Thrust Augmenting Ejectors, Part II

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The solution of the equations representing the flow of a compressible fluid through an ejector has been shown to possess two distinctly different results after complete mixing. Part I of this study reported the analysis and described the performance of ejectors configured under the first solution where the flow after mixing is subsonic. The second solution to the ejector flow equations where the flow after mixing is supersonic provides a basis for selection of an optimal and a limiting ejector configuration for any given set of flight and injected gas characteristics. These special ejector configurations provide very high ideal thrust augmentations while translating from zero to supersonic velocities. Maps showing this ideal performance over large ranges of flight and injected gas characteristics are presented. Consideration is given to the influence of realistic, nonisentropic outlets as required for starting the supersonic flow (swallowing the starting shock wave) and for return of the supersonic mixed flow to ambient pressure. The data presented are limited to ejectors having a constant area mixing duct whose cross section is equal to 25 times that of the minimal area of the exhaust flow from the gas generator.

Nomenclature

a	= primary jet area
a_*	= primary jet throat area or area at ambient pressure exhaust
M	= Mach number
$\dot{m}$	= mass flow rate
P_0	= stagnation pressure
P	= pressure
r	= entrainment or mass flow ratio ($=\dot{m}_i/\dot{m}_p$)
S	= total entropy
T	= temperature
T_0	= stagnation temperature
U	= secondary or mixed flow velocity
V	= primary or injected flow velocity
X	= duct width or area
α	= area ratio ($=X_2/a_1$)
α_*	= area ratio ($=X_2/a_*$)
γ	= ratio of specific heats (C_p/C_v), $=1.4$ for data presented
ΔP	= primary jet pressure rise ($=P_{0p}-P_{0\infty}$)
ΔS	= total entropy production due to mixing
ΔT	= primary jet temperature rise ($=T_{0p}-T_{0\infty}$)
ϕ	= thrust augmentation

Subscripts

i	= induced or secondary flow
p	= primary flow
1,2,3	= ejector stations
∞	= ambient or freestream conditions

Introduction

A COMPRESSIBLE flow analysis of the flow through a thrust augmenting ejector has been described in Ref. 1 for ejectors in which the mixing process occurs in a duct of constant cross section. In that analysis it was shown that the flow after complete mixing has two distinctly different characteristics, depending upon which solution to the flow equations is chosen. One flow is always subsonic or sonic after mixing, regardless of the characteristics of the two flows at the start of the mixing process. This situation is called the first solution, and the performance of ejectors designed under this solution has been discussed in Part I.

The second solution results in a supersonic or sonic flow after mixing, regardless of the characteristics of the two flows at the start of mixing. This second solution, although previously described by Keenan et al.,[2] has not been utilized in the analysis or the design of thrust augmenting ejectors prior to the disclosure by the present authors in Ref. 3. One possible reason for this neglect appears to be related to the fact that the second solution, under certain conditions, represents flows which violate the Second Law of Thermodynamics. However, there do exist practical conditions at which the second solution represents realistically achievable flows having very desirable ejector performance, and which do not violate the Second Law of Thermodynamics.

Using the notation and station designation described on Fig. 1, the analyses presented in Refs. 1 and 3 provide a means for the determination of the performance and specification of the geometry of thrust augmenting ejectors designed under either the first or second solution and operating under any given set of flight and injected gas conditions. Under the assumption of constant area mixing, ejector geometry consists of the cross section of the mixing duct (X_2) in relation to that of the minimum cross section (a_*) of the mass flow from the gas generator, and the general shapes of the inlet and outlet.

The minimum cross section (a_*), as defined in this document, is either the throat area of the gas generator's discharge to ambient pressure when the pressure ratio is supercritical, or the exit area of the gas generator's discharge to ambient pressure when the pressure ratio is subcritical. The general shape of the inlet and outlet are determined from the requirement for isentropic ingestion of the secondary flow and the discharge of the mixed flow through the inlet and outlet, respectively, as described by the analysis. Thrust augmentation is defined as the ratio of the net thrust of the ejector to the net isentropic thrust of its gas generator operating as a free jet at the same flight condition and utilizing the same mass flow and stagnation conditions as those of the primary jet of the ejector.

With any given set of flight and injected gas characteristics, and mixing duct size in relation to the cross section of the primary flow, there exist certain specific ejector inlet and outlet geometries which provide either a local maximum performance or a limiting performance. The local maximum refers to an ejector configuration which produces a local mathematical maximum thrust augmentation in the

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relationship between thrust augmentation and the Mach number of the secondary flow at the start of the mixing (M_I). This optimization procedure was discussed in detail in Ref. 1.

Under the second solution this local maximum always occurs when the secondary flow at the start of mixing is in the transonic or supersonic range. The limiting performance always occurs when the secondary flow at the start of mixing is subsonic (for all conditions examined to date). It corresponds to the situation where the total entropy of the mixed flow is equal to the sum of the total entropies of the primary and secondary flows at the start of mixing—a limit imposed by the Second Law of Thermodynamics. Obviously the inherent production of entropy or the irreversibility of the flow process due to phenomena such as skin friction, heat transfer across the ejector boundaries, vorticity production, and shock waves will alter the flow and performance from that predicted by ideal calculations at the limiting point and the local maximum point. Specific examples of the influence of major losses are presented in Part 1,[1] Ref. 3, and in this document. Other losses including the external drag due to skin friction or shock waves could have a substantial effect on overall aircraft performance, but the evaluation of those effects are intimately dependent upon the particular design and therefore are not estimated in this general study.

Ideal Performance of Second Solution Ejectors

The ideal performance of second solution ejectors is evaluated under the assumption that the primary and secondary flows enter the ejector isentropically from their source and the outlet flow discharges isentropically to ambient pressure after complete mixing. As previously indicated, the performance of thrust augmenting ejectors operating at any given set of flight and injected gas conditions is strongly dependent upon the Mach number of the secondary flow at the start of mixing. The existence of a local maximum at a transonic or supersonic secondary flow at the start of mixing and a subsonic limiting value of the Mach number of the secondary flow at the start of mixing—limited by the Second Law of Thermodynamics—have been verified by numerous computations and these criteria will be utilized in describing optimal, ideal ejector performance in the following discussions.

Second Solution Ejectors with Transonic or Supersonic M_I

The ideal performance of second solution thrust agumenting ejectors designed to operate with transonic or supersonic secondary flow at the start of mixing—at their local maximum performance point—is described on maps of constant augmentation lines plotted on surfaces of primary jet stagnation properties on Fig. 2 for flight Mach numbers of 0, 0.65, and 2. For purposes of comparison, performance at each flight speed is based upon a fixed ejector cross section (X_2) in relation to the cross section of the mass flow from the gas generator (a_*), i.e., $\alpha_* = X_2/a_* = 25$.

