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Analysis and Evaluation of an Integrated Laminar Flow Control Propulsion System

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Problems of Laminar Flow Control and the Use of Suction Air in Determining Aircraft Performance

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Nomenclature

AR	wing aspect ratio
c, c^*	chord length
C_a , C_L	coefficient of lift
C_D	coefficient of total drag
C_{Di}	coefficient of induced drag
C_{D0},C_f	coefficient of parasite drag
C_p	coefficient of pressure
C_q	volume coefficient of suction
C_{D_s}	coefficient of suction drag
C_{D_w}	coefficient of wing drag
D	airframe drag
e	lift efficiency
F	dimensionless frequency, thrust
h	heating value of fuel
k	1/pARe
m	mass flow rate
M	Mach number
p	power, pressure
p_s	total ideal suction power
p_m	power required to maintain flow
PSFC	power specific fuel consumption
q	dynamic pressure
R	range
Re, R	Reynolds number
R_f	recovery factor
S	wing planform area
S_1	equivalent suction area
SFC	specific fuel consumption
T	temperature
TSFC	thrust specific fuel consumption
u	x- component of the velocity in the boundary layer
U	velocity in the freestream
V	velocity

W	weight
W_E	airplane fuel empty weight
W_G	airplane take-off gross weight

Greek Symbols

b	flap deflection angle
s	spatial amplification rate of disturbances
r	density
t	thrust
w, u	suction velocity normal to wing surface area
y	angle of wave number vector
h	efficiency
D	incremental change

subscripts

A	airplane A
bl	boundary layer thruster
C	airplane C
d	total drag
e	exit plane
eff.	effective drag or drag coefficient
f	fuel
i	inlet to propulsion system
LFC	laminar flow control
m	maximum
0, •	overall or stagnation value, freestream
p	propulsion
s	suction
ps	pumping system
t	thermal
tr	transfer

1. Introduction

Reduction of drag has been a major goal of the aircraft industry as no other single quantity influences the operating costs of transport aircraft more than aerodynamic drag. It has been estimated that even modest reduction of frictional drag could reduce fuel costs by anywhere from 2 to 5%. Current research on boundary layer drag reduction (see Bushnell [1]) deals with various approaches to reduce turbulent skin friction drag as a means of improving aircraft performance. One of the techniques belonging to this category is laminar flow control in which extensive regions of laminar flow are maintained over aircraft surfaces by delaying transition to turbulence through the ingestion of boundary layer air. While problems of laminar flow control have been studied in some detail the prospect of improving the propulsion system of an aircraft by the use of ingested boundary layer air has received very little attention.

An initial study for the purpose of reducing propulsion system requirements by utilizing the kinetic energy of boundary layer air was performed in the Mid-1970's at NASA Lewis [2]. This study which was based on ingesting the boundary layer air at a single location, did not yield any significant overall propulsion benefits and therefore the concept was not pursued further. However, since then it has been proposed that if the boundary layer air were ingested at various locations on the aircraft surface instead of just at one site an improvement in the propulsion system might be realized. The present report provides a review of laminar flow control by suction and focuses on the problems of reducing skin friction drag by maintaining extensive regions of laminar flow over the aircraft surfaces. In addition, it includes an evaluation of an aircraft propulsion system that is augmented by ingested boundary layer air.

1.1 The LFC Concept

The laminar flow control concept consists of making use of the available kinetic energy of ingested boundary layer air in augmenting the thrust provided by the main engines through an auxiliary device which we shall call a boundary layer thruster (BLT). The components of the boundary layer thruster are a suction compressor and an auxiliary nozzle. The suction compressor is powered by one of the turbines of the main air-breathing engines. The operation is much like that of an aft-fan operating by the input of power in a turbofan engine by a turbine. The transmission efficiency involved in the conversion of output power from the turbine to the suction compressor is considered to be 100%. Boundary layer air is withdrawn from the upper and lower surfaces of each wing through suction slits into a collection surface as the schematics of Figure A.1 indicate. The air is then conveyed by suction ducts and compressed internally by the suction compressor before it passes through a converging-diverging nozzle (in the case of supersonic speeds) before being ejected aft of the fuselage to provide the additional thrust. This simplified thrusting system allows us to model the internal fluid mechanics in a simple way and to provide a measure of the performance of the thruster as a function of the exit velocity ratio. The suction slits are aligned in such a way to provide maximum flow per unit slot area and are sized and spaced spanwise so that they do not contribute to transition of the laminar boundary layer to a turbulent one (see [9]). The detailed construction of the collection surface has previously been considered by Boeing [9]. The relations involved in determining the system performance, the results obtained and the computer program used are provided in Appendix C.

2. Review of the available literature on laminar flow control

Under certain conditions undesirable dead regions are created in liquid and gas flows. These cause very prejudicial losses of energy. These losses can be avoided or reduced by drawing off small quantities of fluid from the surface into the interior of the body and thus preventing the development of turbulent regions. Boundary layer control by suction applied to wings insures an increase in maximum lift and permits using thick wing sections without excessive wing section or profile drag. One of the earliest experiments were carried by O. Shrenk [3] who investigated a large number of different arrangements of suction slits and their effect on maximum lift. It was shown by Shrenk that high lift coefficients were obtainable at certain suction volumes. In 1940 Shrenk [4] showed that boundary layer suction was more 'favorable' for airfoils with higher thickness ratios, in the sense that lower suction volumes are needed to achieve the desired lift coefficient (and hence a smaller expenditure of suction power) for an airfoil with a 20% thickness ratio in contrast to an airfoil with a 12% thickness ratio. Subsequent photographs taken during the flight test also show that an increase in the angle of deflection of the flapped airfoil is more favorable for laminarization of the upper surface of the airfoil and subsequent increase in lift and reduction of drag. However, the main thrust of the experiment was performed with the objective of studying the variation of lift with suction and this suggests to us that any study be it experimental or otherwise should be directed or aimed at maximizing certain aspects of aircraft performance. If range is the parameter of interest then the study should be carried out with the intent of maximizing the product of $\eta_p\, C_L/C_D$ for a conventional airplane. It should be noted that the studies [3] and [4] were carried out with suction employed on the upper surface of the airfoil in contrast to a study aimed primarily at the reduction of drag which would involve suction over both surfaces of the airfoil. Since in this case depending on the suction distribution there would be relatively no appreciable increase in maximum lift as acceleration of the boundary layer takes place on both surfaces with little relative (with respect to the upper surface) increase of the pressure distribution on the lower surface of the airfoil. One of the earliest flight tests that enhanced the prospects of laminar flow control by suction was the Miles experimental airplane. These tests indicated a reduction of about 22% in profile drag.

Later in 1946 Smith and Roberts of the Douglas Aircraft Company published their findings [5] regarding the prospects of laminar flow control. In that paper they discuss the possibility of the separation of the main boundary layer flow for the potential flow over a flat plate obtained by the superposition of a rectilinear flow and a sink; in particular, that the increase in pressure downstream of the slot may result in an adverse pressure gradient and subsequent separation. Thus, if the flow into a given slot is increased the closing streamline reaches further into the higher energy layers of the local flow field and a possibility of unstable flow appears. The authors mention that separation has been encountered by them in tests of boundary layer on a wing. It is surprising because it contradicts the usual belief that boundary layer removal always reduces separation. The increase in friction coefficient accompanying increased suction may be adequately demonstrated by Figure 1 of Appendix D, which however does not account for separation, as reported by Schlichting [6] from the results obtained by R. Iglish [7] for the continuous suction over a flat plate from a laminar boundary layer. It is interesting to note that with higher suction flow rates the friction coefficient becomes independent of viscosity and the drag obtained is that due to the sink effect of suction for a body immersed in a frictionless flow.

Increased suction results in increased suction power and hence increase in total power expenditure in keeping the flow system in operation. This fact is the main cause that suction systems should be designed to operate at the minimum sufficient suction power needed to keep the flow stable. However, the flow pattern over a wing is more complicated than that over a flat plate and an optimum suction distribution is required to minimize disturbances and keep the flow pattern laminar. The above paper also mentions that the flying qualities of a jet aircraft with boundary layer removal are exceptionally good particularly during takeoff and landing. In relevance to this is the reduced angle of incidence for a flapped airfoil at a given flap deflection with boundary layer suction. It should be mentioned however that the title " The Jet Airplane Utilizing Boundary Layer Air for Propulsion " is somewhat misleading in the context of propulsive enhancements, for the paper is based in its entirety on aerodynamic performance and the reduction of drag and increase in maximum lift rather than the use of boundary layer air for propulsion. Stability analysis and suction flow rates are not given due to the lack of sufficient research pertaining to air requirements and stability of boundary layer flows at that time. It is interesting to note the results presented regarding the hypothetical study of the application of boundary layer control to actual aircraft reveal a considerable increase in range with the use of boundary layer suction. The performance comparison for three hypothetical airplanes are presented in Figures 2 and 3; airplane A with reciprocating engines, B with turbojet engines and C with turbojet engines with boundary layer inlets. It is found that the boundary layer control jet airplane excels the conventional in its payload carrying capability to about 2020 miles, whereas a jet airplane with ramming intake can excel it up to only 1,310 miles. These ranges are carried at 430 m.p.h., 400 m.p.h., and 200 m.p.h., respectively, for the boundary layer intake jet, ramming intake jet, and conventional airplane.

Pfenninger in 1949 (see[8]) showed, with the use of suction slots, that with ingestion of small quantities of air (C_q= 0.0014 to 0.0018; where $C_q = -[\rho\omega]_s / [\rho u]_\infty$) over both surfaces of an airfoil of 17% thickness ratio the boundary layer can be kept completely laminar with a reduction in the profile drag to about one-half its turbulent value at Re = 2.4 x 10^6 . Some of the problems faced in maintaining laminar boundary layers will be discussed briefly in the following introduction.

3. Flow Problems Over Swept wings

The drag of an aircraft at cruise flight conditions is about 60% friction drag [...]for present-day transport aircraft with turbulent boundary layers on their wetted surfaces. For underwater vehicles, the friction drag is about 90% of the total drag. In each case laminarizing the boundary layer offers substantial improvement in surface friction which in some cases may amount to 50% reduction of profile drag.

Drag reductions of this magnitude are possible using extended natural laminar flow (NLF) or controlled laminar flow (LFC). The former principally applies to maintaining favorable pressure gradients along the wing surface to accelerate and stabilize the boundary layer by minimizing surface waves and discontinuities. The latter relies upon suction through slots in the wing or suction through a porous surface in order to prevent transition. The hybrid concept is another method which has evolved over the past years. Hybrid laminar flow control (HLFC) technique is a means of reducing airplane wing friction drag by combining suction laminar flow control near the leading edge (forward of the front spar only) with pressure distribution tailoring or natural laminar flow in the midchord section. This allows for maintaining laminar flow up to 75% wing chord. It appears that full chordwise suction inhibits the effectiveness of laminar flow control and lessens the benefits of drag reduction. On the other hand, sweep angles typical of modern commercial transport aircrafts are still somewhat higher than those for which substantial NLF has been demonstrated. This is how the hybrid concept originated. This method was successfully used by the Boeing Commercial Airplane Company (BCAC) in 1982 (see [9]). Considerable savings in wing profile drag with the deployement of HLFC can be seen from Figures 4 and 5 below.

Basic to the use of suction in laminar flow control is an understanding of the mechanism of boundary layer transition and the types of instabilities that occur over a swept wing (see [10]), since stability of the flow dictates the maximum allowable suction flow rate that is to be ingested. However, as we shall see in **4.1** wherein the concept of a propulsive efficiency greater than one is introduced and the *relative* comparison between a boundary layer ingesting engine and an air-breathing engine is made, the concept of a maximum value of suction flow is irrelevant. On a high speed swept-wing four basic types of boundary layer instabilities can occur: 1) viscous or " Tollmein- Schlichting " instability; 2) inflectional or cross-flow instability; 3) dynamic or " Taylor-Goertler " instability; and 4) leading-edge attachment line contamination.

Tollmien-Schlichting (T-S) instability depends upon the action of viscosity to transfer energy from the mean flow to the boundary disturbance. Amplification of T-S disturbances is small in regions of favorable pressure gradients and large in regions of adverse pressure gradients. Moderate suction quantities may be employed to stabilize the T-S disturbances.

The strong flow acceleration in the leading-edge region of swept wings induces a severe boundary layer cross flow and requires strong local suction. The effect of sweep and pressure gradient on the amplification ratio of disturbances is clearly seen from the results of Runyan and Steers [11].

Taylor-Goertler instability occurs primarily in the flow over concave surfaces. Most supercritical wing sections however do not contain any concave surfaces; as such, this type of instability is not a factor.

Turbulence originating from a leading-edge roughness or a turbulent boundary layer starting at the wing-fuselage intersection may spread in both the spanwise and chordwise directions. This is referred to as leading-edge attachment line contamination and may be reduced substantially by reducing sweep angle and by removing the entire turbulent attachment-line boundary layer and re-establishing a laminar layer by means of suction.

