ANALYSIS AND OPTIMIZATION OF SCRAMJET INLET PERFORMANCE

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ABSTRACT

For one-dimensional flow in an inlet, theoretical considerations show that if any four flow quantities are measured and used as the independent variables, then the remaining five dependant variables can be calculated. The exit pressure and exit area are proposed as two of the independent variables. This leads to convenient and physically meaningful depiction of inlet performance in terms of contraction and compression ratios. The conventional "available energy" measures of inlet performance η_{pt}, η_{el}, η_{ke}, η_{th}, η_{Kd}, and a new exergy based term (η_x), are shown to be contradictory. This suggests the use of engine performance as an arbiter of inlet performance.

Engine cycle calculations have been performed as a function of compression and contraction ratios. Design points are identified for the inlets which yeild highest engine performance throughout a typical flight corrodor.

NOMENCLATURE

η_{pt}	- Total pressure recovery	
η_{el}	- Polytropic efficiency	
η_{th}	- Thermodynamic efficiency	
η_{ke}	- Kinetic energy efficiency	
η_{Kd}	- Kd efficiency	
η_x	- Exergy efficiency	
A	- Area	m^2
P	- Static Pressure	Pa
α	- Contraction ratio (A_1/A_2)	
π	- Compression ratio (P_2/P_1)	
Pt	- Total Pressure	Pa
T	- Temperature	K or R
M	- Mach number	
Tt	- Total temperature	K or R
Isp	- Specific impulse	seconds
Cp	- Specific heat at constant pressure	KJ/Kg^0C
Cv	- Specific heat at constant volume	KJ/Kg^0C
γ	- Specific heat ratio	
ρ	- Density	Kg/m^3
V	- Velocity	m/s
Ht	- Total enthalpy	KJ/Kg
h	- Static enthalpy	KJ/Kg
τ	- Heat loss parameter	
s	- Entropy	KJ/Kg^0C

SUBSCRIPTS

1 - Inlet entry plane
2 - Inlet exit plane
t - Total condition

INTRODUCTION

The growing economic and strategic significance of placing human and material payloads into low earth orbit has guided the technological search for more cost efficient delivery systems.

Recent growth of key aerospace technologies has stimulated a renewed interest in air breathing propulsion systems for low earth orbit payload delivery. The U.S. National Aerospace Plane (NASP) project was devised in response to the need for improved cost efficiency over traditional Shuttle and expendable launch capability.[1]

For the NASP project, much attention has been directed to the high specific impulse potential of the scramjet.[5] This engine will power the aerospace plane through the majority of its trajectory into orbit. The scramjet engine consists of an air inlet, a combustion chamber and an exhaust nozzle. Of vital importance to engine propulsive efficiency, and hence vehicle payload capacity, is the precise optimization of the aerodynamic design of the scramjet engine and its components. In this paper, we will deal particularly with one of these components namely the air intake, examining its effect on the overall engine performance.

In aircraft propulsion systems, the inlet provides the means of channeling freestream air into the engine for the use of its oxygen content for combustion with injected fuel. In so doing it also reduces the Mach number, thus allowing a more efficient heat addition in the combustion chamber. This deceleration brings about inviscid and viscous losses through the boundary layer and shock wave formation. These losses are technically both of a viscous origin caused by the entropy production of viscous dissipation. Several different measures of efficiency have been applied to the scramjet inlet, all somehow attempting to measure this entropy production.[3,8]

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Total pressure recovery (ηpt), Kinetic energy efficiency (ηke), Polytropic efficiency (ηel), Thermodyanmic efficiency (ηth), and Kd efficiency(ηKd) are terms which are all commonly applied.
The definition and significance of each of these parameters is discussed in References 3 and 8 (Curran, Billig, and Van Wie). A new efficency term based on exergy (ηx), will be introduced to account more fully for the non-adiabatic nature of real inlets. Owing to the complexity of the scramjet engine cycle, the wide range of scramjet operating conditions, and the many possible ways of measuring performance, a single universally accepted measure of hypersonic intake efficiency has not been formulated.[2]

In a turbojet or ramjet flying at supersonic speed with a subsonic combustion system, final intake compression is usually accomplished by a normal shock. This characteristically causes subsonic flow and a significant reduction in total pressure. The resulting total pressure determines the static pressures in the combustion chamber and the nozzle. And these in turn govern the engine thrust. The total pressure loss (or recovery) is a useful measure of performance for an inlet whose task is to reduce the supersonic freestream Mach number to a subsonic value. The specification of such an inlet's performance, then, is adequately reflected in this single term called the ηpt efficiency.[3]

In a supersonic combustion process, total pressure recovery is measured after a final deceleration through an oblique shock which results in a supersonic (lower than freestream) Mach number at the combustion entry. The loss of total pressure is less significant. To define the performance of a scramjet inlet, therefore, requires the specification of an <u>efficiency</u> term, like total pressure recovery, as well as a <u>capability</u> term. The diffuser's capability expresses the amount of diffusion in terms of either contraction (area) ratio (A_1/A_2), compression (static pressure) ratio (P_2/P_1) or entry to exit Mach number. Measures of both capability and efficiency are required in order to define the pressures in the combustor and nozzle so as to obtain engine thrust. Or fundamentally, any two terms such as compression ratio and contraction ratio are sufficient to define the operating conditions, including any one of the efficiency measures, for an inlet operating at a given freestream Mach number if there is no mass spillage and the flow is adiabatic.

Our intention is to demonstrate the practical usefulness of the intake compression and contraction ratios as measures of intake performance. We will also show how these can be related to various measures of efficiency for perfect as well as calorically imperfect gas flows, with and without heat transfer. An assessment of the efficacy of the various efficiency parameters will be presented by comparing changes of inlet performance, as measured by various parameters, with the resulting changes in engine performance as assessed by engine cycle calculations. The latter applies a parametric study to a generic engine design and typical flight corridor freestream conditions in the calculation of inlet dependent engine specific impulse. Inviscid designs for real Prandlt-Meyer type inlets are assessed by this technique for their effect on engine specific impulse and a capacity for performance optimization will be demonstrated.

In the following section we will demonstrate the interdependence of total pressure recovery to the inlet effectiveness parameters for ideal and calorically imperfect air under non-adiabatic compression.

<u>AIR INLET PERFORMANCE MEASUREMENT</u>

For the inlet such as shown in Fig. 1 we consider the quasi-one-dimensional flow between stations (1) and (2) at the entry and exit respectively.

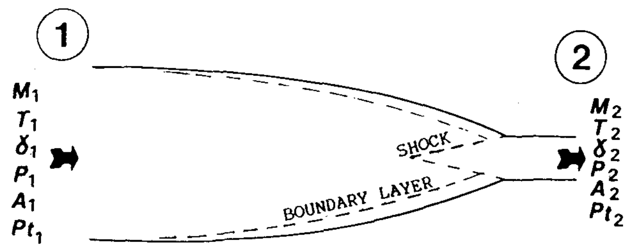


FIG. 1 -Inlet entry and exit flow conditions.