Ejectors which are stationary with respect to the freestream velocity component in the thrust direction must accelerate the ingested fluid to transonic or supersonic speeds when designed under this criterion. This involves a large expansion and a large recompression for ingestion and return of the flow to ambient pressure. The ideal performance of stationary ejectors requiring supersonic ingested flow at the start of mixing may be of limited practical interest and is presented for observation of performance trends as a function of flight and injected gas characteristics.

As shown on the lower part of Fig. 2, the ideal thrust augmentation of stationary ejectors designed under the transonic or supersonic M_I criterion is quite large at low primary stagnation conditions and decreases with increasing primary jet stagnation temperature and pressure. It is interesting to note however, that the local maximum performance under this criterion occurs at the upper choking

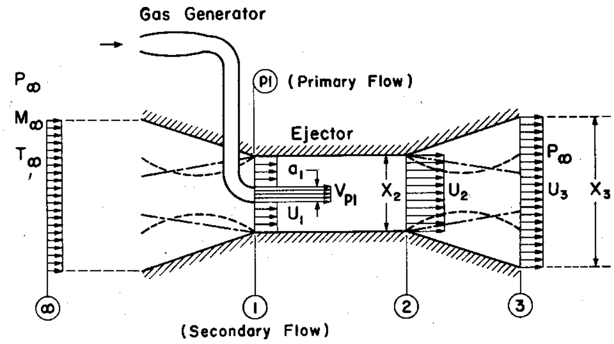

Fig. 1 Schematic representation of ejector.

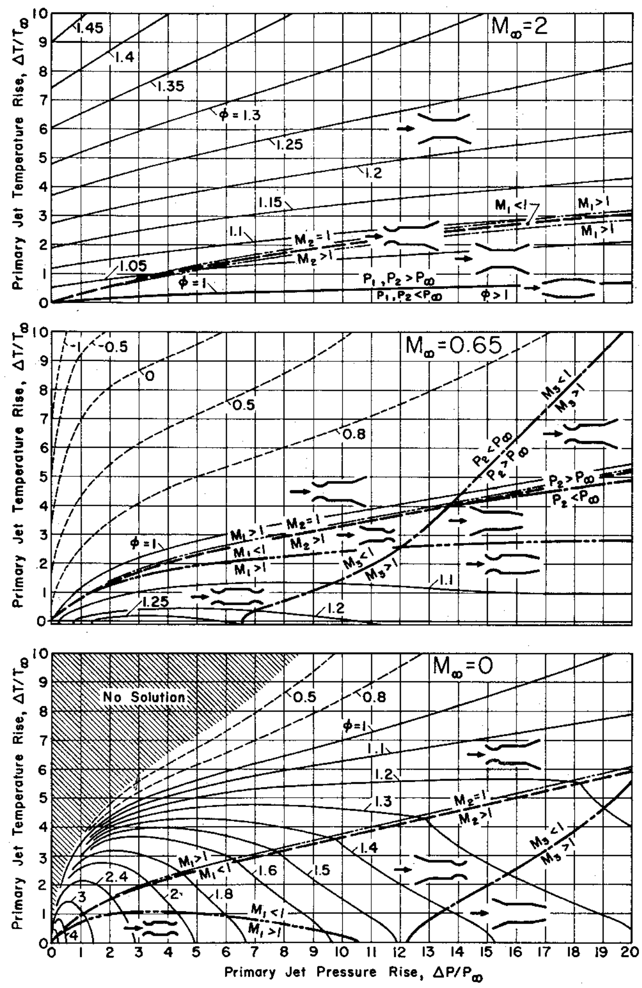

Fig. 2 Ideal thrust augmentation, optimal second solution ejectors with transonic or supersonic M_I; $\alpha_* = 25$.

point when the injected gas stagnation temperature is large. At higher temperatures, the optimization procedure for ejectors designed under this criterion results in nonproductive performance ($\phi < 1$, as shown by the dashed lines), and eventually the solution vanishes, as illustrated by the cross-hatched portion of the figure, due to a deficiency of the mixed flow kinetic energy required to return the flow to ambient pressure after mixing at the upper choking point. However, it should be noted (as dicsussed in Part I) that a trivial point ($\phi = 1$) always exists at a supersonic value of M_I which can always replace the nonproductive or "no-solution" region of the map for ejectors designed under this criterion.

Ideal inlets must be accelerating (converging or converging/diverging) and outlets may be either converging, diverging, or converging/diverging, depending upon the stagnation properties of the primary jet as shown on the same figure.

The center part of Fig. 2 displays an example of the performance of second solution ejectors operating in the mid-subsonic speed range and designed under the same criterion. The primary jet stagnation pressure varies over the range $\Delta P/P_\infty = 0$ to 20 ($P_{0p}/P_\infty = 1.3283$ to 21.3283) and the primary jet stagnation temperature varies over the range $\Delta T/T_\infty = -0.0845$ to 10 ($T_{0p}/T_\infty = 1$ to 11.0845). The example in the center of Fig. 2 represents flight at a Mach number of 0.65.

The ideal thrust agumentation achievable under this design criterion for ejectors operating in the mid-subsonic speed range is very low over the entire range of primary jet stagnation conditions studied. Generally, in this mid-subsonic range of flight Mach numbers, the appearance of the map is quite similar to that of the stationary ejector ($M_\infty = 0$, shown on the bottom portion of the figure), when designed under this criterion, except for the fact that the band where $M_1 < 1$ is narrower, and the triangular region where $P_2 > P_\infty$ appears on the upper right hand corner of the map. This appears to be a result of the similarity of the accelerating inlets which are required for these two flight Mach numbers. Evidently the large acceleration of the secondary flow prior to mixing is not desirable in terms of achievable performance.

At supersonic flight speeds, the use of transonic or supersonic secondary flow at the start of mixing becomes of practical interest, since in most cases the inlet need be only converging or diverging and the difficulty of providing a sonic throat is avoided. Under these conditions the beneficial effects of high temperature injected gas and ram compression combine to provide very acceptable performance.

The upper part of Fig. 2 is a map of isoaugmentation lines for ejectors designed under the second solution with the transonic or supersonic M_1 optimization criterion and translating at a Mach number of 2. Contrary to the relationship illustrated for subsonic flight speeds, the ideal thrust augmentation increases with increasing primary jet stagnation temperature and a compressive inlet ($P_1 > P_\infty$) and an accelerating outlet ($P_2 > P_\infty$) are required for ideal performance over most of the range studied. The optimal augmentation occurs at the upper choking point ($M_2 = 1$) in most regions of the map. In the region representing low-temperature injected gas, the optimal thrust augmentation occurs at mixed flow Mach numbers larger than 1.0, but this region also provides very poor performance, as indicated. Thus at this speed, ejectors have their most favorable characteristics when driven by high temperature gas generators operating at their upper choking point. It should be noted that the narrow band where $M_1 < 1$, represents a convergent/divergent inlet which is required to compress the freestream to a subsonic value of M_1 to achieve the optimal performance. Since the performance when $M_1 = 1$ within this band is only degraded slightly from the optimal value shown on the map, the narrow band with convergent/divergent inlets can be replaced with convergent inlets without noticeable alteration to the appearance of the map.