Particular attention is paid to the cross flow and T-S instabilities in connection with the results of Mack (see [12]) based on his investigation of the stability of the laminar boundary layer on two transonic wings of infinite span with distributed suction. Both wings have supercritical airfoil sections; one has a sweep angle of 23 deg with $M_\infty = 0.82$ and $c^* = 1.96$m, the other has a 35 deg sweep with $M_\infty = 0.891$ and $c^* = 2.0$m . It is seen from Fig. 6 for the 35 deg wing that their is a considerable shift of the curve of maximum spatial amplification rate (σ_m) of stationary ($F = 0$) or cross flow disturbances downwards. It also appears that with suction applied at the leading edge the peak of the curve decreases. The effect of the sweep angle on the cross flow is evident from the comparison of the results of the 35 deg wing with those of Fig.7 for the 23 deg wing where the maximum value of σ_m is less than 5×10^{-3}. Compressibility effects tend to dampen the T-S disturbances ($\psi = 0$) in the mid-chord region. The design suction of the 23 deg wing is 60-70% of that of the 35 deg wing but it still controls the instability of these waves in this region as is shown by the large decrease in σ_m with suction. The pressure gradient on the upper surface of the 23 deg wing in the vicinity of the mid-chord region is nearly zero.

So far the foregoing discussions have focused on the problems of laminar flow control and a review of some of the literature delineating the benefits in drag reduction offered by LFC. Nothing has been stated regarding the possible improvements in the propulsive system of an aircraft with LFC. The object of the following discussions will be to examine the boundary layer from a propulsion point of view and to show that the kinetic energy of boundary layer air may be utilized in augmenting the propulsive efficiency of an aircraft by the use of a boundary layer thruster consisting of a suction compressor and a converging nozzle. The range equation for a non-conventional aircraft (one using boundary layer air for propulsion) will be re-examined taking into effect the improvements in the propulsive efficiency and the L/D ratio .

4. Performance Prediction

4.1 *The available energy in the wake of a boundary layer and its utilization in the increase in propulsive efficiency*

Ackeret [13] seems to have been the first to demonstrate the inherent advantage of the withdrawal of the boundary layer into the surface of a body which is propelled through fluid. He drew upon the fact that the available wake kinetic energy in a boundary layer is substantial. For simplicity consider a two-dimensional flat plate in a stream (U,0,0) of incompressible flow as shown in Fig. 8. Let the velocity near the trailing edge be (u,v,0). The drag per unit span is given by,

$$D = \int_{-\infty}^{\infty} \rho u\,(U - u)\,dy \tag{1}$$

and the power P_m required to maintain the flow is,

$$P_m = \rho\, U^3 c \int_{-\infty}^{\infty} \left(\frac{u}{U}\right)\left(1 - \frac{u}{U}\right) d\left(\frac{y}{c}\right) \tag{2}$$

If suction is now applied whereby the entire fluid within the boundary layer is withdrawn at the trailing edge into the surface and its total pressure is restored to the freestream value, which assumes no frictional losses in the ducting system and considers the pump efficiency to be 100%, then the total suction power required is the rate of change of kinetic energy between the inlet to the slots at the trailing edge and the exit to the duct. This suction power is given by

$$P_s = \int_{-\infty}^{\infty} \rho u\, 1/2\,(U^2 - u^2)\,dy \tag{3}$$

or

$$P_s = \rho U^3 c \int_{-\infty}^{\infty} \left(\frac{u}{U}\right)\left(1 - \frac{u}{U}\right)\left\{1/2\left(1+\frac{u}{U}\right)\right\} d\left(\frac{y}{c}\right) \tag{4}$$

Comparison of eqs. (3) and (4) reveals that $P_s < P_m$. The term P_s is also called the *unavailable thermal energy* (see Ackeret [13]). For a laminar boundary layer (Blasius profile) this is about 78.7% of the product of plate friction drag times the freestream velocity and the available wake kinetic energy is about 21.3% of P_m. It is thus seen that if the flow in the wake is ingested and ejected with a freestream velocity U the entire momentum loss in the boundary layer can be overcome and the suction power required to do so would be less than that needed to maintain the flow system.

The ratio of the thrust , obtained in acceleration of ingested flow from the boundary layer , to the frictional drag, may be shown using Fig. 1 by the following numerical examples. Assuming an asymptotic suction profile with $C_q = 3.75 \times 10^{-3}$, $C_f = 0.9 \times 10^{-4}$ the value of the thrust to drag ratio is approximately 83.3% when the ingested flow is accelerated to freestream velocity. With a suction quantity of 14×10^{-4} the ratio is 99% when the suction flow is accelerated to a velocity of $V_e = 1.2\ U_\infty$.

Greater gains are obtainable when suction is applied steadily over the plate and laminar flow is maintained in the boundary layer instead of a turbulent flow. This point will be emphasized in subsequent discussions. It is also seen that the ratio P_m / P_s provides a measure of the propulsive efficiency which in this case is greater than one. The *Froude efficiency of propulsion* has always been defined as the ratio of the useful work done to the energy imparted to the fluid and the attainment of a value greater than one is not mere speculation especially in view of the principle of aircraft propulsion by wake regeneration as has been pointed out by Davidson [14] and its utilization in the Ogee scheme.

4.2 *The Range of a Subsonic Airplane With Actively Controlled Boundary Layer From a Propulsion Point of View*

The same bleed-off boundary layer air that is used to improve the lift-drag ratio of the airframe is considered as the inlet air of the auxiliary propulsor to increase its efficiency. The primary points made, that are in disagreement with some of the existing studies are:

(1) that it is incorrect to charge the same friction drag of the airframe to the inlet momentum of the propulsor.

(2) While it may give the correct range it does not give the correct view of the airplane to improve the lift-drag ratio of the vehicle at the expense of a system that produces thrust by the burning of fuel.

The initial motivation for the use of active boundary layer control on aircraft surfaces was the growing need to conserve energy. The initial studies related to laminar flow control were led by NASA Langley and concentrated on the improvement in airframe L/D (see refs. [1] and [15]) although some attention was given to the arrangement of the propulsion system (see [16]). The range contribution of the propulsion system was not thoroughly analyzed, this will be the purpose of the ensuing discussion. In particular, it will be shown how the range is maximized by integrating the airframe boundary layer with the propulsion system in order to improve the airplane lift-drag ratio and the propulsive efficiency in combination. The term *conventional aircraft* will denote an aircraft powered by a conventional engine (air-breathing engine or propfan) and will be referenced as airplane A, while the non-conventional term applies to an aircraft powered by an air-breathing engine and a boundary layer thruster and it will be referenced as airplane C.

The *Brequet range equation* assumes cruise flight at constant velocity V_0, with the thrust F equal to the drag D and the lift L equal to the weight W. This equation may be written as

$$R = h \eta_0 L / D \ln \left(\frac{W_G}{W_E} \right) \tag{5a}$$

where

$$\eta_0 = \eta_p \times \eta_t \times \eta_{tr} \tag{5b}$$

This equation was originally derived assuming that the lifting and propulsion systems were separate systems. In the following analysis the fuel heating value, h , the thermal or cycle efficiency, η_t , and the transfer efficiency, η_{tr} , are all assumed constant.*

The propulsion efficiency , η_p , the thrust per unit mass flow rate and the airplane L/D ratio will be discussed as they relate to a conventional aircraft. Finally, the product of the propulsive efficiency and the lift - drag ratio will be dealt with as it applies to an active boundary layer control airplane. The air-fuel ratio and the weight of the suction system-thruster configuration will be neglected in the present analysis.

4.3 *Propulsion Efficiency*

The propulsive efficiency, η_p , is defined as the useful work output per second of the propulsion system, FV_0 , divided by the energy input to the jet $1/2\, m (V_e^2 - V_i^2)$. The latter can, in the limit, be the shaft input to the propeller or the fan of a high bypass ratio fan. Figure 9 is a schematic of the power flow for an aircraft employing a propfan and a boundary layer thruster.

The propulsive efficiency is given by,

* note that η_t is constant at the value it would have if the inlet for the power producing unit (not the thrust producer) were in the freestream (see Fig. 10 of Ref. 15).

$$\eta_p = \frac{F\,V_0}{E\,(\text{jet})} = \frac{\dot{m}\,(V_e - V_i)\,V_0}{1/2\,\dot{m}\,(V_e^2 - V_i^2)}$$

$$= \frac{2}{V_e / V_0 + V_i / V_0} \tag{6}$$

For a propeller in the freestream $V_i / V_0 = 1.0$ and in the limit of $V_e / V_0 = 1.0$ eq. (6) reveals that for these conditions $\eta_p = 1.0$. In a boundary layer thruster using the airframe boundary layer the intake drag is charged to the airframe by virtue of the frictional process occuring in the boundary layer. In the limit of zero inlet momentum and $V_e / V_0 = 1.0$, it is found that $\eta_p = 2.0$. This value of the propulsive efficiency is achieved considering an ideal intake system with zero losses. The attainment of zero velocity of boundary layer air is possible at the expense of friction. In the case of a flat plate this may be realized in the limit of an infinitely long plate as has been discussed by Pfenninger [17]. In such a case the propulsive efficiency may exceed unity. It is also worth noting that if

$$\eta_{pi} = \frac{\dot{m}\,V_i\,V_0}{1/2\,\dot{m}\,V_i^2} = \frac{2}{V_i / V_0} \tag{7}$$

and

$$\eta_{pe} = \frac{\dot{m}\,V_e\,V_0}{1/2\,\dot{m}\,V_e^2} = \frac{2}{V_e / V_0} \tag{8}$$

then from eq. (6)

$$\eta_p = \frac{2}{2 / \eta_{pe} + 2 / \eta_{pi}} \tag{9}$$

so that for $\eta_p = 1.0$; $\eta_{pe} = \eta_{pi} = 2.0$, for example.

This is the result described on page 16 in appendix B of ref. 16, although not directly in these terms. Equation (9) and the last form of eq. (6) imply that the exit and inlet terms add together, the next to the last form of eq. (6) shows that the inlet term, V_i, subtracts from the thrust and energy input to the engine.

4.4 *Thrust per mass flow rate of air, F / m ,through the propulsor*

One of the distinct advantages of suction from the boundary layer in relation to the freestream is that it provides a larger thrust per pound of ingested flow. Considering the basic thrust equation

$$\frac{\dot{F}}{\dot{m}\,V_0} = \frac{V_e}{V_0} - \frac{V_i}{V_0} \tag{10}$$

for which $V_i / V_0 = 1$, in the limit, for a propeller or a high by-pass ratio fan (propfan), it can be seen from Table 1. that for the same value of V_e / V_0 and in the limit for a boundary layer control system $V_i / V_0 = 0$, the thrust per unit mass of ingested flow for the boundary layer thruster can be many times that of a conventional propeller system or an air-breathing engine.

4.5 *Airframe Maximum Lift-Drag Ratio*

The airplane lift-drag ratio in eq.(5) assumes that the propulsion system and the airframe are separate. This case will be considered initially. For this case

$$\frac{L}{D} = \frac{C_L}{C_{D0} + K\,C_L^2} \tag{11}$$

where the coefficients are based on the wing plan form area; i.e., $C_L = L/q_0S$ where $q_0 = 1/2\ \rho V_0^2$ and $K \equiv 1 / \pi(AR)e$ where AR is the wing aspect ratio and e is the lifting efficiency. The term KC_L^2 is the induced drag coefficient, C_{Di}. The L/D ratio may be maximized for constant K and C_{D0} as follows

$$\frac{d(L/D)}{dC_L} = 0 \tag{12}$$

Here

$$C_{D_i} \equiv K\,C_{L_{opt}}^2 = C_{D0} \tag{13}$$

where

$$C_{L_{opt}} = \sqrt{\frac{C_{D0}}{K}} \tag{14}$$

It is easy to show that

$$(L/D)_{max} = \frac{C_{L_{opt}}}{2\,C_{D0}} = \frac{1}{2}\sqrt{\frac{1}{K\,C_{D0}}} \tag{15}$$

i.e., the maximum lift-drag ratio occurs where the induced drag C_{Di} equals the drag at zero lift or the parasite drag, C_{D0}.

4.6 *Maximizing the Range by integrating the propulsion system with the airframe*

The conventional airplane or reference airplane A has a common propulsion system which overcomes the parasite drag and the induced drag and is completely separate from the airframe. The non-conventional airplane, airplane C, has separate thrusters for the boundary layer and induced drag systems. In current practice the range is maximized by maximizing the L/D ratio and the propulsive efficiency independently . It will be shown however, that the use of an integrated system results in a smaller value of the lift coefficient which implies that the airplane altitude is considerably reduced. The inherent advantage in flying at a higher altitude is an increase in the thermal efficiency of the air-breathing engine; however, flying at lower altitude results in an increase in the inlet flow rate to both the boundary layer thruster and the air-breathing engine for the same corrected flow rate and the same 'match' point (see [17]).