Flow behaviour in an inlet is governed by the equations of conservation of mass, momentum and energy and the equation of state of the gas. Furthermore, the change of properties from state (1) to (2) is influenced by the presence of mass flow (spillage), forces acting on the fluid between the two stations and heat transfer to the walls. The efficiency of the process can be evaluated (or specified) from a knowledge of the change of entropy between stations (1) and (2). Thus we are left with five equations in the nine unknowns P_2, ρ_2, T_2, V_2, s_2, A_2, $\dot{m}$, f and Q. We can solve for any five of these provided the other four are measured or otherwise specified. A typical practical case is shown in the table which lists the nine variables in question. A minimum of four variables have to be known either from measurements or the truth of obvious assumptions. In this case we show the exit pressure P_2, the exit area A_2 and the force of the inlet on the fluid to be measured.

Quantity	Symbol	Measure (min	Assume 4)	Calculate (max 5)
pressure	P_2	★		
density	ρ_2			★
enthalpy	h_2			★
velocity	V_2			★
entropy	s_2			★
flow area	A_2	★		
mass addition	$\dot{m}$		★(=0)	
force on flow	f	★		
heat addition	Q			★

TABLE 1. -The nine principal inlet flow parameters that are applied to performance assessment.

We assume, also, that the inlet does not spill or acquire mass. In this case we can calculate the five remaining quantities by solving the following five equations:

$$\rho_1 V_1 A_1 + \dot{m} = \rho_2 V_2 A_2 \qquad (1a)$$

$$P_1 A_1 - P_2 A_2 - f = \rho_1 V_1 A_1 (V_2 - V_1) \qquad (1b)$$

$$h_1 + V_1^2/2 + Q = h_2 + V_2^2/2 \qquad (1c)$$

$$P_2 = P_2(\rho_2, h_2) \qquad (1d)$$

$$s_2 = s_2(P_2, h_2) \qquad (1e)$$

What we normally associate with efficiency is resident in the equations for entropy $s_2 = s_2(P_2, T_2)$. For example if the inlet is isentropic then $s_2 = s_1$ and we end up with one less variable and one less equation. Or, if we can assume that the flow is adiabatic, Q=0, then we are relieved of having to measure the force exerted on the fluid by the inlet. There is no fundamental difference between the measured/assumed and the calculated variables and we can think of the experimental task being done when we have knowledge of any four of them. The data reduction task is then to solve for the other five. Which variables to measure and which to calculate depends on our ability to readily measure some quantities. For example, in the table shown, the pressure, P_2, can be readily measured; the area, A_2, is found from the physical dimensions of the model; the force, f, is equal and opposite to the force exerted by the fluid on the inlet and can be measured by a load cell; and flow spillage can be convincingly assumed to be zero on a given inlet. We are then in a position to calculate ρ_2, h_2, V_2, s_2 and Q. The above example has shown that from an experimental viewpoint it is convenient to think of pressure and area as the measured values of inlet performance along with a measured inlet drag, f, and mass spillage, m. Consequently we will display inlet performance parameters on graphs with the <u>contraction ratio</u> and the <u>compression ratio</u> as abscissa and ordinate respectively, keeping in mind that in the most general case a four-dimensional plot is really required to represent the four "independent", or measured variables P_2, ρ_2, A_2, $\dot{m}$ and Q.

INLET EFFICIENCY

In the previous section we discussed how flow properties in an inlet could be measured and calculated. We now want to show how measures of inlet efficiency are calculated from these properties and demonstrate the usefulness of some of these measures.

It is desirable to attach a number to a particular inlet operating at some specified conditions such that when changes are made in the design or operating conditions of the inlet, and the number increases, then the performance of the engine to which the inlet is attached also increases. If one, or perhaps several, such numbers could be identified then the development and design of intakes could proceed without considering their integration into any particular engine. We will define several engine efficiency parameters and compare them on the basis of contraction ratio, $\alpha = A_1/A_2$, and compression ratio, $\pi = P_2/P_1$.

<u>TOTAL PRESSURE RECOVERY</u> [ηpt]. For a calorically perfect gas, adiabatic flow and no spillage, area ratio can be stated in terms of the total and static pressure ratios:

$$\alpha = \frac{\pi \left(\left(\frac{2}{\gamma-1}\right) \tau \left\{ \beta \left(\frac{\pi}{\eta_{pt}} \right)^{\frac{1-\gamma}{\gamma}} - 1 \right\} \right)^{1/2}}{M_1 \left(\frac{\pi}{\eta_{pt}} \right)^{\frac{\gamma-1}{2\gamma}}} \qquad (2)$$

$$\beta = 1 + \frac{\gamma-1}{2} M_1^2$$

The Mach number at the exit can then be found from:

$$M_2^2 = \frac{2}{\gamma-1} \left\{ \beta \left(\frac{\eta_{pt}}{\pi} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right\} \qquad (3)$$

Figure 2a shows curves of ηpt and M_2 in the (α, π)-plane. Negative values of logα represent a diverging duct and are of no interest to inlet designers. It is interesting to note that for every given efficiency (ηpt) there is a maximum value of $\log_{10} A_1/A_2$ and that the duct becomes choked at this condition. Using measured values of P_1, P_2, A_1, and A_2, one can then use this plot to find the total pressure recovery provided the Mach number is 8.33, there is no flow spillage and the gas is calorically perfect with γ=1.4.

Operating Line of Real Hypersonic Inlets. We will now consider the application of the pressure-area diagram in the performance assessment of real hypersonic inlets. The Prandtl-Meyer inlet is a typical example. It consists of planarly symmetric (2D flow) which starts from the freestream with a centered Prandtl-Meyer compression followed by a region of uniform flow which is terminated by a single oblique shock (figure 2a). The flow starts off parallel to the freestream at the beginning of the Prandtl-Meyer compression is the turned through some angle into the uniform region and is again turned back by the same angle by the shock to become uniform and parallel to the freestream at the exit of the inlet. By varying the Mach number in the uniform region, it is quite easy to calculate all the flow properties as well as the geometry of the inlet. Such a calculation will yield a line in the (α,π) - plot, which may be called the "operating line" of the Prandtl-Meyer inlet.

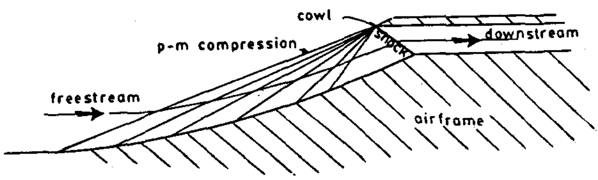


FIG. 2a-Typical Prandtl-Meyer inlet compression sequence.