Effect of Translational Motion

The influence of flight Mach number on the performance of thrust augmenting ejectors can be illustrated more effectively by mapping isoaugmentation lines on a surface of flight Mach number vs injected gas pressure ratio, for a fixed primary jet stagnation temperature ratio. Maps of this type were prepared for second solution ejectors at two temperatures ratios. The first was that corresponding to a laboratory condition where the primary jet is derived from stored, compressed air. For that case the stagnation temperature of the pressurized air is assumed equal to the ambient temperature. The second temperature ratio selected for mapping was that corresponding to a moderate temperature in view of materials limitations imposed by conventional model fabrication techniques for sea level laboratory testing. For that case the stagnation temperature is assumed to be 816°C (1500°F) at sea level conditions.

Cold Primary Gas Ejectors

Figure 3 presents the ideal thrust augmentation of an ejector, assuming the geometry of the ejector is that derived from the second solution with optimal transonic or supersonic secondary flow at the start of mixing. Under the conditions shown on Fig. 3, the thrust augmentation achievable at high flight Mach numbers is small. The assumption that the primary gas stagnation temperature is equal to that of the ambient temperature represents a cooled primary gas, since

$$\frac{\Delta T}{T_\infty} = \frac{T_{0p} - T_{0\infty}}{T_\infty} = -\frac{\gamma - 1}{2} M_\infty^2 \text{ when } T_{0p} = T_\infty \quad (1)$$

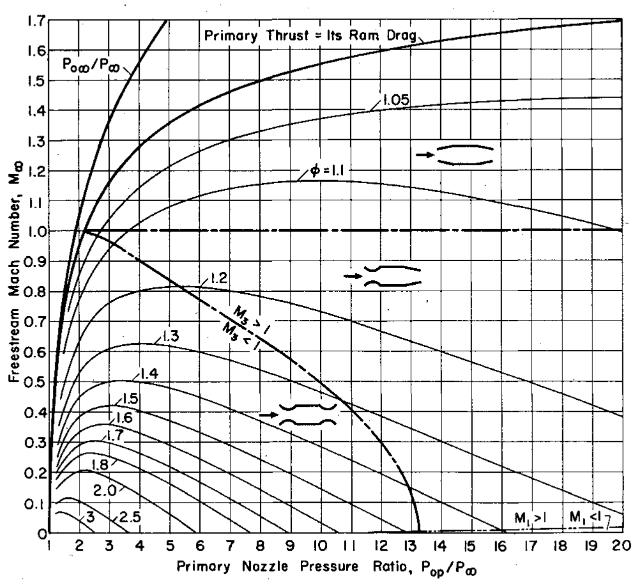

Fig. 3 Ideal thrust augmentation, optimal second solution ejectors with transonic or supersonic M_1; $\alpha_* = 25$, $T_{0p} = T_\infty$.

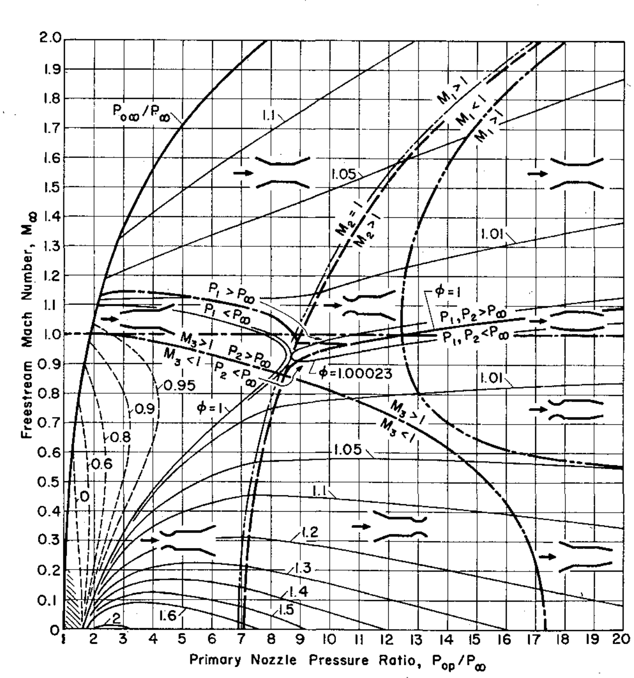

Fig. 4 Ideal thrust augmentation, optimal second solution ejectors with transonic or supersonic M_1; $\alpha_* = 25$, $T_{0p}/T_\infty = 3.7$.

As a result of the cooled primary jet gas, the primary jet stagnation pressure must be higher than that of the freestream stagnation pressure if the net thrust of air-breathing gas generators are to be positive ($V_{p\infty} > U_\infty$). The line representing $V_{p\infty} = U_\infty$ is marked as "primary thrust = its ram drag." As indicated, performance at high freestream Mach numbers is limited by the available primary jet momentum corresponding to the low-temperature injected gas. However, large thrust augmentations are achievable at lower translational speeds.

The geometries of the inlet and outlet are depicted schematically on Fig. 3, assuming isentropic flow through the inlet and outlet. Since $M_2 > 1$, $P_1 < P_\infty$, and $P_2 < P_\infty$ over the entire map, the inlets are all accelerating and the outlets are supersonic diffusers.

Heated Primary Gas Ejectors

The ideal thrust augmentation of ejectors operating with heated primary injected gas at a stagnation temperature ratio of 3.7 [equivalent to 816°C (1500°F) at sea level], and designed under the second solution at the optimal transonic or supersonic M_1 is shown on a surface of flight Mach number vs primary jet pressure ratio on Fig. 4. Since the temperature ratio is fixed, the corresponding temperature at high altitude will be much smaller. For example, at an altitude of 11 km (36,000 ft) the stagnation temperature would be only 528°C (982°F).

Under the conditions stated on Fig. 4, the performance of ejectors designed under this criterion is divided by a band in which the maximum thrust augmentation is 1.00023. The right portion of this band surrounds the line in which $P_1 = P_2 = P_\infty$ for the unchoked mixed flow ($M_2 > 1$). The performance inside the left portion of this band is mostly "nonproductive" ($\phi < 1$, dashed lines) or "no solution" (shaded area) exists and can be replaced by the trivial point $\phi = \alpha = 1$, $\Delta S = r = 0$, as discussed earlier. Comparison of this band and a similar band which exists on the optimum first solution shown in Part I of this document[1] indicates a close relationship. As illustrated on Fig. 4, ejectors operating below this band have characteristics which are similar to those with cold primary jet injection (Fig. 3). These ejectors generally require accelerating inlets for ingestion of subsonic freestream flow and supersonic diffusers as outlets. Ejectors operating above this band generally require compression inlets for ingestion of supersonic freestream flow and supersonic (accelerating) nozzles to discharge the mixed flow.

