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A HEAT TRANSFER INVESTIGATION OF EJECTOR SYSTEMS WITH 90° TURNS

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Abstract

Results are presented from a test program that evaluated the heat transfer characteristics of a series of ejector systems that turned the rocket exhaust gases through 90°. The ejector systems covered a range of designs that utilized both subsonic and supersonic turning of the gases within a fixed height. A series of tests with heated nitrogen was made for each ejector, during which measurements of local pressures and wall temperatures were made to provide the data necessary to evaluate the heat-transfer conditions. The results from three of these systems are discussed in detail to illustrate the differences in thermal behavior that can be obtained during the turning of the gases. The maximum heating rate was reduced by a factor of 7 when the ejector had a long radius, as compared to a short radius 90° turn and by a factor of 5 by permitting the gases to shock down to subsonic flow prior to entering the short radius bend. A method of converting the scale-model heat-transfer coefficient data to any other scale size, working fluid, nozzle chamber temperature or chamber pressure and an empirical correlation of the maximum heating rates is presented.

Introduction

Rocket engines for upper stage application use large area ratio nozzles that require development testing to be done at least partially in facilities with ejector systems.[1] The advent of more complex rocket systems, such as throttling chemical engines and nuclear engines, also requires that these ejector systems must operate over a wide range of pressure ratios and be capable of testing the engine (and, in some cases, a complete stage) in a vertical attitude. Ejector systems that turn the exhaust gases through 90° or more are desirable to minimize the cost and size of the facilities for testing these engines. However, turning the gases in the ejector system complicates the thermal design of the ejector because of the increased heating rates experienced in the turning region. The thermal design of the ejector is further complicated by the use of high energy propellants that produce higher heating rates than usually experienced.

No information was available in the literature on heating rates in ejector systems that turned the gas flow, and very little was available on heating rates to be expected in straight ejector systems. Qualitative data was obtained in work at JPL that indicated that the initial impingement area and the exit area of a straight ejector system were the two most critical heating locations.[2] It was, therefore, necessary to evaluate the heat transfer characteristics of turning ejector systems experimentally through a scale model test program. The goal of this program was to find the best compromise between aerodynamic and heat transfer requirements for an ejector system to fit within a given envelope. The results of the aerodynamic portion of the program have been published earlier and only the heat transfer portion of the program will be discussed in this paper.[3,4,5,6]

Test Procedures

The hot gas supply system used for these tests consisted of a stored energy heater fired by a gas-air burner that preheated stainless steel tubing to approximately 1400°F. The working fluid was then introduced to the heater and flowed through the heater to the test nozzle for the ejector system. Both nitrogen and hydrogen were used as test fluids with most of the tests made with nitrogen. Nitrogen was chosen as the primary test fluid in order to obtain Reynolds numbers close to those produced by the full scale engine while giving model heat transfer conditions that were measurable and did not require too much scaling of results. An additional factor in the selection of nitrogen was its cost and safety in handling.

To evaluate local heat transfer conditions in the ejectors, a series of tests were made with each ejector that produced a step function heat input to the wall of the duct. This was accomplished by using a burst diaphragm just upstream of the test nozzle and preheating the feed line up to the diaphragm with a pre-fire bleed. The transient response of thermocouples on the ejector walls were then used to compute local heating rates to the duct walls. The test nozzles used during this test program were 40:1 contoured nozzles and a 25:1 conical nozzle and required a pressure ratio of roughly 30 and 16 atmospheres respectively to start the ejector system. Tests were made over a range of chamber pressures between 20 atmospheres (with a secondary ejector system) and 70 atmospheres with most of the tests being conducted at 50 atmospheres.[3,5]

Tests were conducted on eleven ejector designs that investigated various methods of turning the exhaust gases.[3] This paper discusses the results obtained for three of these systems that illustrate the differences obtained during the program by different methods of turning the gases. Figures 1, 2 and 3 show the three ejector systems discussed in this paper.

The first ejector, shown in Figure 1, turned the exhaust gases supersonicly around a short radius elbow and was the first design tested during the program.

