimensional elastic slab problem is extremely complicated. The two-dimensional response of an elastic slab to wavelike disturbances has been examined extensively by Nonwieler. (See ref. 61.) At this point, however, the Green function type of solution for the elastic slab has not been developed.

Particle Additives

In 1948, Toms (ref. 88) and Oldroyd (ref. 89) reported on a discovery that the injection of small amounts of polymers into turbulent liquid flows reduced the drag force. This phenomenon has since been named the Toms effect and has found considerable application in the design of high-speed underwater vehicles. Since that time, hundreds of papers have been published on the subject of the Toms effect. Drag reductions of 50 percent (ref. 90) have been reported in pipe flows and nearly 70-percent reductions for flow past a sphere (ref. 91). Recent work on the Toms effect has been surveyed by Landahl (ref. 92) and Granville (ref. 93). At this time, the mechanism responsible for the drag reduction is not well understood.

More recently, some attention has been given to the possibility of injecting particles into air flows to produce the same drag reduction effect. Although the problem is very similar in that an attempt is made to alter the character of a turbulent flow, the approach is very different. That is, there evidently is no material analogous to a polymer which can be added to an air flow. Aside from the difference in bonding between liquid molecules and gas molecules, the low air density is not compatible with any other material which has sufficiently large molecules to simulate polymer injection.

As an alternative, small particles with significantly different mass densities have been employed in attempts to alter the frictional characteristics of turbulent air flows. A tabulation of representative experimental results is given in table II. Sproul (ref. 94) reported that L.W. Briggs in 1945 found that when dust was suspended in air in a duct flow, the pressure drop decreased by 13 percent from its "clean" value. Saffman (ref. 95) reports that Kazakevich and Krapivin (ref. 96) observed that same effect. It is interesting to note that numerous investigators were observing that the drag increased when particles were injected into the flow. (See, for example refs. 97 and 98.) These early experiments have been tabulated by Pfeffer et al. (refs. 97 and 104).

TABLE II.- SUMMARY OF RESULTS DEALING WITH PARTICLE ADDITIVES IN TURBULENT AIR FLOWS

Investigator	Reference	Geometry	Characteristic dimension, cm	Flow velocity, m/sec	Reynolds number	Particle size, μm	Particles	Mass flow ratio, $\dot{m}_p/\dot{m}_a$	Change in skin friction, percent
Mehta et al. (1957)	98	Pipe	1.27	3 to 27	0.1 to 0.6×10^5	36 to 97	Glass	0.5 to 2	+40 to -30
Sproull (1961)	94	Annulus	0.5 to 0.75			1 to 10	Limestone, talc	0.21	-13
Soo & Trezek (1966)	99	Pipe	12.7	19 to 43	1 to 3	36	Magnesia	0.1 to 3	+2 to -6
Doig & Roper (1967)	100	Pipe	4.3	6 to 11	2 to 4.5	304 to 756	Glass	0 to 4.4	+10 to +50
McCarthy & Olson (1968)	101	Pipe	2.54	100 to 192	1 to 10	3 to 50	Lucite, glass, calcium carbonate	0.01 to 0.6	+1 to -30
Boyce & Blick (1969)	102	Pipe Flat plate	7.0 25		0.1 to 0.6 6 to 15	15 to 1680 100 to 1680	Silica dust, glass Glass	0.2 to 4 0.8 to 4	-10 to -30 -20 to -50
Pfeffer & Rossetti (1971)	103	Pipe	2.54	15	0.1 to 0.4	10 to 59	Glass	0.01 to 2	+40 to -75
Kane & Pfeffer (1973)	104	Pipe	2.21	15	0.1 to 2.5	10 to 60	Glass	0 to 3.2	+35 to -35

The reasons for the wide variation in the experimental results can be attributed to the different particle sizes employed, the Reynolds numbers characterizing the particular experiment, and the ratio of the mass flow rate of the particles to the mass flow rate of the air.

In order to extend this work into areas of aeronautical significance, Boyce and Blick (ref. 102) have investigated the flow of particles in the turbulent boundary layer on a flat plate. They found that skin friction could be reduced as much as 50 percent by injecting particles upstream of a flat test plate and allowing the particles to be convected downstream into the plate boundary layer. Their observations also indicated that the drag reduction was influenced by particle size as well as by the ratio of the particle mass flow rate to the air mass flow rate. (See fig. 11.) Note in figure 11 the disturbing result that massive particle additions are required in order to achieve large decreases in skin friction. The 50-percent reduction reported in reference 102 was with 100 micron particles and a particle mass flow rate about 4 times larger than the associated boundary-layer mass flow rate. However, this large ratio of particle to boundary-layer mass flow rate necessary to produce a significant skin-friction reduction is probably misleading. That is, for particle injection in both liquid (refs. 92, 105, and 106) and gas (refs. 101 and 103) flows, there is strong experimental and theoretical evidence suggesting that only the small-scale intense turbulent eddies in a "buffer zone" or thin region just outside the laminar sublayer need to be altered in structure to reduce the Reynolds stress (and thus the skin friction). Consequently, the particle additives should probably be concentrated in this region only (say through slot injection at the wall) instead of saturating the entire flow as in reference 102.

The results in air flows are in marked contrast with the results in liquid flows (only small mass additions of polymers are required for drag reduction in liquids). Mass additions as small as a few parts per million or less have been found to cause significant drag reductions in liquid flows. (See fig. 12.) However, Sproull's earlier results were somewhat more encouraging because a relatively small particle mass flow rate (about 20 percent of the air mass flow rate) was required in order to reduce the pressure drop by 13 percent.

It is apparent that there are fundamental differences in the air and liquid drag reduction mechanisms. The relative mass ratios of the additive and fluid have already been mentioned. In addition, the particle size, shape, and structure may also be significant. In order to find the basic mechanisms responsible for drag reduction in liquids and gases, many theoretical models have been proposed. Unfortunately, these theoretical studies have concentrated almost exclusively on the Toms effect.

Since both systems involve turbulent boundary layers, there must be some commonality between the behavior of polymers in liquids and particles in gases with regard to their influence on the turbulent structure. For that reason, the theoretical work for liquids and gases is surveyed here with the hope that the actual mechanisms may be discovered hidden in these theories.

Saffman (ref. 95) has presented the only theoretical discussion concerned directly with the effect of particles on turbulent skin friction although much discussion related to particle flows in fluidized beds is available. (See, for example, Baw and Peskin's (ref. 107) study of the influence of gas-solid suspensions on the turbulent spectrum.) Saffman's work might best be described as a classical linear stability theory approach. He presented a model which incorporated dust particles in the fluid flow equations in order to determine their influence on the transition from laminar to turbulent flow. Subsequently, it was found that the onset of turbulent flow was influenced by two parameters.

One parameter represented the relative concentrations of particles and air. The other parameter was called the "relaxation time" which actually was determined by the particle size and mass. Saffman discovered that fine dust (small relaxation time compared with characteristic flow time) destabilized the flow whereas the coarse dust (large relaxation time) had a stabilizing influence. He also theorized the mechanism by which dust particles could damp turbulent oscillations; relative motions between dust particles and turbulent eddies will dissipate energy because of the drag between the particles and air, and the inertia of the particles will cause the particles to absorb energy from the turbulent fluctuations.

Many theories have been presented to explain how polymers in very low concentrations reduce the drag in liquids. One theory discussed by Davies (ref. 108) is very similar to Saffman's discussion. He points out that polymer molecules have sufficient size to exhibit elastic properties. In the case of large-amplitude eddies, the molecules are too small to cause any alteration in the turbulent structure. However, in the case of small-amplitude high-frequency turbulent fluctuations, this elastic structure can dissipate significantly the energy contained in these eddies. Dye experiments have verified this idea, wherein the same relaxation time concept was used as a governing parameter.