For Mach 8.33 inviscid flow, the Prandtl-Meyer Inlet operating line is shown in Figure 2b. The usefulness to the designer of plotting efficiency in terms of compression and contraction ratio is apparent when we consider this operating line of a real inlet. The range of inlet capability is visible at a glance. More importantly, the efficiency of a given inlet can be determined or a selection of a more isentropic inlet can be made. The inviscid design point of a Prandtl-Meyer type inlet, presently under evaluation at the Ryerson/U of T Guntunnel, is indicated on this operating line.

Total Pressure Ratio for Calorically Imperfect Gas. The design of an inlet for hypersonic application will require the consideration of deceleration and compression induced temperature effects that are beyond the range of accuracy of the ideal gas model. A sound theoretical assessment of inlet performance must therefore account for caloric imperfections.

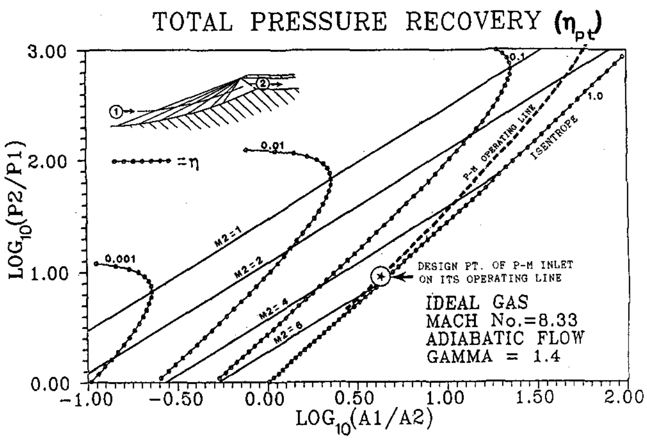


FIG. 2b -Lines of constant total pressure recovery are plotted as a function of inlet pressure ratio and area ratio for an ideal gas. Lines of constant downstream Mach number are shown. The performance range for Mach 8.33 Prandtl-Meyer type inlets can be assessed.

Higher temperature in the diffuser air causes vibrational molecular motion that will change the value of Cp, Cv and their ratio γ = Cp/Cv The complexity of the calorically imperfect gas model does not lend itself to the same explicit equations as the ideal gas model.

The equations for calorically imperfect air are applied to the derivation of the Figure 2c P-A diagram.[4] The lines of constant ηpt from Figure 2b are included for comparison to the imperfect gas total pressure recovery lines. this demonstrates the accuracy of the ideal gas assumption up to the line of about 800K. Another temperature line at 3000K has been included in these plots to show the limit of the accurate application of the caloric gas equations. Beyond this downstream temperature, thermal imperfections and molecular dissociation effects take place.

Heat Loss in the Inlet. Figure 2d demonstrates the influence of heat transfer on the efficiency lines distribution at Mach 15. This applies a 10% enthalpy loss for comparison to the adiabatic case.

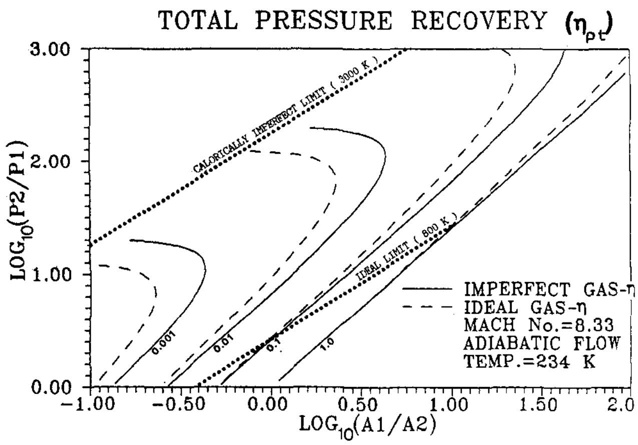


FIG. 2c–Total pressure recovery is derived for both the ideal and calorically imperfect gas models. The temperature limit of the accurate application of each is indicated.

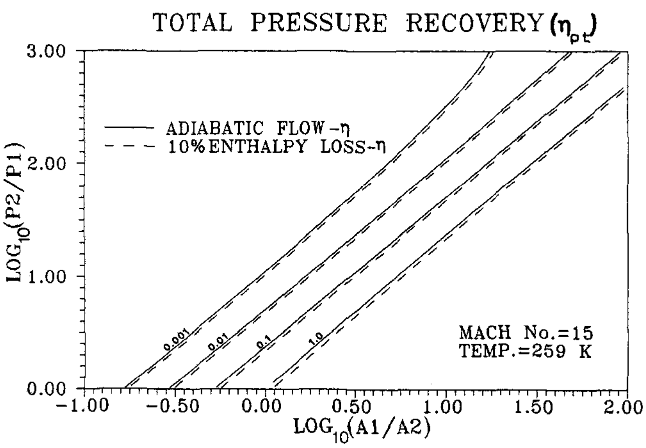


FIG. 2d–The effect of heat transfer on the distribution of the Mach 15 total pressure recovery is demonstrated.

KINETIC ENERGY EFFICIENCY [ηke]. Using the simplifying assumption of an ideal gas, the remaining available energy terms are easily derived from total pressure recovery (see Refs. 3 and 8)

Kinetic energy efficiency is a term that is often applied to subsonic combustion inlets.

For an ideal gas, kinetic energy efficiency can be shown to be a function of total pressure ratio through

$$\eta_{ke} = \left(\frac{1 - \left(\frac{1}{\eta_{pt}} \right)^{\frac{\gamma-1}{\gamma}}}{\left(\frac{\gamma-1}{2} \right) M_1^{\,2}} \right) + 1 \qquad (4)$$

From this we derive Fig.3. This equation demonstrates a disadvantage of the kinetic energy efficiency term. Values approaching unity are incurred not only as ηpt approaches one but also as the Mach number increases. Thus it gives misleadingly high values at high hypersonic conditions.

THERMODYNAMIC EFFICIENCY [ηth]. Also known as the "effectiveness" this term is interconvertible with ηpt by the following;[2]

$$\eta_{th} = 1 - \frac{\left(\frac{\gamma-1}{\gamma}\right) \ln\left(\frac{1}{\eta_{pt}}\right)}{\left(\frac{h_1}{h_2} - 1 \right)} \qquad (5)$$

Lines of constant ηth efficiency are derived with respect to area ratio and pressure ratio in Figure 4.

PROCESS EFFICIENCY [Kd]. The Kd term is similar in nature to ηke. This can also be derived from ηpt by the ideal gas assumption;[2]

$$\eta Kd = 1 - \frac{\left(\frac{1}{\eta_{pt}} \right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{h_2}{h_1} - 1 \right)} \qquad (6)$$

which gives us Figure 5.