The net thrust produced by airplane C is given by

$$F_c = \dot{m}_c (V_e - V_0) + \dot{m}_{bl} V_e \tag{16}$$

and the power P_c of this aircraft is

$$P_c = 1/2\dot{m}_c (V_e^2 - V_0^2) + 1/2\dot{m}_{bl} V_e^2 \tag{17}$$

In the subsequent analysis it is assumed that the thrust provided by the main engine overcomes the induced drag while that provided by the boundary layer thruster overcomes the parasitic drag. The propulsive efficiency for this system may be written as

$$\eta_p = \frac{\text{useful energy out}}{\text{jet energy in}} = \frac{D\,V_0}{\dfrac{D_0 V_0}{\eta_{pbl}} + \dfrac{D_i V_0}{\eta_{pi}}} = \frac{C_{D0} + K C_L^2}{\dfrac{C_{D0}}{\eta_{pbl}} + \dfrac{K C_L^2}{\eta_{pi}}} \tag{18}$$

From the above equation and the range equation, eq. (5),

$$R \approx \text{const.}\ \eta_p \frac{L}{D} = \frac{C_{D0} + K C_L^2}{\dfrac{C_{D0}}{\eta_{pbl}} + \dfrac{K C_L^2}{\eta_{pi}}} \frac{C_L}{C_{D0} + K C_L^2}\ \text{const.} = \frac{C_L}{\dfrac{C_{D0}}{\eta_{pbl}} + \dfrac{C_{Di}}{\eta_{pi}}}\ \text{const.} \tag{19}$$

The optimum lift coefficient, the value that maximizes the product of η_p L/D is found from

$$\frac{d(\eta_p L/D)}{dC_L} = 0 \tag{20}$$

where the resulting lift coefficient is

$$C_{L_{opt}} = \sqrt{\frac{C_{D_0}}{K} \frac{\eta_{pi}}{\eta_{bl}}} \tag{21}$$

Thus the ratio of the range of the non-conventional airplane to the conventional airplane is

$$\frac{R}{R_A} = \sqrt{\frac{\eta_{pbl}}{\eta_{pi}}} \tag{22}$$

which for $(V_e/V_0)_{bl} = 1.0$, $(V_e/V_0)_i = 1.25$, $\eta_{pbl} = 2.0$ and $\eta_{pi} = 0.89$ the range ratio is 1.5.

From the preceding analysis and subject to the underlying assumptions it is seen that the range of the non-conventional aircraft employing a boundary layer thruster is approximately 50% greater than that of the conventional. It is estimated that for a parasite drag coefficient of 0.015 the change in altitude is about 9,000 ft. for a conventional aircraft flying at 40,000 ft. with a wing aspect ratio of 7.0 and a lifting efficiency factor of 0.92.

The preceding analysis was performed without recourse to the flow pattern over the aircraft surfaces; the presumption being made that the boundary layer was turbulent and that it remained unchanged for the case of the non-conventional aircraft. The main purpose of bleeding the boundary layer off the airframe is to convert it to a laminar layer. This conversion results in a considerable reduction in the friction coefficient as may be seen from figs. 10 and 11 for the flow over a flat plate (see [4]). At a Reynolds number of Re = 10^7 the boundary layer is usually turbulent and the ratio of the turbulent skin friction coefficient to the laminar one is 8 : 1. If suction is applied such that the friction coefficient with boundary layer suction is twice the laminar value with no suction, the ratio of maximum L/D for the bleed case to the non-bleed case is 2.0 from eq. (15). The ratio of the corresponding lift coefficients becomes 1/2 which would indicate an optimum cruise altitude of 16,000 ft. lower than for the conventional aircraft with a turbulent boundary layer for the same wing loading W/S.

5. Conclusion

A brief study on the use of suction air and the associated propulsive benefits has been made. It has been shown that the intake mass flow from the boundary layer offers more thrust per pound of ingested air than the freestream. In particular, it was shown that in the re-acceleration of boundary layer air to freestream velocity the concept of a propulsive efficiency greater than one is not far-fetched. It has also been demonstrated that the propulsion of boundary layer air via an auxiliary propulsor entails a different perspective of the *Brequet* range equation; specifically, one that deals with an integrated system and which incorporates the propulsive efficiency of the thruster and the lift-drag ratio in determining the aircraft range at subsonic speeds. With this view in mind, the possibility of flying at lower altitudes to attain the desired range is realized.

Bibliography

1. Bushnell D. M., " Turbulent Drag Reduction for External Flows," AIAA 83-0227, Presented at the 21st Aerospace Sciences Meeting, Reno Nevada; January 10-13, 1983.

2. Eisenberg J. D., " Boundary Layer Ingestion," NASA Lewis Research Center Internal Memorandum, March 12, 1976.

3. Shrenk O., " Experiments with a Wing Model from which the Boundary is Removed by Suction," N.A.C.A . TM. NO. 534, June 1928.

4. Shrenk O., " Boundary Layer Removal by Suction," N.A.C.A. TM NO.974, Dec. 1940.

5. Smith A.M.O. and Roberts E. Howard, " The Jet Airplane Utilizing Boundary Layer Air for Propulsion," Journal of the Aeronautical Sciences, Feb. 1947.

6. Schlichting H. Boundary Layer Theory, Seventh Edition; McGraw-Hill, NewYork 1987.

7. Iglish R., " Exact Calculation of Laminar Boundary Layer in Longitudinal Flow Over a Flat Plate with Homogeneous Suction," N.A.C.A. TM NO. 1205, 1940.

8. Pfenninger W., " Experiments on a Laminar Suction Airfoil of 17 Percent Thickness," Journal of the Aeronautical Sciences, pp. 227-236; April 1949.

9. Boeing Commercial Airplane Company, " Hybrid Laminar Flow Control Study, Final Technical Report, NASA CR-165930, October 1982.

10. Pfenninger W., " Flow Problems of Swept Low-Drag Suction Wings of Practical Construction at High Reynolds Numbers," Annals of the New York Academy of Sciences, vol. 154, Art. 2, pp. 672-703, November 1968.

11. Runyan L. J. and Steers L. L., " Boundary Layer Stability Analysis of a Natural Laminar Flow Glove on the F-111 Tact Airplane," Viscous Flow Drag Reduction,

Progress in Astronautics and Aeronautics," Vol.72; pp. 17-32 edited by G.R. Hough, AIAA 1980.

12. Mack L.M.," Compressible Boundary-Layer Stability Calculations for Sweptback Wings With Suction," AIAA Journal, Vol. 20, No.3, March 1982.

13. Ackeret J., (1938). Probleme des Flugzeugantriebs in Gegenwart und zukunft. *Schweiz, Bauztg. **112**, 1.*

14. Davidson I. M.," Some notes on Aircraft Propulsion by Wake Regeneration," *Annals of The New York Academy of Sciences, vol. 154, Art. 2, pp. 641-651*, November 22, 1968.

15. Brooks C. W. Jr., Harris D. C., and Harvey W. D., " The NASA Langley Laminar-Flow-Control Experiment on a Swept, Supercritical Airfoil," NASA T.M. 4096. March 1989.

16. Conners J. W., Pfenninger W., and Smith C.B., " Propulsion Systems for Laminar Flow Aircraft," IAS Paper No. 61-52; Presented at the IAS 29th Annual Meeting, New York, New York; January 23-25,1961.

17. Bathie W. W., *Fundamental of Gas Turbines*, John Wiley & Sons, New York 1984.

18. Mack L. M. Boundary-Layer Linear Stability Theory. AGARD Rep. No. 709 (Special Course on Stability and Transition of Laminar Flows), Von Karman Inst., Rhode-St.-Genese, Belg. 1984.

19. W. M. Douglass., " Propulsive Efficiency with Boundary Layer Ingestion," Report Number MDC J0860, IRAD Line Item Description No. D11-70-107, Douglas Aircraft Company; August 21, 1970.

20. T. G. Lang., " Torpedo Drag Reduction," DEFENSE TECHNICAL INF., NAVORD Report 6451, May 1959.

21. P. M. H. W. Vigjen., S. S. Dodbele., B. J. Holmes., and C. P. van Dam., " Effects of Compressibility on Design of Subsonic Fuselages for Natural Laminar Flow," *Journal of Aircraft*, vol. 25, No. 9, September 1988.

22. W. D. Harvey.," Boundary Layer Control for Drag Reduction," International Pacific Air & Space Technology Conference Melbourne, Australia , November 13-17, 1987.

23. J. E. Linden and F. J. O'Brimski., " Some Procedures for Use in Performance Prediction of Proposed Aircraft Designs," Society of Automotive Engineers Paper No. 650800, National Aeronautic and Space Engineering and Mabufacturing Meeting, Los Angeles, Calif. October 4-8, 1965.

Appendix A

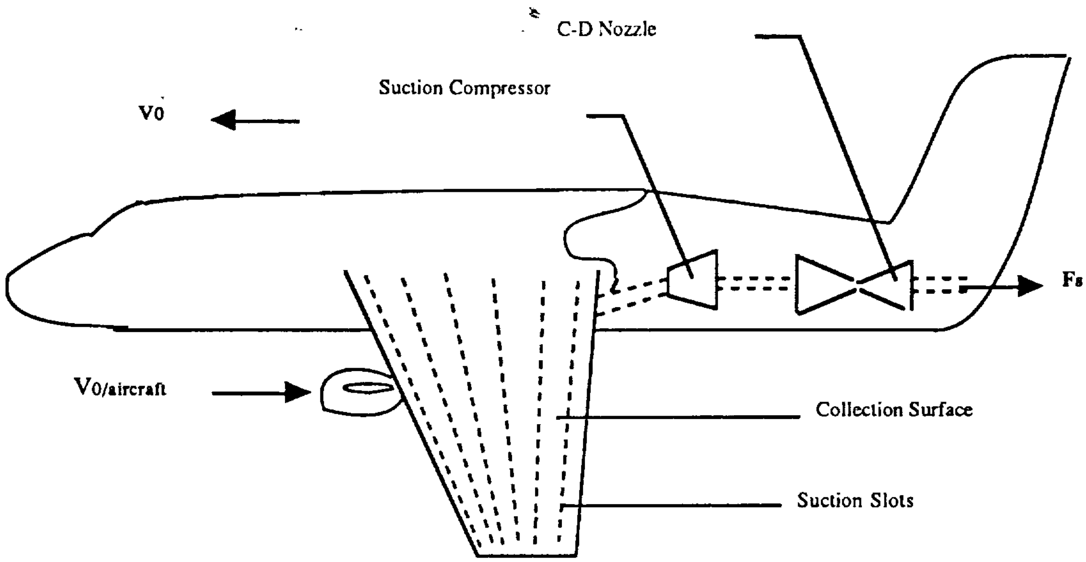


Figure A.1 - Schematic of Auxiliary Propulsion System

A-1 Derivation of the Payload equation

The payload equation of a propulsive system may be derived as follows , this is done for a conventional aircraft, i.e. an aircraft not employing a boundary layer thruster, for an airplane at cruise.

The range equation may be written in alternative form as

$$x = 863.5 \frac{\eta}{c} \frac{c_L}{c_d} \log_{10}\left(\frac{w_1}{w_2}\right) \qquad \text{(miles)} \tag{A.1}$$

The initial overall weight of the aircraft at takeoff, w_1, is composed of the weight of fuel, w_f, the structural weight, w_{st}, and payload weight, w_L,

$$w_1 = w_f + w_{st} + w_L \tag{A.2}$$

Let us initially consider that the takeoff weight is equivalent to the cruise weight at a certain altitude at zero range (this is not entirely correct and varies with the type of aircraft and its takeoff speed.)*

Substituting the expression for the payload into the range equation,

$$\frac{c\,x}{863.5\,\eta\,\frac{c_L}{c_d}} = \log_{10}\left[\frac{1+\frac{w_{st}}{w_f}+\frac{w_L}{w_f}}{\frac{w_{st}}{w_f}+\frac{w_L}{w_f}}\right] \tag{A.3}$$

$$10^{\frac{c\,x}{863.5\,\eta\,\frac{c_L}{c_d}}} = \frac{1+\frac{w_{st}}{w_f}+\frac{w_L}{w_f}}{\frac{w_{st}}{w_f}+\frac{w_L}{w_f}}$$

$$\frac{w_L}{w_f}\left[10^{\frac{c\,x}{863.5\,\eta\,\frac{c_L}{c_d}}} - 1\right] = 1 + \frac{w_{st}}{w_f}\left[1 - 10^{\frac{c\,x}{863.5\,\eta\,\frac{c_L}{c_d}}}\right] \tag{A.4}$$

$$\frac{w_L}{w_f} = \frac{1}{\left[10^{\frac{c\,x}{863.5\,\eta\,\frac{c_L}{c_d}}} - 1\right]} - \frac{w_{st}}{w_f}$$