The second ejector, shown in Figure 2, also turned the exhaust gases supersonicly but used a long radius elbow to avoid excessive compression of the gases on the outside wall of the duct. The third ejector, shown in Figure 3, turned the gas subsonicly through a short radius elbow of a larger diameter than the other ejectors. Ejectors 1 and 2 were tested with a 40:1 contoured nozzle and Ejector 3 was tested with a 25:1 conical nozzle. All of the ejectors were constructed of stainless steel tubing with a wall thickness of 1/8 inch. Between 40 and 150 thermocouples were spot welded on the outside of the ejector walls at points selected to provide data on the variation of the heat transfer rate along the duct. Figure 4 illustrates the type of instrumentation used on these ejectors. The walls were then insulated with asbestos felt and fiberglas batting to eliminate heat losses from the exterior of the duct. The thermocouple output was monitored through a sampling switch and recorded on magnetic tape. The sampled data were then reduced and heat transfer coefficients computed through use of a digital computer program. The gas flow conditions were kept constant over the full duration of the test and chamber pressure and temperature were monitored and recorded with the thermocouple data.

Data Analysis Procedures

Mathematical Model

If the ejector wall is considered to be thermally thin (no temperature drop through the wall), with zero conduction of heat along the wall; if radiation of energy is neglected, and if the outside of the ejector is considered to be perfectly insulated, then the rate of rise of the wall temperature can be equated to the convective heat transfer rate into the wall by the following energy balance:

$$\rho c \, b \, \frac{dT_w}{dt} = h \, (T_r - T_w) \qquad (1)$$

Equation (1) can be used to relate the wall temperature to heat transfer conditions in several ways. The method used during this work was selected to minimize experimental errors through use of an integral method of comparing the test results with the mathematical model. Equation (1) was solved for wall temperature as a function of time for the case when the specific heat of the wall material and the heat transfer coefficient were linear functions of the wall temperature, and the recovery temperature was a step function of time. This led to the differential equation

$$\rho c_o \, (1 + B \, \theta_w) \, b \, \frac{d\theta_w}{dt} = h_o \, (1 + A'\theta_w) \, (\theta_r - \theta_w) \qquad (2)$$

and solution

$$\ln \left[\frac{\theta_r - \theta_w}{\theta_r - \theta_i}\right] + \frac{1 - B/A'}{1 + B \, \theta_r} \ln \left[\frac{1 + A' \, \theta_i}{1 + A' \, \theta_w}\right] = \frac{h_o \, (1 + A' \, \theta_r) \, (t - t_i)}{\rho c_o \, b \, (1 + B \, \theta_r)} \qquad (3)$$

Examination of Equation (3) shows that the function of ejector-wall temperature on the left side of the equation is linearly related to time; a fact which allowed statistical methods to be used in interpreting the test data in terms of ejector heat transfer conditions.

By using test data within the region of application of Equation (3), a least-squares regression curve of the following form was calculated for each data point

$$y = a_o + a_1 t \qquad (4)$$

where

$$y = \ln \frac{\theta_r - \theta_w}{\theta_r - \theta_i} + \frac{1 - B/A'}{1 + b\,\theta_r} \ln \frac{1 + A'\,\theta_i}{1 + A'\,\theta_w} \qquad (5)$$

The slope, "a_1", was then related to the heat transfer coefficient with the wall at the recovery temperature by the relation:

$$h_r = h_o \; (1 + A'\,\theta_r) = \rho\, c_o\, b\, (1 + B\,\theta_r)\, a_1 \qquad (6)$$

The limits chosen for utilization of the test data were based on keeping the radiation effects below 10% of the convective heat transfer rate and introducing no more than 10% error due to the assumption of a step variation in gas recovery temperature. The steady-state temperatures of the duct wall were used to determine the radiation cut-off temperature by providing a combined estimate of the shape factor and effective emissivity at each location, while a solution to Equation (1), with an exponential variation in recovery temperature of the gas, provided an estimate of the initial data point time where Equation (3) applied.

Additional parameters were calculated from the test data, including the standard error of data fit, the standard error of the intercept, the slope of the regression line, and the correlation coefficient of the data with the regressive curve.

The coefficient B was used to match the published specific heat data for Type [illegible] stainless steel over the full temperature range.

<u>Data Interpretation</u>

Interpretation of the scale model heat transfer data through the use of a [illegible] correlation was not possible due to the lack of knowledge on the local flow

conditions in the ejectors. Consequently, it was necessary to assume that the heat transfer coefficient could be correlated by an equation of the type

$$Nu = C\, Pr_f^{.4} Re_f^{.8} \qquad (7)$$

where the Reynolds number exponent and the film temperature for definition of the gas properties were known. With these assumptions, a comparison could be made between the data and a turbulent pipe flow correlation. This comparison lumped all the unknown factors into the coefficient of the equation and gave the results in terms of a multiplying factor times the turbulent correlation equation. Bartz's simplified equation (7) was selected as the reference correlation equation because of its wide use in nozzle heat transfer calculations. This led to a scaling relationship between the scale model heat transfer data and the full scale condition as follows:

$$\frac{h}{h_{sm}} = \frac{w^{.8} D_{sm}^{1.8}\, \phi\, (1 + T_w/T_r)_{sm}^{.8}}{w_{sm}^{.8} D^{1.8}\, \phi_{sm}\, (1 + T_w/T_r)^{.8}} \qquad (8)$$

where

$$T_f = (T_w + T_r)/2 \qquad (9)$$

$$\phi = \frac{c_p^{.4}\, k^{.6}}{\mu^{.6}} \quad \text{(evaluated at the film temperature)} \qquad (10)$$