POLYTROPIC EFFICIENCY [ηel]. This term is calculated as follows;[2]

$$\eta_{el} = 1 - \frac{\left(\frac{\gamma-1}{\gamma}\right) \ln\left(\frac{1}{\eta_{pt}}\right)}{\ln \frac{h_2}{h_o}} \qquad (7)$$

The polytropic efficiency is less sensitive a parameter than all the other terms except ηpt. It tends to drop considerably in value for small inlet capability change. This makes it a useful parameter when comparing efficiencies of different inlets.

The ηel distribution is plotted in Figure 6 for Mach 8.33.

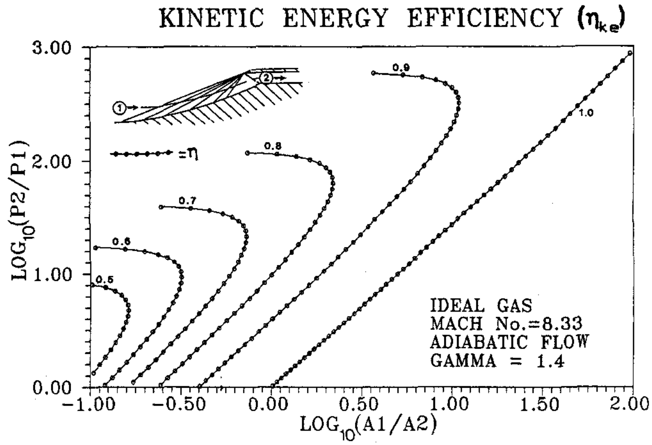


FIG. 3

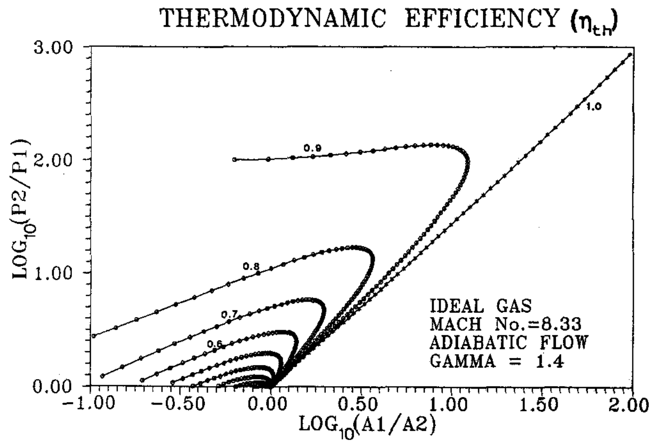


FIG. 4

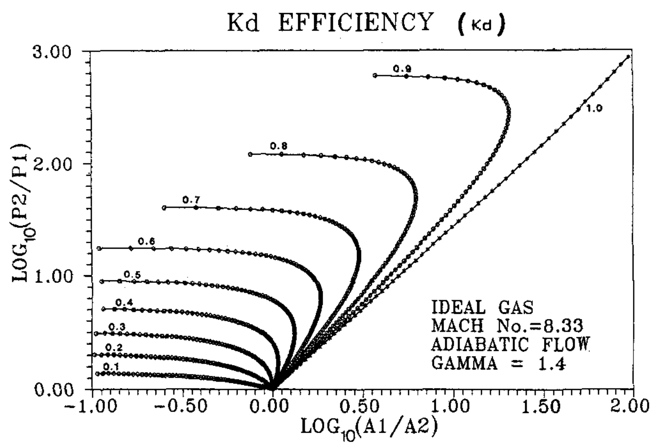


FIG. 5

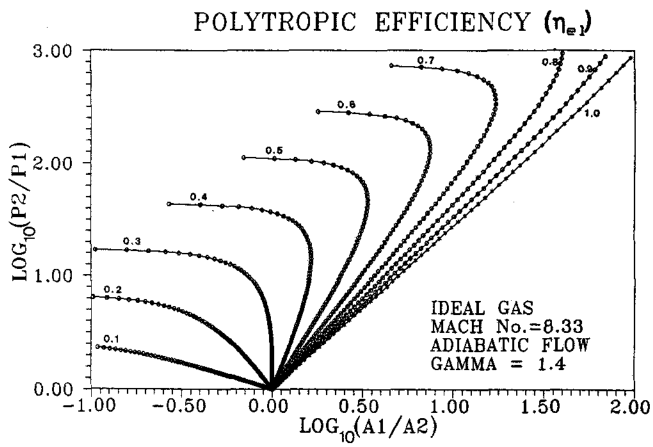


FIG. 6

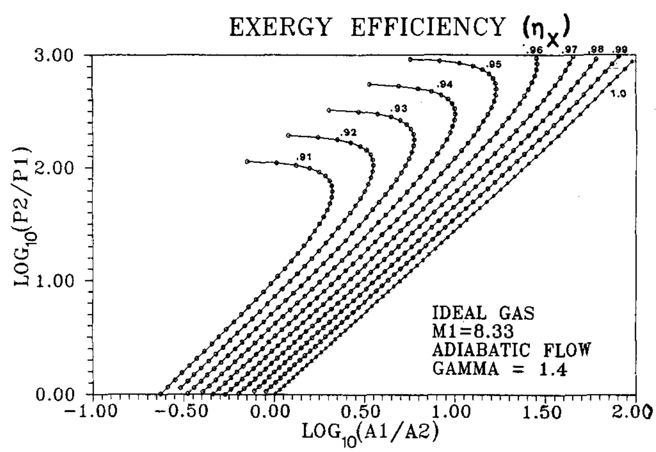


FIG. 7

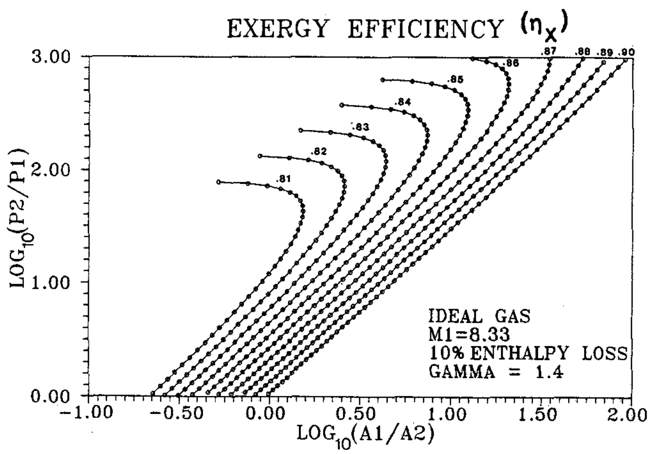


FIG. 8

FIG. 3 - 8. The "available energy" efficiency terms are compared on plots of compression ratio and contraction ratio for an ideal gas at Mach 8.33. Many are indicating distinctly different directions for inlet performance improvement. The effect of enthalpy loss on the distribution of the exergy lines is demonstrated in Figures 7 and 8.