Since the assumed primary jet stagnation temperature ratio is only 3.7, which is not very high for supersonic flight, relatively low ejector thrust augmentation can be expected at high flight speeds as illustrated on Fig. 4 and the top portion of Fig. 2.

Limiting Second Solution Ejectors (Subsonic M_1, $\Delta S = 0$)

As described in Refs. 1 and 3, the ideal change of total entropy decreases from some positive value to negative values as the Mach number of the secondary flow at the start of mixing decreases below its lower choking point or below 1, when the second solution is utilized. The point where the total entropy change becomes zero is a limit under the Second Law of Thermodynamics and therefore the range of smaller values of secondary flow Mach numbers is not considered in this document. Maps have been prepared for ejectors operating under this limiting condition. Figure 5 illustrates the variation of thrust augmentation on a surface of primary jet stagnation properties for this type of ejector having area ratios (α_*) of 25 and flight Mach numbers of 0, 0.65, and 2.

The lower portion of Fig. 5 illustrates the thrust augmentation achievable by ideal second solution ejectors at the limiting point, operating at rest or thrusting normal to the undisturbed stream. Ideal thrust agumentations are very large over the entire practical range of primary jet stagnation conditions and decreases slightly with increasing stagnation

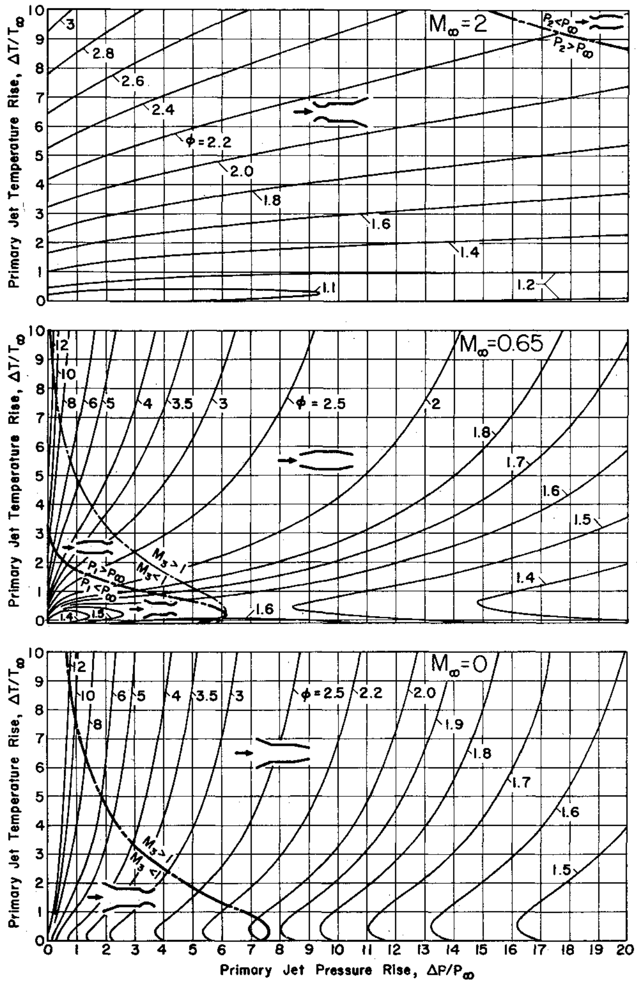

Fig. 5 Ideal thrust augmentation, limiting second solution ejectors; $\alpha_* = 25$.

pressure. It is important to observe that the ideal thrust augmentation increases with increasing primary jet stagnation temperature over most of the range studied, as illustrated on Fig. 5.

The inlet geometry for stationary ejectors designed under this limiting criterion is always convergent, since the flow must be accelerated from zero velocity only to a subsonic speed prior to mixing. However, since $P_2 < P_\infty$ over the entire map the outlet is either converging (supersonic discharge) or converging/diverging (supersonic diffuser for subsonic discharge) to achieve isentropic return to ambient pressure.

Second solution ejectors with secondary flow Mach numbers at the limit point where the total entropy change is zero, display very excellent performance in the mid-subsonic range of flight speed, particularly with heated primary injection. The center portion of Fig. 5 is a map of ideal isoaugmentation lines on a surface of primary jet stagnation characteristics, for second solution ejectors designed under this criterion. As shown, the ideal thrust augmentation achieves very large values over the entire range of primary jet characteristics, with maximum performance at the low stagnation pressure and high stagnation temperature region. Ideal thrust augmentation increases with increasing primary jet stagnation temperature at virtually all regions of the map. Thus the best performance is achieved with a ramjet-type gas generator, although excellent ideal thrust augmentation is available with turbojet- or turbofan-type gas generators.

The ejector geometry required for ideal flow patterns is also shown schematically on the same portion of Fig. 5. The inlet is required to accept freestream flow and to provide for the achievement of the limiting subsonic secondary flow Mach

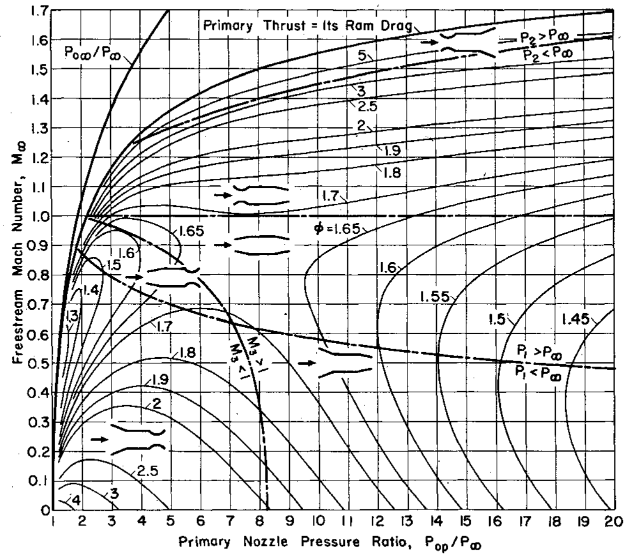

Fig. 6 **Ideal thrust augmentation, limiting second solution ejectors;** $\alpha_* = 25$, $T_{0p} = T_\infty$.