Discussion of Results

Before discussing the heat transfer data obtained during this investigation, a brief discussion of the gas flow characteristics of these ejector systems is desirable. When an ejector system "starts" an oblique shock is formed at the point of impingement of the gases on the duct wall that essentially produces subsonic flow downstream of the shock and hence throughout the rest of the ejector.[3] If the chamber pressure of the engine rises above the "start" pressure, the shock structure in the ejector will develop to produce an increased pressure ratio across the ejector and will eventually produce supersonic flow throughout the ejector unless some means is used to stabilize the shock structure in the system. Thus, two types of turning are possible for ejector systems to be used at pressure ratios 2 to 10 times the "start" pressure ratio. The normal type of converging-diverging ejector will produce supersonic flow in the turning elbow while a restricted outlet ejector can in some cases produce subsonic gases in the turning elbow. Both types of ejectors are discussed in this paper. Ejectors 1 and 2 produced supersonic gases in the elbow at high pressure ratios, while Ejector 3 produced subsonic flow.

Figure 5 summarizes the testing results for Ejector 1 ($R/D = 2$) and 2 ($R/D = 7.88$) as the normalized heat transfer coefficient vs L/D. The peak heating rates occur on the turning radius. The reference heat transfer coefficient h_{ref} is the calculated value based on Bartz's equation and the assumptions of shockless supersonic one-dimensional flow. The maximum heat transfer coefficients for Ejectors 1 and 2 are respectively 40 times and 7 times that obtained from Bartz' equation and the aforementioned assumptions. The maximum heat transfer rates obtained in Ejector 2 for similar testing conditions are shown to be reduced by a factor of 6 from those obtained on Ejector 1 which is a dramatic demonstration of the configuration effect on heat transfer rates.

The heat transfer data presented was obtained from the impingement side of the ejector. The heat transfer coefficients obtained from the inner wall at the 90° location of the turn was approximately 1/3 the value obtained from the impingement side (180° from the inner wall) for Ejector 3. This was predicted by a figure titled "Heat Transfer Coefficient in a 90° bend for Turbulent Subsonic Flow".[8] The heat transfer coefficients on the inner wall 180° from the region of maximum heating of Ejectors 1 and 2 were approximately 1/50 and 1/4 that of the impingement side.

Additional data obtained from pressure measurements, spark shadowgraph, and water table hydraulic analogy tests indicated that the high heat transfer rates in the sharp bend ejector are in part caused by the shock structure in the elbow. The sharp bend ejector appeared to have flow separation in the inside of the elbow and a resulting strong curved shock near and parallel to the outside of the elbow. This results in an extremely non-uniform flow distribution. The large radius ejectors had a complex but fairly uniform shock system throughout their length which allowed a more uniform distribution of flow, and therefore less severe and more uniform heat flux distribution.

Ejector 3, Figure 3 was designed to allow the flow to shock down to subsonic flow prior to entering the elbow. The results of this test are shown in Figure 6. The peak heating rate is still located in the 45° portion of the 90° elbow but is approximately 1/5 the magnitude of the peak heating experienced in Ejector 1 which had approximately the same turning radius. The ratio h_{max}/h_{ref}, as shown in Figure 7 for Ejector 3 is approximately $\frac{1}{2}$ that for Ejector 1. Because of the larger flow area and the high-mach number used in obtaining h_{ref} in the elbow, however, the absolute magnitude, h_{max}, is actually 1/5 that obtained in Ejector 1.

