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ANALYSIS OF ROCKET-POWERED EJECTORS FOR PUMPING LIQUID OXYGEN AND LIQUID HYDROGEN

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16. Abstract

A preliminary analysis of the use of rocket-powered ejectors for pumping liquid oxygen and liquid hydrogen in rocket engines was made. The drive gas is the exhaust gas of a smaller hydrogen-oxygen rocket engine. The analysis is one-dimensional and does not include shock or friction losses. For a nominal drive rocket chamber pressure of 600 psia (4.14 N/m^2 abs), ideal discharge pressures over 2500 psia (17.25×10^6 N/m^2 abs) for oxygen and 400 psia (2.75×10^6 N/m^2 abs) for hydrogen were calculated. Ejector mass ratios (ratio of oxygen or hydrogen mass flow to drive gas flow) resulting in good performance were on the order of 300 for oxygen and 200 for hydrogen.

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SUMMARY

The application of rocket-powered ejectors for pumping liquid oxygen and liquid hydrogen was investigated. The drive fluid of the ejector is the exhaust gas of a hydrogen-oxygen rocket engine. The analysis is one dimensional. An average linear wall pressure distribution and complete mixing were assumed for the mixer analysis. Friction and shock losses were not considered. Cycle parameters were varied to determine their effect on the ejector discharge pressure. For a nominal drive rocket chamber pressure of 600 psia (4.14×10^6 N/m^2 abs) ideal pump discharge pressures over 2500 psia (17.25×10^6 N/m^2 abs) for oxygen and 400 psia (2.75×10^6 N/m^2 abs) for hydrogen were calculated. Ejector mass ratios resulting in good performance were on the order of 300 for oxygen and 200 for hydrogen. Ejector performance is highly dependent on mixer area ratio, mixer pressure ratio, and mixer wall pressure distribution. Drive rocket chamber pressure and equivalence ratio and suction liquid temperature have a small effect on discharge pressure. However, the drive rocket equivalence ratio and suction liquid temperature have a more significant effect on pump volume capability.

INTRODUCTION

The use of ejectors for pumping liquid propellants in rocket engines may be an attractive system if high discharge pressures can be obtained along with high mass flow ratios. The ejector is simple and reliable since it has no moving parts. Pumping is accomplished by the action of a high velocity drive fluid on the liquid being pumped. Although the ejector cycle efficiency is lower than that of mechanical turbopumps, it is a more simple pumping system and large savings in engine weight may be achieved by substitution of the ejector for conventional mechanical turbopumps. The potential advantages of low weight and long lifetime would be especially attractive for a low cost orbital transportation system.

A schematic of an ejector system is shown in figure 1. The drive gas or liquid is accelerated through a nozzle and enters the mixing section at a high velocity. The liquid being pumped, called the suction fluid, enters the mixer at a relatively low velocity. During the mixing process the drive gas imparts momentum to the suction liquid, and the mixed fluid leaves the mixer at a higher velocity than the suction fluid. The drive gas may or may not be condensed. The mixture then enters the diffuser where the dynamic pressure is converted to a static discharge pressure. Depending on the liquids involved, large increases in the pressure of the suction liquid are theoretically possible. For example, test results of a steam ejector (ref. 1) show that, using saturated steam at a total pressure of 200 psia (1.38×10^{6} N/m^2 abs), it was possible to pump room temperature water from 14.7 to 200 psia (10.14×10^{4} to 1.38×10^{6} N/m^2 abs). The mass ratio (ratio of mass flow of suction liquid to drive gas) was 10.3. In reference 2 an analytical and experimental study was carried out for water, alcohol, and gasoline ejector pumps. The experimental results for alcohol showed ejector discharge pressures about 10 percent higher than the drive fluid stagnation pressures for a mass ratio of 6 or 7.

The application of the ejector for pumping liquid propellants for a rocket engine has been the subject of a number of studies dating as early as 1936. In reference 3 it was suggested that part of each propellant be vaporized in the cooling jacket of the rocket engine and then be used for the drive gas of an ejector for pumping the propellant. A similar approach was used in the analytical study of reference 4 for storable propellants. The results indicated that ejector discharge pressures higher than the drive fluid stagnation pressures were theoretically obtainable with a 50 percent diffusion efficiency. In the same study the drive fluid for oxygen and hydrogen ejector pumps were assumed to be main engine combustion gases tapped from the combustion chamber and mixed with a portion of the suction liquids. The results for hydrogen were unattractive but for oxygen ejector discharge pressures higher than the main engine chamber pressure were calculated.

The present report considers another approach, one in which the drive fluid is the exhaust gas of a rocket engine. This permits a higher drive fluid energy level and

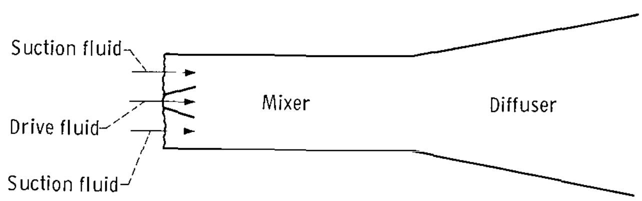

Figure 1. - Schematic of ejector.

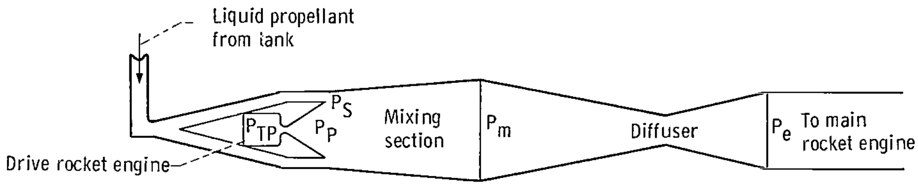

Figure 2. - Schematic of rocket propellant ejector.

therefore a much higher mass ratio capability. A schematic diagram of this system is shown in figure 2. The drive rocket engine may be located in the main propellant supply line. The drive gas can be obtained from either a separate rocket engine, or tapped from the main engine if ejector discharge pressures higher than the main engine chamber pressure can be obtained.

This report presents the results of an analytical investigation of pumping liquid hydrogen and liquid oxygen using this approach. The figure of merit used is the ejector discharge pressure. Cycle parameters were varied to determine their effect on the ejector discharge pressure. The parameters considered are shown in table I.

Since this study is of a preliminary nature, a number of simplifying assumptions were made. A one-dimensional flow model was assumed. An average linear wall pressure distribution in the mixer and complete mixing were also assumed. Friction and

TABLE I. - PARAMETERS CONSIDERED IN THE STUDY

Parameter	Range of values
Mass ratio, m_S/m_P	
Hydrogen	0 to 200
Oxygen	0 to 300
Drive rocket equivalence ratio, φ_P	
Hydrogen	1.0 to 8.0
Oxygen	0.10 to 1.0
Drive rocket exit static pressure, P_P, psia (N/m^2 abs)	30 to 45 (20.7×10^4 to 31.03×10^4)
Drive rocket chamber pressure, P_{T_P}, psia (N/m^2 abs)	60 to 1000 (41.37×10^4 to 690×10^4)
Suction liquid temperature, T_S, ^oR (K)	
Hydrogen	30 to 40 (16.65 to 22.2)
Oxygen	118 to 162 (65 to 90)
Mixer pressure ratio, P_m/P_P	1.0 to 0.04

shock losses in the mixer and diffuser were not considered. Ideal drive rocket performance was used and possible ignition problems at very low or very high equivalence ratios were not considered. It was also assumed that when complete condensation of the drive gas occurred, the thermodynamic properties of the mixture were those of liquid oxygen or hydrogen.

SYMBOLS

A	cross sectional area, ft^2; m^2
g	gravitational constant; ft/sec^2; m/sec^2
h	enthalpy, Btu/slug; J/kg
Δh	heat of vaporization
J	mechanical equivalent of heat, 778 ft-lbf/Btu; 1 N-m/J
M	Mach number
$\mathscr{M}$	molecular weight, lbm/mole; g/mole
m	mass flow rate, slug/sec; kg/sec
N	mole fraction
P	pressure, lbf/ft^2 abs; N/m^2 abs
R	universal gas constant, 1545 ft-lbf/(mole)(^{o}R); 8.31 J/(mole)(K)
S	entropy, Btu/(slug)(^{o}R); J/(kg)(K)
T	temperature, ^{o}R; K
V	velocity, ft/sec; m/sec
v	specific volume, ft^3/slug; m^3/kg
X	quality of mixture (fraction of vapor content)
γ	ratio of specific heats
ρ	density, $slug/ft^3$; kg/m^3
φ	equivalence ratio (fuel-oxidant ratio/stoichiometric fuel-oxidant ratio)

Subscripts:

e	diffuser exit
g	gas

L liquid

m mixer exit

P drive rocket

S suction fluid

T stagnation conditions

V vapor

W water

1 mixer entrance

METHOD OF ANALYSIS

Mixer Analysis

The mathematical model for this ejector is explained with the aid of figure 2. The drive rocket gas enters the mixing section at conditions specified by the drive rocket chamber pressure P_{T_P}, the drive rocket pressure ratio P_{T_P}/P_P, and the drive rocket equivalence ratio φ_P. The static pressure of the suction liquid P_S is assumed to be equal to the drive rocket nozzle exit static pressure P_P. The suction liquid is stored at a stagnation pressure of 50 psia (34.48×10^4 N/m^2 abs) and temperature T_S. For a specified equivalence ratio and chamber pressure, the thermodynamic properties of the drive rocket gas entering the mixer at the pressure P_P were determined from the method of reference 5. The thermodynamic properties of the suction fluid were determined from references 6 to 8 for the temperature T_S.

