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EXTERNAL FINS AND EJECTOR ACTION FOR REDUCING THE INFRARED EMISSION OF ENGINE EXHAUST DUCTING

G. James Van Fossen, Jr.

Lewis Research Center

and U.S. Army Air Mobility R&D Laboratory

Cleveland, Ohio 44135

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16. Abstract

An analytical investigation was conducted to determine the feasibility of using external fins and ejector action on the exhaust ducting of a helicopter to reduce the infrared emission of the aircraft. Temperatures were calculated for both circular disk fins and pin fins. Results show that combining ejector action with fins can lower the metal temperature to acceptable levels at least for high flight speeds.

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EXTERNAL FINS AND EJECTOR ACTION FOR REDUCING THE INFRARED EMISSION OF ENGINE EXHAUST DUCTING

by G. James Van Fossen, Jr.

Lewis Research Center
U.S. Army Air Mobility R&D Laboratory

SUMMARY

An analytical investigation was conducted to determine the feasibility of using external fins and ejector action on the exhaust ducting of a helicopter to reduce the infrared emission of the aircraft. Both circular disk fins and pin fins were investigated. Conditions used in the study simulated the exhaust of the Army's OH-58 helicopter.

Results of the study show that neither the fins alone nor the ejector action alone is capable of reducing the metal temperature to an acceptable level. Combining external fins with ejector action, however, brings the metal temperature to an acceptable level at the higher flight speeds.

INTRODUCTION

This report covers an analytical investigation of the feasibility of using external fins and ejector action to entrain cool ambient air to cool the exhaust duct of a helicopter engine and thereby to reduce its infrared emission. Some infrared suppressors in use are complex heat exchangers which require an engine driven blower and involve a considerable penalty in engine power. An alternative is to use the forward velocity of the aircraft and/or the rotor downwash for cooling purposes. This would eliminate the need for direct power extraction. Manufacturing costs for this alternative system promise to be lower than for other suppressors because of reduced complexity.

The purpose herein is to demonstrate analytically the feasibility of this alternative concept. The analysis was conducted for turbine exhaust conditions that matched those of the Army's OH-58 helicopter. The air velocity over the duct was varied from zero to the maximum forward flight speed of the OH-58. The effects of using circular disk fins and pin fins with and without ejector action were investigated.

SYMBOLS

A	area, m
b, C	empirical constants used in eq. (11)
C_p	specific heat at constant pressure, J/kg-K
D	cylinder diameter, m
D_0	pin diameter, m
h	convective heat-transfer coefficient, W/m-K
k	thermal conductivity, W/m-K
$\mathscr{L}$	duct length, m
m	annular fin parameter defined by eq. (14), m^{-1}
$\dot{m}$	mass flow rate, kg/sec
N	pin fin spacing to diameter ratio
n	pin fin parameter defined by eq. (16), m^{-1}
Pr	Prandtl number
p	pressure, N/m
R	gas constant for air, N-m/kg-K
Re	Reynolds number
r	radius, m
T	temperature, K
V	velocity, m/sec
Γ	radius of curvature of duct, m
δ	annular fin thickness, m
η	annular fin efficiency defined by eq. (13)
ν	kinematic viscosity, m^2/sec
ρ	density, kg/m
τ	duct wall thickness, m

Subscripts:

c	coolant
eff	effective

ex turbine exhaust

f film

g hot gas

m metal

s surface

1 nozzle exit

2 ejector inlet

3 ejector outlet

Superscript:

total conditions

CONFIGURATIONS AND CONDITIONS

Two configurations were studied:

(1) The turbine exhaust run through a plain pipe (i. e., no ejector action), figure 1(a)

(2) The turbine exhaust run through a nozzle and ejector assembly to mix cool ambient air with the hot exhaust gas, which reduced the heat transferred from the exhaust gas to the metal, figure 1(b)

The external surfaces of the plain pipe and the ejector were equipped with fins. These provided six cases for analysis of duct metal temperatures: (1) no fins, (2) no fins with ejector, (3) circular disk fins, (4) circular disk fins with ejector, (5) pin fins, and (6) pin fins with ejector. Figure 1 shows the configurations used. In all cases the duct was considered to have a 90° bend to prevent direct viewing of other hot components. Air flow over the duct was assumed to be perpendicular to its axes in all cases.