The test data obtained for these ejectors showed that a wide variation in heating rates are possible in 90° turn ejector systems, and that the heating rates are directly associated with the gas dynamics of the system. When compared to the heating rates to be expected in the supersonic nozzle of the same area ratio, the test data ranged from 1/3 to 15 times the computed value. In selecting an ejector design, the maximum heat transfer rate is usually the critical value and hence this value was selected to relate to the geometry of the ejector system. Figure 7 shows a plot of the maximum observed heat transfer coefficient for each ejector system normalized by dividing by the heat transfer coefficient computed by Bartz's equation for supersonic flow at that area ratio versus the dimensionless turning diameter of the ejector. The location of the peak heat transfer coefficients was in the turning section. For the range of ejector systems tested, the data is summarized by the following equation.

$$\frac{h_{max}}{h_{ref}} = 4.5 \exp(2.15\ D/R_c) \qquad (11)$$

where

$$h_{ref} = .026\ Pr_f^{.4}\ Re_f^{.8}\ k_f/D \qquad (12)$$

It can be seen that the peak heat transfer coefficient for Ejector 1 falls above the curve by a factor of 2.6. This was due to the pronounced flow separation discussed previously and which was corrected on later supersonic turning systems that were tested with the same turning radius.[4] When flow separation was minimized, the rest of the systems produced data that could be predicted by Equation (11) within ± 20%. A consequence of this correlation is the existence of an area ratio for the elbow to produce a minimum heat transfer rate to the ejector when it is necessary to turn the exhaust gases in a fixed height.

For a fixed height, the relationship of ejector diameter with height is (see Figure 8)

$$H = \frac{D_1 - D_2}{2 \tan \alpha_1} + R_c + 1/2\ D_2 = \text{constant} \qquad (13)$$

for a supersonic turn ejector and

$$H = \frac{D_1 - D_2}{2 \tan \alpha_1} + \left(\frac{L}{D_2}\right) D_2 + \frac{D_3 - D_2}{2 \tan \alpha_2} + R_c + \frac{1}{2}\ D_3 = \text{constant} \qquad (14)$$

for a subsonic turn ejector.

The reference heat transfer coefficient given in Equation 12 is proportional to $D_3^{-1.8}$, therefore, equation 11 can be written

$$h = K_1\ D_3^{-1.8}\ e^{2.15\ D/R_c} \qquad (15)$$

where $D_3^{-1.8}$ is the diameter of the ejector in the elbow.

For a good aerodynamically designed ejector, the diameter D_1 is known (slightl larger than the exit diameter of the nozzle to be tested), the angles α_1 and α_2 shoul probably be between 4 and 8°, and for a subsonic turn ejector, the elbow diameter should be between 1.5 and 2 D_2 and L/D_2 between 2 and 8 depending on the magnitude of the pressure to be recovered, P_1/P_a, and the geometry of the ejector aft of the elbow. The radius of curvature, R_c, can now be considered a primary function of the elbow diameter and equations (13) and (15), or (14) and (15) can be solved to determi the values of D and R_c, consistent with the fixed height, that yield the lowest values of heat transfer coefficient, h.

The small range of area ratios tested during the investigation makes application of Equation (11) to systems differing from the ones tested here questionable, even though the correlation predicted both the subsonic flow and supersonic flow data quite well.

Concluding Remarks

When it is necessary to turn the flow in an ejector through 90° for disposal purposes, the major factor affected by the turning is the heat transfer in the elbow region. Supersonic turning must be used for small heights for the best aerodynamic performance. For a supersonic turn ejector, care must be taken to insure that flow separation does not occur as this can produce very large heating rates in the elbow as demonstrated by the test results of Ejector 1. The test results for Ejectors 2 and 3 demonstrate that it is possible to turn the exhaust gases in the ejector system with only a moderate increase in heating rate over that obtained in a straight ejector system.

The test results for a series of ejector systems were correlated in terms of the dimensionless turning radius to predict the maximum heating rate to be expected in a well designed ejector. Although the range of test conditions was limited, the correlation can be used to produce preliminary estimates of the type of configurations most suitable for a given application. This work is a beginning effort towards the understanding of the heat transfer problems in ejector systems, and though much work remains, it is felt that the use of this work will lead to improved facility capabilities in the near future.

Nomenclature and Symbology

A'	coefficient of heat transfer coefficient variation with temperature
B	coefficient of specific heat variation with temperature
b	wall thickness
L_c	length of second throat
c	specific heat at constant pressure
h	heat transfer coefficient
H	height
k	thermal conductivity
K	constant
m	molecular weight
Nu	Nusselts number
P	pressure
R'	universal gas constant
R_c	radius of elbow (to centerline of elbow)
Re	Reynolds number
Pr	Prandtl number
t	time
T	temperature, °R
$\dot{w}$	flow rate

Greek Letters

γ	ratio of specific heats
ρ	density
θ_w	wall temperature
θ_r	recovery temperature of gases
α	contraction or expansion half angle
ϕ	junction of fluid transport properties viscosity