EXERGY EFFICIENCY [η_x]. The available energy or exergy of a flowing mass of a gas is defined as

$$B = ht - T_0 s \tag{8}$$

where ht is the total enthalpy defined by $h + V^2/2$, T_0 is a reference temperature and s is the entropy. The quantities ht and $T_0 s$ have the units [J/kg] hence they, as well as the exergy, are extensive properties. The change in exergy between any two states 1 and 2 is

$$B_1 - B_2 = ht_1 - ht_2 - T_0 (s_1 - s_2) \tag{9}$$

The difference $B_1 - B_2$ is called a loss of available energy since it represents a generally undesirable feature in a flow system. Any expression of inlet efficiency is a reflection of such a loss. It is therefore postulated that an accurate efficiency measure must account directly in its derivation for the non-adiabatic nature of real inlets.

Efficiency Based on Exergy. On the basis of an input exergy we define an exergy efficiency

$$\eta_x = \frac{B_2}{B_1} \tag{10}$$

If we take the state 1 as the reference state then $T_1 = T_0$ and $s_1 = s_0$, so that,

$$\eta_x = \frac{ht_2}{ht_1} - \frac{T_1(s_2 - s_1)}{ht_1} \tag{11}$$

This is the general definition of exergy efficiency in a flow system insofar as it is not restricted to perfect or ideal gases. Also we note that since it deals with total enthalpies then it must be sensitive to heat addition or removal between the states 1 and 2 as well as to losse measured by the entropy change $s_2 - s_1$. We will now attempt to state η_x in terms of the total temperature change and the total pressure change.

Heat Addition in an Ideal Gas. If Q joules of heat are added to every unit mass of a gas between states 1 and 2 then:

$$ht_1 + Q = ht_2 \tag{12}$$

If we are dealing with an ideal gas (R and Cp constant), then we can introduce the Mach number M_1 by

$$ht_1 = C_p\, Tt_1 = C_p\, T_1\left(1 + \frac{\gamma-1}{2} M_1^2\right) \tag{13}$$

Using equations (11) and (12) in equation (10) gives

$$\eta_x = \frac{ht_1 + Q}{ht_1} - \frac{1}{1 + \frac{\gamma-1}{2} M_1^2} \cdot \frac{s_2 - s_1}{C_p} \tag{14}$$

or

$$\eta_x = \frac{Tt_2}{Tt_1} - \frac{1}{1 + \frac{\gamma-1}{2} M_1^2} \ln \frac{Tt_2}{Tt_1} + \frac{\frac{\gamma - 1}{\gamma}}{1 + \frac{\gamma-1}{2} M_1^2} \ln \frac{Pt_2}{Pt_1} \tag{15}$$

This expression is interesting in that it shows the dependence of the exergy efficiency on heat addition and total pressure recovery. Note that the effect of total pressure recovery decreases with an increase in Mach number whereas the effect of heat addition is only partly dependent on Mach number. The expression (15) shows that exergy efficiency is decreased by a removal of heat ($Tt_2 < Tt_1$) and a loss in total pressure recovery ($Pt_2 < Pt_1$). For adiabatic flow, (Q=0), the exergy efficiency becomes

$$\eta_x = 1 + \frac{\frac{\gamma - 1}{\gamma}}{1 + \frac{\gamma-1}{2} M_1^2} \ln \frac{Pt_2}{Pt_1} \tag{16}$$

This expression is convenient for evaluating the exergy efficiency of the inviscid flow outside the thermal boundary layer where the total temperature is constant.

Figure 7a shows the exergy efficiency term plotted for adiabatic flow. The distinct usefulness of the η_x parameter, however, emerges only when the realistic effects of heat transfer to the inlet walls are considered. Figure 7b is an exergy efficiency derivation under the condition of 10% loss of total enthalpy. The exergy efficiency at any given design point falls off considerably. The significance of the sensitivity of this parameter to the effects of heat transfer will be observed in the following section.

ASSESSMENT OF INLET EFFICIENCY PARAMETERS

It would be desirable if any one of the efficiency parameters were such that an increase in the parameter value (reflecting an improvement in inlet performance) would lead to a corresponding improvement in the engine to which the inlet is supplying air. This would then allow the development of the inlet without reference to the rest of the engine simply by seeking higher values of the parameter in question.

We will show that this desirable situation is not realized, first of all by showing that the various efficiency parameters do not point in the same direction. That is, they are generally mutually inconsistent. And secondly, we will show that the parameters will not always point towards improved engine performance.

Consider the pressure-area diagram of figure 9, where the distributions of both ηpt and Kd are compared on a reduced scale for a simplifying case of ideal non-adiabatic inlet flow. The operating point of a particular inlet is shown as (1) on this figure. The performance of this inlet is such as to give a total pressure recovery of .1 and a Kd efficiency of .7. The performance of this inlet is now improved so that its operating point is now at (2) where the total pressure recovery is .316 instead of .100. The "improved" total pressure recovery has in fact decreased the inlets Kd figure from .7 to .6 - implying a significant performance deterioration as measured by Kd.

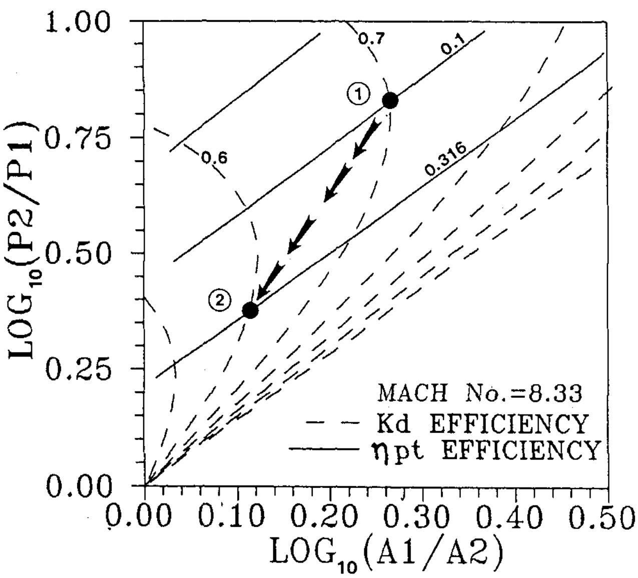


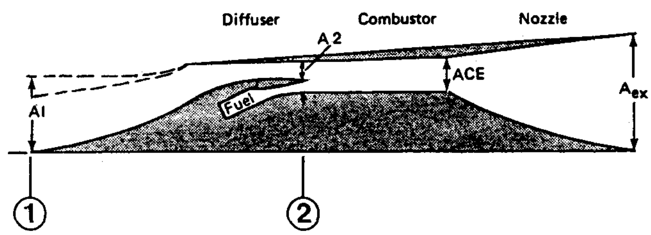
FIG. 9a–The directions indicated for inlet performance improvement are mutually inconsistant. Here, a hypothetical design change seems to improve efficiency by pt while decreasing the Kd efficiency.