Since hydrogen and oxygen have very low vapor temperatures (162° R (90 K) for LOX and 36.7° R (20.4 K) for LH_2 at 1 atm), vaporization of these liquids may occur when they mix with the hot drive rocket exhaust gas. The particular technique of solution for the mixer exit conditions depends on whether the exit fluid is all liquid, all gas or a mixture of both. If the fluid is a liquid or mixture the conservation of mass, energy, and momentum equations are solved for a particular value of pressure yielding the other properties such as velocity and area ratio. If the fluid is a gas, the mixer exit temperature is used as the independent variable. Details of these solutions are given in the appendix.

Diffuser Analysis

If the flow at the mixer exit is a liquid, the diffuser exit pressure is

$$P_e = P_m + \left(\frac{\rho_m}{2}\right)V_m^2 \tag{1}$$

(Since the velocity at the diffuser exit is negligible, total and static conditions are assumed to be identical.) If the flow is a mixture, Mollier charts from references 6 to 8 are employed to determine P_e by following a constant entropy path from the mixer entrance conditions of P_m, h_m, and S_m, to the diffuser exit conditions at h_{T_m}.

If the flow at the mixer exit is a gas, the following isentropic relations for an ideal gas are used to determine P_e:

$$M_m = V_m\left(\frac{\mathscr{M}_m}{\gamma_m g R T_m}\right)^{1/2} \tag{2}$$

where γ_m is determined from the thermodynamic data of reference 5. Then

$$\frac{P_e}{P_m} = \left(1 + \frac{\gamma_m - 1}{2} M_m^2\right)^{\gamma_m/(\gamma_m - 1)} \tag{3}$$

and

$$P_e = P_m\left(\frac{P_e}{P_m}\right) \tag{4}$$

RESULTS AND DISCUSSION

Thermodynamic Considerations

For the ejector considered in this report the suction fluid is liquid which is drawn into the mixer and accelerated by the drive rocket jet. The mixture is compressed in the diffuser while being decelerated. A pressure is achieved that can be greater than the drive rocket chamber pressure. The available energy from the drive rocket is $m_P \int v_V \, dP_P$ which may be equated (assuming no losses) to the change in energy for the diffusion process which is $(m_P + m_S)\int v_L \, dP_{diffuser}$. Since v_L is much smaller than v_V, it is possible for the increase in pressure in the diffuser $dP_{diffuser}$ to be higher than the pressure drop in the drive rocket nozzle dP_P even though the mass of the mixture $(m_P + m_S)$ is much larger than that of the drive rocket m_P. A 100 percent conversion of the available energy to pressure does not occur because some of the kinetic energy of the drive gas is used in heating the suction liquid and possibly in some degree of vaporization. If vaporization occurs, not only is the kinetic energy of the mixture reduced but there is also a decrease in density. As mentioned previously, therefore, the kinetic energy cannot be converted to as high a pressure because of the larger specific volume of the mixture.

Figure 3 shows the mixing and diffusion paths for two cases having mass ratios of 300 (case A) and 100 (case B). The mixing process is shown as paths between h_S, P_S and h_m, P_m. The diffusion processes are the lines between h_m, P_m, and h_{T_m}, P_e following isentropic paths in both cases. Less vaporization and heating of the LOX occurs in the mixing process of case A than that of case B. This is seen by the lower quality of the flow after mixing of case A. Since the specific volume of the flow of case A is much lower than that of case B, the kinetic energy is converted to a much higher pressure at the diffuser exit. In figure 3 this is shown as a constant entropy line with a

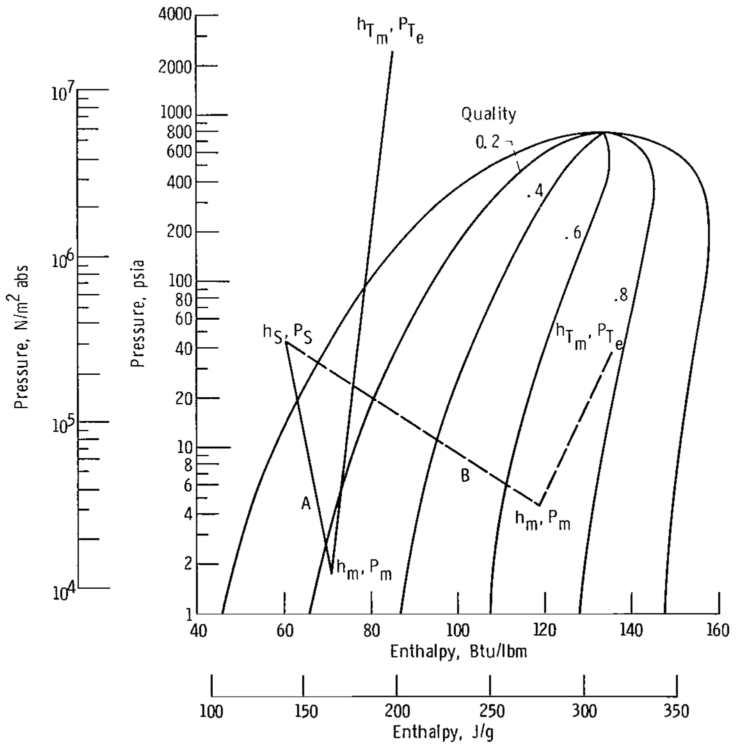

Figure 3. - Mollier diagram for oxygen.

steeper pressure enthalpy slope for case A than for case B.

It is seen therefore that as a pump the ejector operates best when the flow at the mixer exit is a liquid or low quality mixture and the mixer exit temperature is as low as possible.

The energy used in heating and the density of the flow after mixing have significant effects on the cycle parameters that will be discussed in the following sections. The cycle parameters are the mass ratio m_S/m_P, drive rocket equivalence ratio φ_P, mixer pressure ratio P_m/P_P, drive rocket chamber pressure P_{T_P}, drive rocket nozzle exit static pressure P_P, and the suction liquid temperature T_S. For convenience table II presents some physical properties of the suction liquids, LOX and LH_2.

TABLE II. - PHYSICAL PROPERTIES OF HYDROGEN AND OXYGEN

Property	Hydrogen	Oxygen
Molecular weight	2.016	32.00
Triple point values		
Temperature, ^{O}R; K	25.19; 13.994	98.18; 54.54
Pressure, psia; N/m^2 abs	1.023; 7.053×10^3	0.022; 151.69
Boiling values		
Temperature, ^{O}R; K	36.48; 20.268	162.34; 90.19
Pressure, psia; N/m^2 abs	14.7; 1.014×10^4	14.7; 1.014×10^4
Critical point values		
Temperature, ^{O}R; K	45.97; 25.54	278.92; 154.96
Pressure, psia; N/m^2 abs	187.67; 1.294×10^6	736.3; 5.08×10^6
Heat of vaporization, Btu/lbm; J/g	192; 447.6	91.5; 213.28
Liquid specific heat, Btu/(lbm)(^{O}R); J/(g)(K)	1.72; 9.47	0.423; 1.7
Density, lbm/ft^3; kg/m^3	4.42; 70.8	71.24; 1141.1

Liquid Oxygen Ejector

Effect of mass ratio and drive rocket equivalence ratio. - A decrease in mass ratio decreases the amount of LOX that must be accelerated to the mixer exit velocity by the drive rocket gas. The mixer exit velocity therefore increases. However, the degree of vaporization increases and the density decreases with decreasing mass ratio.

The drive rocket equivalence ratio has a similar effect. As the drive rocket equivalence ratio is increased up to an equivalence ratio of one, the available energy from the drive rocket increases but the energy expended in heating and vaporization of the suction fluid also increases.

Figure 4 shows the effect of drive rocket equivalence ratio φ_P and ejector mass ratio m_S/m_P on the discharge pressure. The suction liquid LOX is at a temperature of 162^{O} R (90 K) which is the saturation temperature at 1 atmosphere. However, the tank

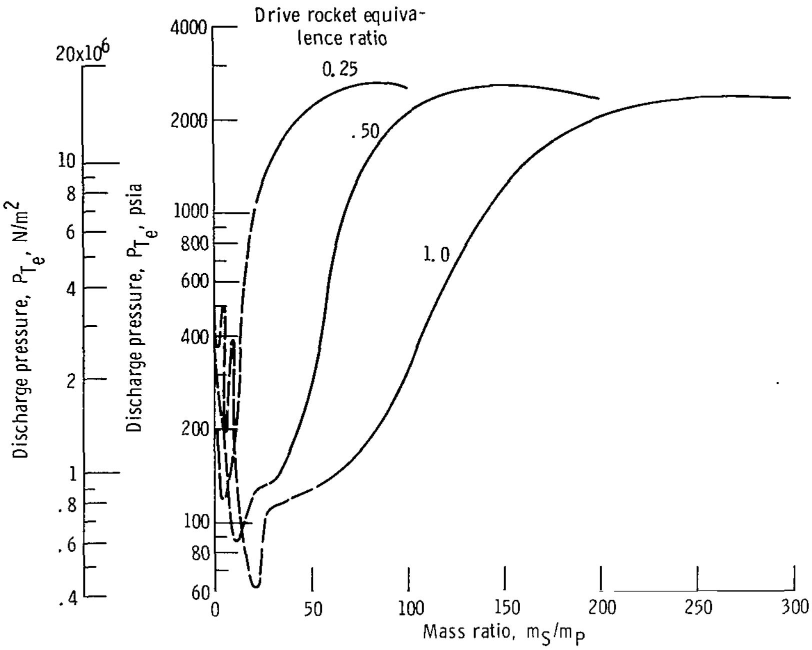

Figure 4. - Effect of drive rocket equivalence ratio and mass ratio on LOX ejector discharge pressure. LOX total pressure, 50 psia (34.48×10^4 N/m^2 abs); LOX temperature, 162° R (90 K); drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs); mixer exit pressure, 2 psia (1.38×10^4 N/m^2 abs).

is pressurized to 50 psia (34.48×10^4 N/m^2 abs) so that the oxygen is in effect subcooled. The drive rocket engine has a chamber pressure of 600 psia (4.14×10^6 N/m^2 abs) and a nozzle exit static pressure of 45 psia (31.03×10^4 N/m^2 abs). The dashed portions of the curves indicate complete vaporization of the LOX and the flow at the mixer exit is a gas. At mass ratios in the solid part of the curves the flow is a mixture of liquid and vapor which decreases in quality with increasing mass ratios.