Subscripts

1,2,3,...	station numbers or locations
a	ambient
c	chamber
f	gas film
i	initial
o	extrapolated to initial wall temperature or outside
r	recovery
sm	scale model
t	time
w	wall
∞	free stream
ref	reference

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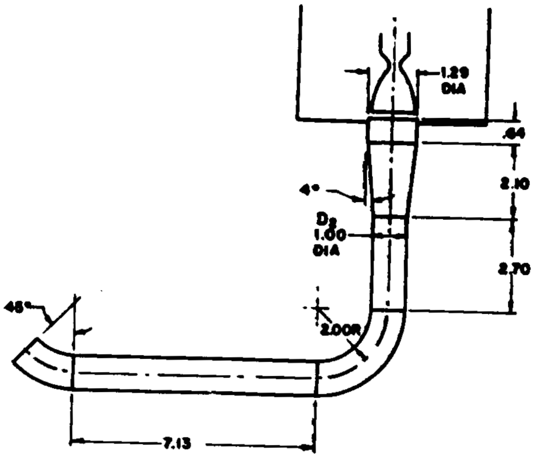
NOTES.

1. ALL DIMENSIONS ARE MULTIPLES OF D_2
2. DIAMETERS ARE INTERNAL
3. D_2 = 4.76 inches FOR SCALE MODEL
4. 40/1 CONTOURED NOZZLE
5. $A_{d1}/A^* = 58$

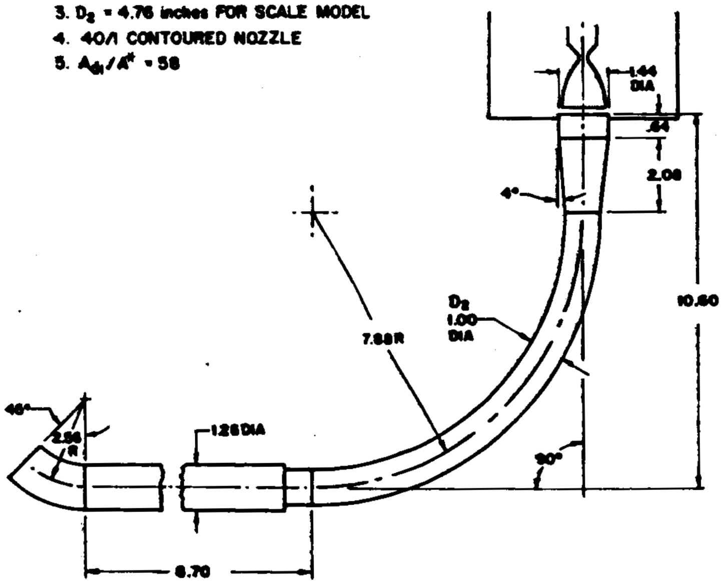


EJECTOR SYSTEM NO. 1

FIGURE 1

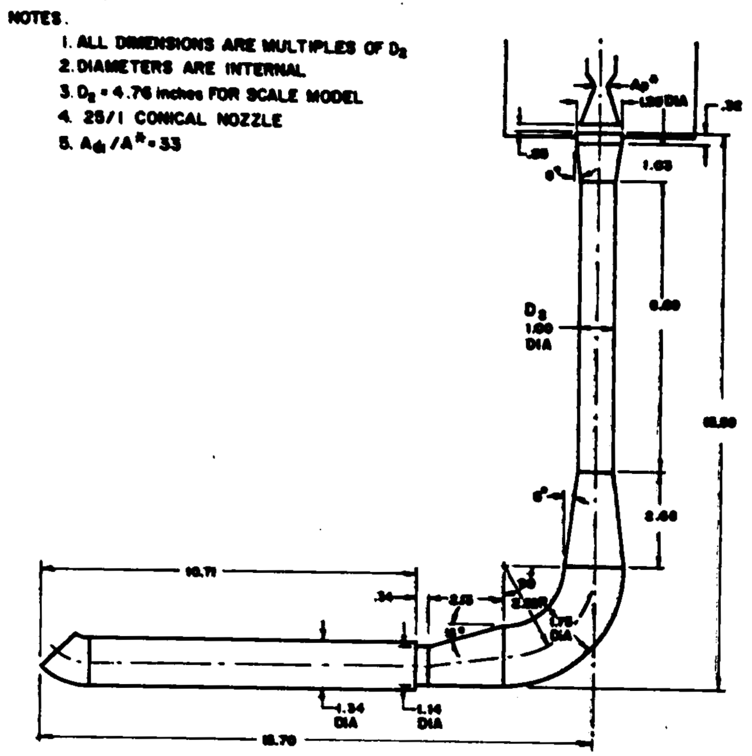
NOTES.