The payload to overall initial mass ratio is given as

$$\frac{w_L}{w_1} = \frac{\frac{w_L}{w_f}}{1 + w_L/w_f + w_{st}/w_f}$$

Now let

$$[\,c\,/\,863.5\,\eta\,\tfrac{c_L}{c_d}\,] = \beta$$

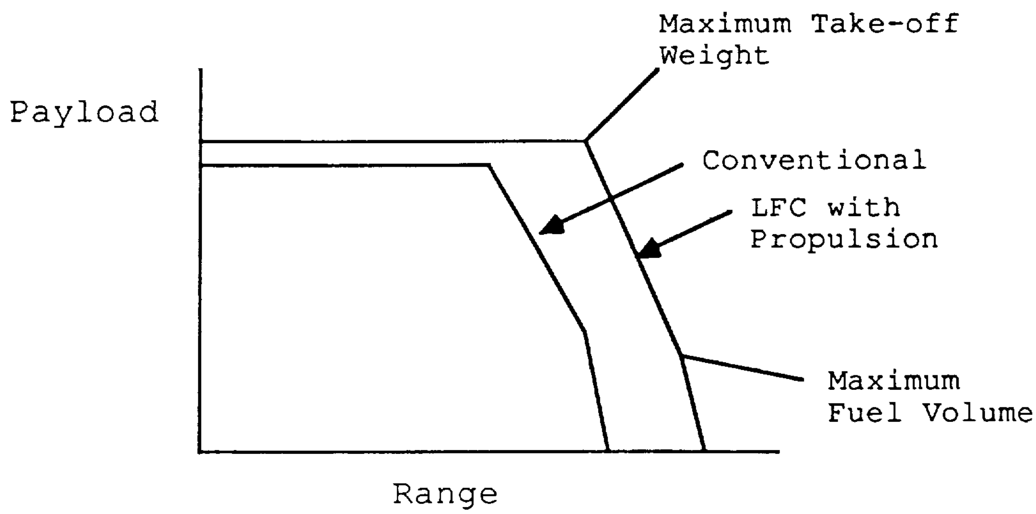
then

$$\frac{w_L}{w_1} = \frac{(1 + w_{st}/w_f)}{10^{\beta x}} - \frac{w_{st}}{w_f} \tag{A.5}$$

---

* Note that if we were considering a non-conventional aircraft the weight of the suction system-thruster configuration must be included as part of the structural mass of the aircraft. The lubricating oil is included in the total fuel consumption.

The ratio $w_L/w_1 = 1$ represents the total weight at zero range (or take-off weight). The diagram shown below is a typical payload-range diagram of aircraft capability. The diagonal range line is limited either by maximum takeoff weight or by the fuel capacity of the aircraft.The outer curve represents the projected curve for the non-conventional aircraft employing laminar flow control with propulsion and the possibility of maximizing the payload capability over any given range of the aircraft. A lower value of the parameter β indicates an increase in the payload as suggested by equation (3).



A-2.1 The propulsive efficiency

η in the above expression is the propulsive efficiency of the entire propulsive device. If we have an aircraft powered by a single engine then η is the propulsive efficiency of that engine. Now suppose we have the same aircraft equipped with a boundary layer thruster (a nonconventional engine) and an air-breathing engine(a conventional engine) what would be the net propulsive efficiency?

First, let us consider an aircraft with two <u>conventional</u> engines, the propulsive efficiency is given by

$$\eta_p = \frac{P_T}{P_e} = \frac{\text{total thrust power}}{\text{total power output of engine(s)}}$$

$$P_T = (F_1 + F_2)\, U \quad , \quad P_e = P_T + (K.E)_c$$

Let us suppose that the two engines have different jet velocities,

$$(K.E)_e = (K.E)_{e1} + (K.E)_{e2}$$

where

$$(K.E)_{e1} = \frac{\dot{m}_{a1}}{2}(1 + f_1)\, v_{e1}^2 = \frac{\dot{m}_{a1}}{2}(1 + f_1)(v_{j1} - U)^2$$

$$(K.E)_{e2} = \frac{\dot{m}_{a2}}{2}(1 + f_2)\, v_{e2}^2 = \frac{\dot{m}_{a2}}{2}(1 + f_2)(v_{j2} - U)^2$$

or we can obtain η_p directly from the ratio of useful output over input and neglecting the fuel-air ratios

$$\eta_p = \frac{\dot{m}_{a1}(v_{j1} - U)\, U + \dot{m}_{a2}(v_{j2} - U)\, U}{\dot{m}_{a1}(v_{j1}^2 - U^2)/2 + \dot{m}_{a2}(v_{j2}^2 - U^2)/2}$$

The above analysis, however, is done with undue regard to the airframe aerodynamics. In other words, what effect do two jets emanating at different velocities have on the drag. Another question in connection with the airframe is how would the engines be mounted such that we have two different mass flow rates issuing into the engines.

One question in connection with the term efficiency is this: In dealing with the boundary layer thruster can we speak of both a thermal efficiency and a propulsive efficiency of the boundary layer thruster? We may answer this question in the following manner:

If we are looking at an air-breathing engine we may define both a thermal and a propulsive efficiency. The thermal efficiency as a result of the diffuser or inlet - compressor-burner or combustion chamber - turbine - configuration, and the propulsive efficiency if a propulsive device is attached to this main section. The boundary layer thruster on the other hand is a propulsive device and can only possess a propulsive efficiency.

The thermal efficiency of a device is defined by the work done over the net quantity of heat added. This parameter cannot apply to a boundary layer thruster since there is no net heat added (the entire process may be considered adiabatic) and the work may or may not exist depending on the particular thrusting device employed. If the device is an accelerating device such as a nozzle the net work done is zero. On the other hand for a suction compressor the net work done is not zero.

A-2.2 On the total drag or total thrust

When dealing with the total drag of an aircraft why are we concerned with drag values of the components of the entire aircraft? One major contribution of boundary layer suction is the considerable reduction of drag over that of a conventional aircraft; as such, an accurate prediction of drag is important for estimating the benefits of boundary layer suction. Let us first consider the estimation of drag of a conventional aircraft fitted with a single engine.

(i) method A (direct approach):

Suppose we have an aircraft fitted with a single engine traveling at certain altitude with a given speed. With these values we can determine by a thermodynamic analysis of the engine cycle the thrust generated. A question at this point is how are we sure that the thrust generated is the correct thrust needed to propel the airplane at the given speed? If we can determine the necessary thrust then we know that this is the total reaction of the air upon the aircraft.

(ii) method B (indirect approach):

This approach relies on determining the drag directly from knowledge of the drag values of the components of the aircraft

If we consider the use of a boundary layer thruster in conjunction with the air-breathing engine, then for suction over the wing the entire wing drag (neglecting compressibility effects) is the sum of wake drag,suction drag and induced drag. This must be less than the profile drag of an unsucked wing of the same planform to justify the use of suction. The maximum lift varies considerably with suction since for suction over the top surface of the wing the flow is accelerated with the consequent reduction of pressure over that surface.

Appendix B

B-1. Thermodynamic relations used in modeling the operation of the boundary layer thrusting device.

The following section deals with the governing equations used in modeling the boundary layer thruster based on the simplified schematics shown below. The process of the deceleration of air from freestream conditions to the boundary layer edge is considered to be an isentropic process. The collection surface may be taken as a flat plate with equality of the static pressure at the surface with the local pressure at the boundary layer edge. process 1-2 from the collection surface to the entrance of the suction compressor inlet is considered to be an adiabatic process with input of approporiate pressure drop values into the computer program. The compression process is also taken as adiabatic. The relevant equations appropriate to the individual processes are given below.

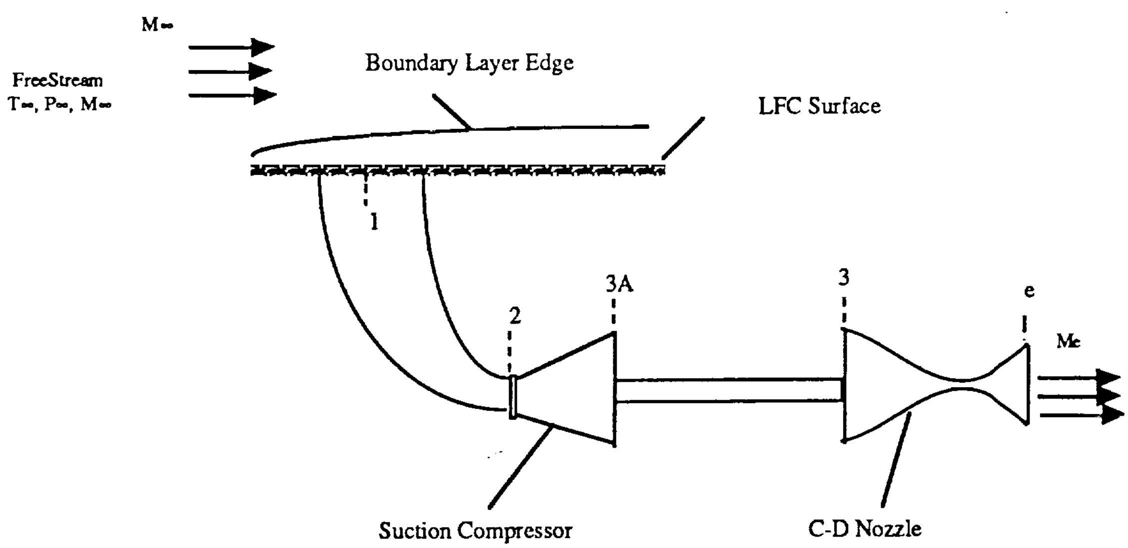


Figure B.1 - Schematic of Boundary Layer Thrusting Device

a. *Isentropic flow of air from freestream condtions to local values at the boundary layer edge.*

Certain conventional defintions are given below :

$$M_\infty = \frac{V_\infty}{a_\infty} = \frac{V_\infty}{\sqrt{\gamma R T_\infty}} \tag{B.1}$$

$$h_{T\infty} = h_\infty + \frac{V_\infty^2}{2}$$

$$C_p T_{T\infty} = C_p T_\infty + \frac{M_\infty^2}{2} \gamma R T_\infty$$

$$\frac{T_{T\infty}}{T_\infty} = 1 + \frac{\gamma - 1}{2} M_\infty^2 \tag{B.2}$$

for an isentropic process $Pv^\gamma =$ constant, therefore

$$\frac{P_{T\infty}}{P_\infty} = \left(\frac{T_{T\infty}}{T_\infty}\right)^{\frac{\gamma}{\gamma - 1}} \tag{B.3}$$

by definition the dimensionless pressure coefficient is given by

$$C_p = \frac{p - p_\infty}{1/2\, \rho_\infty V_\infty^2}$$

the local pressure is P_1 and

$$C_{p1} = \frac{p_1 - p_\infty}{1/2\, \rho_\infty V_\infty^2}$$

from which follows that

$$\frac{p_1}{p_\infty} = 1 + C_{p1} \frac{M_\infty^2}{2} \gamma \tag{B.4}$$

The magnitude of the adiabatic wall temperature T_{aw} relative to the one-dimensional mean values of the static temperature T and the stagnation temperature T_0 is expressed by the recovery factor R_f, where

$$R_f = \frac{T_{aw} - T}{T_0 - T}$$

The average stagnation temperature in the external flow is taken as the freestream total temperature. The assumption is made that the total pressure of the flow at station 1 (the LFC surface) is the same as the external static pressure i.e.; $P_{T1} = P_1$. The local temperature and pressure values at the boundary layer edge are related by the following equation

$$T_{local} = T_\infty \left(\frac{p_{local}}{P_\infty}\right)^{\frac{\gamma - 1}{\gamma}} = T_\infty \left(\frac{p_{T1}}{p_\infty}\right)^{\frac{\gamma - 1}{\gamma}}$$

b. *adiabatic process in suction duct : process 1-2*

The adiabatic wall temperature is taken as the stagnation temperature at the LFC surface $T_{aw} = T_{T1}$ and since process 1-2 is adiabatic, $T_{aw} = T_{T1} = T_{T2}$. Using the definition of the recovery factor given above, the expression for the total temperature at the entrance to the compressor T_{T2} may be found as follows.

$$\left(T_{T\infty} - T_{local}\right) R_f = T_{T2} - T_{local}$$

$$T_{T2} = T_{local} + \left(T_{T\infty} - T_{local}\right) \sqrt{Pr}$$

where for a laminar boundary layer the Prandtl number is approximately 0.7.

$$\begin{aligned}
T_{T2} &= T_\infty \left(\frac{p_1}{p_\infty}\right)^{\frac{\gamma-1}{\gamma}} + \sqrt{Pr}\left(T_{T\infty} - T_\infty \left(\frac{p_1}{p_\infty}\right)^{\frac{\gamma-1}{\gamma}}\right) \\
&= T_\infty \left(\frac{p_1}{p_\infty}\right)^{\frac{\gamma-1}{\gamma}} + \sqrt{Pr}\, T_{T\infty} - T_\infty \sqrt{Pr}\left(\frac{p_1}{p_\infty}\right)^{\frac{\gamma-1}{\gamma}} \\
&= T_\infty \left(1 - \sqrt{Pr}\right)\left(\frac{p_1}{p_\infty}\right)^{\frac{\gamma-1}{\gamma}} + T_\infty \sqrt{Pr}\,\frac{T_{T\infty}}{T_\infty} \\
&= T_\infty \left[\left(1 - \sqrt{Pr}\right)\left(\frac{p_1}{p_\infty}\right)^{\frac{\gamma-1}{\gamma}} + \sqrt{Pr}\,\frac{T_{T\infty}}{T_\infty}\right]
\end{aligned} \tag{B.5}$$

The relative pressure loss between the collection surface and the inlet to the compressor is

$$\frac{p_{T1} - p_{T2}}{p_{T1}} = \frac{p_1 - p_{T2}}{p_1}$$

$$\frac{p_{T2}}{p_\infty} = \frac{p_1}{p_\infty}\left(1 - \frac{\left(p_1 - p_{T2}\right)}{p_1}\right) \tag{B.6}$$

c. *adiabatic compression process across suction compressor : process 2-3A*

This process may be represented on the h,T- s diagram with the isentropic path shown as 2-3A'.