At a mass ratio of zero the theoretical discharge pressure is equal to the drive rocket chamber pressure of 600 psia (4.14×10^6 N/m^2 abs). As the mass ratio increases, the amount of drive rocket energy used in heating and vaporization increases resulting in the rapid decrease in discharge pressure shown in figure 4. The two maxima points result from the energy release caused by condensation and freezing of the primary rocket water vapor.

In the solid part of the curves where the flow is a mixture the vaporization loss decreases and the mixer exit density increases with increasing mass ratio. The discharge pressure is seen to increase until a maximum is reached. After this point the quality of the mixture is low and decreases slowly with further increases in mass ratio. However, the mixer exit velocity continues to decrease due to the increasing amount of suction liquid that is accelerated to the mixer exit velocity. Therefore, as seen in figure 4 the discharge pressure decreases with further increases in mass ratio.

The mass ratio that maximizes the discharge pressure also increases with increasing drive rocket equivalence ratio. The maximum discharge pressures decrease moderately as drive rocket equivalence ratio increases. The exit pressures are about four times higher than the total pressure of the drive rocket. For the conditions assumed bleeding drive gas off the main rocket engine might be feasible.

Effect of mixer pressure ratio. - A decrease in the mixer exit pressure increases the mixer exit velocity, thereby increasing the kinetic energy that may be converted to pressure in the diffuser. To investigate this further the mixing pressure ratio was varied to determine this effect on the ejector discharge pressure. In practice such changes in mixer exit pressure would be achieved by varying the cross-sectional area of the mixer. Figure 5 shows the variation of pump discharge pressure with mixer pressure ratio. At a pressure ratio of 1.0 the discharge pressures are slightly greater than the drive rocket nozzle exit static pressure. As mixer pressure ratios decrease, the diffuser exit pressure also decreases to values less than the drive rocket exit static pressure. A minimum diffuser exit pressure is attained at about a P_m/P_p of 0.3, where the rapid increase in kinetic energy (proportional to the square of the mixer exit velocity) begins to

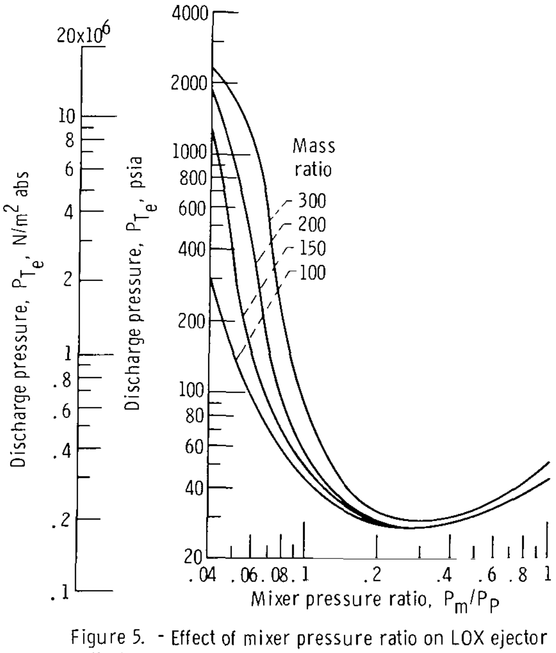

Figure 5. - Effect of mixer pressure ratio on LOX ejector discharge pressure. LOX total pressure, 50 psia (34.48×10^4 N/m^2 abs); LOX temperature, 162 R (90 K); drive rocket equivalence ratio, 1.0; drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs).

offset the decreasing mixer exit pressure. Thus the drive rocket exit pressure is seen to increase rapidly at pressure ratios less than 0.3.

For mixer pressure ratios between 0.2 and 1.0, where kinetic energy conversion in the diffuser is small, mass ratio is seen in figure 5 to have a small effect on diffuser exit pressure. The slope of the isentropic lines as illustrated in figure 3 is not important where the isentropic paths are small. For mixer pressure ratios below 0.2, the effect of mass ratio increases, corresponding to the trends noted in the discussion of figure 4.

Figure 6 shows the variation of mixer exit velocity with pressure ratio. The velocity is seen to increase with decreasing mass ratio and pressure ratio. Also indicated in the figure are the mixer exit Mach numbers. It is seen that at a mixer exit pressure ratio of 0.04 where high discharge pressures result, mixer exit Mach numbers are on the order of 3.5. Subsonic flow is not found until pressure ratios are from 0.5 to 1 where ejector performance is poor. Therefore, to obtain high discharge pressures, mixing occurs in a supersonic stream. In practice, this could lead to added problems in mixing and diffusion that are not encountered in subsonic flow.

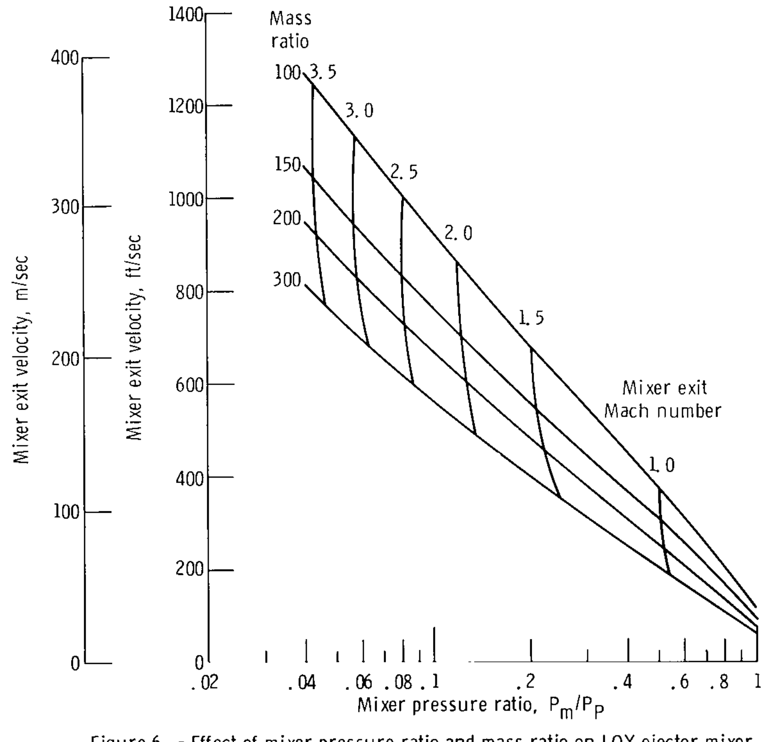

Figure 6. - Effect of mixer pressure ratio and mass ratio on LOX ejector mixer exit velocity. LOX total pressure, 50 psia (34.48×10^4 N/m^2 abs); LOX temperature, 162° R (90 K); drive rocket equivalence ratio, 1.0; drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs).

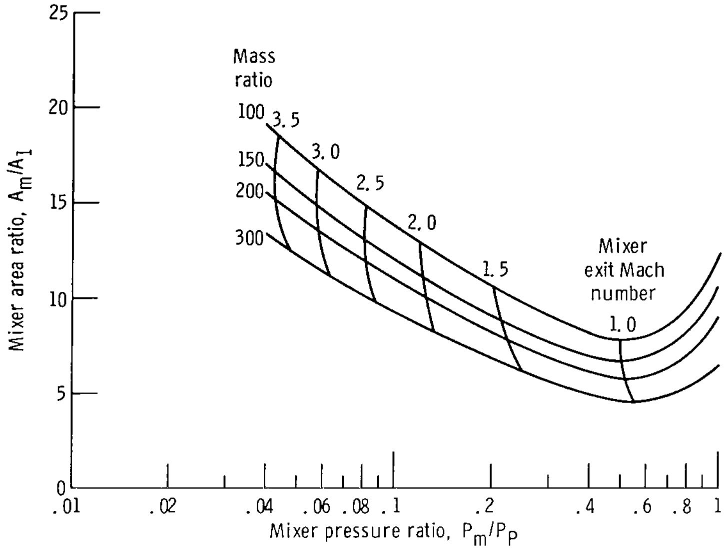

Figure 7. - Effect of mixer pressure ratio and mass ratio on LOX ejector mixer area ratio. LOX total pressure, 50 psia (34.48×10^4 N/m^2 abs); LOX temperature, 162 R (90 K); drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); drive rocket equivalence ratio, 1.0; drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs).