1. ALL DIMENSIONS ARE MULTIPLES OF D_2
2. DIAMETERS ARE INTERNAL
3. D_2 = 4.76 inches FOR SCALE MODEL
4. 40/1 CONTOURED NOZZLE
5. $A_{d1}/A^* = 58$



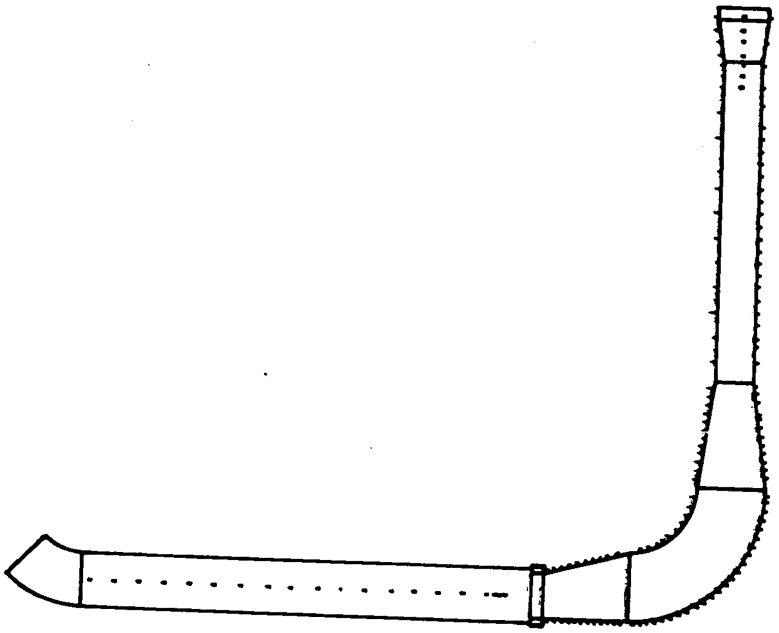
EJECTOR SYSTEM NO. 2

FIGURE 2


NOTES.
1. ALL DIMENSIONS ARE MULTIPLES OF D_2
2. DIAMETERS ARE INTERNAL
3. D_2 = 4.76 inches FOR SCALE MODEL
4. 25/1 CONICAL NOZZLE
5. $A_{d1}/A^* = 33$