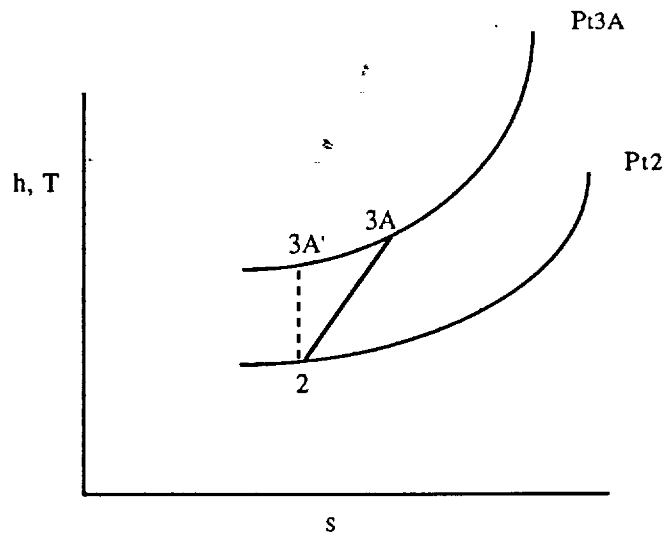


Figure B.2 - Compression Path of suction flow air across adiabatic compressor.

The adiabatic compressor efficiency is defined as,

$$\eta_c = \frac{h_{T3A'} - h_{T2}}{h_{T3A} - h_{T2}} = T_{T2}\left(\frac{T_{3A'}/T_{T2} - 1}{T_{T3A} - T_{T2}}\right)$$

rearranging,

$$T_{T3A} = T_{T2}\left[\frac{1}{\eta_c}(T_{3A'}/T_{T2} - 1) + 1\right] \tag{B.7}$$

but

$$\frac{T_{T3A'}}{T_{T2}} = \left(\frac{p_{T3A'}}{p_{T2}}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{p_{T3A}}{p_{T2}}\right)^{\frac{\gamma-1}{\gamma}}$$

therefore,

$$T_{T3A} = T_{T2}\left[\left(\frac{1}{\eta_c}\left(\left(\frac{p_{T3A}}{p_{T2}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right) + 1\right)\right] \tag{B.8}$$

The steady flow energy equation per unit mass is given by,

$$h_2 + \frac{V_2^2}{2} + gz_2 \pm q_{ext} + w_c = h_{3A} + \frac{V_{3A}^2}{2} + gz_{3A} \tag{B.9}$$

where q_{ext} is the external heat loss or gain per unit mass of air flow into the suction compressor, and w_c is the work added to the system per unit mass flow of air. Neglecting potential energy changes and since the process is adiabatic the above equation becomes

$$h_2 + \frac{V_2^2}{2} + w_c = h_{3A} + \frac{V_{3A}^2}{2}$$

$$h_{T2} + w_c = h_{T3A}$$

substituting for T_{T3A}, w_c is given by

$$w_c = c_p\, T_{T2} \frac{1}{\eta_c}\left[\left(\frac{p_{T3A}}{p_{T2}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{B.10}$$

d. *process 3A - 3 :* The air flow form the exit of the suction compressor to the entrance to the C-D nozzle is considered to be adiabatic. The total pressure loss $P_{T3A} - P_{T3} / P_{T3A}$ is taken as an input into the code.

e. *process 3-e :* The nozzle expansion process may be represented on the h-s diagram as shown in figure 3.C.

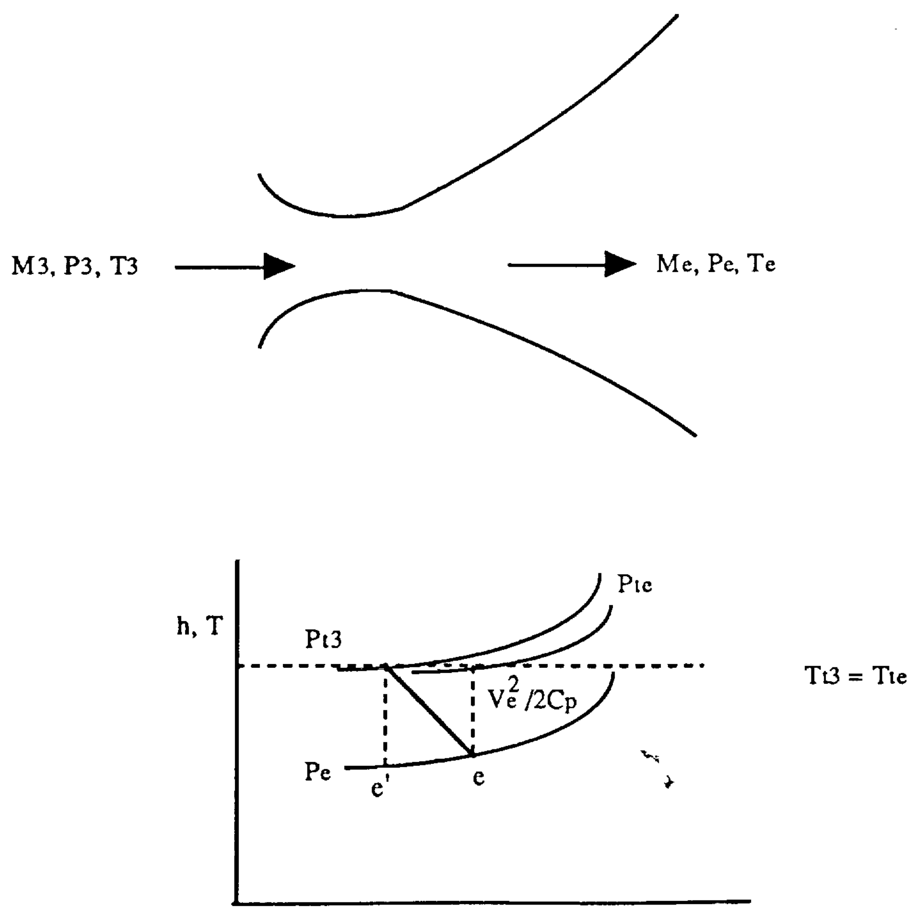


Figure B.3 - Expansion Process Through C-D Nozzle

The adiabatic nozzle efficiency is defined as

$$\eta_n = \frac{h_{T3} - h_e}{h_{T3} - h_{e'}} = \frac{c_p (T_{T3} - T_e)}{T_{T3} - T_{e'}} \tag{B.11}$$

where,

$$T_{T3} - T_e = \frac{V_e^2}{2\, c_p}$$

therefore,

$$\eta_n = \frac{V_e^2 / 2\, c_p}{T_{T3} - T_{e'}} = \frac{V_e^2 / 2\, c_p}{(1 - T_{e'} / T_{T3})\, T_{T3}}$$

but,

$$\frac{T_{e'}}{T_{T3}} = \left(\frac{p_{e'}}{p_{T3}}\right)^{\frac{\gamma-1}{\gamma}}$$

here $P_{Te}' = P_e = P_\infty$ and the expression for the exit velocity becomes,

$$V_e = \sqrt{2\, c_p\, \eta_n\, T_{T3} \left(1 - \left(\frac{p_\infty}{p_{T3}}\right)^{\frac{\gamma-1}{\gamma}}\right)} \tag{B.12}$$

the ratio of the nozzle thrust power to the compression power is given by $V_e\, V_\infty / w_c$. The Mach number in terms of the exit temperature is given by $M_e = V_e / (\gamma R T_e)^{1/2}$. The exit nozzle area may be found as follows.

$$\frac{\dot{m}}{A} = \rho V = p\, V / R\, T = \frac{p}{\sqrt{\gamma R T}} \sqrt{\frac{\gamma}{R}} \sqrt{\frac{T_0}{T}} \frac{1}{\sqrt{T_0}}$$

$$= \sqrt{\frac{\gamma}{R}} \frac{p}{\sqrt{T_0}} M \sqrt{1 + \frac{\gamma - 1}{2} M^2} \tag{B.13}$$

p may be eliminated using

$$\frac{p_0}{p} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

therefore,

$$\frac{\dot{m}}{A} = \sqrt{\frac{\gamma}{R}} \frac{p_0}{\sqrt{T_0}} \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{-\gamma}{\gamma - 1}} \left(1 + \frac{\gamma - 1}{2} M^2\right)^{1/2} M$$

$$= \sqrt{\frac{\gamma}{R}} \frac{p_0}{\sqrt{T_0}} \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{-\gamma}{\gamma - 1} + 1/2} M$$

$$= \sqrt{\frac{\gamma}{R}} \frac{p_0}{\sqrt{T_0}} \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{-(\gamma + 1)}{2(\gamma - 1)}} M$$

$$= \sqrt{\frac{\gamma}{R}}\frac{p_0}{\sqrt{T_0}}\frac{M}{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{(\gamma+1)}{2(\gamma-1)}}}$$

in terms of the exit area and properties at the exit A_e is

$$A_e = \frac{\dot{m}_{air}\sqrt{RT_{T3}}}{P_{Te}\sqrt{\gamma}\,M_e\left(1+\frac{\gamma-1}{2}M_e^2\right)^{\frac{-(\gamma+1)}{2(\gamma-1)}}} \qquad \text{(B.14)}$$

where P_{T_e} is the total pressure at the exit of the nozzle given by,

$$p_{Te} = P_\infty\left(\frac{T_{T3}}{T_e}\right)^{\frac{\gamma}{\gamma-1}}$$

The numerical code implementing the above equations is given Appendix C together with the numerical values obtained for the input parameters given below. Figures B.4 and B.5 are the performance plots of the boundary layer thrusting device based on these numerical values. The ideal curve, curve A of Figure B.4, represents a zero total pressure drop in the duct leading from the LFC surface to the inlet of the suction compressor and for that leading from the exit plane of the compressor to the inlet plane of the C-D nozzle with ideal efficiencies of 1 for the compressor and the nozzle. Curve B represents a zero drop in total pressure with efficiencies of 0.8 and 0.98 for the compressor and nozzle respectively. It is seen that the ideal curve models very closely eq. (6) with $V_i = 0$. Figure B.5 shows that the optimum value of the exit velocity is the freestream value for the lowest coefficient of incremental drag as derived in the following section.