The area ratios for the mixer are shown in figure 7. The mixer area ratio is seen to increase with decreasing mixer pressure ratio and mass ratio. It may be noted that mixer area ratios are greater than one for the range of pressure ratios and mass ratios considered.

Figure 8 shows the variation of diffuser area ratio with diffuser pressure ratio for mixer pressure ratios of 0.10 and 0.04. At a mixer pressure ratio of 0.10 complete condensation does not occur in the diffuser. The diffuser area ratio therefore varies with pressure ratio in much the same manner as a normal gas diffuser. That is, the flow is compressed and decelerated from the entrance Mach number of 2.37 to a critical area or throat where the velocity is sonic at a diffuser pressure ratio of 16.5 and area ratio of 0.125. The diffuser area ratio then increases with increasing pressure ratio up to stagnation conditions at the diffuser exit area ratio of 0.2 and pressure ratio of 23.5.

The variation of area ratio with diffuser pressure ratio for a mixer pressure ratio of 0.04 is quite different from that of an ideal gas. The entrance Mach number is 3.74. As the flow is compressed in the diffuser, the Mach number at first decreases until the saturated liquid point is approached. Here the density increases rapidly with only small increases in pressure, resulting in a rapid decrease in the speed of sound. The velocity, however, is not decreasing as fast which results in an increase in Mach number. For example, just prior to the saturated liquid point the Mach number is 15.76. After complete condensation has occurred at an area ratio of 0.004 and pressure ratio of 54 the

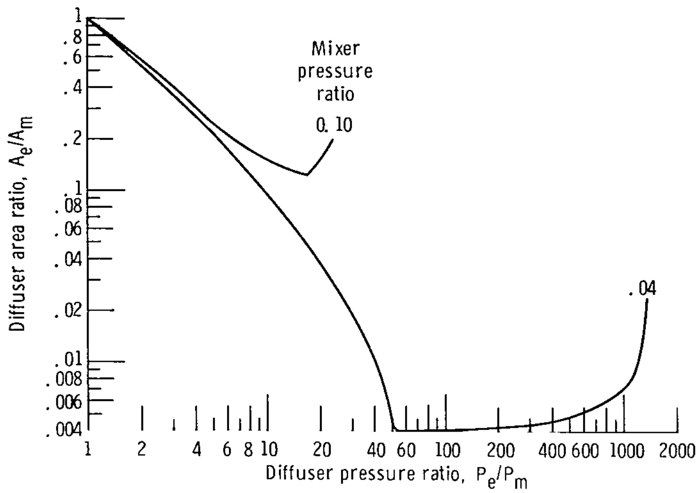

Figure 8. - Variation of LOX ejector diffuser area ratio with diffuser pressure ratio. LOX total pressure, 50 psia (34.48x10^4 N/m^2 abs); LOX temperature, 162 R (90 K); drive rocket equivalence ratio, 1.0; drive rocket chamber pressure, 600 psia (4.14x10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03x10^4 N/m^2 abs); mass ratio, 300.

density changes very little and there is a rapid increase in the speed of sound through a sonic throat. This results in a rapid decrease in Mach number dropping to a subsonic value of 0.234. As seen in figure 8 then the large change in density between the diffuser entrance and saturation point is reflected in a wide variation in area ratio.

Effect of drive rocket chamber pressure. - Increasing the drive rocket pressure ratio P_{T_P}/P_P increases the velocity of the drive gas and decreases its temperature. This would have a tendency to improve ejector performance since heating of the suction liquid decreases and the drive gas has a higher kinetic energy.

Figure 9 shows that the effect of chamber pressure on ejector discharge pressure is small for a wide range of chamber pressures. At a mass ratio of 250 increasing the chamber pressure from 60 to 1000 psia (41.4×10^4 to 6.895×10^6 N/m^2 abs), a factor of 16.66, increases the discharge pressure only by a factor of 1.14. This can be explained with the aid of the momentum equation (A2) in the appendix. At high mass ratios the velocity term in equation (A2) $V_P/(1 + m_S/m_P)$ indicates that large changes in drive rocket velocity result in relatively small changes in mixer exit velocity. For example, for a drive rocket chamber pressure of 300 psia (2.07×10^6 N/m^2 abs), equivalence ratio of 1, and nozzle exit pressure of 45 psia (31.03×10^4 N/m^2 abs), the drive gas velocity is 8200 ft/sec (2500 m/sec). Increasing the drive rocket chamber pressure to 600 psia (4.14×10^6 N/m^2 abs) increases the drive gas velocity to 9544 ft/sec (2910 m/sec), an increase of 1344 ft/sec (410 m/sec). For a mass ratio of 300, therefore, this would con-

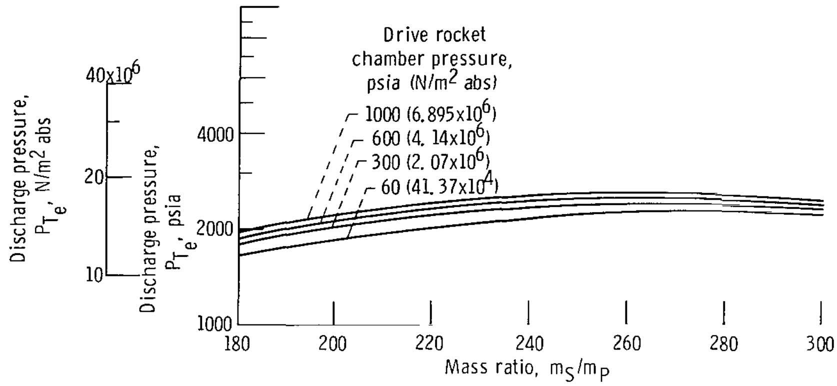

Figure 9. - Effect of drive rocket chamber pressure on LOX ejector discharge pressure. Drive rocket equivalence ratio, 1.0; drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m² abs); LOX total pressure, 50 psia (34.48×10^4 N/m² abs); LOX temperature, 162 R (90 K); mixer exit pressure, 2 psia (1.38×10^4 N/m² abs).

tribute an increase of only 4.5 ft/sec (1.375 m/sec) to the mixer exit velocity. In terms of ejector discharge pressure this would mean an increase of only 45 psia (31.03×10^4 N/m^2 abs). It can be seen, therefore, that low drive rocket chamber pressures are adequate for the LOX ejector pump.

Effect of drive rocket nozzle exit pressure. - Calculations have shown that the pressure force conversion to velocity in the mixer (third term on the right side of eq. (A2)) contributes a major part of the mixer exit velocity at low mixer pressure ratios. This means that the mixer exit velocity is greatly influenced by the drive rocket exit static pressure P_P. For example, a drive rocket with an equivalence ratio of 1, chamber pressure of 600 psia (4.14×10^4 N/m^2 abs), and nozzle exit pressure of 45 psia (31.03×10^4 N/m^2 abs) has a mixer exit velocity of 816 ft/sec (249 m/sec) of which the contribution by the pressure force conversion is 758 ft/sec (232 m/sec) or about 93 percent. Figure 10 shows the effect of nozzle exit pressure. The nozzle exit pressures are restricted to values less than the LOX tank pressure of 50 psia (34.48×10^4 N/m^2 abs), otherwise the LOX will not flow into the mixer. It is seen that the ejector performance drops rapidly with decreasing nozzle pressure. At a mass ratio of 300 decreasing the exit pressure from 45 to 30 psia (31.03×10^4 to 20.7×10^4 N/m^2 abs) decreases the discharge pressure from 2330 to 650 psia (16.1×10^6 to 4.5×10^6 N/m^2 abs), a decrease of 72 percent. This effect becomes more pronounced with decreasing mass ratio due to the increase in vaporization loss.

Effect of suction liquid temperature. - One means of reducing vaporization loss is to increase the heat sink capability of the LOX through subcooling. There are, however, practical difficulties in subcooling LOX below the 1-atmosphere vapor temperature. Figure 11 shows that the effect of the LOX temperature on ejector discharge pressure is small. However, it becomes more significant as the mass ratio is decreased. This is

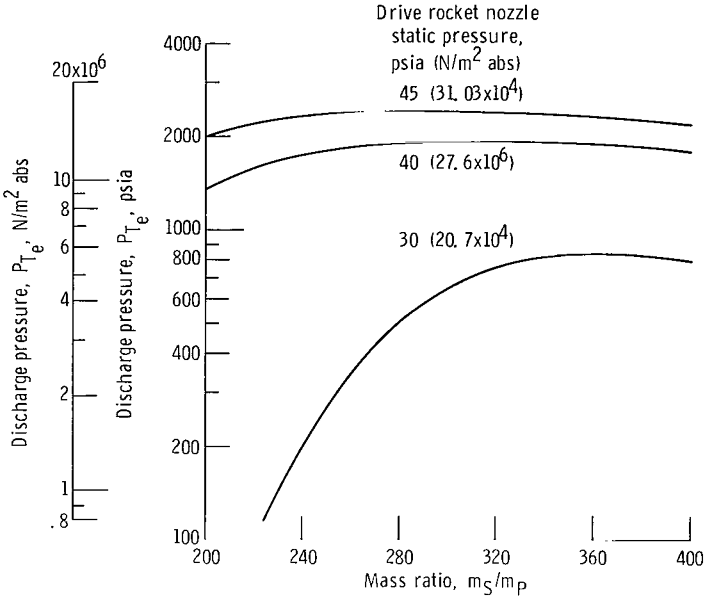

Figure 10. - Effect of drive rocket nozzle static pressure on LOX ejector discharge pressure. LOX total pressure, 50 psia (34.48×10^4 N/m^2 abs); LOX temperature, 162 R (90 K); drive rocket equivalence ratio, 1.0; drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); mixer exit pressure, 2 psia (1.38×10^4 N/m^2 abs).