EJECTOR SYSTEM NO. 3

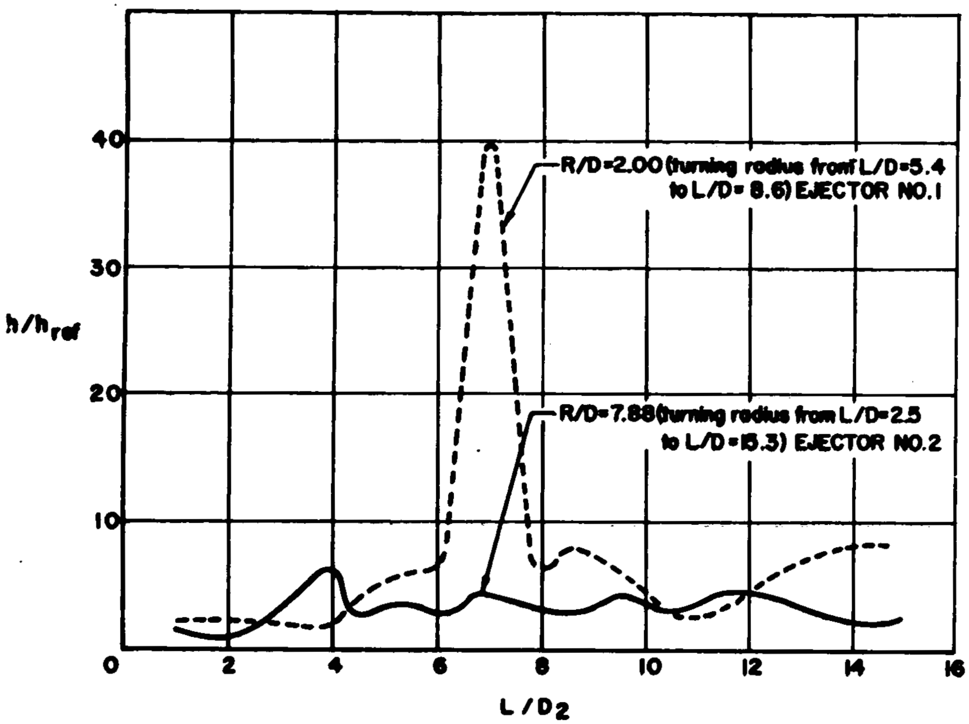
FIGURE 3



THERMOCOUPLE LOCATIONS FOR
EJECTOR NO. 3

FIGURE 4

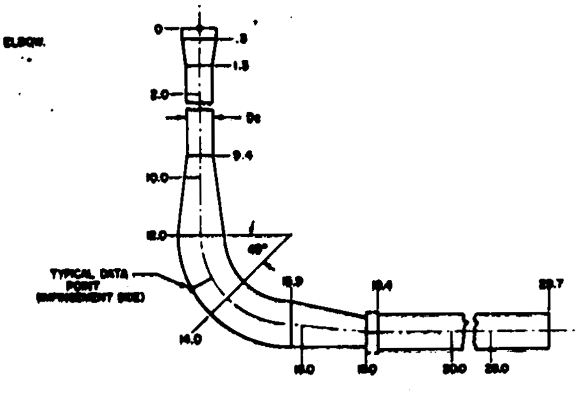
NOTES.
1. $A_e/A^* = 40$ (CONTOURED NOZZLE)
2. $A_{d1}/A^* = 58$
3. $A_{d1}/A_{d2} = 1.66$
4. h = GAS SIDE HEAT TRANFER COEFICIENT ON IMPINGEMENT SIDE OF EJECTOR
5. $h_{ref} = .026 (Re_f)^{.8} (Pr_f)^{.4} (\frac{K}{D})$ ASSUMING ONE-DIMENSIONAL SHOCKLESS SUPERSONIC FLOW.



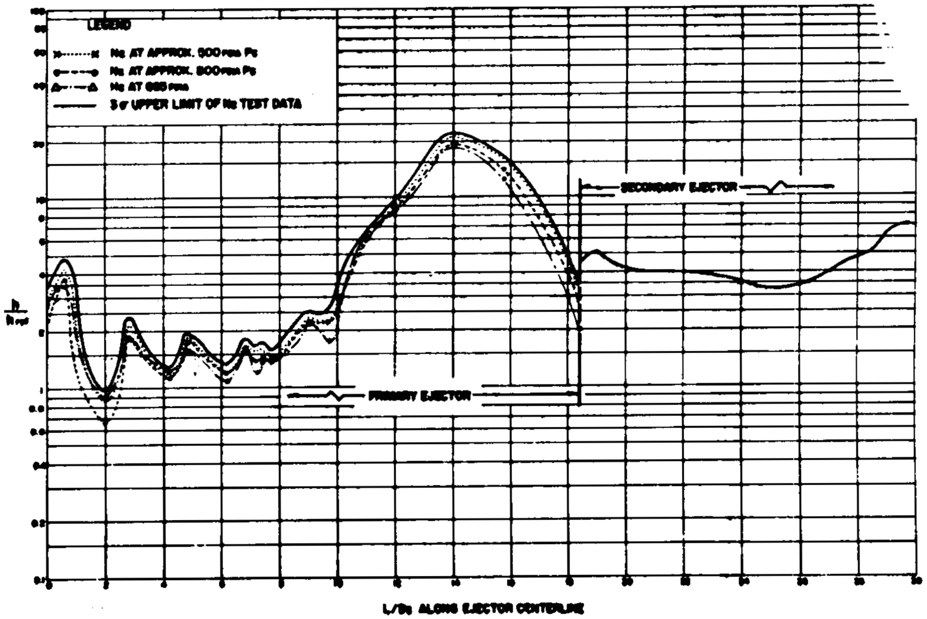
EFFECTS OF TURNING RADIUS ON HEAT TRANSFER COEFFICIENT DISTRIBUTION FOR EJECTORS 1 & 2

FIGURE 5

NOTES.
1. EJECTOR NO. 3
2. POINTS TAKEN ON IMPINGEMENT SIDE OF ELBOW.