Calculations for cases 1, 3, and 5 were performed for a duct size of 15.24 centimeters (6 in.) in diameter and 0.610 meter (2 ft) long. The radius of curvature of the 90° bend was 17.78 centimeters (7 in.).

Ejector and nozzle diameters were chosen to conform to the constraints of the OH-58 application. The ejector diameter was 20.32 centimeters (8 in.), and the turbine exhaust nozzle diameter was 14.29 centimeters (5.625 in.). The radius of curvature of the 90° bend in the ejector was the same as that for the plain pipe.

Turbine exhaust gas flow was 0.907 kilogram per second (2 lbm/sec) at 811 K (1000° F). Ambient air temperature was assumed to be 308.3 K (95° F).

The circular disk fins used in this feasibility study were 0.159 centimeter (0.0625 in.) thick with a spacing of 0.635 centimeter (0.25 in.). These fins were 2.54 centimeters (1 in.) high. The pin fins used in this study were 0.3175 centimeter

(0. 125 in.) in diameter, 9 diameters long, and spaced at 3 diameters. All the fins were made of aluminum, as were the duct and ejector walls (both 0. 3175 cm (0. 125 in.) thick).

ANALYSIS

It was assumed that a one-dimensional thermal analysis of the plain duct or ejector wall would be sufficient for this feasibility study. Velocity variations around the outer surface of the duct or ejector, which will surely occur in practice, are not considered in this analysis.

Ejector Flow

The purpose of the ejector is to mix cool ambient air with the hot exhaust gas. The ejector action thus reduces the amount of heat that must be removed by the fins to lower the metal temperature. As such, it is desirable to mix as much ambient air as possible with the exhaust gas; however, consideration must be given to duct size and engine back pressure constraints, both of which will impose practical limits.

A one-dimensional mass, momentum, and energy balance was used to model the ejector. The model, for the sake of simplicity, assumed complete mixing. The ejector is shown in figure 2. Station 0 is the turbine exit position, station 1 the exhaust nozzle exit, station 2 the ambient air inlet, and station 3 the mixed exhaust outlet. The assumptions used in the ejector analysis were the following:

(1) Friction can be neglected.

(2) Flow in the ejector is adiabatic and incompressible.

(3) $p_1 = p_2$.

(4) $p_2' = p_3$.

(5) Complete mixing occurs before station 3.

(6) The gas in the ejector is a perfect gas.

(7) The specific heat is constant.

(8) The turbine exhaust flow rate is independent of back pressure p_1.

(9) $A_1 + A_2 = A_3$.

Conservation of mass for the ejector gives

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \tag{1}$$

conservation of momentum gives

$$p_1A_1 + p_2A_2 - p_3A_3 = \dot{m}_3V_3 - \dot{m}_2V_2 - \dot{m}_1V_1 \tag{2}$$

and conservation of energy gives

$$\dot{m}_1\left(T_1 + \frac{V_1^2}{2C_p}\right) + \dot{m}_2\left(T_2 + \frac{V_2^2}{2C_p}\right) = \dot{m}_3\left(T_3 + \frac{V_3^2}{2C_p}\right) \tag{3}$$

Applying assumptions 3 and 4 to equation (2) and rearranging gives

$$\rho_3 V_3 - \rho_1 V_1^2\left(\frac{A_1}{A_3}\right) = \rho_2 V_2^2\left(\frac{A_2}{A_3} - 0.5\right) \tag{4}$$

where

$$\dot{m} = \rho V A \tag{5}$$

and

$$\rho = \frac{P}{RT} \tag{6}$$

Equation (3) was solved for the mixed temperature in terms of the other parameters:

$$T_3 = \frac{-1 + \sqrt{1 + \frac{2}{C_p}\left(\frac{R\dot{m}_3}{P_3 A_3}\right)^2\left(\frac{\dot{m}_1 T_1' + \dot{m}_2 T_2'}{\dot{m}_3}\right)}}{\frac{1}{C_p}\left(\frac{\dot{m}_3 R}{P_3 A_3}\right)^2} \tag{7}$$

where

$$T' = T + \frac{V^2}{2C_p} \tag{8}$$

is the total temperature. Given $\dot{m}_1$, T_1, P_3 equations (4) and (7) were solved simultaneously by the following procedure:

(1) Guess an initial $\dot{m}_2$.
(2) Calculate $\dot{m}_3$ using equation (1).
(3) Calculate P_2 using assumption 4.
(4) Calculate T_3 from equation (7).