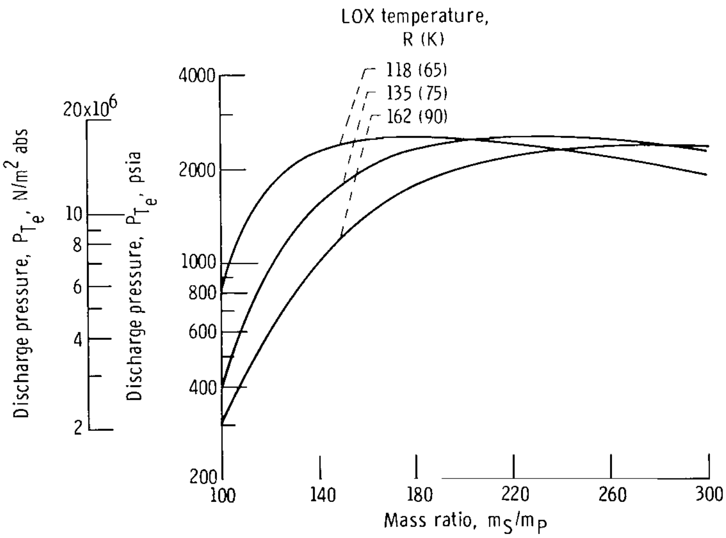

Figure 11. - Effect of LOX temperature on LOX ejector discharge pressure. LOX total pressure, 50 psia (34.48×10^4 N/m^2 abs); drive rocket equivalence ratio, 1.0; drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs); mixer exit pressure, 2 psia (1.38×10^4 N/m^2 abs).

due to the fact that the heat sink of the LOX is decreasing due to the lower mass ratios which increases the vaporization loss. The advantage of subcooling appears to be largely in maintaining high discharge pressures at low mass ratios where vaporization losses are greater.

Liquid Hydrogen Ejector

The results for the parametric study of the liquid hydrogen ejector are similar to those of the LOX ejector in that the effects of the various parameters are similar. However, the properties of the two liquids are different and cause the level of ejector performance to be different. The liquid temperature of LOX is higher than that of LH_2, but both are low enough to condense the drive gas in the mixer. Therefore, the heat transfer from the drive gas is about the same in both ejectors. Liquid hydrogen has a much higher heat sink capability than LOX which enables the LH_2 to absorb more heat before vaporization occurs than LOX. The most significant factor that causes the differences between the LH_2 ejector and the LOX ejector is the difference in density. The density of LH_2 is 4.42 lbm/ft^3 (73.8 kg/m^3) or about one-sixteenth that of LOX.

In the Thermodynamic Considerations section, it was indicated that the energy required to compress the mixture in the diffuser is $-\int v_L \, dP$. Since the specific volume of hydrogen is much greater than that of LOX, more energy is required to obtain the same pressure increase in the diffuser. Therefore, it may be expected that the performance of the hydrogen ejector will not be as good as that of the oxygen ejector. This is seen to be the case in figure 12 which shows the effects of the drive rocket equivalence

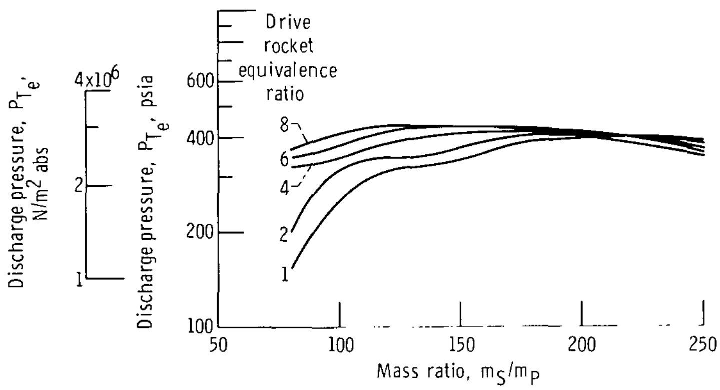

Figure 12. - Effect of drive rocket equivalence ratio and mass ratio on LH_2 ejector discharge pressure. LH_2 total pressure, 50 psia (34.48×10^4 N/m^2 abs); LH_2 temperature, 36.5° R (20.3 K); drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs); mixer exit pressure, 2 psia (1.38×10^4 N/m^2 abs).

ratio and the mass ratio on ejector discharge pressure. The equivalence ratios are restricted to one or greater to avoid combustion in the mixer. The performance is seen to be much lower than that of the oxygen ejector (fig. 4). The maximum discharge pressures are on the order of 430 psia (2.97×10^6 N/m^2 abs). Since this is less than the drive rocket total pressure of 600 psia (4.14×10^6 N/m^2 abs), self-pumping by bleeding from the main rocket engine is not possible for this chamber pressure as it is for the LOX ejector. The mass ratios that maximize the discharge pressure are seen to range from 120 at an equivalence ratio of 8 to 200 at an equivalence ratio of 1.

In figure 13 it is seen that the effect of mixer pressure ratio on discharge pressure is the same for the LH_2 ejector as for the LOX ejector (fig. 5). The discharge pressure increases rapidly at mixer pressure ratios less than 0.3.

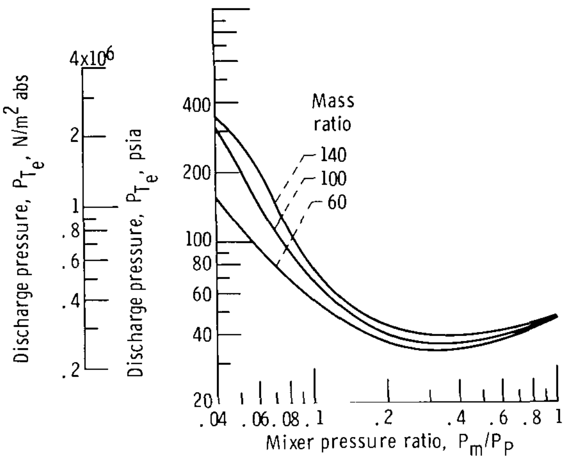

Figure 13. - Effect of mixer pressure ratio on LH_2 ejector discharge pressure. LH_2 total pressure, 50 psia (34.48×10^4 N/m^2 abs); LH_2 temperature, 36.5° R (20.3 K); drive rocket equivalence ratio, 1.67; drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs).

The mixer exit velocities shown in figure 14 are somewhat higher than those of the oxygen ejector (fig. 6) due to the lower mass ratios. The mixer exit Mach numbers are seen to be about the same as those of the oxygen ejector, indicating that the best performance for the LH_2 ejector is also obtained with supersonic mixing.

Figure 15 shows that the mixer area ratios are significantly smaller for the LH_2 ejector than for the LOX ejector (fig. 7). For a mass ratio of 100, the area ratio ranges from 3.65 at a pressure ratio of 1 to 5.6 at a pressure ratio of 0.04. For the LOX ejector at the same mass ratio and mixer pressure ratios, the area ratio varies from 12.3

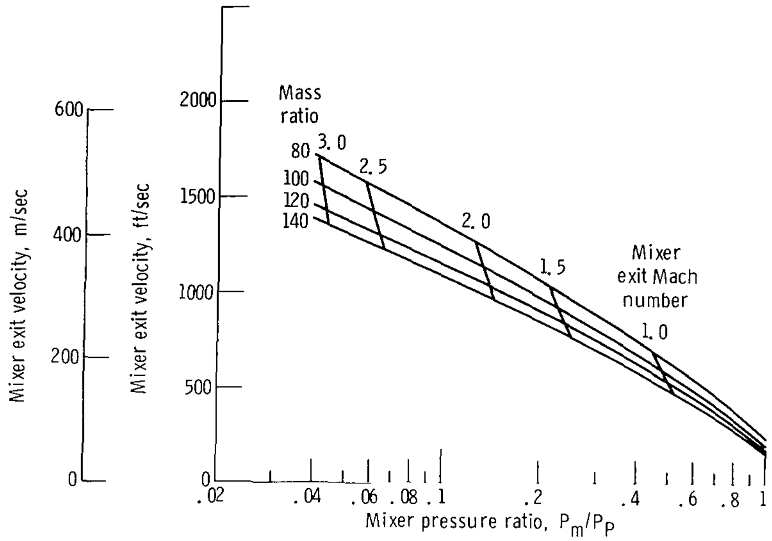

Figure 14. - Effect of mixer pressure ratio and mass ratio on LH_2 ejector mixer exit velocity. LH_2 total pressure, 50 psia (34.48×10^4 N/m^2 abs); LH_2 temperature, 36.5 R (20.3 K); drive rocket equivalence ratio, 1.67; drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs).