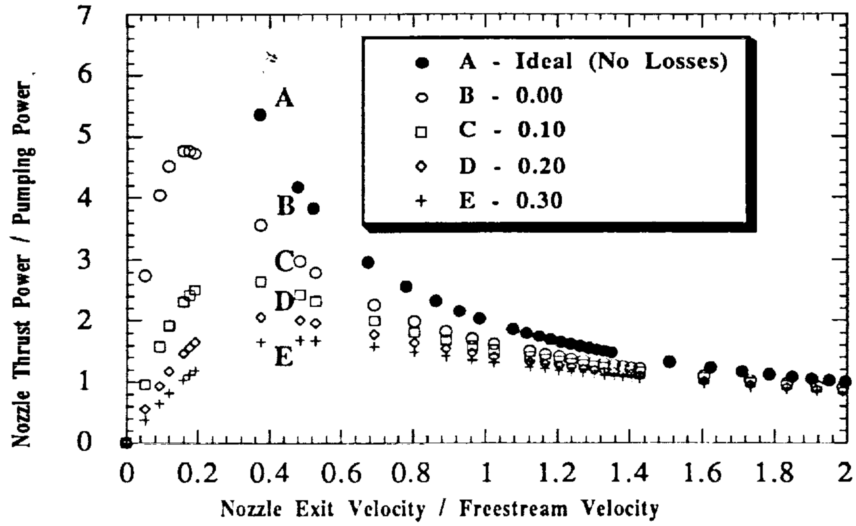


Fig. B.4 - Thermodynamic Performance of LFC Pumping System

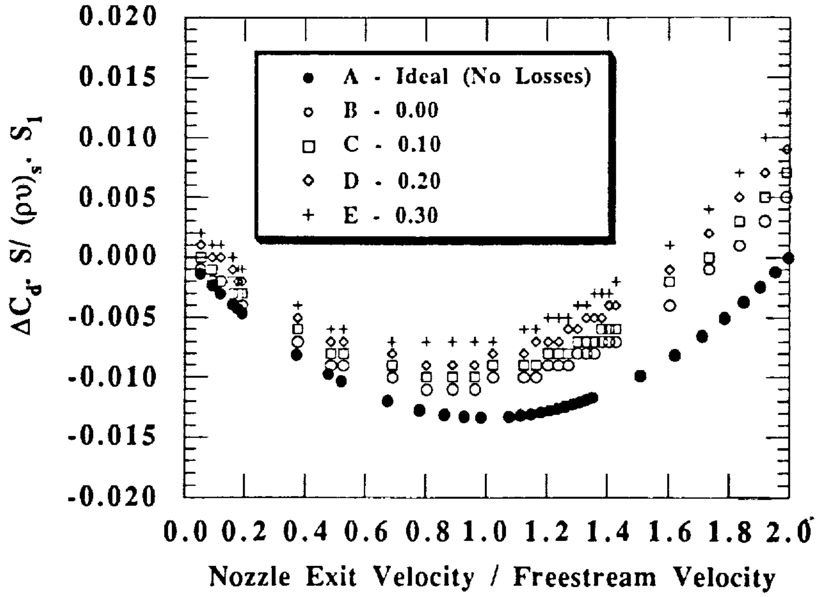


Fig. B. 5 - variation of incremental drag per suction flow rate per suction area ratio

The input flow parameters representing the non-ideal cases are as follows:

$M_\infty = 2.2$

$T_\infty = 216.65$ K at 60,000 ft.

$\rho_\infty = 0.11532$ kg/m^3

$c_{p1} = 0.0$

$C_p = 1011.5$ kJ/ kg. k

$R_f = 0.7$

$\eta_n = 0.98$

$\eta_c = 0.8$

$R = 287$ kJ/kg. k

$\gamma = 1.4$

PSFC = 0.3308 lbm / hr - hp

TSFC = 1.28 lbm / hr - lbf

$$\frac{p_{T3A} - p_{T3}}{p_{T3A}} = 0.05$$

$$\frac{p_1 - p_{T2}}{p_1} = 0.00\ ,\ 0.10\ ,\ 0.20\ ,\ 0.30$$

C.2 - *On the minimization of overall fuel flow.*

The total amount of fuel required for the operation of an air vehicle coupled with a single (or multiple) conventional air-breathing engine and a boundary layer thruster is the sum of of the fuel flow required by the air-breathing engine plus the additional fuel required to provide auxiliary shaft power to the LFC compressor,

$$(\dot{m}_f)_{total} = (\dot{m}_f)_{main\ engine} + (\dot{m}_f)_{LFC\ pump}$$

By definition, the thrust - specific - fuel consumption TSFC is

$$TSFC = \frac{(\dot{m}_f)_{main\ engine}}{\tau}$$

where $\tau_{main\ engine}$ is the thrust provided by the *main engine*

$$\tau_{main\ engine} = \text{total drag} - \tau_{nozzle} = D_{total} - \tau_{nozzle}$$

where τ_{nozzle} is the thrust provided by the LFC thruster. The power-specific-fuel - consumption is given by :

$$PSFC = \frac{(\dot{m}_f)_{LFC\ pump}}{P_{pump}}$$

The pump efficiency η_{ps} is given by

$$\eta_{ps} = \frac{\tau_{nozzle}\, V_\infty}{P_{pump}}$$

$$\therefore \qquad \tau_{nozzle} = \frac{\eta_{ps}\,P_{pump}}{V_\infty}$$

assuming a transmission efficiency of $\eta_{tr} = 1.0$ in the conversion of shaft power from the turbine to the auxiliary compressor, the total fuel flow rate required is,

$$\Rightarrow \qquad (\dot{m}_f)_{total} = TSFC\,(D_{total} - \tau_{nozzle}) + PSFC\,P_{pump}$$

$$= TSFC\,(D_{total} - \tau_{nozzle}) + \frac{PSFC}{TSFC}\,P_{pump} = TSFC(D_{eff.})$$

where the effective drag is given by

$$D_{eff.} = D_{total} - \eta_{ps}\frac{P_{pump}}{V_\infty} + \frac{PSFC}{TSFC}\,P_{pump}$$

By definition the lift coefficient is given by $C_L = 2\,L / \rho_\infty V_\infty S = L / qS$. The effective drag may then be written as

$$C_{Deff.} = \frac{D_{eff.}}{q\,S} = \frac{D_{total} + \left(\frac{PSFC}{TSFC} - \frac{\eta_{ps}}{V_\infty}\right) P_{pump}}{q\,S}$$

The total drag coefficient is $C_{D_{total}} = D_{total} / qS$ therefore,

$$C_{Deff.} = C_{Dtotal} + \left(\frac{PSFC}{TSFC} - \frac{\eta_{ps}}{V_\infty}\right)\frac{P_{pump}}{q\,S}$$

$$\therefore \quad \frac{L}{D_{eff.}} = \frac{C_L\,q\,S}{C_{Deff.}\,q\,S} = \frac{C_L}{C_{Dtotal} + \left(\frac{PSFC}{TSFC}\,V_\infty - \eta_{ps}\right)\frac{P_{pump}}{S\,q\,V_\infty}}$$

the term

$$\left(\frac{PSFC}{TSFC}\,V_\infty - \eta_{ps}\right)\frac{P_{pump}}{S\,q\,V_\infty}$$

is defined as the fuel-equivalent drag increment ΔC_d. The pump power in the above expression P_{pump} is the suction mass flow rate multiplied by the suction compressor work done per unit mass flow rate as provided by eq.(10) above. The results presented for the parameter $\Delta C_d\,S / (\rho\upsilon)_s\,S_1$ are shown in figure B.5, which is the incremental drag as defined above per suction flow rate per suction area ratio, which takes into account the equivalent suction area S_1 and the volume flow rate of ingested boundary layer air.

Appendix C

Figures

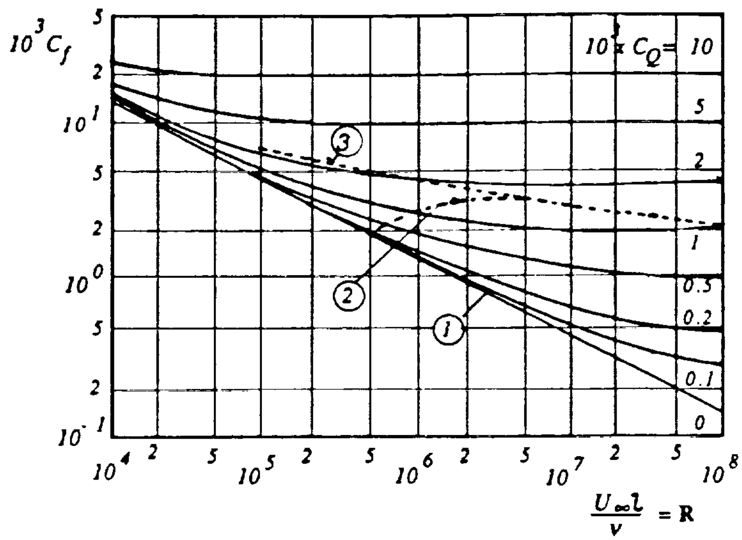


Figure 1. - Drag coefficients for the flat plate at zero incidence with uniform suction.
Curves (1), (2) and (3) refer to no suction
(1) laminar
(2) transition from laminar to turbulent
(3) fully turbulent

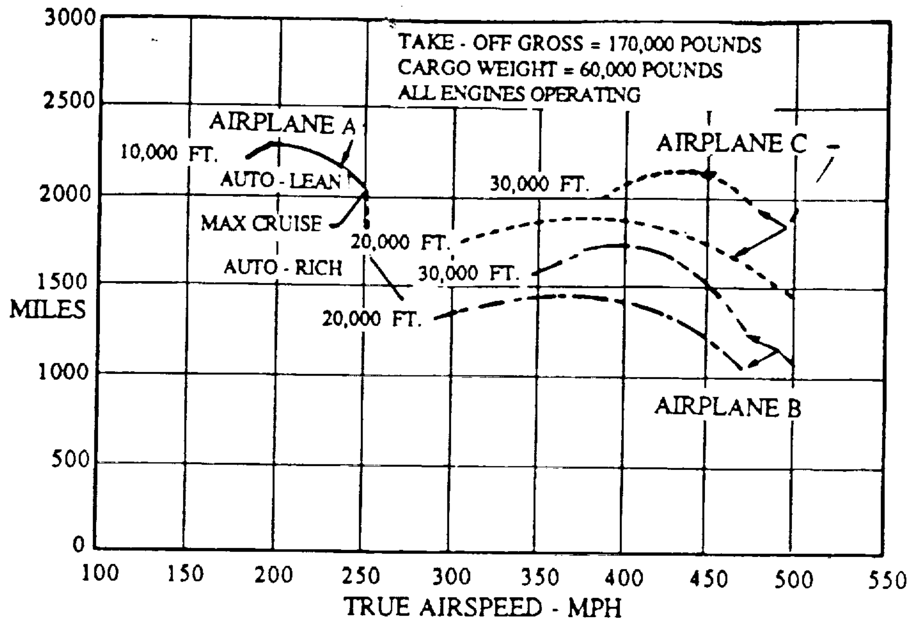


Figure 2. - Comparison of cruising range.