Early work on the Toms effect (see, for example, refs. 109 and 110) centered on non-Newtonian behavior of these liquid-polymer solutions. However, these rheological theories are incomplete because some very good drag reducing additives (guar gum, for example) exhibit no such non-Newtonian effects. Furthermore, rod-like particle suspensions ($\dot{m}_p/\dot{m}_a < 0.1$ percent) in a Newtonian solvent have produced a 50-percent reduction in turbulent skin friction. (See ref. 111.) Recent experimental work has shown that some polymer additives alter the turbulent structure in such a way that there is more resistance against eddies moving perpendicular to the wall than there is against eddies moving in the flow direction. (See refs. 112 and 113.) This type of action could cause significant drag reduction with only a moderate reduction in the turbulent intensity as discussed by Fortuna and Hanratty. (See ref. 113.)

Other theoretical approaches to the problem have considered nonuniform concentration of both particles and solids (refs. 106 and 114) and the interactive elastic layer. (See refs. 115 and 116.) An extensive survey of related theoretical material is contained in reference 92 by Landahl.

Combining the favorable effects of slot injection and particle injection is another interesting possibility. For instance, the authors believe that the cooling heat sink potential of liquid hydrogen (which is a prime fuel source for proposed supersonic and hypersonic vehicles) could be used to liquefy the air brought onboard for conventional slot injection. The injection of the liquid air droplets may result in greater film cooling and skin-friction reduction effectiveness. For a supersonic vehicle, where only specific areas require active cooling, a large part of the total hydrogen fuel heat sink will be available.

Miscellaneous Approaches

This section could appropriately be labeled advantageous utilization of fundamental principles of fluid mechanics to reduce friction drag. Essentially, the miscellaneous drag reduction techniques all have attempted to use natural phenomena such as boundary-layer separation, natural suction, natural injection, and advantageous aerodynamic shaping to effect significant drag reduction. For instance, from a basic fluid mechanics standpoint, it is known that when a boundary layer (laminar or turbulent) approaches separation, the surface shear decreases and ideally goes to zero at separation. Accordingly, a few investigations (refs. 117 to 119) were conducted at incompressible speeds wherein the proper adverse pressure gradient was imposed upon the tunnel-wall turbulent boundary layer to establish an incipient separation condition. Measured values of skin friction were either extremely low (ref. 119) or effectively zero (ref. 118) in the region of pressure rise. Even though Stratford (ref. 118) maintains that the near separated turbulent boundary-layer flow had a "good margin of stability," these types of flows (nearly separated) are typically very sensitive to small changes (especially increases) in the pressure gradient. That is, a small increase in the adverse pressure gradient could produce immediate separation. For this reason, it would not appear to be practical to design airfoil or fuselage surfaces for regions of near separated flow, since the instability of the flow to small perturbations in local conditions may cause control problems.

Another design tactic, which employs the influence of a favorable ($dp/dx < 0$) pressure gradient on delaying transition has been used to construct "laminar airfoils." (See ref. 1.) By keeping the point of maximum thickness, and thus minimum pressure, as far rearward as possible, long runs of laminar flow can be achieved, with significant drag reduction (50 percent). The form drag associated with these types of airfoils is low also, since boundary-layer separation can be delayed or prevented. (See ref. 120.) However, there are three negative aspects concerning the application of laminar airfoils. First, for Reynolds numbers greater than about 5×10^6 (at subsonic speeds), the point of instability suddenly shifts forward toward the leading edge whereupon most of the airfoil boundary layer becomes turbulent (ref. 1); at supersonic and hypersonic speeds, a higher degree of stability will probably exist. Secondly, in order to maintain laminar flow for Reynolds numbers below about 5×10^6, extremely smooth airfoil surfaces must be maintained to prevent tripping of the boundary layer. For supersonic and hypersonic speeds, surface roughness is not as critical. Third, the desired shift in minimum pressure to the rear can be achieved over only a narrow range of angle of attack. (See ref. 1.)

In the same category as the two previous discussions (controlling the pressure gradient, or body contour, to maintain near separated turbulent flow or laminar flow) is the method of "blending" aircraft surfaces to reduce the wetted area. Proper blending of the wing-body, wing-nacelles, and vertical-tail—body configuration can help minimize wave drag and increase lift at supersonic speeds. Since the blending of aircraft surfaces generally results in cleaner aerodynamic shapes with longer runs of high Reynolds number (lower skin friction) flow, skin-friction drag is also slightly reduced. Possible reductions in skin-friction drag realized by proper blending are generally on the order of only a few percent.

Another possible drag reduction scheme involves the combination of suction and mass injection in one system. That is, suction slots on the windward (high pressure) side of an airfoil could be used to maintain laminar flow (low skin friction), and the mass flow through the suction slots could then be injected through tangential slots into the turbulent boundary layer on the leeward (low pressure) side of the airfoil (reduction of turbulent C_f). Mass flow rates are typically of the same order for both suction and mass injection systems. Ideally, the natural pressure differential across an airfoil could possibly provide some, if not all, of the desired mass flow rate necessary to maintain a suction-mass injection system. However, the "bleeding" of air from the high to low pressure side may have a detrimental effect on the lift generated, depending on the mass flow rates involved. To illustrate the feasibility of using the aerodynamic pressure differential as a suction source, in reference 121 a flat plate was constructed wherein streamwise suction slots were formed by spacing longitudinal rods various distances apart. With the slot surface alined at $\alpha = 5^\circ$ and 10° in a Mach 8 free-stream flow, sufficient pressure differential across the model surface existed to maintain sonic cross flow through the gaps in the rods. Subsequently, for the largest gap size, laminar flow was established over the whole test surface ($R_x \approx 8 \times 10^6$), where, with no gap, transition occurred at about $R_x \approx 1.5 \times 10^6$.

Most of the drag reduction techniques discussed in this section are not as well developed as those previously reviewed in the first four sections, as indicated by the fewer references cited. However, the sparseness of the literature may be indicative of a lack of consideration rather than a lack of potential.

CONCLUDING REMARKS AND RECOMMENDATIONS

In view of the pressing need to conserve our fuel resources, high priority must be assigned to research efforts to define and develop in ground facilities, and later validate and demonstrate in flight tests, aerodynamic concepts for minimizing the turbulent skin-friction drag. Particular emphasis should be given to studies in the speed range applicable to the current and next generation of subsonic transports.

This review has indicated that each of the four concepts considered for reducing skin friction are potentially viable systems. Suction and gaseous injection (slot film cooling) perhaps are closer at hand since a considerable amount of theoretical and successful experimental work has been accumulated in these areas. Skin-friction reduction with compliant walls or through particle addition (in air) is more in the development stage in terms of aircraft application. This is in great part due to the fact that the basic mechanism by which the turbulent structure is altered and the Reynolds stress is reduced for these two latter concepts is at present not completely understood. In light of this, considerable theoretical and experimental development work must be performed with the compliant walls and particle injection concepts to improve our confidence level and to verify that an actual drag reduction does exist. Specific conclusions and recommendations for each drag reduction method follow.

Suction

Laminar flow control by suction may be a fertile area with significant potential rewards for subsonic as well as supersonic transports. However, no significant experimental development effort is currently underway. Selected wind-tunnel tests in which critical areas are extensively studied, such as critical roughness heights, would be of particular interest. A fruitful course to pursue at this point would be to extend the practical working knowledge gained with the X-21A vehicle to a larger vehicle, perhaps a subsonic transport. A flight-experimental-development program wherein the wings of a large subsonic transport are modified for laminar flow control is perhaps the next logical step to determine the feasibility of a full-scale operational suction system.