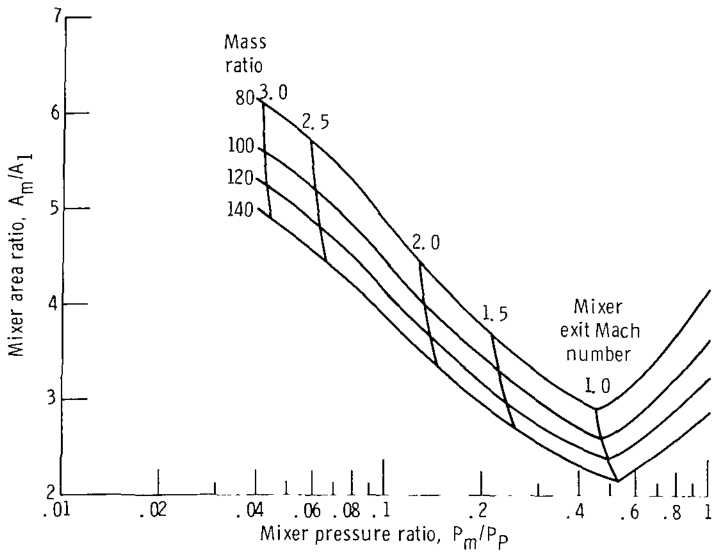

Figure 15. - Effect of mixer pressure ratio and mass ratio on LH_2 ejector mixer area ratio. LH_2 total pressure, 50 psia (34.48×10^4 N/m^2 abs); LH_2 temperature, 36.5 R (20.3 K); drive rocket equivalence ratio, 1.67; drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs).

to 19. This is due to the fact that the density difference between mixer inlet and exit is much greater for the LOX ejector than for the LH_2 ejector. For example, at a mass ratio of 100 and mixer pressure ratio of 0.04 the LOX enters the mixer with a density of 71.16 lbm/ft^3 (1140 kg/m^3) and the mixture leaves with a density of 0.0708 lbm/ft^3 (1.134 kg/m^3). The LH_2 enters the mixer with a density of only 4.42 lbm/ft^3 (70.8 kg/m^3) and the mixture leaves with a density of 0.055 lbm/ft^3 (0.881 kg/m^3).

Figure 16 shows the variation of the diffuser area ratio with diffuser pressure ratio is similar to that of the LOX diffuser (fig. 8). Condensation of the mixture occurs in the diffuser for a mixer pressure ratio of 0.04 but does not occur for a mixer pressure ratio of 0.1. For the mixer pressure ratio of 0.04 the critical area ratio is 0.032 for the LH_2 ejector compared to 0.004 for the LOX ejector, which is a result of the difference in density between the two liquids.

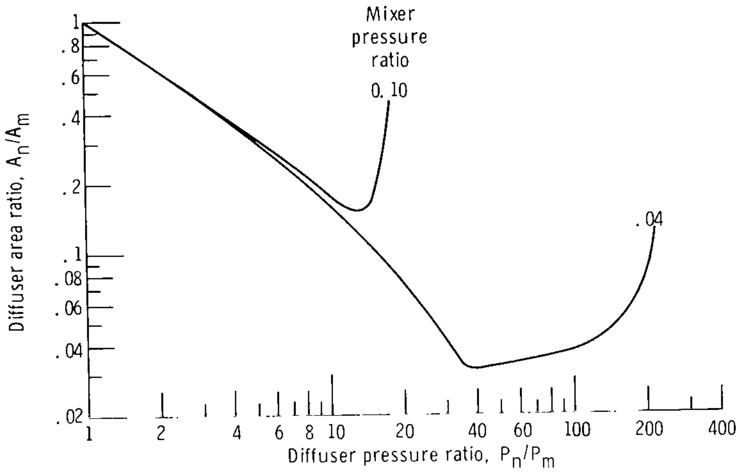

Figure 16. - Variation of LH_2 diffuser area ratio with diffuser pressure ratio. LH_2 total pressure, 50 psia (34.48x10^4 N/m^2 abs); LH_2 temperature, 36.5 R (20.3 K); drive rocket equivalence ratio, 1.67; drive rocket chamber pressure, 600 psia (4.14x10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03x10^4 N/m abs); mass ratio, 160.

The effect of drive rocket chamber pressure on LH_2 ejector discharge pressure (fig. 17) is also small. For example, near the maximum discharge pressure increasing the chamber pressure from 60 to 1000 psia (41.4×10^4 to 6.895×10^6 N/m^2 abs) raises the discharge pressure from 380 to 410 psia (2.62×10^6 to 2.82×10^6 N/m^2 abs) at a mass ratio of 200.

In figure 18 it is seen that reducing the drive rocket nozzle exit static pressure from 45 to 35 psia (31.03×10^4 to 24.1×10^6 N/m^2 abs) reduces the maximum discharge pressure from 410 to 255 psia (2.82×10^6 to 1.76×10^6 N/m^2 abs). This is a 38 percent re-

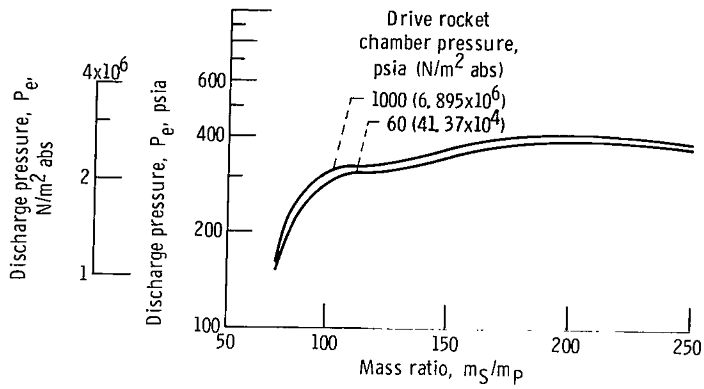

Figure 17. - Effect of drive rocket chamber pressure on LH_2 ejector discharge pressure. LH_2 total pressure, 50 psia (34.48×10^4 N/m^2 abs); LH_2 temperature, 36.5° R (20.3 K); drive rocket equivalence ratio, 1.67; drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs); mixer exit pressure, 2 psia (1.38×10^4 N/m^2 abs).

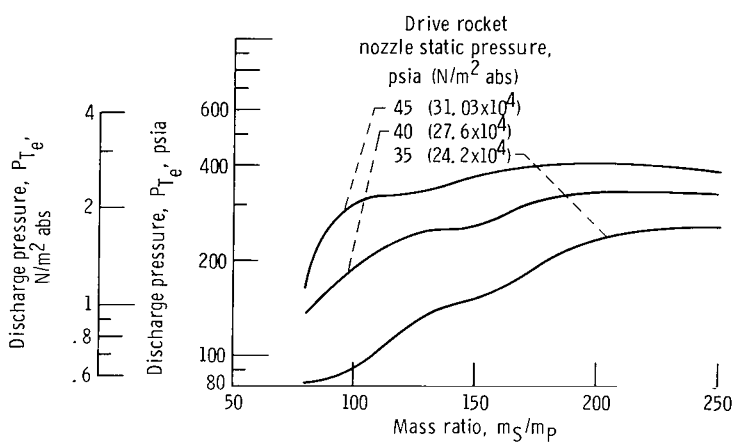

Figure 18. - Effect of drive rocket nozzle static pressure on LH_2 ejector discharge pressure. LH_2 total pressure, 50 psia (34.48×10^4 N/m^2 abs); LH_2 temperature, 36.5° R (20.3 K); drive rocket equivalence ratio, 1.67; drive rocket chamber pressure, 600 psia (4.14×10^6 N/m^2 abs); mixer exit pressure, 2 psia (1.38×10^4 N/m^2 abs).

duction which is less than that of the LOX ejector (fig. 10) which has a 65 percent reduction in discharge pressure for the same decrease in drive rocket exit static pressure. On the other hand since the performance of the LH_2 ejector is so much lower than that of the LOX ejector the effect of drive rocket nozzle exit static pressure is more significant for the LH_2 ejector.

The effect of suction liquid temperature for the LH_2 ejector is the same as for the LOX ejector (fig. 11) as seen in figure 19. As in the LOX ejector an increase in temperature increases the mass ratio that maximizes the discharge pressure.

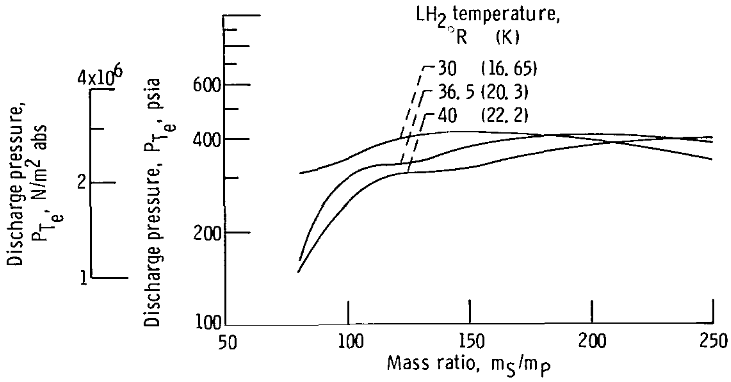

Figure 19. - Effect of LH_2 temperature on LH_2 ejector discharge pressure. LH_2 total pressure, 50 psia (34.48×10^4 N/m^2 abs); drive rocket equivalence ratio, 1.67; drive rocket total pressure, 600 psia (4.14×10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs); mixer exit pressure, 2 psia (1.38×10^4 N/m^2 abs).