(5) Use the Newton-Raphson technique to compute a new guess for $\dot{m}_2$ from equation (4).

(6) Test for convergence:

(a) If converged, stop.

(b) If not converged, go back to step 2.

Once the nozzle exit pressure p_1 was known, the turbine back pressure p_0 was computed from compressible flow relations.

Duct Internal Heat-Transfer Coefficient

The heat-transfer coefficient on the inside of the duct was calculated from the pipe equation for turbulent flow:

$$h_g = 0.020 \frac{k_g}{D} (Re_D)^{0.8} Pr_g^{1/3} \left(\frac{T_b}{T_s}\right)^{0.15} \left[1 + \left(\frac{D}{\mathscr{L}}\right)^{0.7}\right] \left[1 + 3.54 \left(\frac{D}{2\Gamma}\right)\right] \tag{9}$$

The latter terms in brackets were added for entrance length and curvature effects (see refs. 1 and 2). All the gas properties were evaluated at the film temperature:

$$T_f = \frac{1}{2} (T_s + T_g) \tag{10}$$

Duct External Heat-Transfer Coefficient

No fins. - The heat-transfer coefficient on the exterior surface for the no fin case was taken as the average heat-transfer coefficient on a cylinder in crossflow. This can be expressed as (see ref. 2)

$$h_c = C \frac{k_c}{D} \left(\frac{V_\infty D}{\nu_c}\right)^b \tag{11}$$

where C and b are empirical constants whose numerical values vary with the Reynolds number. The properties in equation (11) were evaluated at the film temperature (eq. (10)).

Circular disk fins. - Ellerbrock and Biermann (ref. 3) measured the average heat-transfer coefficient over the surface of three different diameter finned cylinders. The cylinder diameters used were 9.30, 11.84, and 16.10 centimeters (3.66, 4.66, and

6.34 in.), which are in the size range of the exhaust duct being considered. A wide range of fin thicknesses, spacings, and heights were considered.

Data are presented in reference 3 for coolant flow parallel to the plane of the fins (i.e., perpendicular to the axis of the cylinder) and for flow at 45° to the plane of the fins. In reference 4 Shey and Biermann present data which indicate that the 45° case gave the largest heat-transfer coefficients. The lowest heat transfer was obtained at 90° to the plane of the fins; however, no heat-transfer coefficients for this case are available. The data of Ellerbrock and Biermann (ref. 3) were used to evaluate the heat-transfer coefficient for the 0° case.

An effective heat-transfer coefficient which allows a cylinder with fins to be analyzed as if it were a cylinder with no fins was calculated from

$$h_{c,\,eff} = h_c\left(1 - \frac{2\pi r_1 \delta}{A}\right) + \frac{2\pi\left(r_2^2 - r_1^2\right)\eta h_c}{A} \tag{12}$$

where A is the surface area of the finless duct per fin, r_2 and r_1 are the outer and inner radii of the circular disk fins, respectively, and h_c is the average heat-transfer coefficient from reference 3. The fin efficiency η is

$$\eta = \frac{2r_1}{\left(r_2^2 - r_1^2\right)m}\left[\frac{I_1(mr_2)K_1(mr_1) - I_1(mr_1)K_1(mr_2)}{I_0(mr_1)K_1(mr_2) + I_1(mr_2)K_0(mr_1)}\right] \tag{13}$$

where

$$m = \sqrt{\frac{2h_c}{k_m \delta}} \tag{14}$$

δ is the fin thickness, and I_0, I_1, K_0, and K_1 are the modified Bessel functions of order zero and one. Equation (13) was obtained using the analysis presented in reference 5.

Pin fins. - Average heat-transfer coefficients for a 15.24-centimeter (6-in.) diameter cylinder with pin fins on its surface are given in reference 6. An effective heat-transfer coefficient due to the presence of the pins is given by

$$h_{c,\,eff} = h_c\left(1 - \frac{\pi}{4N^2}\right) + \frac{\pi k_m n}{4N^2}\left[\frac{\sinh(nl) + \left(\frac{h_c}{nk_m}\right)\cosh(nl)}{\cosh(nl) + \left(\frac{h_c}{nk_m}\right)\sinh(nl)}\right] \tag{15}$$

where

$$n = \sqrt{\frac{4h_c}{k_m D_0}} \tag{16}$$

It was assumed that the heat-transfer coefficient h_c was uniform over the sides of the pins, the ends of the pins, and the surface of the duct between the pins.