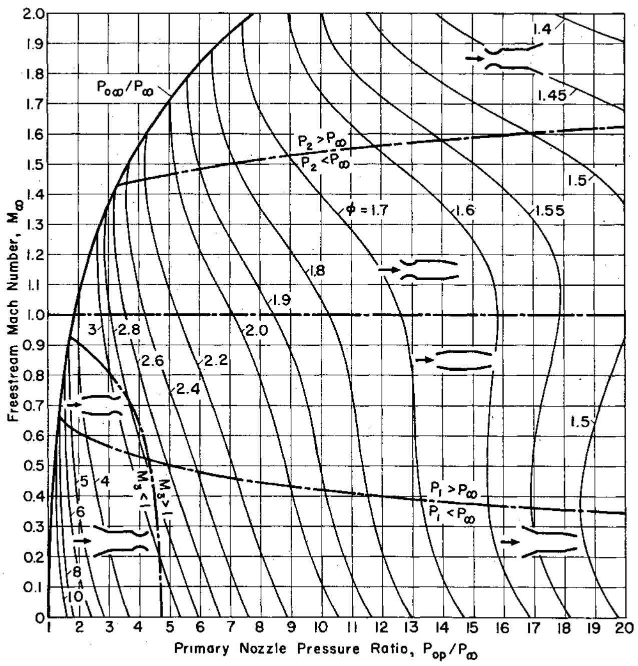

Fig. 7 **Ideal thrust augmentation, limiting second solution ejectors;** $\alpha_* = 25$, $T_{0p}/T_\infty = 3.7$.

number at the start of mixing. In the mid-subsonic flight speed range this requires either converging (accelerating) or diverging (diffusing) inlets, since the secondary flow at the start of mixing is subsonic throughout the ingestion process. Since $P_2 < P_\infty$ over the entire map, the outlet required for return of the supersonic mixed flow to ambient pressure may be a converging supersonic diffuser (at high primary nozzle pressure ratios), or a converging/diverging supersonic diffuser (at lower primary nozzle pressure ratios).

As flight speed increases to supersonic values, the performance of second solution ejectors with subsonic secondary flow at the start of mixing continues to display excellent ideal thrust agumentation over most of the practical range of injected gas characteristics.

The top part of Fig. 5 is a map of isoaugmentation lines on a surface of primary jet stagnation characteristics, for limiting second solution ejectors operating at a flight Mach number of 2. The advantage previously observed, resulting from high temperature primary gas injection at supersonic speeds, is very evident in ejectors designed under this criterion. As illustrated, the maximum ideal performance occurs at high stagnation temperatures and low primary jet stagnation pressure ratios, with a slow decrease in performance resulting from increasing primary jet pressure ratios.

Due to the requirement for isentropic compression from supersonic to subsonic flow at the inlet, it is necessary that this element of the ejector be a convergent/divergent supersonic diffuser. As an alternative, a shock wave system can be employed to achieve the required flow at the start of mixing with a compromise in performance. Design of such inlets is not uncommon, since conventional engine inlets for supersonic aircraft pose the same problem. The compromised performance encountered by the use of nonisentropic inlets is very acceptable as discussed earlier in Part I of this document.[1] Outlets required to return the mixed supersonic flow to ambient pressure are very simple and consist primarily of divergent supersonic nozzles since $P_2 > P_\infty$ except for injected gas conditions corresponding to the top right corner of the map where $P_2 < P_\infty$ and convergent supersonic diffusers are required.

Effect of Translational Motion

Isoaugmentation lines were plotted on a surface of flight Mach number vs primary nozzle pressure ratio for second solution ejectors designed under the limit point ($\Delta S = 0$) and operating with fixed temperature ratio injected gas and $\alpha_* = 25$. Temperature ratios representing cold gas ($T_{0p}/T_\infty = 1$) and heated gas ($T_{0p}/T_\infty = 3.7$) were utilized.

The situation where $T_{0p}/T_\infty = 1$ represents gas that is stored in a pressure vessel and cooled below its isentropic compression temperature. Thus it is not comparable to flight conditions, but is considered useful for purposes of laboratory investigations. The situation where $T_{0p}/T_\infty = 3.7$ represents injected gas with heat added after compression. The temperature ratio chosen represents 816°C (1500°F) at sea level, a temperature which is easily achievable with materials used in conventional model fabrication.

Cold Primary Gas Ejectors

Figure 6 illustrates the ideal limiting performance of second solution ejectors with cold, pressurized primary gas ($T_{0p} = T_\infty$). It is extremely interesting to note that under these conditions, the thrust augmentation is very high over most of the range of flight conditions and pressure ratios illustrated on Fig. 6. This is due to the fact that under the condition where $T_{0p} = T_\infty$, the secondary flow stagnation temperature is higher than that of the primary fluid (except during stationary operation, where the stagnation temperatures are equal) and the influence of heat addition previously discussed as being beneficial to ejector performance is also operative at high flight speeds in this reverse situation. As indicated and previously discussed, cold primary gas is not representative of high flight Mach number/low primary nozzle pressure ratio conditions due to the absence of net injected momentum when air-breathing gas generators are considered.

Heated Primary Gas Ejectors

Figure 7 illustrates the ideal performance of limiting second solution ejectors with heated primary gas injection. The primary gas is assumed to have a temperature ratio of 3.7, which is equivalent to a stagnation temperature of 816°C (1500°F) at sea level conditions, and 528°C (982°F) at an altitude of 11 km (36,000 ft). Temperatures encountered in high speed propulsion systems can be considerably larger than these, therefore the temperature ratio of 3.7 can not represent a realistic situation for high speed flight.

As illustrated on Fig. 7, the ideal thrust augmentation is very large over most of the range of conditions depicted, despite the limitation of primary jet stagnation temperature utilized for this map. It is important to recognize that at a freestream Mach number of 2 for example, the freestream stagnation temperature ratio is 1.8. Thus the value of $\Delta T/T_\infty = 1.9$ at the conditions utilized for Fig. 7 is a small value compared to those which exist in modern propulsion systems during supersonic flight. Therefore the advantage attributed to the injection of hot gas (equivalent to those encountered in propulsion systems during high speed flight) is not clearly evident on Fig. 7.

As can be observed on Fig. 7, subsonic discharge occurs only during subsonic flight with relatively low primary nozzle pressure ratios. Thus in that region of the map outlets are supersonic convergent/divergent diffusers. For flight Mach numbers above about 1.5, the appropriate outlets are accelerating supersonic nozzles. However, at supersonic freestream Mach numbers the inlets required for isentropic ingestion are convergent/divergent supersonic diffusers as required to compress the freestream flow to the limiting subsonic flow.

Nonisentropic Second Solution Ejector Outlets

The flow after complete mixing in second solution ejectors is always supersonic or sonic. Therefore, as in supersonic wind tunnels, special attention must be given to the starting problem. In addition, it is essential to provide an outlet geometry capable of maintaining the supersonic flow with the proper characteristics at the conclusion of mixing and with an efficient return to ambient pressure.