Ejector Configurations

Figure 20 shows a possible ejector configuration for pumping LOX to a discharge pressure of 1100 psia (7.6×10^6 N/m^2 abs). The flow rate of 3900 pounds per second (1773 kg/sec) is comparable to that of the F-1 engine. The cross-sectional areas of the drive rocket, mixer, and diffuser were determined from the theoretical results discussed

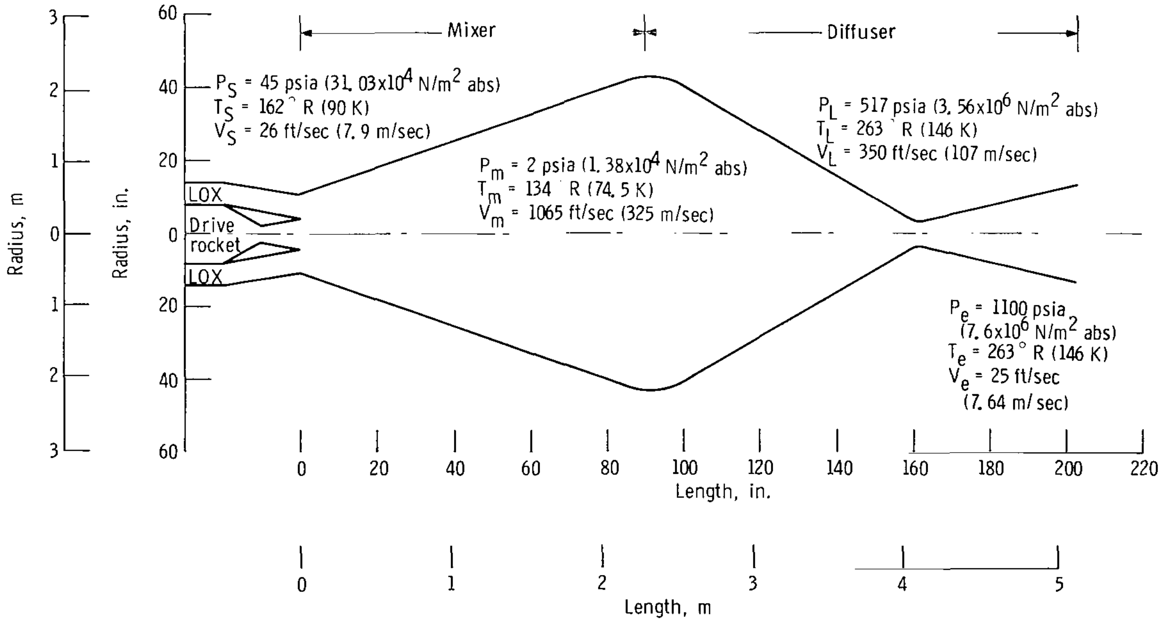

Figure 20. - LOX ejector configuration with LOX/LH_2 drive rocket. LOX weight flow rate, 3900 lb/sec (1773 kg/sec); LOX total pressure, 50 psia (34.48×10^4 N/m^2 abs); drive rocket total pressure, 300 psia (2.07×10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03×10^4 N/m^2 abs); drive rocket equivalence ratio, 1; mass ratio, 135.

earlier. The lengths of the various components are arbitrary.

The mixer area ratio is about 16 resulting in a rather large exit diameter of 86 inches (2.17 m). The diffuser entrance to throat area ratio is also seen to be large, on the order of 170. This could cause the diffuser to be quite long especially since the flow entering the diffuser is supersonic. The ejector then may be quite large. In fact, this configuration would be comparable in size to the F-1 engine.

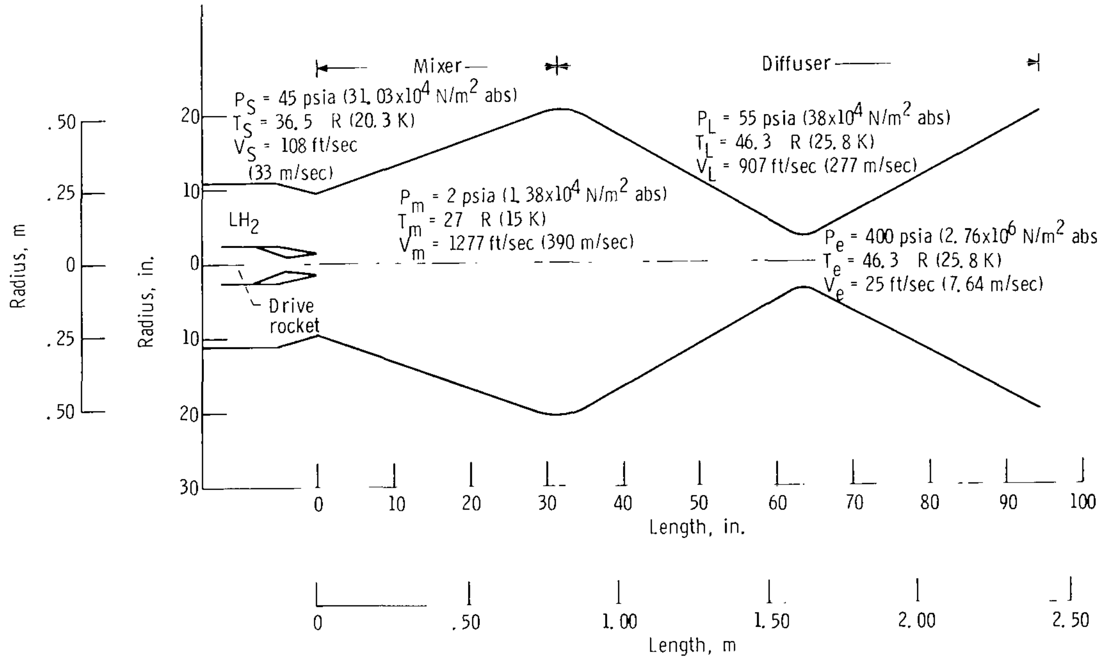

Figure 21. - LH_2 ejector configuration with LOX/LH_2 drive rocket. LH_2 weight flow rate, 1000 lb/sec (454 kg/sec); LH_2 total pressure, 50 psia (34.48x10^4 N/m^2 abs); drive rocket total pressure, 300 psia (2.07x10^6 N/m^2 abs); drive rocket nozzle static pressure, 45 psia (31.03x10^4 N/m^2 abs); drive rocket equivalence ratio, 1.67; mass ratio, 180.

Figure 21 shows a possible LH_2 ejector configuration for a rocket engine of about the same thrust level as that discussed for the LOX ejector (about 2 million pounds (8.9 million newtons)). It should be pointed out that, since the LH_2 ejector discharge pressure is much lower than that of the LOX ejector (about 400 psia or 2.75×10^6 N/m^2 abs) compared to 1100 psia or 7.6×10^6 N/m^2 abs), the main engine supplied by this ejector would be larger for the same thrust level. The LH_2 ejector is seen to be about one-half as large as the LOX ejector with a diameter of 40 inches (1.02 m). However, since this LH_2 weight flow (780 lb/sec or 354 kg/sec) is about one-fifth that of the LOX ejector, an LH_2 ejector pumping the same weight flow would be much larger than the LOX ejector.

CONCLUDING REMARKS

A preliminary analysis of the use of rocket-powered ejectors for pumping liquid oxygen and liquid hydrogen in rocket engines has been made. The drive gas for the ejectors is the exhaust gas of a hydrogen-oxygen rocket engine. Although the ejector cycle efficiency is lower than that of conventional pumps such as turbopumps, the simplicity of this cycle offers advantages over conventional pumps in reliability, development, and possibly weight. This could be especially significant in applications where high pressure, high thrust, low weight, and a long lifetime through many cycles of operation are required such as in a low cost orbital transportation system. However, the mixer and diffuser ducts required in the ejector could be very large.

Ideal pump discharge pressures over 2500 psia (17.25×10^6 N/m^2 abs) were calculated for the LOX ejector having a drive rocket chamber pressure of 600 psia (4.14×10^6 N/m^2 abs). The ideal discharge pressures calculated for LH_2 are about 430 psia (2.97×10^6 N/m^2 abs). The pumping volume capabilities appear attractive for both ejectors. For the LOX ejector, mass ratios over 300 are obtainable with discharge pressures over 2000 psia (13.8×10^6 N/m^2 abs). For the LH_2 ejector, mass ratios are about 200 with discharge pressures of 400 psia (2.75×10^6 N/m^2 abs).

Ejector performance is highly dependent on mixer area ratio and pressure ratio. Area ratios greater than one and pressure ratios less than one are necessary for good ejector performance. Drive rocket exit static pressure has a major effect on ejector performance. Increasing the drive rocket exit pressure increases ejector discharge pressure.

For a specified drive rocket exit pressure, the chamber pressure has a small effect on ejector performance. Increasing the drive rocket chamber pressure from 60 to 600 psia (41.4×10^4 to 4.14×10^6 N/m^2 abs) increased the discharge pressures by 8 to 15 percent.

The drive rocket equivalence ratio and suction liquid temperature have a more significant effect on the volume pumping capabilities than on the discharge pressure. For the LOX ejector, increases in the drive rocket equivalence ratio up to one and increases in suction liquid temperature improved the volume pumping capabilities and decreased the discharge pressures slightly. It should be noted that drive rocket cooling problems and oxidation of combustor and nozzle walls result from oxygen rich combustion in hydrogen-oxygen rocket engines. For the LH_2 ejector, decreasing the drive rocket equivalence ratio to one and increasing the LH_2 temperature improves the volume pumping capability and decreases the discharge pressure somewhat.