Gaseous Injection

Slot injection for supersonic and hypersonic vehicles offers an attractive potential in light of recent hypersonic results. Hopefully, future hypersonic studies at Langley with swept and multiple slots will indicate that additional gains in skin-friction reduction and surface cooling are feasible. Furthermore, an up-to-date systems analysis may verify that hypersonic slot injection is a prime candidate for a structural cooling and drag reduction system. Continuing efforts should be undertaken to optimize the entire skin-friction reduction and cooling system, with particular emphasis on reducing the ram drag penalty charged against the system for bringing the air coolant onboard. Additionally, slot injection studies (including direct measurement of skin friction) are needed at high subsonic speeds since careful, reliable measurements in this speed range are virtually nonexistent.

Compliant Wall

If wind-tunnel studies verify that appropriately selected compliant walls (depending on Mach number and dynamic pressure) can provide significant skin-friction drag reductions, then material-structure experts will have an incentive to develop similar materials for aircraft application of this "simple" drag-reduction concept. Future compliant wall studies should concentrate on the Mach number range from 0.6 to 3 for flows where the dynamic loads are sufficient to allow reasonable materials to be tested. Selection of compliant materials is the key issue, and isolation of the parameters which govern the interactions between the wall and the turbulent boundary layer is critical.

Particle Additives

Future efforts in particle additive research should concentrate on defining the basic mechanism responsible for the observed drag reduction. Therein, a more intelligent means of selecting injection particles can be made; particle injection studies to date have not utilized optimum particle size or distribution. Experimental efforts in the supersonic and hypersonic speed range utilizing tangential slot injection of these "advanced generation" particles (including liquid air droplets) should provide interesting results. As with the compliant wall concept, the main problem is to develop and discover the optimum material or substance to produce the desired effect.

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Hampton, Va., November 8, 1973.

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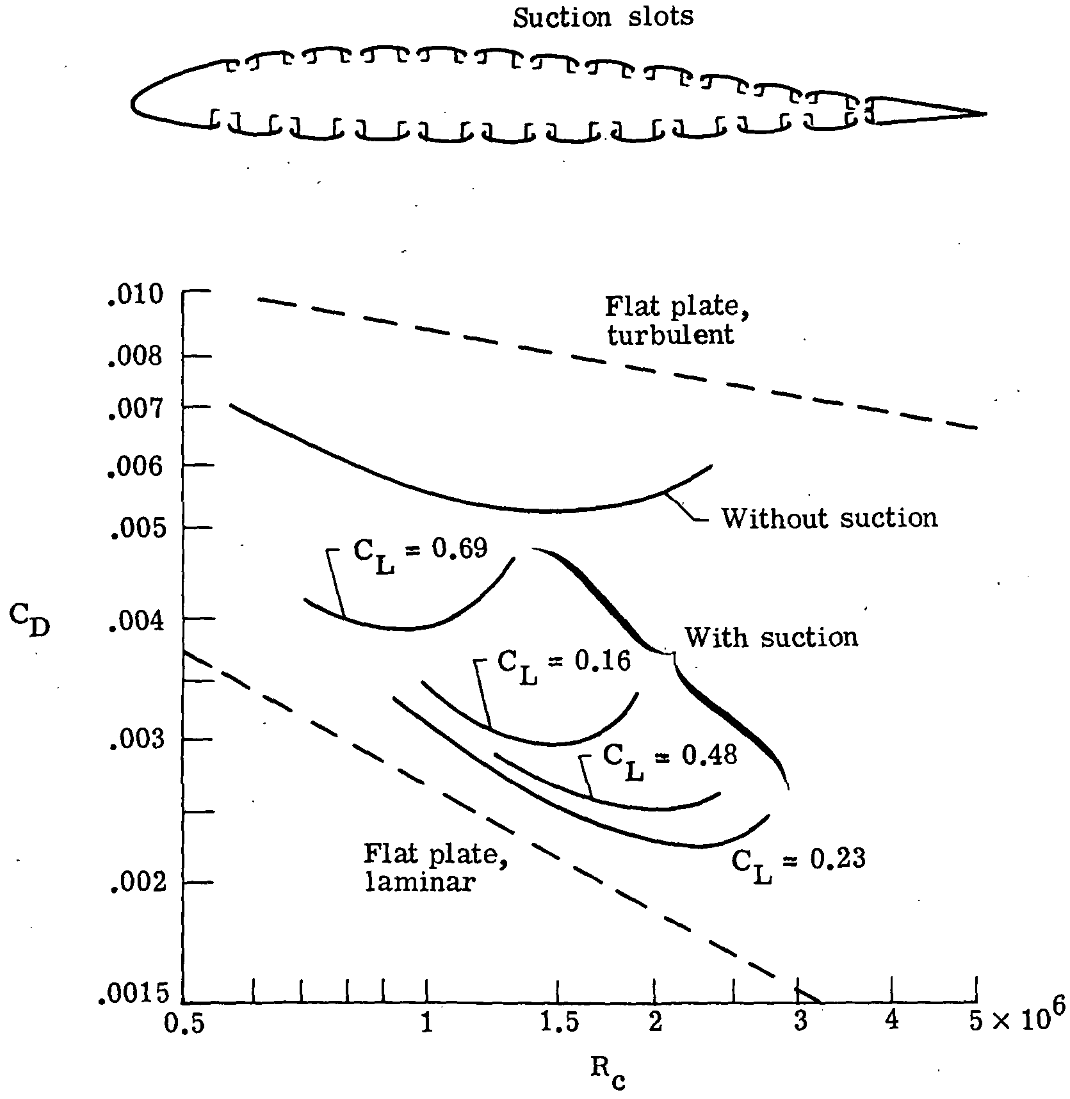


Figure 1.- Total drag reduction on airfoil with suction slots (from Schlichting, ref. 1).