Obviously, then, these two parameters not only indicate a different magnitude of change (i.e. .316/.1 = 3.16 and .6/.7 = .87) but changes in different directions as well. Thus for the purpose of judging improvement in engine performance, either total pressure recovery or Kd must be misleading for the conditions given. It should be noted that there are many points (1) and (2) on the contraction/compression diagram where both parameters would indicate changes in the same direction, although not necessarily the same magnitude. In an attempt to resolve this dilemma and to decide which parameter is right or which parameter, even though not always right, is the best, we will select as an arbiter the engine performance and consider the inlet attached to a representative scramjet engine. An improved inlet is then, by definition, the one that produces an improved engine performance.

ANALYSIS OF THE INLET INFLUENCE ON ENGINE PERFORMANCE

Engine Cycle Calculations. The Ramjet Performance Analysis (RJPA) is a one-dimensional engine cycle simulation program developed by the Applied Physics Laboratory at Johns Hopkins University.[2] It can be applied to engine cycle simulation of scramjets as well as ramjets, gas generators and rockets.

Figure 9b is a typical scramjet cross section showing the four flow planes; freestream, diffuser exit, combustor exit, and nozzle exit. Our interest is in the influence on engine performance of the scramjet inlet diffusion process for the Mach 8.33 to 25 freestream conditions. It is therefore necessary to fix the combustor and nozzle in order to avoid comparison of dissimilar engine cycles (so called "rubber engines").



A1 -- INLET CAPTURE AREA (changes for each P-A diagram point)
A2 -- INLET EXIT AREA (fixed at .258 m² (400 in.²))
ACE-- AREA OF COMBUSTOR EXIT (fixed at .348 m² (540 in.²))
Aex-- NOZZLE EXIT AREA (fixed at 3.54 m² (5500 in.²))

FIG. 9b–Typical scramjet profile showing the geometric dependant and independant design variables for the cycle simulations.

The components for this study will be fixed geometrically with a combustor entry (A_2) of .258 m^2 (400 in.^{2}), combustor exit of .348 m^2 (540 in.^{2}), nozzle exit area of 3.54 m^2 (5500 in.^{2}). Since the downstream area A_2 has been set at .258 m^2, the inlet capture area (A_1 in figure 9b) will be the only changing geometric variable.

The fuel used is hydrogen with a frozen (uncombusted) mass fraction of .05. The stoichiometric fuel/air ratio at combustion is .029164. The ratio of chemical recombination of species in the nozzle has been set at 2/3 equilibrium to 1/3 frozen. The freestream conditions correspond to the 1/2 atmosphere dynamic pressure path in the flight corridor.

The JHU/APL RJPA program was used to calculate scramjet engine performance as measured by specific impulse Isp for various values of inlet contraction A_1/A_2 and compression P_2/P_1 ratios.