The mixer wall pressure distribution has a significant effect on ejector performance. The presented results were based on the idealized case with no shock or friction losses assuming complete mixing and an average wall pressure distribution in the mixer. The experimental work of others has shown that the real ejector is far from ideal. More detailed analysis, experiment, and vehicle integration studies will be required to see how much of the potential advantages predicted here can be realized in practice.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 25, 1970,
124-04.

APPENDIX - MIXING ANALYSIS

The trial solution assuming the flow is a liquid is carried out for a specified mixer exit pressure P_m.

From conservation of momentum,

$$m_m V_m = m_S V_S + P_S A_S + m_P V_P + P_P A_P + \int_1^m P\, dA - P_m A_m \qquad \text{(A1)}$$

The mixer entrance area is:

$$A_1 = A_P + A_S$$

Assuming $P_P = P_S$ and

$$\int_1^m P\, dA = \frac{(P_P + P_m)}{2} (A_m - A_1)$$

then

$$V_m = \frac{V_S}{1 + \dfrac{m_P}{m_S}} + \frac{V_P}{1 + \dfrac{m_S}{m_P}} + P_P \frac{\left(1 + \dfrac{A_P}{A_S}\right)\left(1 - \dfrac{P_m}{P_P}\right)\left(1 + \dfrac{A_m}{A_1}\right)}{2\rho_S V_S \left(1 + \dfrac{m_P}{m_S}\right)} \qquad \text{(A2)}$$

where

$$\frac{A_P}{A_S} = \frac{\rho_S V_S}{\rho_P V_P} \frac{m_P}{m_S} \qquad \text{(A3)}$$

$$\frac{A_1}{A_S} = 1 + \frac{A_P}{A_S} \qquad \text{(A4)}$$

$$\frac{A_m}{A_1} = \frac{\dfrac{A_m}{A_S}}{\dfrac{A_1}{A_S}} = \frac{\rho_S V_S \left(1 + \dfrac{m_P}{m_S}\right)}{\rho_m V_m \left(1 + \dfrac{A_P}{A_S}\right)} \qquad \text{(A5)}$$

$$\rho_S = f(P_P)$$

$$\rho_m = f(P_m)$$

Values of the densities of liquid oxygen and hydrogen were taken from references 7 and 8. For the oxygen ejector the mole fraction of water in the drive gas is

$$N_W = \frac{2\varphi_P}{1 + \varphi_P} \tag{A6}$$

For the hydrogen ejector

$$N_W = \frac{1.0}{\varphi_P} \tag{A7}$$

Then

$$\frac{m_W}{m_P} = \frac{18\ N_W}{\mathscr{M}_P}$$

$$\frac{m_W}{m_m} = \frac{\dfrac{m_W}{m_P}}{1 + \dfrac{m_S}{m_P}} \tag{A8}$$

From conservation of energy

$$h_{T_m} = \frac{\left(h_S + \dfrac{V_S^2}{2J}\right)}{\left(1 + \dfrac{m_P}{m_S}\right)} + \frac{\left(h_P + \dfrac{V_P^2}{2J}\right)}{\left(1 + \dfrac{m_S}{m_P}\right)} + \frac{\Delta h_W m_W}{m_m} \tag{A9}$$

and

$$h_m = h_{T_m} - \frac{V_m^2}{2J} \tag{A10}$$

where

Δh_W energy release by condensation of water from primary rocket (This includes the heat of fusion of $T_m < 273$ K.)

m_W/m_m weight fraction of water in mixture

If h_m is less than the saturated liquid enthalpy, the mixture is a liquid and this solution is accepted. If h_m is greater than the saturated liquid enthalpy, a second trial solution is made assuming the flow at the mixer exit is a mixture. The quality of the mixture is given by

$$X = \frac{(h_m - h_L)}{\Delta h} \tag{A11}$$

Combining equations (A10) and (A11) results in:

$$X = \frac{h_{T_m} - \frac{V_m^2}{2J} - h_L}{\Delta h} \tag{A12}$$

The specific volume of the mixture is

$$v_m = \left[X v_V + (1 - X) v_L\right]\left(1 - \frac{m_W}{m_m}\right) + \frac{v_W m_W}{m_m} \tag{A13}$$

where v_W is the specific volume of ice and the following properties are found from Mollier charts in references 7 and 8 for a specified P_m:

h_L enthalpy of saturated liquid

Δh heat of vaporization

v_V specific volume of vapor

v_L specific volume of liquid

Combining equations (A12) and (A13) gives

$$v_m = \frac{1}{\Delta h}\left[\left(h_{T_m} - h_L\right)\left(v_V - v_L\right)\left(1 - \frac{m_W}{m_m}\right)\right.$$

$$\left. - \frac{V_m^2}{2J}\left(1 - \frac{m_W}{m_m}\right)\left(v_V - v_L\right) + \Delta h\, v_L\left(1 - \frac{m_W}{m_m}\right) + \Delta h\left(\frac{m_W}{m_m}\right) v_W\right] \tag{A14}$$

$$\rho_m = \frac{1}{v_m} \tag{A15}$$

Combining equations (A2) to (A5) yields the following quadratic:

$$\left(1 + \frac{m_P}{m_S}\right)V_m^2 = V_m\left[V_P \frac{m_P}{m_S} + V_S + \frac{P_P\left(1 - \frac{P_m}{P_P}\right)\left(1 + \frac{A_P}{A_S}\right)}{2\rho_S V_S}\right] + \frac{P_P\left(1 - \frac{P_m}{P_P}\right)\left(1 + \frac{m_P}{m_S}\right)}{2\rho_m} \tag{A16}$$

Combining equations (A14) to (A16) the mixer exit velocity may be determined from the following quadratic:

$$V_m^2\left[2\ \Delta h\left(1 + \frac{m_P}{m_S}\right) + \frac{P_P\left(1 - \frac{P_m}{P_P}\right)\left(1 + \frac{m_P}{m_S}\right)\left(v_V - v_L\right)\left(1 - \frac{m_W}{m_m}\right)}{2J}\right]$$

$$- V_m\left[V_S + V_P \frac{m_P}{m_S} + \frac{P_P\left(1 - \frac{P_m}{P_P}\right)\left(1 + \frac{A_P}{A_S}\right)}{2\rho_S V_S}\right]2\ \Delta h - P_P\left(1 - \frac{P_m}{P_P}\right)\left(1 + \frac{m_P}{m_S}\right)$$

$$\times \left[\left(h_{T_m} - h_L\right)\left(v_V - v_L\right)\left(1 - \frac{m_W}{m_m}\right) + \Delta h\ v_L\left(1 - \frac{m_W}{m_m}\right) + \Delta h\left(\frac{m_W}{m_m}\right)v_W\right] = 0 \tag{A17}$$

The remaining flow properties may then be determined from equations (A3) to (A5) and (A10).

If h_m is less than the saturated vapor enthalpy, the mixer exit flow is a mixture and this solution is accepted. If h_m is greater than the saturated vapor enthalpy, the flow is a gas. For this condition the mixer exit temperature T_m is used as the independent variable. For a specified mixer exit temperature the mixer exit enthalpy is determined using the method of reference 5. The mixer exit velocity is then

$$V_m = \sqrt{\frac{\left(h_{T_m} - h_m\right)}{2J}} \tag{A18}$$

By using the equation of state for ρ_m, equation (A5) becomes

$$\frac{A_m}{A_1} = \rho_S V_S \frac{\left(1 + \frac{m_P}{m_S}\right)}{\left(1 + \frac{A_P}{A_S}\right)} \frac{gRT_m}{P_m \mathscr{M}_m V_m} \tag{A19}$$

The pressure P_m may then be determined by combining equations (A2) to (A4) and (A19) resulting in the following quadratic:

$$P_m^2 \frac{\left(1 + \frac{A_P}{A_S}\right)}{2\rho_S V_S} + P_m \left[\left(1 + \frac{m_P}{m_S}\right)V_m - \frac{V_P m_P}{m_S} - \frac{P_P\left(1 + \frac{A_P}{A_S}\right)}{2\rho_S V_S} - V_S + \frac{gRT_m\left(1 + \frac{m_P}{m_S}\right)}{2\mathscr{M}_m V_m}\right] - \frac{P_P gRT_m\left(1 + \frac{m_P}{m_S}\right)}{2\mathscr{M}_m V_m} = 0 \tag{A20}$$

The energy equation (A9) is solved first assuming condensation of the water vapor from the primary rocket. If P_m is less than the vapor pressure of water for the temperature T_m, equation (A9) is adjusted to account for the energy used in vaporization of the water and Δh_W is set equal to zero. The pressure P_m is then solved by iteration using equations (A9), (A18), and (A20).

After determining P_m, the mixer exit density is calculated from the following equation of state:

$$\rho_m = \frac{P_m \mathscr{M}_m}{gRT_m} \tag{A21}$$

If the water vapor is condensed, the density is adjusted assuming the volume occupied by the water is negligible compared to the gas volume. Equations (A6) and (A7) are used to determine that the number of moles of the gaseous part of the flow at the mixer exit is

$$N_g = 1 - N_W \tag{A22}$$

If it is assumed that P_m, T_m, and $\mathscr{M}_m$ are unchanged, the density is then

$$\rho_m = \frac{P_m \mathscr{M}_m}{N_g g R T_m} \tag{A23}$$

The mixer area ratio is then found from equation (A5).

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