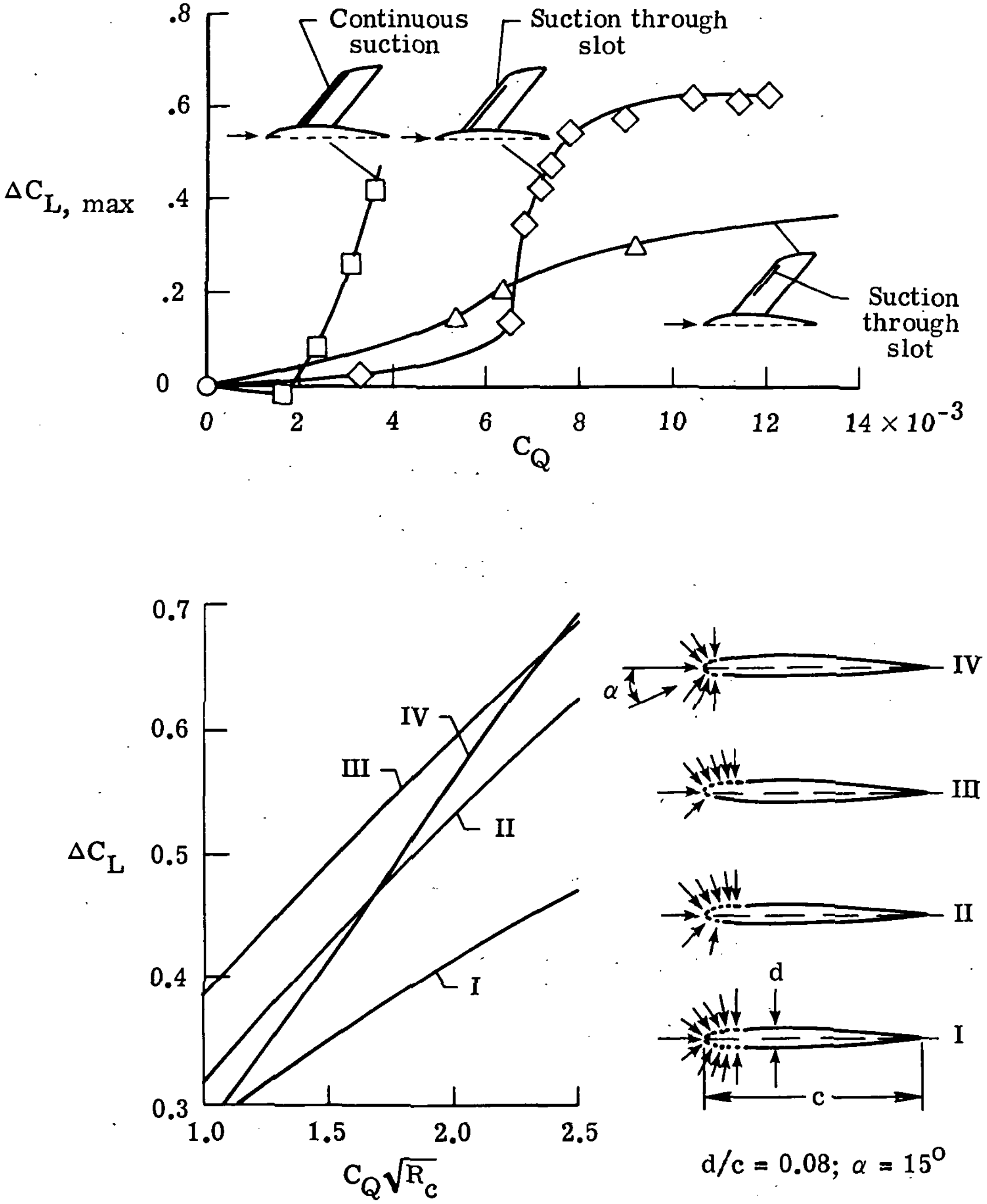
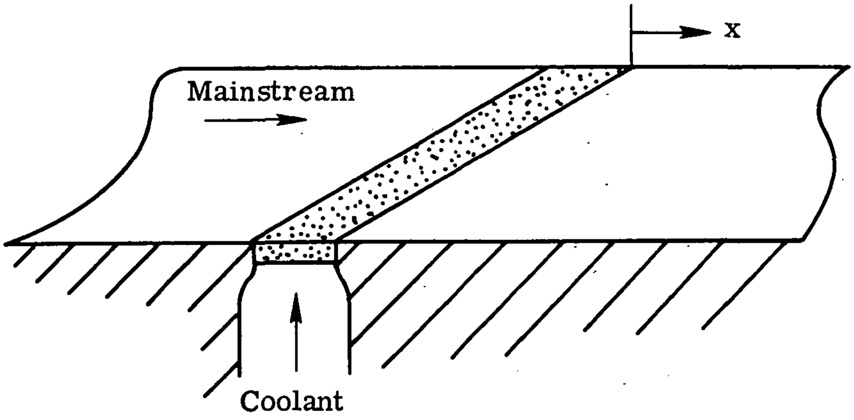
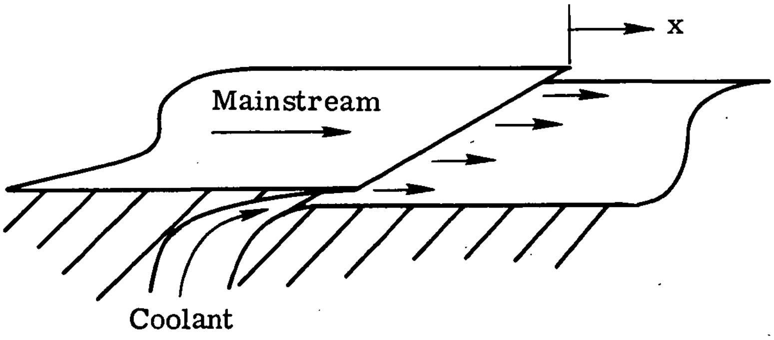


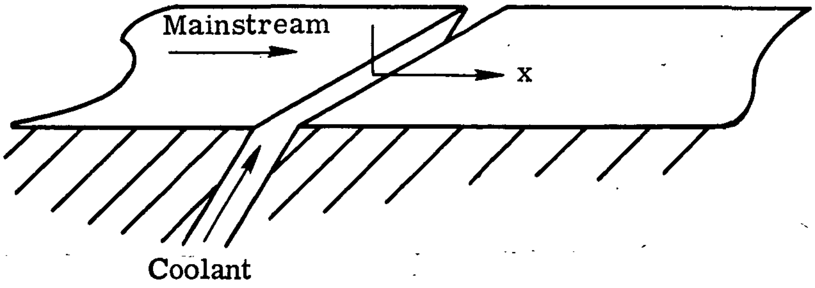
Figure 2.- Effect of suction geometry and mass flow rate on lift (from Schlichting, ref. 1).



(a) Porous slot.



(b) Tangential injection.



(c) Slot angled to free stream.

Figure 3.- Representative two-dimensional film cooling geometries (from Goldstein, ref. 40).