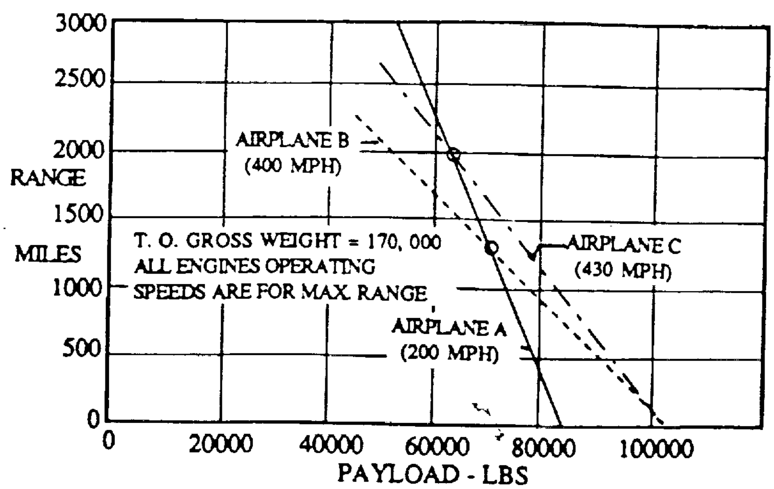


Figure 3. - Comparison of maximum range vs. pay load

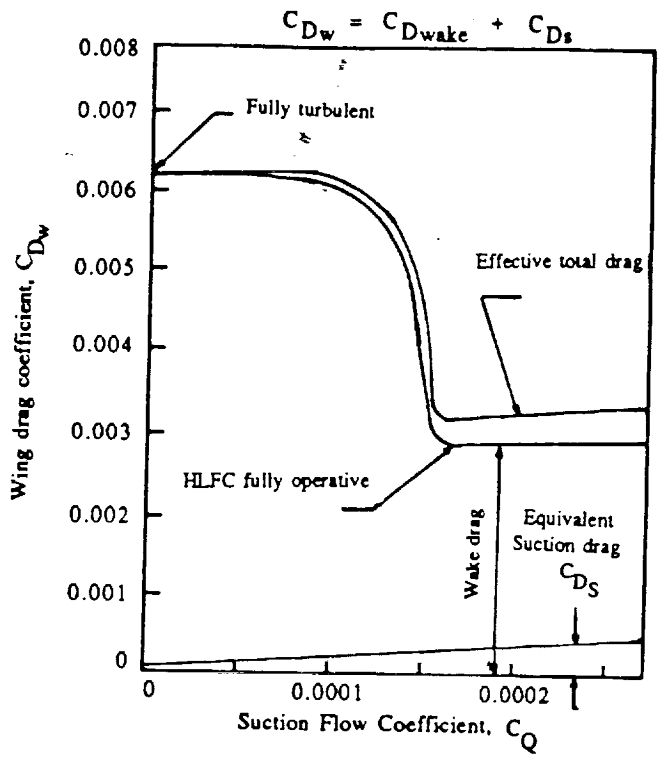


Figure 4. - Components of Wing Profile Drag With HLFC

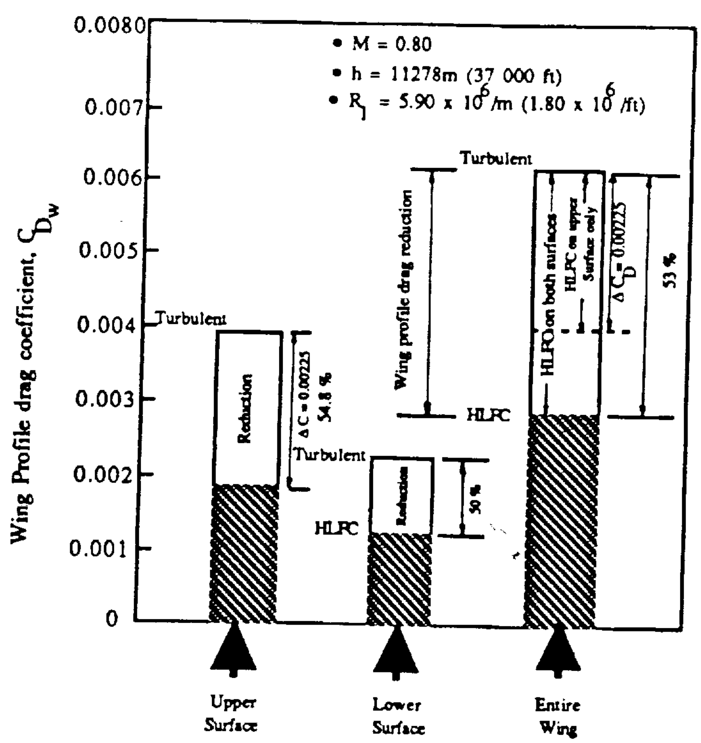


Figure 5. - Effect of HLFC on Wing Profile Drag

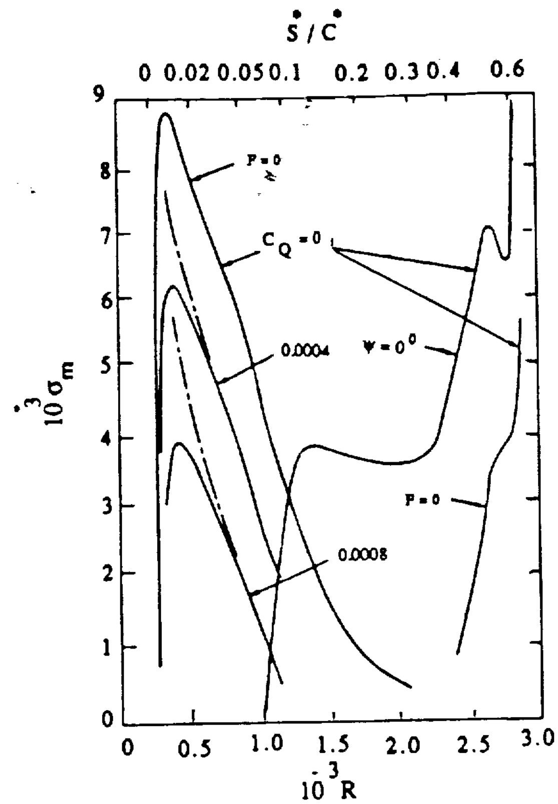


Figure 6. - Distribution of Maximum Spatial Amplification Rate of Disturbances along Wing Chord for a 35 deg Sweep.

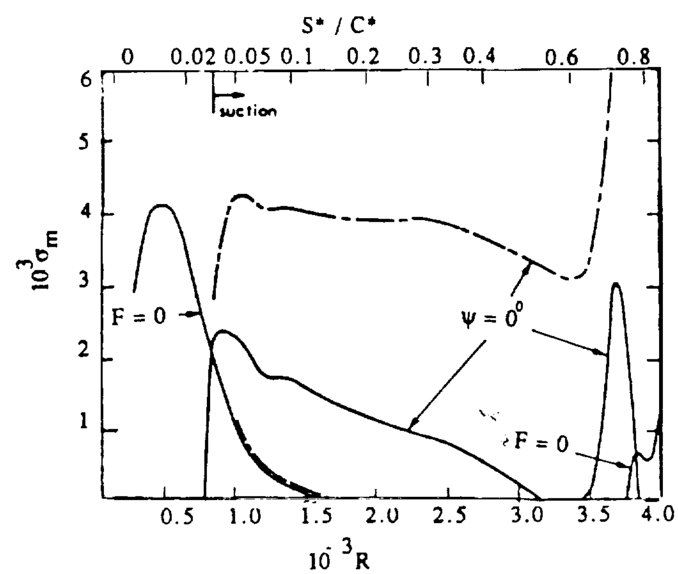


Figure 7. - Maximum Amplification Rate of Stationary (Cross Flow) Waves & Travelling (T--S) Waves for a 23 deg Sweep.

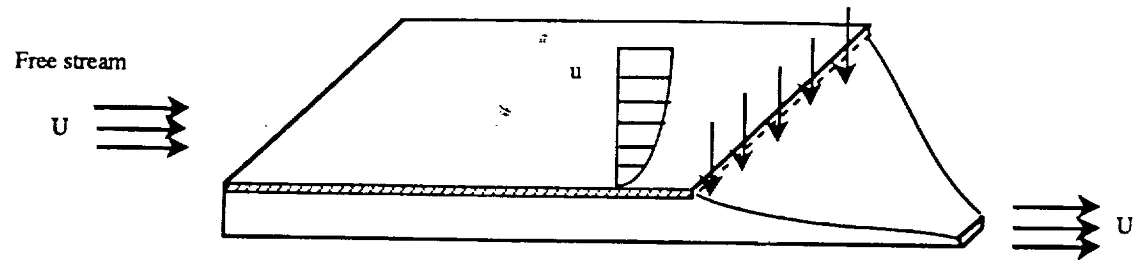


Fig. 8 - Schematic of re-acceleration of ingested flow at the trailing edge of a flat plate to freestream velocity

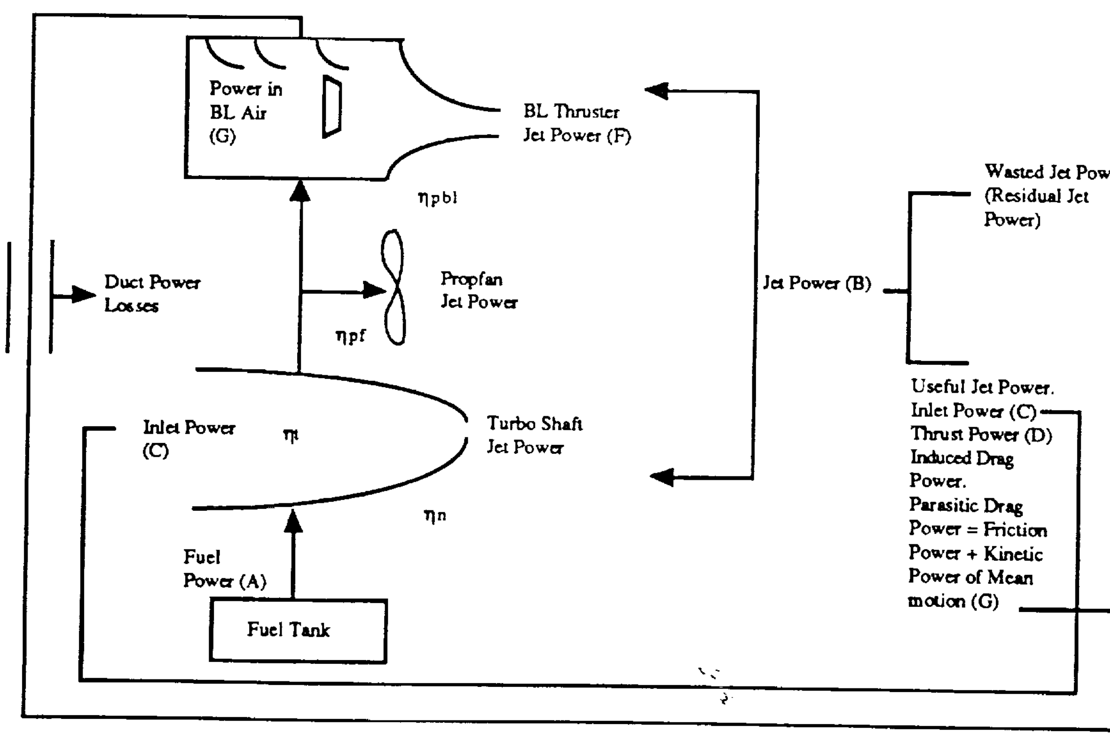


Fig. 9. - Power Flow Diagram for a Jet Airplane Employing a Boundary Layer Thruster.

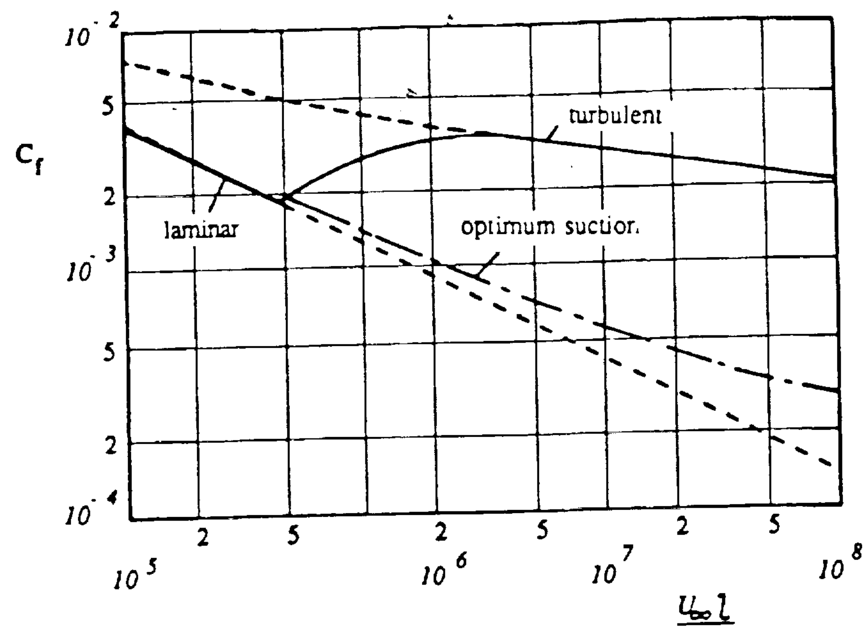


Figure 10. - Coefficient of skin friction of a flat plate at zero incidence. *Optimum suction* denotes smallest volume coefficient required to maintain laminar flow.