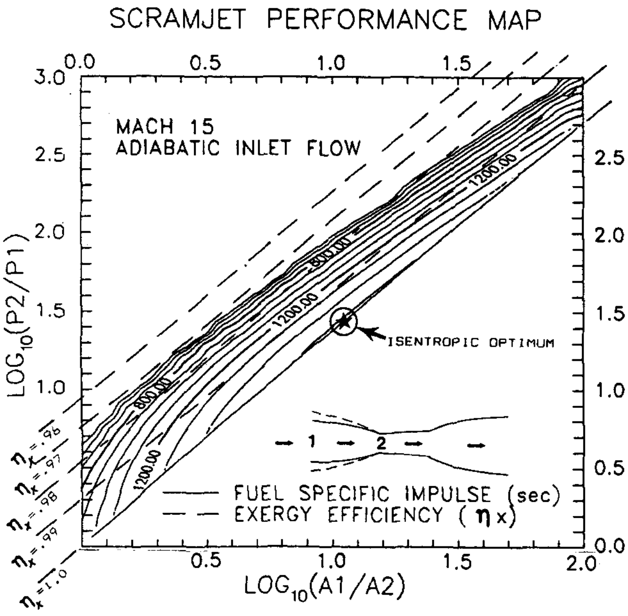


FIG. 9c

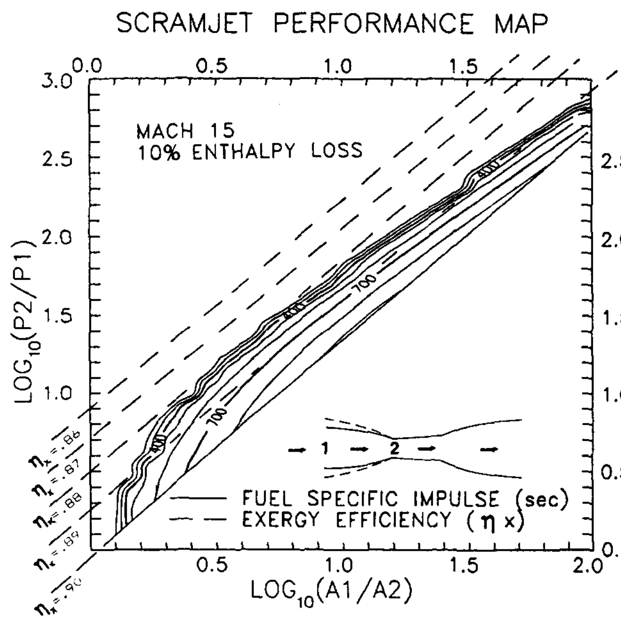


FIG. 9d

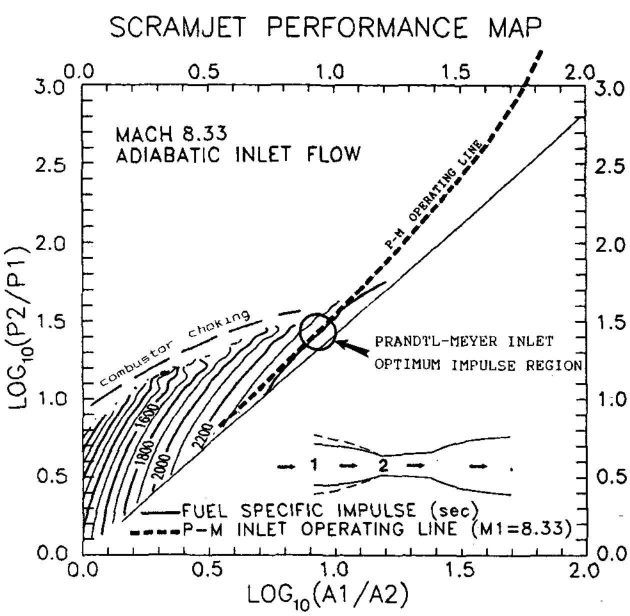


FIG. 9e

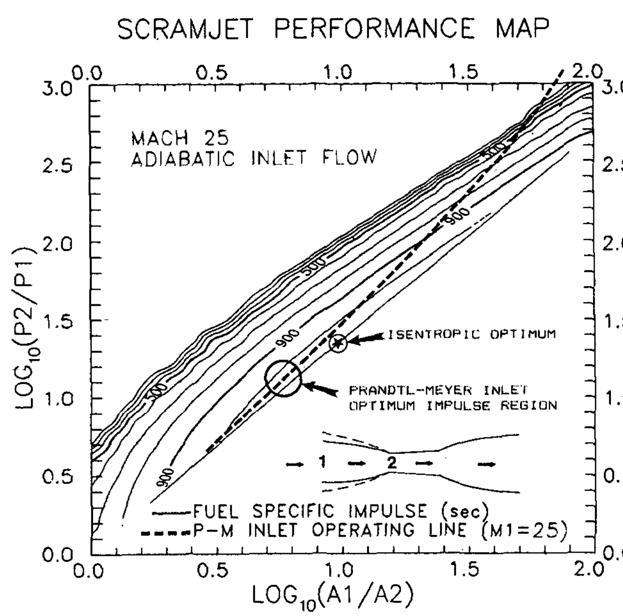


FIG. 9f

FIG. 9c-f. Engine cycle calculations have been performed for a fixed engine design with inlets represented by the complete range of design possibilities on the pressure-area diagram. The inlet influence on engine performance is clearly not accurately predicted by any of the efficiency terms including ηx, shown for comparison in Figures 9c and 9d. Design points of maximum impulse are indicated on both the isentrope and the Prandtl-Meyer operating lines in Figures 9e and 9f.

DISCUSSION OF RESULTS

SCRAMJET ENGINE PERFORMANCE MAPS

In figures 9c - f, the solid lines show engine performance as a function of inlet contraction and compression ratios. These are called Scramjet Engine Performance Maps. On Fig. 9c, the highest Isp contour shown is for 1500 sec. and this occurs near the lower straight diagonal line which represents the isentropic inlet. The Isp = 500 sec. contour is the lowest of the contour lines. The waviness of the contours at low values of Isp is thought to be due to real gas effects for it is near these values where the combustor becomes choked resulting in high temperatures at the end of combustion.

The real magnitude and distribution of the inlet's influence on engine performance is clearly demonstrated on the performance maps. It is immediately apparent that a design increase of any of the efficiency terms, such as the ηx shown, will not necessarily lead to improved engine performance.

We note that at a given contraction ratio engine performance is improved by a decrease in compression ratio and at a given compression ratio engine performance is improved by an increase in contraction ratio. Also there exists a point (A_1/A_2 = 10 and P_2/P_1 = 26.3) where an isentropic inlet gives the highest engine performance of Isp = 1500+ sec. This demonstrates the existance of an optimum operating point. We have also plotted lines of constant efficiency as expressed by the exergy efficiency ηx, and from these it is apparent that there is a maximum value of Isp on every constant ηx curve at specific values of inlet compression and contraction. However, a line of constant ηx does not necessarily represent a realistic intake. A practical intake consists of a plausible construct of compression waves, shock waves and boundary layers. The operating line of the Prandtl-Meyer type inlet is shown on the performance maps of Mach 8.33 and Mach 25 (Fig. 9e and f), the capacity for real inlet performance optimization becomes apparent. At Mach 8.33 the values of engine specific impulse attain a maximum (of about 2400 sec) at A_1/A_2 = 8.32 and P_2/P_1 = 25.1. This then represents the best operating condition for the Prandtl-Meyer inlet at a Mach number of 8.33. Given the optimum parameters, the inlet geometry is easily calculated. It is realized that , because of the simplifying assumptions, the above numbers are approximate. However, they serve the purpose of illustrating the existance of the optimum rather than pinpointing its exact value which is always dependant on the given engine design criteria.

The Mach 15 condition performance map of figure 9d demonstrates the effect on the engine cycle of a 10% enthalpy loss in the inlet. The decline in engine peformance that is indicated is predicted by the non-adiabatic ηx efficiency, also shown. The nature of the Exergy efficiency does seem to indicate an inlet performance decline under enthalpy loss that reflects the real losses to the engine.

Figure 9g is a 3-dimensional representation of the Figure 9c performance map. The rise in specific impulse toward the peak at the isentropic optimum is apparent.

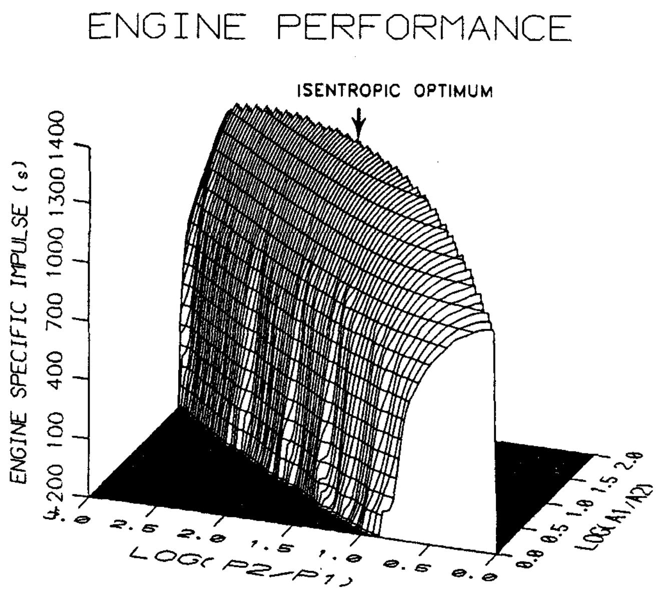


FIG. 9g-The scramjet performance map of Figure 9c is presented in 3-D to demonstrate the rise in impulse toward the isentropic optimum.

Figure 10 shows scramjet specific impulse (Isp) plotted against contraction ratio for various freestream Mach numbers for the Prandtl-Meyer family of inlets. For each freestream Mach number it is apparent that there is a maximum Isp in the neighbourhood of log A_1/A_2 = 0.8. This means that optimum performance can be attained throughout a Mach number range of 8.3 to 25 with an inlet contraction ratio of 6.3. It is further noted that a deviation in area ratio from this optimum through a range of log (A_1/A_2) of .5 to 1.4, which corresponds to contraction ratios from 3.16 to 25.1, produces no more than a 10% deterioration in engine Isp for any Mach number.

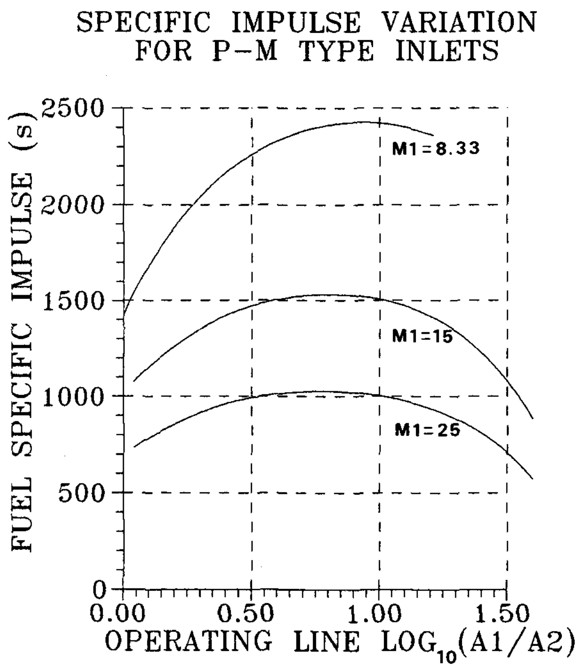


FIG. 10-The area ratios representing the operating lines at three design Mach numbers are plotted against their specific impulse when attatched to the generic engine. The optimum regions are clearly demonstated.