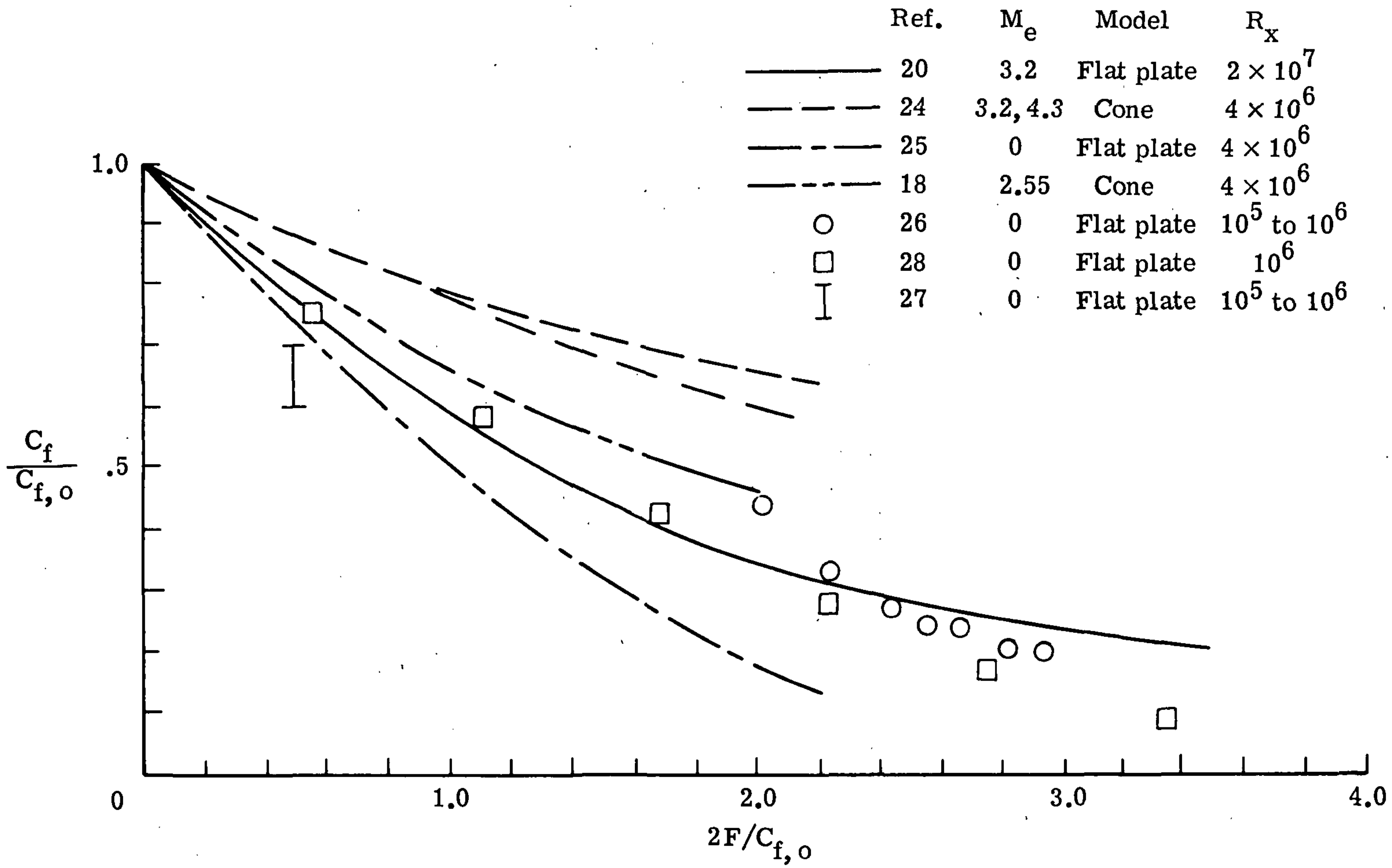
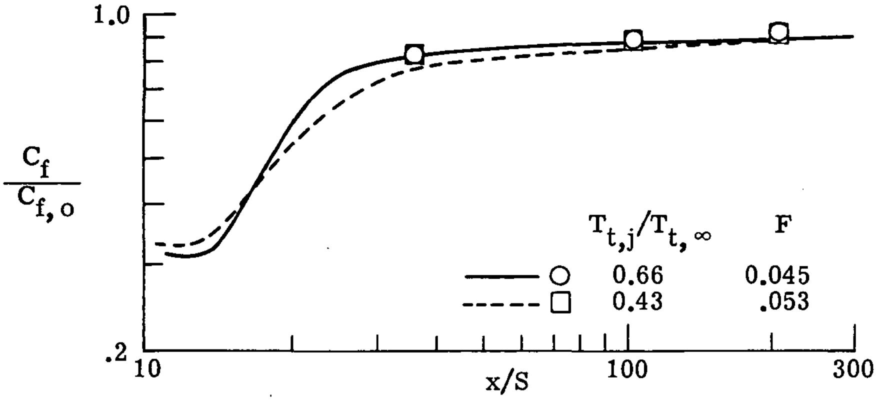
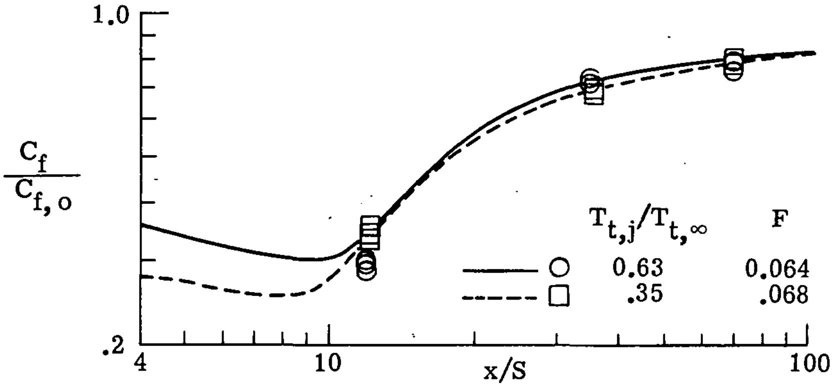


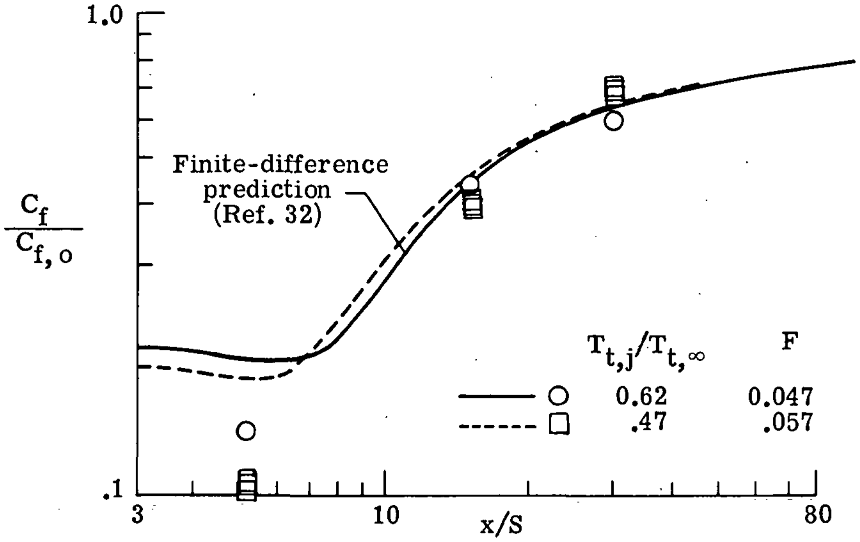
Figure 4.- Typical skin-friction reductions with gaseous injection through a porous surface (from Dershin et al., ref. 20).



(a) S = 0.158 cm.



(b) S = 0.475 cm .



(c) S = 1.11 cm .

Figure 5.- Skin-friction reduction downstream of tangential slots at Mach 6 (from Cary and Hefner, ref. 34).

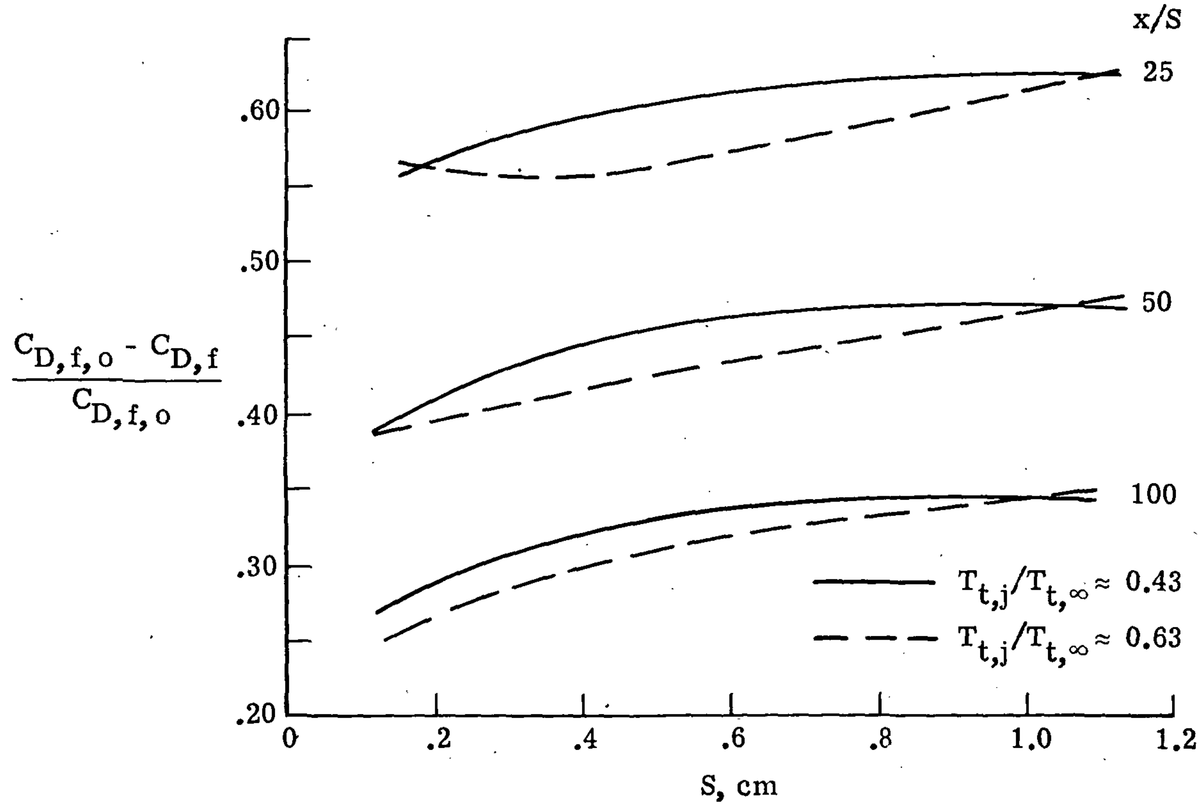


Figure 6.- Total skin-friction drag reduction downstream of tangential slots at Mach 6.