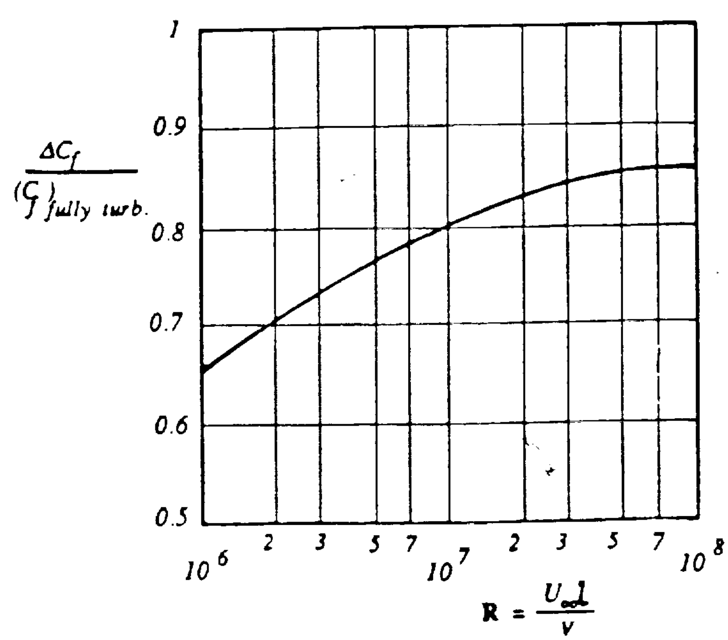


Figure 11. - Relative saving in drag on flat plate at zero incidence with suction maintaining laminar flow at *optimum suction*.

```
FILE: LFCPUMP   FORTRAN   A    UNIVERSITY OF TOLEDO TIME-SHARING SYSTEM
C
C
C
C         THIS PROGRAM SOLVES FOR THE VARIABLE PARAMETERS OF THE THERMO-
C         DYNAMIC RELATIONS APPLIED TO THE LFC PUMPING SYSTEM.
C
C         VARIABLE DIRECTORY  :
C
C         MINF : THE FREE-STREAM MACH #
C         TINF  : THE FREE-STREAM TEMPERATURE
C         PINF  : THE FREE-STREAM PRESSURE
C         DELP2 : THE RELATIVE DROP IN TOTAL PRESSURE BETWEEN STATIONS
C                 1 & 2
C         DELP3 : THE RELATIVE DROP IN TOTAL PRESSURE BETWEEN STATIONS
C                 3A & 3
C         CP1   : PRESSURE COEFFICIENT
C         RP3   : THE RATIO OF TOTAL PRESSURE AT STATION 3 TO THAT AT
C                 FREE-STREAM
C         ETAC  : THE COMPRESSOR EFFICIENCY
C         ETAN  : THE NOZZLE EFFICIENCY
C         GAMA  : RATIO OF SPECIFIC HEATS
C         VE    : NOZZLE EXIT VELOCITY
C         TT3   : TOTAL TEMPERATURE AT STATION 3
C         PT3   : TOTAL PRESSURE AT STATION 3
C         FNOZ  : NOZZLE THRUST
C         PR    : THE PRANDTL NUMBER
C         MAIR  : MASS FLOW RATE OF AIR
C         AE    : NOZZLE EXIT AREA
C         PCOMP : COMPRESSOR WORK PER UNIT MASS OF AIR
C         POWER : RATIO OF NOZZLE THRUST POWER PER UNIT MASS OF AIR TO
C                 PCOMP
C         ME    : EXIT MACH NUMBER
C         VELR  : VELOCITY RATIO
C
C
C
C
          REAL MINF,RP3(33),ME,MAIR,POWER(33),VELR(33),DELP2(4)
          REAL P1(4,33),P2(4,33)
      DATA RP3/0.094,0.095,.096,.098,.099,0.10,.12,.14,0.15,0.2,.25,0.30
     &,.35,0.4,.5,.55,.6,.65,.7,0.75,0.8,0.85,0.9,0.95,1.0,1.5,2.0,2.5,
     &3.0,3.5,4.0,4.5,5.0/
      DATA DELP2/0.00,0.1,0.2,0.3/
C         INPUT THE CONSTANTS OF THE PROBLEM:
          WRITE(5,*)'INPUT THE CONSTANTS OF THE PROBLEM:'
          WRITE(5,*)'MINF,TINF,ROINF,GAMA,R,PR,CP1,ETAC,ETAN'
          READ(5,*)MINF,TINF,ROINF,GAMA,R,PR,CP1,ETAC,ETAN
          WRITE(7,*)'MINF,TINF,ROINF,GAMA,R,PR,CP1,ETAC,ETAN'
          WRITE(7,*)MINF,TINF,ROINF,GAMA,R,PR,CP1,ETAC,ETAN
          PRINT*,'RP3 IS '
          PRINT*,RP3
          DELP3 = 0.00
          CP    = 1011.5
          GAMAR = (GAMA -1)/GAMA
          MAIR = 1.0
```


ORIGINAL PAGE IS
OF POOR QUALITY

```
      N     = 33
C
C     FOR EQUATIONS 1-6 :
C
      PINF = ROINF*R*TINF
      VINF  = MINF*SQRT(GAMA*R*TINF)
      VAR1 = 1 + (GAMA - 1)/2*MINF**2
      VAR2 = VAR1**(1/GAMAR)
      VAR3  = 1 + (CF1/2*GAMA*MINF**2)
      TT2   = TINF*((1-SQRT(PR))*VAR3**GAMAR + SQRT(PR)*VAR1)
      WRITE(6,*)'VINF,VAR1,VAR2,VAR3,TT2'
      WRITE(6,*)VINF,VAR1,VAR2,VAR3,TT2
      DO 2 K = 1,1
      WRITE(7,*)'DELP2,DELP3,CP,GAMAR,MAIR'
      WRITE(7,*)DELP2(K),DELP3,CP,GAMAR,MAIR
      DO 1 I =1,N
      VAR4   = RP3(I)*VAR2
C
C     FOR EQUATIONS 7-15 :
C
      VAR5 = VAR3*(1-DELP2(K))
      VAR6 = 1/VAR4
      VAR7 = VAR4/(1-DELP3)
      VAR8 = VAR7/VAR5
      TT3 = TT2*(1-(1-(VAR8)**GAMAR)/ETAC)
      PAR1 = 2*ETAN*CP*TT3*(1 - (VAR6**GAMAR))
      PRINT*,'PAR1 = ',PAR1
      VE =   SQRT(PAR1)
      PCOMP =  CP*TT2/ETAC*((VAR8**GAMAR) - 1)
      POWER(I) = VE*VINF/PCOMP
      VELR(I) = VE/VINF
      P1(K,I) = VELR(I)
      P2(K,I) = POWER(I)
      TE = TT3 - VE**2/(2*CP)
      ME = VE/SQRT(GAMA*R*TE)
      PTE = PINF*(TT3/TE)**(1/GAMAR)
      DEN = (1+(GAMA-1)/2*ME**2)**(-(GAMA +1)/(2*(GAMA-1)))
      AE = MAIR*SQRT(R*TT3)/(PTE*SQRT(GAMA)*ME*DEN)
C
C     OUTPUT RESULTS :
C
C     WRITE(6,*)'VAR4,VAR5,VAR6,VAR7,VAR8,TT3,PAR1'
C     WRITE(6,*)VAR4,VAR5,VAR6,VAR7,VAR8,TT3,PAR1
C     WRITE(6,*)'VE,PCOMP,VELR,POWER,TE,ME,DEN,AE'
C     WRITE(6,*)VE,PCOMP,VELR(I),POWER(I),TE,ME,DEN,AE
    1 CONTINUE
C     WRITE(7,40)(VELR(I),POWER(I),I=1,N)
C40   FORMAT(' ',2X,F10.5,4X,F10.5)
C     WRITE(6,10)
C     WRITE(6,20)(I,RP3(I),VELR(I),POWER(I),I=1,N)
C10   FORMAT(' ',2X,'I',3X,'RP3',9X,'VELR',11X,'POWER')
C20   FORMAT(' ',2X,I4,5X,F7.4,5X,F10.5,5X,F10.5)
    2 CONTINUE
      WRITE(7,30)(RP3(I),P1(1,I),P2(1,I),P1(2,I),P2(2,I),P1(3,I),
     &P2(3,I),P1(4,I),P2(4,I),I=1,N)
   30 FORMAT(' ',F8.4,2X,F6.4,2X,F6.4,2X,F6.4,2X,F6.4,2X,F6.4,2X,
     &F6.4,2X,F6.4,2X,F6.4)
      STOP
      END
```

Pt3 / Pt∞	(Ve / V∞)1	(Power ratio)1	(Ve /V∞)2	(Power ratio)2
0.094000	0.052300	2.7391	0.053300	0.95830
0.095000	0.091900	4.0429	0.093600	1.5767
0.096000	0.11880	4.5133	0.12110	1.9188
0.098000	0.15930	4.7630	0.16220	2.3041
0.099000	0.17590	4.7599	0.17920	2.4200
0.10000	0.19100	4.7225	0.19460	2.5060
0.12000	0.37560	3.5592	0.38260	2.6436
0.14000	0.48550	2.9738	0.49440	2.4212
0.15000	0.52910	2.7858	0.53880	2.3254
0.20000	0.69110	2.2511	0.70360	1.9967
0.25000	0.80380	1.9863	0.81820	1.8060
0.30000	0.89120	1.8215	0.90690	1.6790
0.35000	0.96280	1.7063	0.97970	1.5866
0.40000	1.0237	1.6198	1.0415	1.5154
0.50000	1.1236	1.4960	1.1430	1.4112
0.55000	1.1658	1.4495	1.1858	1.3712
0.60000	1.2042	1.4098	1.2248	1.3368
0.65000	1.2393	1.3753	1.2605	1.3068
0.70000	1.2718	1.3450	1.2935	1.2801
0.75000	1.3020	1.3181	1.3242	1.2564
0.80000	1.3303	1.2939	1.3528	1.2349
0.85000	1.3568	1.2720	1.3797	1.2154
0.90000	1.3817	1.2521	1.4051	1.1976
0.95000	1.4054	1.2338	1.4291	1.1812
1.0000	1.4278	1.2170	1.4518	1.1661
1.5000	1.6058	1.0985	1.6326	1.0584
2.0000	1.7336	1.0270	1.7622	0.99250
2.5000	1.8339	0.97730	1.8640	0.94630
3.0000	1.9167	0.93970	1.9481	0.91110
3.5000	1.9875	0.90980	2.0199	0.88310
4.0000	2.0495	0.88520	2.0828	0.85990
4.5000	2.1046	0.86440	2.1387	0.84030
5.0000	2.1544	0.84640	2.1892	0.82330
	0.0000	0.0000	0.0000	0.0000

(Ve / V∞) 3	(Power ratio) 3	(Ve / V∞) 4	(Power ratio) 4
0.054500	0.55660	0.055700	0.37810
0.095600	0.94010	0.097900	0.64630
0.12360	1.1712	0.12650	0.81410
0.16560	1.4645	0.16950	1.0384
0.18290	1.5655	0.18720	1.1200
0.19860	1.6474	0.20330	1.1887
0.39040	2.0556	0.39950	1.6435
0.50450	2.0063	0.51610	1.6811
0.54980	1.9641	0.56240	1.6710
0.71770	1.7733	0.73390	1.5742
0.83440	1.6399	0.85300	1.4852
0.92470	1.5440	0.94520	1.4151
0.99880	1.4712	1.0208	1.3592
1.0617	1.4136	1.0849	1.3135
1.1649	1.3269	1.1903	1.2426
1.2086	1.2930	1.2347	1.2143
1.2482	1.2636	1.2751	1.1895
1.2845	1.2376	1.3122	1.1674
1.3181	1.2145	1.3464	1.1476
1.3493	1.1937	1.3782	1.1296
1.3784	1.1749	1.4079	1.1133
1.4058	1.1577	1.4358	1.0983
1.4316	1.1419	1.4621	1.0845
1.4560	1.1273	1.4869	1.0717
1.4791	1.1138	1.5105	1.0598
1.6629	1.0167	1.6978	0.97300
1.7947	0.95640	1.8321	0.91820
1.8981	0.91370	1.9375	0.87910
1.9836	0.88100	2.0246	0.84900
2.0567	0.85490	2.0991	0.82470
2.1206	0.83320	2.1642	0.80450
2.1775	0.81470	2.2221	0.78730
2.2288	0.79880	2.2744	0.77240
0.0000	0.0000	0.0000	0.0000

(Ve / V∞)	(Power ratio)
0.052390	38.167
0.091950	21.750
0.11883	16.830
0.15915	12.566
0.17570	11.383
0.19072	10.487
0.37282	5.3645
0.47961	4.1700
0.52162	3.8342
0.67579	2.9595
0.78147	2.5593
0.86257	2.3187
0.92860	2.1538
0.98441	2.0317
1.0755	1.8595
1.1139	1.7955
1.1486	1.7412
1.1804	1.6943
1.2098	1.6532
1.2370	1.6168
1.2624	1.5843
1.2862	1.5549
1.3087	1.5283
1.3299	1.5039
1.3500	1.4815
1.5092	1.3252
1.6230	1.2323
1.7121	1.1681
1.7857	1.1200
1.8485	1.0819
1.9035	1.0507
1.9524	1.0244
1.9964	1.0018

Appendix D

Definitions and Aerodynamic Terminology.

For a conventional airfoil the total resistance or drag is the sum of the profile drag and the induced drag.

For an airfoil with a suction surface the total resistance or drag is the sum of the wake drag, the induced drag and the suction drag. The wake drag and the suction drag being the profile drag of a suction surface.

Profile drag : is due to the friction of the air along the sides of the airfoil

induced drag : finds its origin in the circumstances that the appearance of the lift is accompanied by the creation of a definite flow pattern in the neighborhood and in the wake of the airfoil, which demands a continuous supply of energy.

Suction drag: is not an actual physical drag acting to oppose the motion of the airfoil through the air,but a drag computed from suction power requirements; however, the suction drag may be considered as an actual physical drag when the suction flow rate is high enough that the effect of suction is felt by the external potential flow. This phenomena is then termed ' the sink effect of suction '.

Parasitic drag: In the complete structure of an aircraft are found various parts either of the structure or of the equipment which, like the body, take no part in the development of lift and the drag of which may be grouped under the general head ' parasitic '. This parasitic drag is made up of the fuselage,landing gear, tail surfaces, etc and of their interference with the wings and between themselves. Interference drag may be as high as the sum of the component of the drag of the component parts tested separately.

Wake drag : The drag obtained by considering a control volume in the wake of the airfoil. This wake is an indication of a momentum deficit due to the presence of the body in a field of flow. A control surface taken upstream and downstream of the body is used in evaluating the profile drag from knowledge of the pressure and velocity distributions in the wake.

Ram drag : represents the loss of momentum associated with a conventional engine.

For an aircraft with no suction surfaces:

total drag = profile drag + induced drag + parasite drag

For an aircraft with suction surfaces:

total drag = (profile drag of non-suction surfaces) + induced drag + parasite drag + suction drag + (wake drag of suction surfaces)

Range: The distance that can be flown with a given amount of fuel.

Endurance: The time of flight with a given amount of fuel. This parameter of performance may be mostly applicable to fighter airplanes rather than commercial subsonic transport aircrafts.

Performance parameters of a propulsive system:

Propulsive Force, = time rate of change of momentum of gases + sum of pressure forces

Propulsive efficiency, = ratio of total thrust power to total engine power output

Thrust specific fuel consumption , tsfc = ratio of total fuel flow rate to total thrust

Brake specific fuel consumption , bsfc = ratio of fuel flow rate to brake horsepower