Fig. 11 shows the inlet and overall engine area ratios for the optimized performance conditions. This figure indicated that best engine performance is obtained throughout the hypersonic Mach number range either by decreasing the inlet area or by increasing the remaining engine areas by 30% as the flight Mach number changes from 8 to 25.

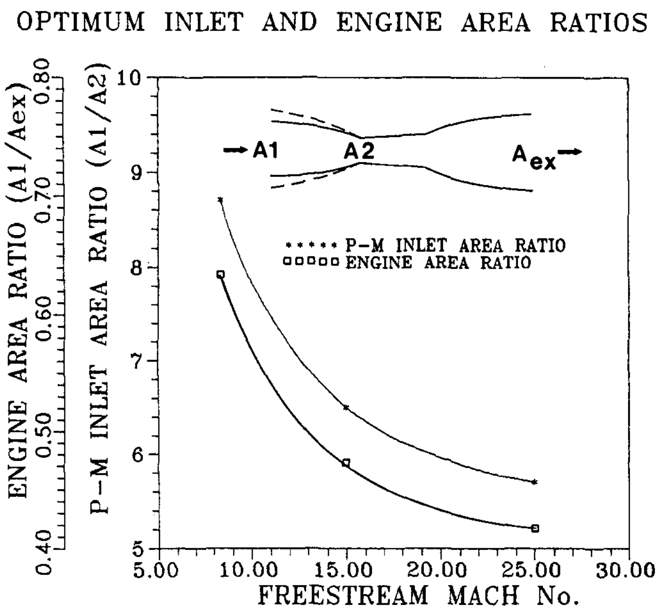


FIG 11.-The optimized inlet and corresponding engine area ratios are shown for each station on the selected flight corrodore.

On figure 12 we have plotted combustor delivery Mach number against freestream Mach number for each of the Prandtl-Meyer optimum inlet conditions. The freestream capture and combustor entry Mach numbers are linearily realted by:

$$M_2 = .71M_1 - 1.21 \qquad (16)$$

This represents a significantly larger fraction (~3/5) than the 1/3 figure which is generally accepted. Further investigation is required to determine potential gains attainable by changing the combustor outlet area.

The combustor delivery temperatures (T_2), also shown, are much lower than 1000K temperature required for spontaneous combustion of hydrogen. At approximately 600K for the range of the flight corridor, an ignition system or pyrophoric fuel would be required.

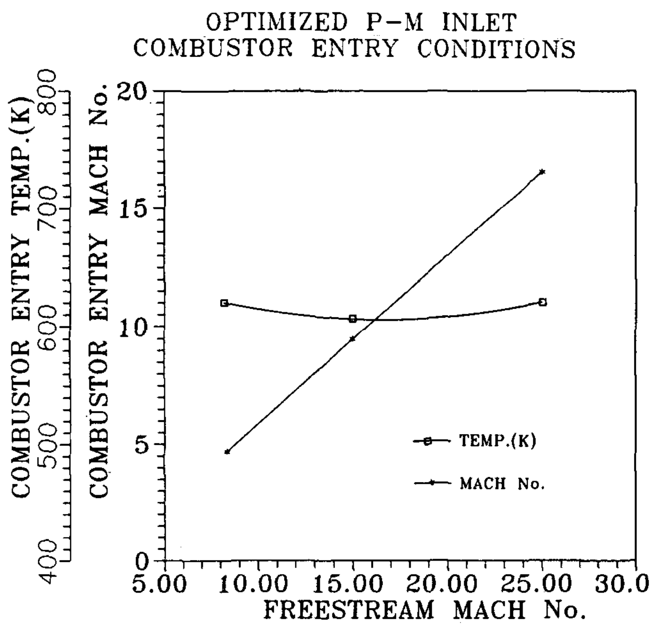


FIG. 12-The combustor delivery Mach number and static temperature are shown for each of the optimized inlets.

It should be quickly pointed out that the locations of the inlet optima studied in this section are dependent on the freestream conditions and the assumptions about the engine that were fixed for this analysis. Performance maps have, however, been generated for different ratios of chemical recombination in the nozzle, various freestream conditions, scramjets with constant pressure combustion processes, and engines with nozzle expansion to the freestream pressure. All results exhibit the same general character giving optimum inlet operating conditions at various points in the contraction/compression regime. The application of this technique to actual inlet design studies for a specific mission would need to consider viscous effects in the inlet and nozzle as well as the finite rate chemistry associated with particular combustion processes and nozzle designs.

CONCLUSIONS

The available energy hypersonic inlet efficiency parameters ηpt, ηke, ηth, ηel, kd and an exergy based term ηx, have been compared on plots of contraction ratio vs. compression ratio. An assessment of intake efficiency has been performed through calculations to obtain scramjet propulsive performance (specific impulse, Isp) also as a function of contraction and compression ratio.

The significant findings of this study are as follows.

1. Caloric gas imperfections need to be considered when calculating inviscid flow in hypersonic air inlets.

2. If any four flow properties at the exit of an inlet are measured then the remaining five can be calculated using the laws of conservation and the equations of state.

3. Depicting inlet performance on a plot of contraction ratio versus compression ratio is a convenient, practical, experiment-oriented approach.

4. Conventional measures of inlet efficiency are mutually inconsistent in measuring inlet performance.

5. Inlet performance must ultimately be judged against the performance of the engine.

6. The use of an efficiency definition based on exergy directly incorporates losses due to viscous dissipation and heat transfer.

7. Engine performance increases at fixed contraction ratio if the compression ratio is decreased or at fixed compression ratio if the contraction ratio is increased.

8. For a given efficiency there is a specific point in the compression/contraction plane which gives the highest engine performance.

9. For a given type of inlet, e.g. isentropic compression followed by an oblique shock, there is a specific design which gives highest engine performance at any given freestream conditions.

11. Within a given family of inlets, near-optimum engine operation can be attained with a constant contraction ratio inlet throughout the hypersonic range of the Mach numbers.

12. The penalty in engine specific impulse for using a Prandtl-Meyer inlet instead of the ideal isentropic inlet is about 3% throughout the hypersonic Mach number range.

13. For the engine investigated, an optimized scramjet inlet will produce a combustor delivery Mach number of approximately .6 that of the freestream. Devlivery temperatures are around 600K.

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