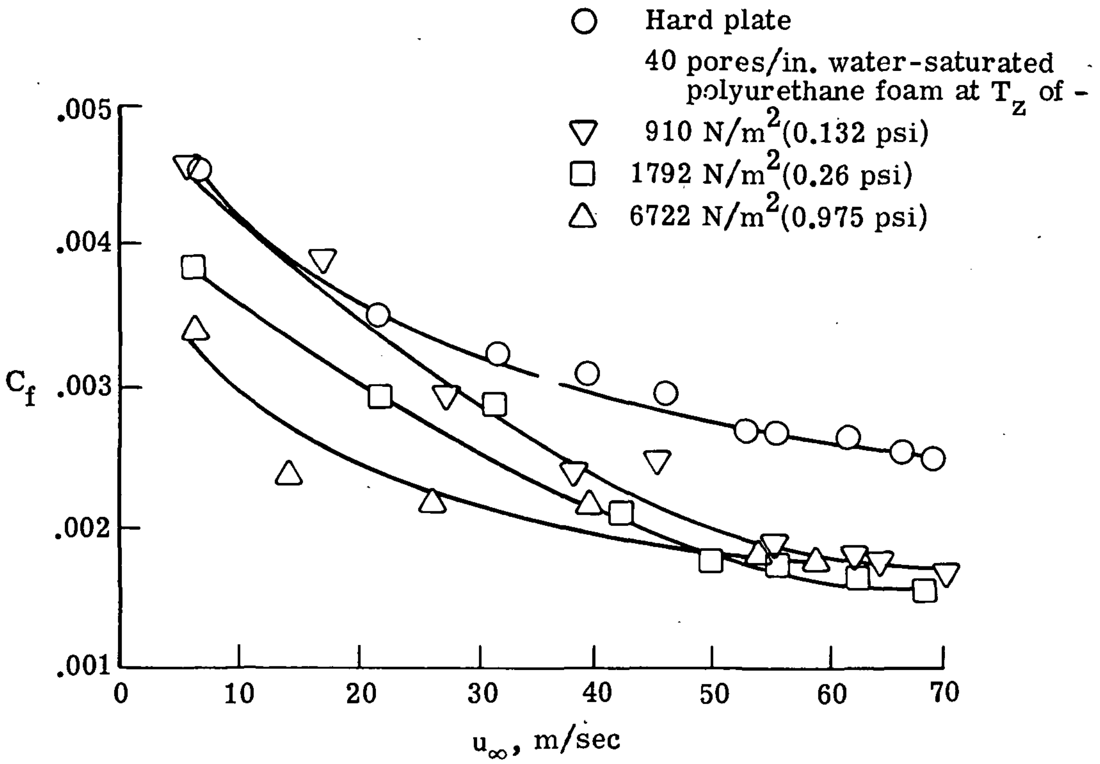


Figure 7.- Local skin-friction coefficient measured on compliant surface by Blick et al. (ref. 78). Fixed transition.

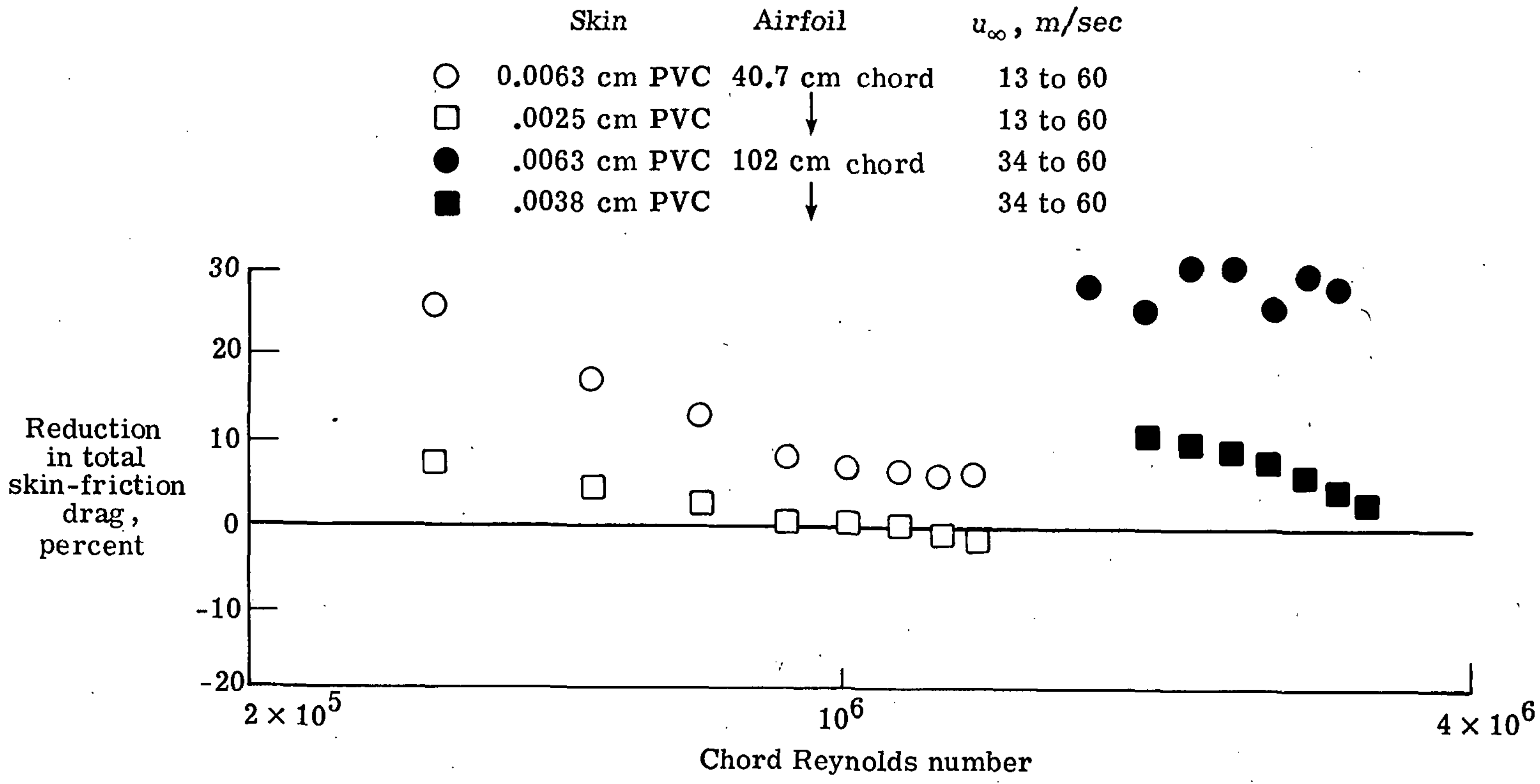


Figure 8.- Skin-friction drag reduction for compliant NACA 0009 airfoil (from Chu, ref. 79). No transition control.