First consider the starting problem. Supersonic wind tunnel design practice indicates that the region downstream of the supersonic section must have a cross section which is sufficiently large to accommodate the mass flow when a normal shock wave exists in the supersonic section. The minimum area capable of "swallowing" the starting shock wave (X_s) is a function of the Mach number (M_2) and the area of the mixing section (X_2) as described in Ref. 4 for example. This relationship is

$$\frac{X_s}{X_2} = \frac{\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} M_2 \left(1+\frac{\gamma-1}{2}M_2^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}}}{\left[\frac{(\gamma+1)M_2^2}{2+(\gamma-1)M_2^2}\right]^{\frac{\gamma}{\gamma-1}}\left[\frac{\gamma+1}{2\gamma M_2^2-(\gamma-1)}\right]^{\frac{1}{\gamma-1}}} \tag{2}$$

This equation represents monotonically decreasing values of X_s/X_2 from a value of 1, as M_2 increases above 1. Thus any given value of X_s/X_2 between 0 and 1 determines a minimum supersonic value of M_2 which can satisfy the starting requirement. Therefore, the starting area ratio can be considered as one of the controlling factors for establishment of the second solution flow.

As discussed earlier there exist three isentropic outlet configurations required to return the mixed flow to ambient pressure for ideal ejector flows, as sketched on Figs. 8a-c. With consideration of the starting problem, these configurations encompass four discrete fixed geometry outlets described on Figs. 8d-g.

Obviously, if P_2 is greater than P_∞ and since M_2 is greater than or equal to 1, the outlet is a diverging nozzle and no starting problem exists since X_3 is always greater than X_2 or X_s. Thus, the isentropic oulet represents a configuration which requires no special starting adjustment and appears as illustrated schematically on Fig. 8d.

If P_2 is less than P_∞, but the mixed flow is compressed to P_∞ and results in a smaller area than X_2, but still larger than X_s, then again no starting problem exists, as illustrated schematically on Fig. 8e. For a realistic estimate of ejector performance under this condition, the system of oblique shock waves shown on Fig. 8e is included in the calculation. Obviously the length of the outlet section is a function of M_2, P_2/P_∞, and the assumed wave pattern.

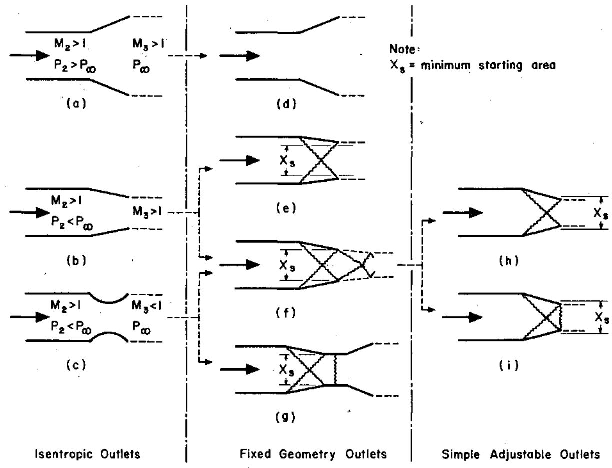

Fig. 8 Schematic outlets for second solution ejectors.

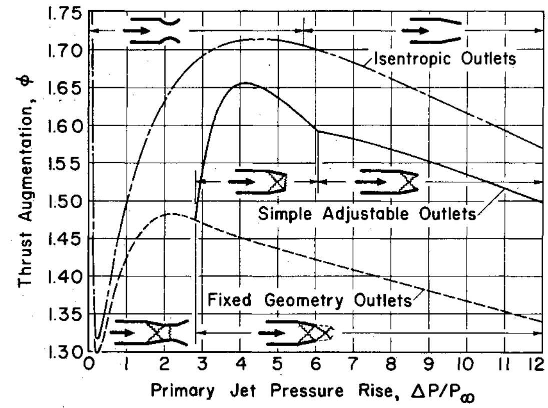

Fig. 9 Influence of outlet wave losses on performance of limiting second solution ejectors; $\alpha_* = 25$, $M_\infty = 0.65$, $T_{0p} = T_\infty$.

When the second solution isentropic outlet has a minimum area (either a sonic throat or its exit area) requirement which is smaller than X_s and results in low supersonic or subsonic velocities in order to return the mixed flow to P_∞, it is impossible to avoid outlet shock waves if the starting problem is considered. These situations result in two types of outlets as illustrated schematically on Figs. 8f and 8g.

If the flow properties are such that a normal shock wave at X_s will result in an exit pressure downstream of the shock wave which is larger than P_∞, then the final compression required to return the flow to P_∞ can be accomplished by a system of oblique shock waves, as illustrated on Fig. 8f, if the minimum starting area (X_s) is used as the exit area. As will be discussed, this situation dominates ejectors which are translating at low subsonic to low supersonic flight speeds, especially when the primary jet stagnation temperature is high.

In some instances a normal shock wave at X_s will result in a pressure downstream of the shock wave which is smaller than P_∞. In that case a weak normal shock wave at the minimum starting area followed by a subsonic diffuser is required to return the mixed flow to ambient pressure. As will be shown, this situation, described schematically on Fig. 8g, applies to ejectors that are translating at subsonic flight speeds with low primary stagnation pressures and temperatures.

When the isentropic outlet is a convergent supersonic diffuser as illustrated on Fig. 8b, the outlet can usually be replaced by outlets 8e and 8f, as far as the starting problem is concerned. Similarly outlet 8c can be replaced by outlets 8f and 8g. The situation where the mixed flow is choked ($M_2 = 1$) and $P_2 < P_\infty$ can be considered as a special case of the outlet type of Fig. 8g when $X_2 = X_s$ and the outlet wave loss is zero.

With outlet configurations as depicted on Figs. 8d-g, the thrust of the ejector can be evaluated by conventional methods utilized for supersonic jets. Figures 8d, 8e, and 8g represent configurations in which the exit pressure is equal to the ambient prressure. In these cases the net ejector thrust is simply

$$F_{ej} = (\dot{m}_i + \dot{m}_p)(U_{exit} - U_\infty) \tag{3}$$

However, for ejector outlet configurations similar to those shown on Fig. 8f, the final flow after the pressure returns to ambient is unknown and the ejector thrust must be evaluated in terms of its exit conditions as follows:

$$F_{ej} = (\dot{m}_i + \dot{m}_p)(U_{exit} - U_\infty) + (P_{exit} - P_\infty)X_{exit} \tag{4}$$

Thrust augmentation is then defined as the ratio of the ejector's net thrust as given by Eq. (3) or (4) to that of the primary jet expanded isentropically to ambient pressure or

$$\phi = \frac{F_{ej}}{\dot{m}_p(V_{p\infty} - U_\infty)} \tag{5}$$

Fixed Geometry Outlets

Using the above method, thrust augmentations were calculated for two-dimensional fixed geometry outlets of the type illustrated on Fig. 8 with realistic shock waves for limiting second solution ejectors translating at a Mach number of 0.65 and assuming that $T_{0p} = T_\infty$ and $\alpha_* = 25$, as a particular example representing easily achievable laboratory conditions. Results shown on Fig. 9 indicate significant performance degradation compared to the ideal limiting second solution ejector as a result of this starting requirement.