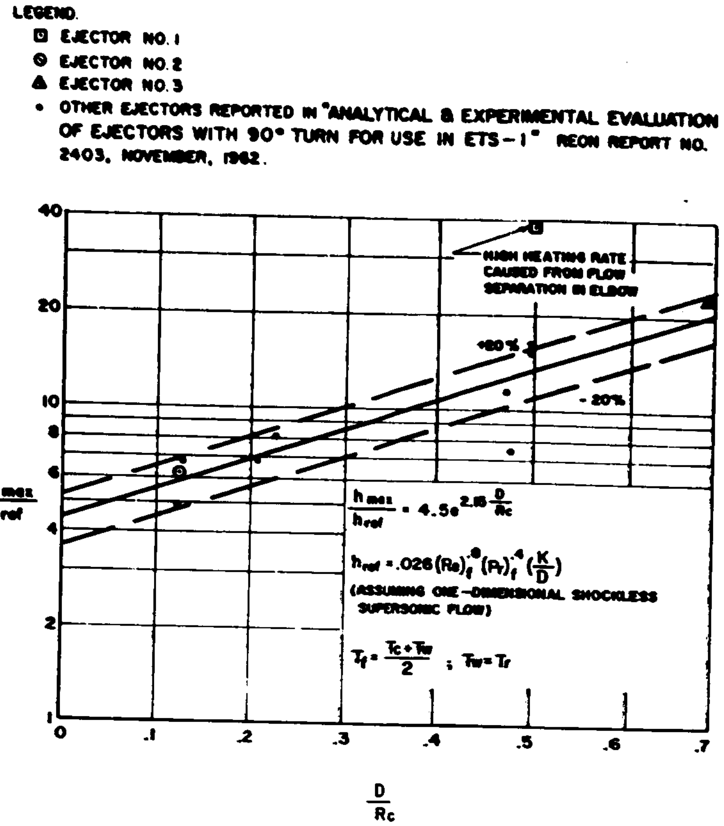


L/De LOCATIONS



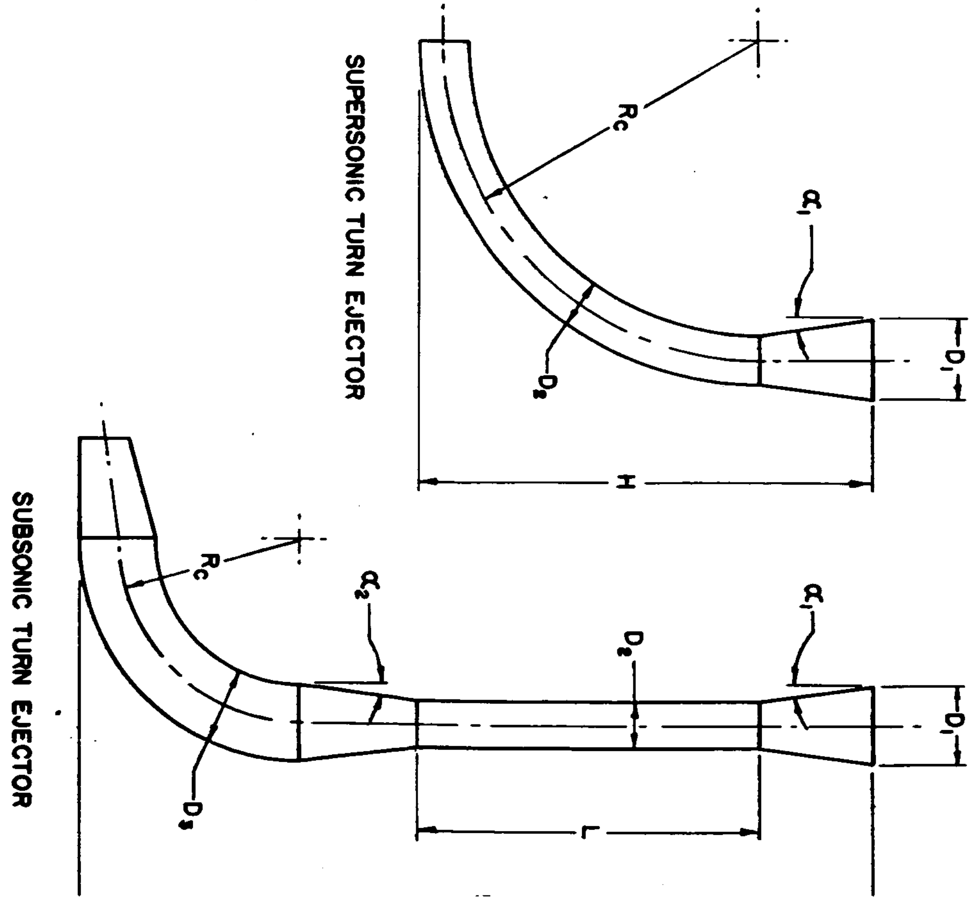
HEAT TRANSFER COEFFICIENTS FOR EJECTOR NO. 3

FIGURE 6



EFFECT OF CURVATURE ON MAXIMUM HEAT TRANSFER IN EJECTORS

FIGURE 7



LOCATION OF EJECTOR DIMENSIONS

FIGURE 8