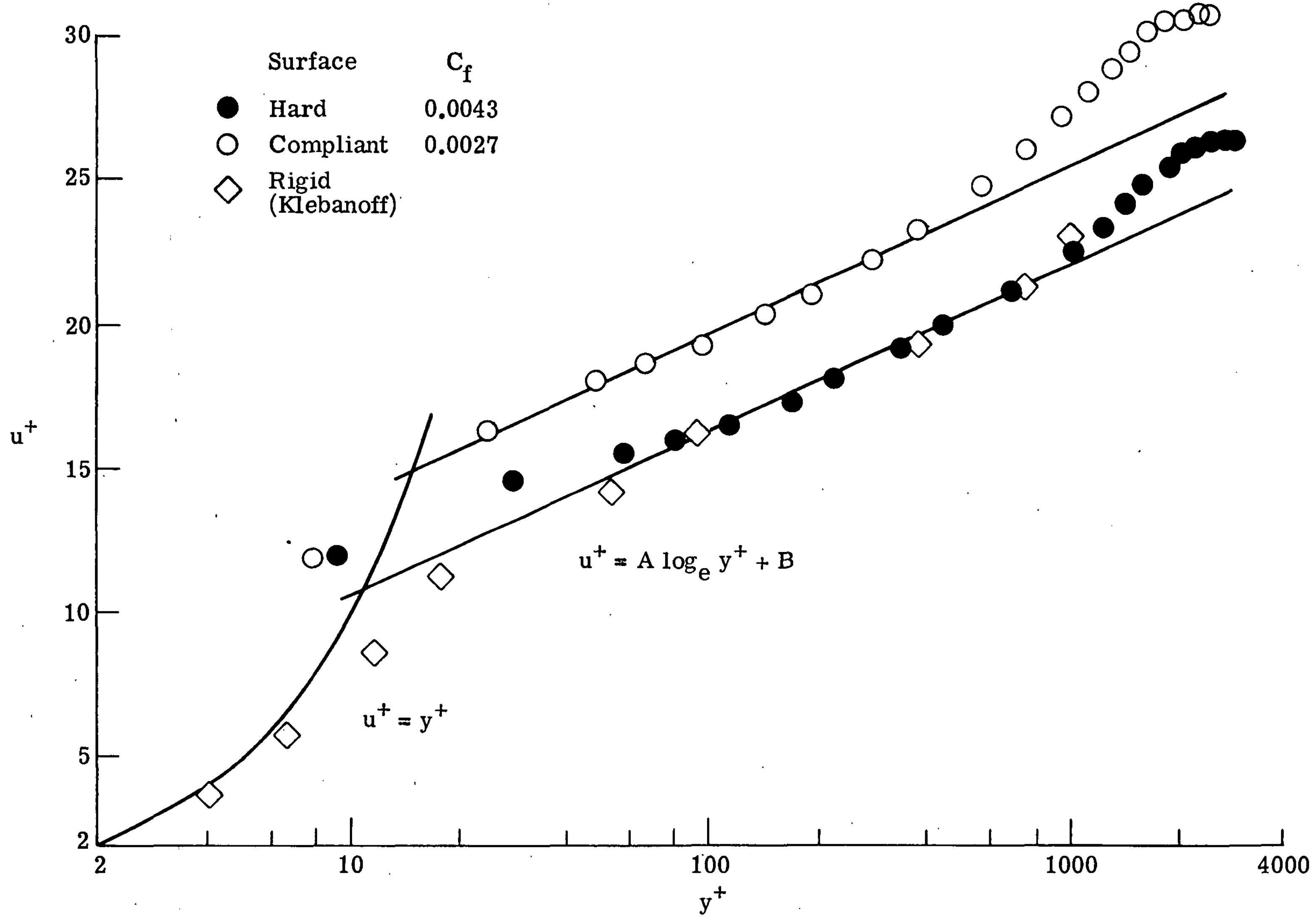


Figure 9.- Comparison of rigid and compliant wall data in "law of the wall" coordinates (from Walters, ref. 77). The constants A and B are 244 and 490 for the hard surface and 244 and 840 for the compliant surface.

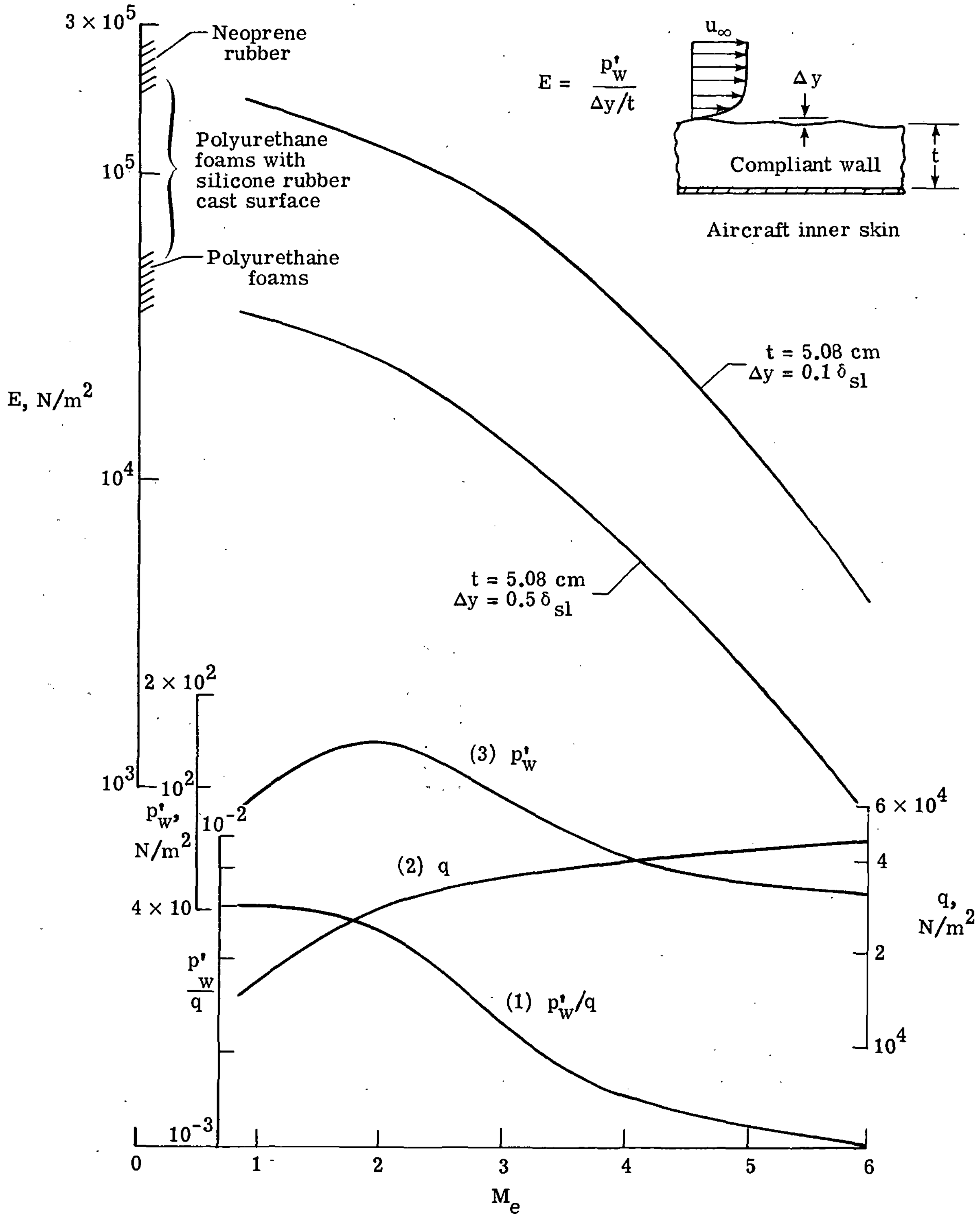


Figure 10.- Variation of compliant material modulus with Mach number.