Despite the adverse influence of the starting requirement, the performance of fixed geometry ejectors is considerably better than that of the ideal, optimal first solution ejector (see Part I), and second solution ejectors with transonic or supersonic secondary flow at the start of the mixing (see bottom line of Fig. 2) at the identical conditions.

Calculations to include a large range of flight Mach numbers and all types of fixed geometry outlets illustrated on Fig. 8 are presented on Fig. 10 for conditions which are identical to those of Fig. 6 ($\alpha_* = 25$ and $T_{0p} = T_\infty$). These fixed geometry outlets provide excellent thrust augmentation over virtually the entire range of flight speeds from the stationary case to supersonic speeds despite the use of cold injected gas and consideration of the outlet wave losses.

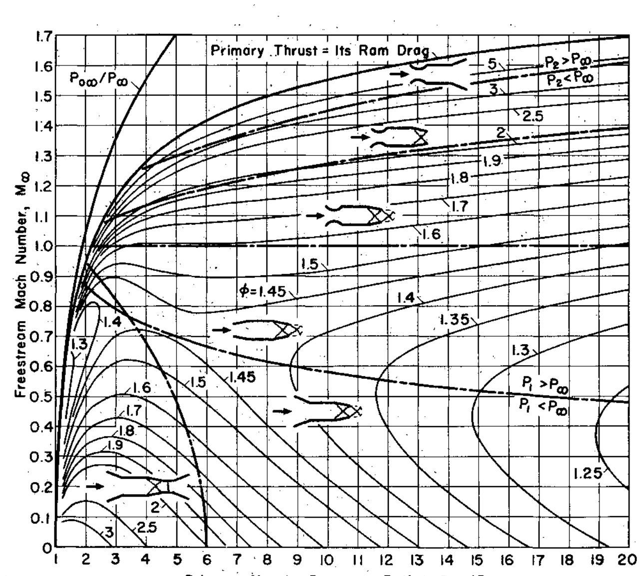

Fig. 10 Performance of limiting second solution ejectors with fixed geometry outlets; $\alpha_* = 25$, $T_{0p} = T_\infty$.

The discussion of the influence of outlet wave losses on the performance of the second solution ejectors will be based upon the limiting second solution ejector criterion because this limiting point is uniquely determined from the parameters in the mixing duct and is independent of outlet losses. On the other hand, the procedure to determine the local optimal performance of the second solution ejector with transonic or supersonic M_l depends on the consideration of outlet wave losses.

Simple Adjustable Outlets

The simple adjustable outlet consists of a flat surface (in a two-dimensional ejector) on either side of the outlet, capable of very small rotation only, as illustrated on Figs. 8f, 8h, and 8i. The concept can conceivably be generalized to axisymmetric situations. In the starting configuration these surfaces are adjusted to provide the required minimum starting area (similar to Fig. 8f; however, the wave pattern is more complex than that shown on Fig. 8f if the length of the rotating surfaces remains unchanged). The surfaces can then be rotated to reduce the outlet area. The reduction of outlet area results in a reduction of the Mach number and an increase of the static pressure at the exit section. Obviously, the Mach number inside the exit section is still supersonic. When the increase of static pressure is sufficient to return the mixed flow to ambient pressure, the external starting oblique wave system will be eliminated during the outlet area adjustment, and the wave pattern associated with the cruise configuration will appear as shown on Fig. 8h, which has a supersonic exit flow. When the increase of static pressure is not sufficient to return the mixed flow to ambient pressure, the external starting oblique wave systems will require larger wave angles, due to the decreasing Mach number, and finally form a normal shock wave at the exit section during the outlet area adjustment as illustrated on Fig. 8i. Since the final compression of the mixed flow is accomplished by a normal shock wave, the discharged flow is subsonic. The final flow at ambient pressure can be determined from the outlet wave pattern and the flow parameters at station 2. The net ejector thrust and thrust augmentation can then be calculated as indicated by Eqs. (3) and (5).

The performance of limiting second solution ejectors with simple adjustable outlets and shock wave patterns corresponding to those illustrated on Figs. 8h and 8i is also illustrated on Fig. 9 as discussed earlier. As indicated on Fig. 9, the achievable thrust augmentation of the ejectors with simple adjustable outlets indicates a recovery of most of the wave losses due to the starting requirement when applicable. Some degradation due to the outlet wave losses can still be observed as the difference between the thrust augmentation of the simple adjustable outlet and the isentropic outlet ejectors.

Where applicable, the simple adjustable outlet offers a practical solution to the nonisentropic outlet for second solution ejectors. The applicable region for simple adjustable outlets with cold gas injection can be visualized by recognition of the fact that outlet wave patterns similar to the illustration on Fig. 8f can be advantageously adjusted to a reduced area (smaller than the starting area) for improved performance. Thus, for example, the simple adjustable outlet is applicable over the wide region shown in Fig. 10 where the outlet wave pattern is similar to that of Fig. 8f. As shown on Fig. 10, for cold primary gas ejectors, the region of applicability for the simple adjustable outlet is restricted to relatively high primary nozzle pressure ratios at low freestream Mach numbers. However, with larger primary jet stagnation temperatures, this restriction is diminished and the region of applicability of the simple adjustable outlet extends to lower primary jet pressure ratios.

Figure 11 illustrates the performance of ejectors with fixed and simple adjustable outlets on a pressure/temperature map for second solution ejectors under the limiting criterion at a freestream Mach number of 0.65 and $\alpha_* = 25$. The solid lines are isoaugmentation lines at the cruise configuration for the

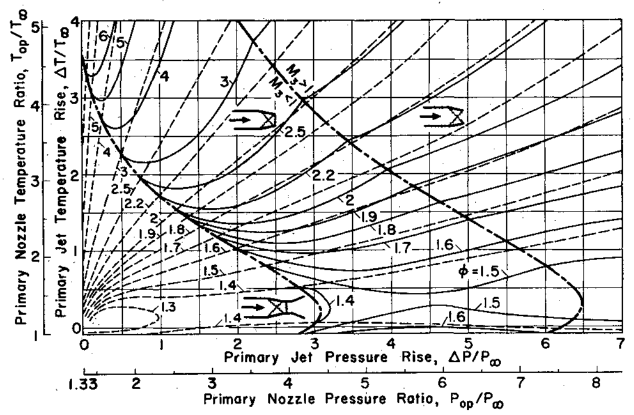

Fig. 11 Performance of limiting second solution ejectors with outlet wave losses; $\alpha_* = 25, M_\infty = 0.65$.

simple adjustable outlet while the dashed lines are isoaugmentation lines for the fixed geometry outlets. The performance of ejectors with isentropic outlets configured and operating under corresponding conditions has been illustrated on the lower left corner of the center portion of Fig. 5. As can be observed on Fig. 11, the region of applicability for the simple adjustable outlet is significantly extended to lower primary nozzle pressure ratios as the primary jet stagnation temperature is increased. Both the fixed and the simple adjustable outlets provide excellent performance at high temperatures with a considerable advantage in the use of the simple adjustable outlet in its region of applicability, as shown on Fig. 11.