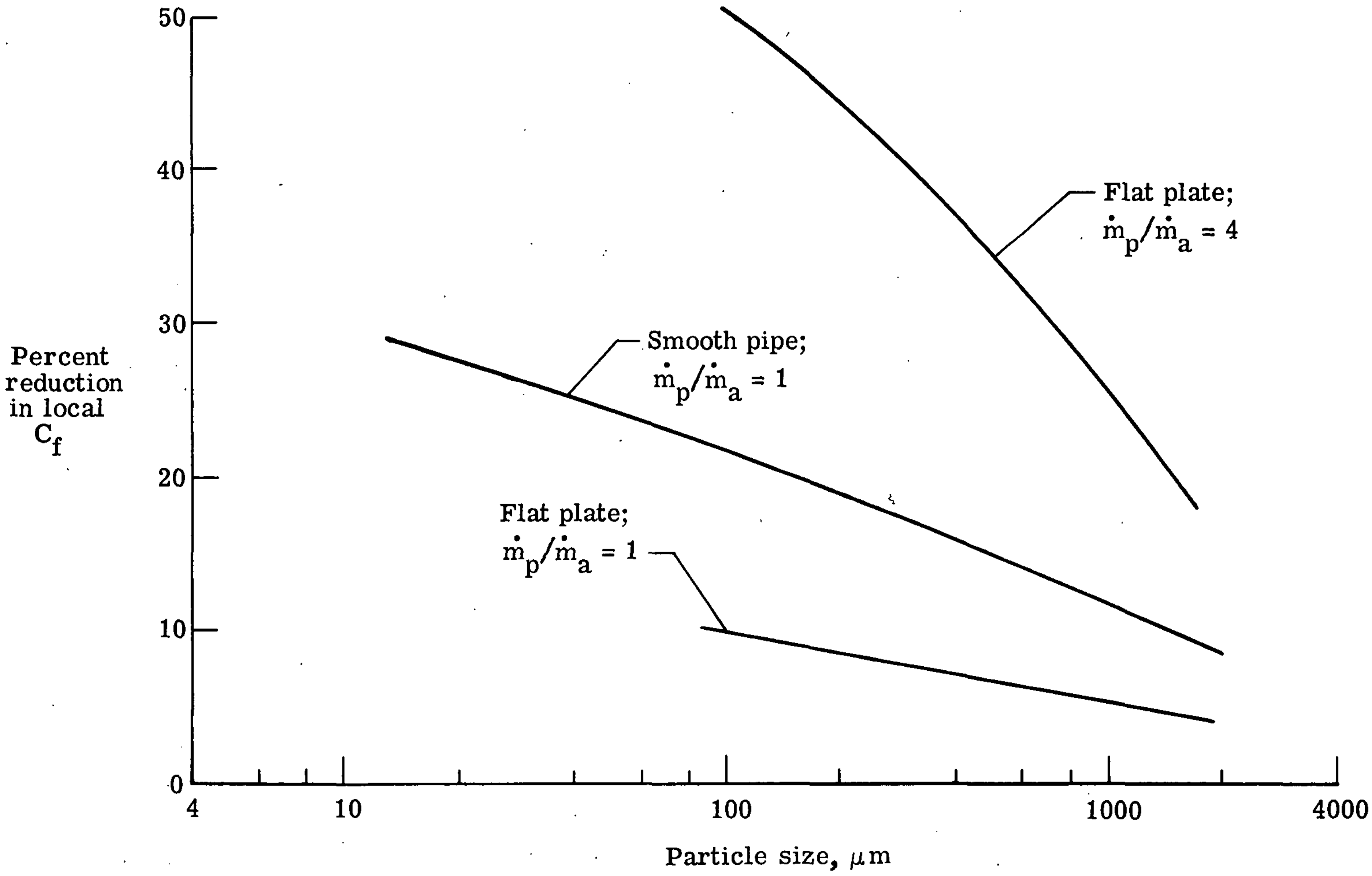


Figure 11.- Effect of particle size and mass flow rate on skin friction reduction in air (from Boyce and Blick, ref. 102).

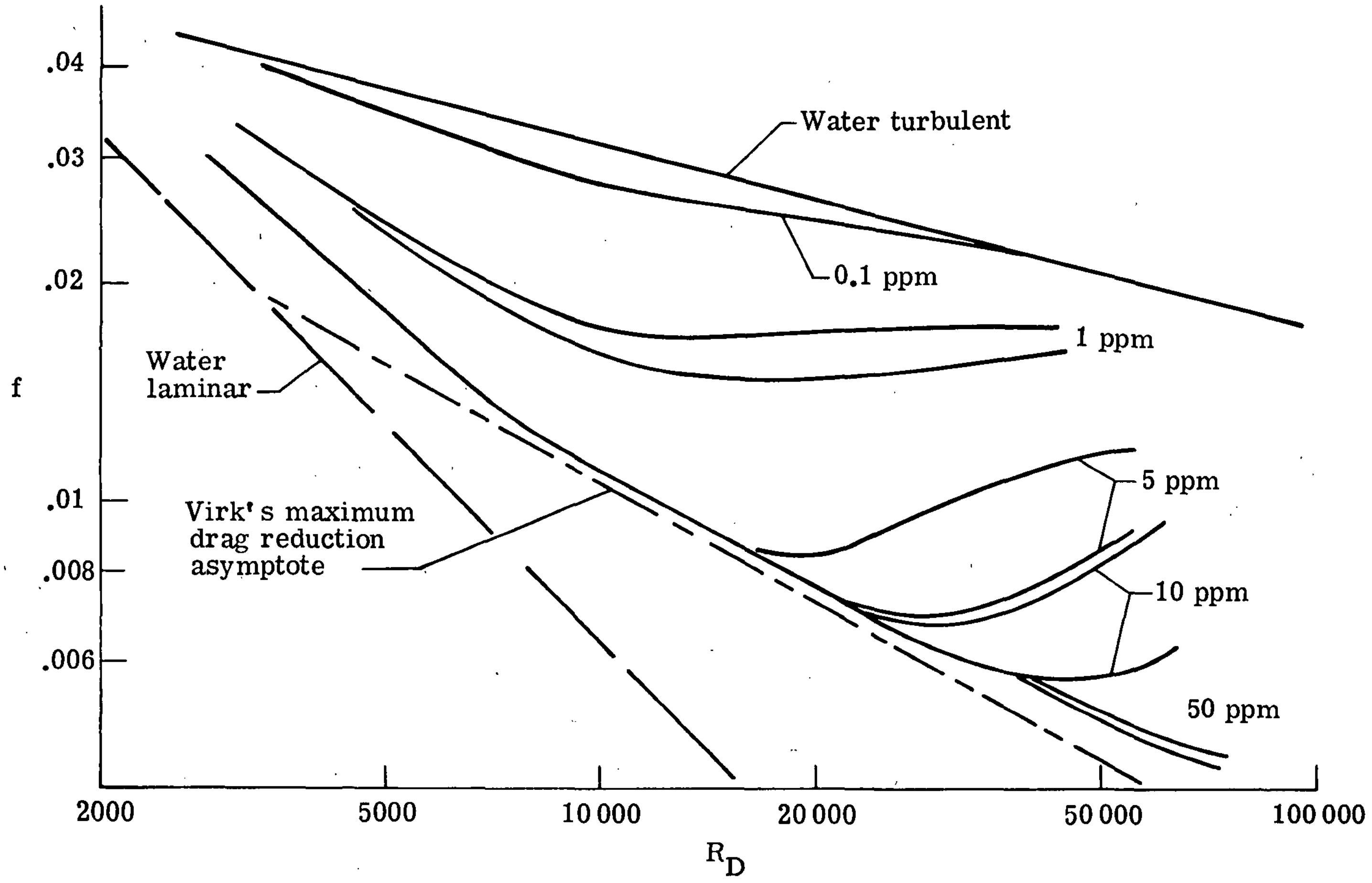


Figure 12.- Pipe flow drag data for solutions of polyethyleneoxide (from Landahl, ref. 92).

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