Figure 12 displays the performance of simple adjustable outlet ejectors (solid lines) in their cruise configuration, in their region of applicability, and the fixed geometry ejectors (dashed lines) in the remaining regions. The performance displayed on Fig. 12 is presented as isoaugmentation lines on a surface of freestream Mach number vs primary nozzle pressure ratio for a primary jet stagnation temperature ratio of 1 and $\alpha_* = 25$. The influence of outlet wave losses can be observed by comparison of Figs. 12 and 6, and the advantage of the simple adjustable outlet compared to the fixed geometry outlet can be observed by comparison of Figs. 12 and 10.

Figure 13 illustrates the ejector performance and configurations with fixed and simple adjustable outlets and with heated primary gas injection, under conditions identical to those displayed on Fig. 7. A comparison of Figs. 12 and 13 indicates that the region of applicability for the simple adjustable outlet is widened as a result of the injection of heated primary gas. In other words, the subsonic freestream velocity, low primary pressure ratio region, which requires an outlet throat and a subsonic diffuser for starting, is considerably narrowed. It also is important to note that, as shown on Figs. 12 and 13, in the region of high supersonic freestream Mach numbers ($M_\infty > 1.3$) the outlet wave losses become unimportant. However, it is also important to note that although the outlet wave losses become unimportant, the major losses during supersonic freestream motion occur at the inlet.

As previously indicated, the data presented on Figs. 12 and 13 represent ejector performance under laboratory conditions and do not represent realistic flight conditions at high speeds due to the assumed primary gas stagnation temperatures.

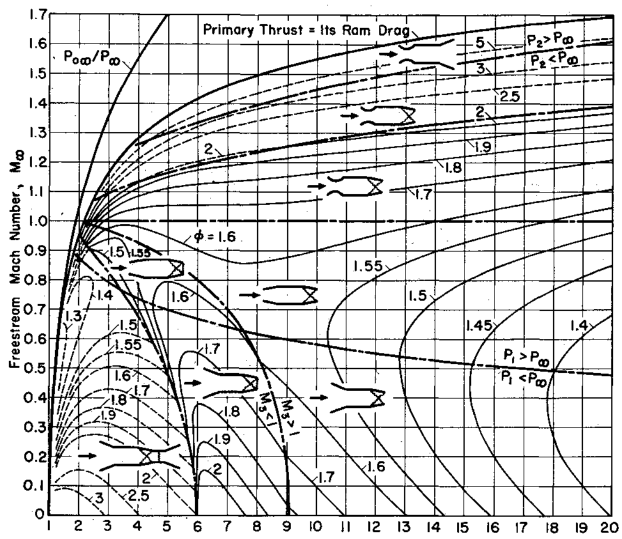

Fig. 12 Performance of limiting second solution ejectors with outlet wave losses; $\alpha_* = 25$, $T_{0p} = T_\infty$.

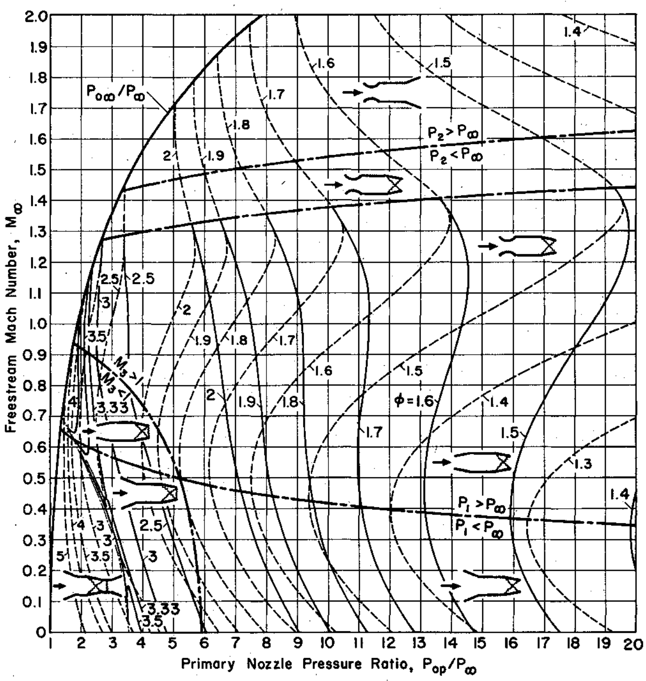

Fig. 13 Performance of limiting second solution ejectors with outlet wave losses; $\alpha_* = 25$, $T_{0p}/T_\infty = 3.7$.

Discussion

It has been shown that the performance of thrust augmenting ejectors depends strongly upon the selection of the inlet and outlet configurations in view of the flight and injected gas characteristics. Traditionally, ejectors have been designed with converging inlets and diverging outlets. This study has indicated that designs of this type are appropriate for first solution ejectors operating at low subsonic flight speeds, and for second solution ejectors operating at supersonic flight speeds. However, it should be recognized that the inlets and outlets of second solution ejectors operating at supersonic flight speeds perform the reverse function from similarly shaped inlets and outlets of first solution ejectors operating at low subsonic flight speeds. Further, it has been shown that the combination of compression inlets (for deceleration of the freestream flow prior to mixing) and high temperature injected gas dominate optimal ejector design for high speed flight.

The very high ideal performance predicted by the analysis of second solution ejectors has stimulated an investigation into the feasibility of achievement of the required flows. Since the flow after complete mixing is supersonic (or sonic), it appears essential to consider the problem of starting, which corresponds to the problem encountered in starting supersonic wind tunnels. Results of that study indicated that in the subsonic or low supersonic flight speed range a starting problem does exist. Outlet configurations required for starting (swallowing the starting shock wave) have been described, and ejector performance has been evaluated for ejectors with those nonisentropic outlet flows (with geometries which are fixed at the starting configuration). Maps were presented for ejector performance over the appropriate range of flight and injected gas characteristics.

After swallowing the starting shock wave and establishing supersonic flow in the mixing section, it is possible to minimize the wave losses by a simple adjustment of the outlet configuration (except for low flight speed, with low primary jet stagnation pressure and temperature). In a two-dimensional ejector, the adjustment of the outlet can be accomplished by a small rotation of the outlet plates. This simple adjustable outlet has been described and the thrust augmentation achievable by ejectors in that configuration has also been mapped over appropriate ranges of flight and injected gas characteristics. It has been shown that even in the range of conditions where the starting problem exists, the performance of ejectors with nonisentropic outlets, including the influence of wave losses, is not seriously degraded by the wave losses.

Acknowledgments

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