Inside Duct or Ejector Surface Temperature

One-dimensional heat flow was assumed through the duct wall. The inside duct wall temperature was calculated since this would be the highest temperature an infrared detector could see. However, for a 0.3175-centimeter- (0.125-in.-) thick aluminum wall the difference between inside and outside wall temperatures would only be about 2 K (3.6° F). The inside duct surface temperature was calculated from

$$T_i = T_g - \frac{T_g - T_c}{\frac{h_g}{h_{c,\,eff}} + \frac{h_g \tau}{k_m} + 1} \tag{17}$$

The calculation procedure was to obtain the exhaust side heat-transfer coefficient using equation (9). Depending on geometry, either equation (11) for no fins, the Ellerbrock and Biermann data for circular fins, or the pin fin data of reference 6 was used to calculate the external heat-transfer coefficient h_c for a given air speed over the duct or ejector. Equation (12) was then used to calculate the effective external heat-transfer coefficient $h_{c,\,eff}$ for the circular fin case, or equation (15) was used to find the effective external heat-transfer coefficient for the pin fin case.

Given the exhaust side convection coefficient and exhaust temperature, the air side effective convection coefficient, the wall thickness, and the wall thermal conductivity, the inside duct or ejector surface temperature was calculated from equation (17).

RESULTS

Results of the ejector flow analysis are shown in figure 3. Figure 3(a) shows the mixed exhaust temperature T_3° as a function of the ejector diameter with the exhaust nozzle diameter as a parameter. As expected, the larger the ejector diameter, the lower the mixed exhaust temperature. The turbine flow rate was assumed constant; therefore, as the engine exhaust nozzle diameter decreased the exhaust velocity increased, which resulted in more cool air being entrained in the ejector. Figure 3(b) shows the turbine exhaust pressure as a function of the exhaust nozzle diameter. For the range of ejector and nozzle diameters investigated, the exhaust pressure was found to be a function of nozzle diameter only. Figure 3(b) shows that the turbine exhaust pressure p_0 changes only slightly (3 percent) for the range of exhaust nozzle diameters investigated; thus, the assumption of constant turbine flow rate is justified. Figure 3(c) shows entrained mass flow $\dot{m}_2$ as a function of the ejector diameter with the exhaust nozzle diameter as a parameter.

Ejector dimensions used in this feasibility study were selected to give the lowest mixed exhaust temperature possible under the constraints of the OH-58 application (see fig. 3). The ejector diameter selected was 20.32 centimeters (8 in.), and the nozzle diameter was 14.29 centimeters (5.625 in.). This gave a mixed exhaust temperature of 619 K (655° F) and increased the turbine exhaust pressure from 101 353 newtons per square meter (14.70 psia) to 101 698 newtons per square meter (14.75 psia). The ejector mass flow was 1.48 kilograms per second (3.27 lbm/sec).

To be effective against modern infrared sensors an infrared suppressing device should lower duct temperatures to about 425 K (305° F). The calculated exhaust duct temperatures for the six cases considered are shown in figure 4 as functions of air speed. This figure shows that fins alone do not lower the temperature of the duct enough to make it acceptable. In addition, the ejector alone is not enough. Combining the fins and ejector action, however, brings the metal temperature to an acceptable level at the higher flight speeds. Although the duct or ejector with the circular disk fins is slightly cooler than the pin fins at the maximum speed, pin fins have an advantage over circular disk fins for this application because their heat-transfer performance will be less sensitive to air flow direction.

Based on the trend of experimental pin-fin data of reference 6, it is quite possible that smaller diameter pins spaced closer together would give higher effective heat-transfer coefficients than those used in this study. This would further reduce the metal temperature; however, such experimental data are not presently available.

Increasing the size of the ejector would allow more cool air to be entrained than was used in this study, but because of size constraints imposed by the OH-58 application the scope of the work was limited. Decreasing the diameter of the exhaust nozzle and thus increasing the exhaust velocity would also increase entrainment. In this case, the increased turbine back pressure might be unacceptable in terms of engine performance.

CONCLUSIONS

This feasibility study demonstrates that either fins on the exterior surface of an exhaust duct or on an ejector can be useful in lowering the duct temperature. Both fins and ejector action are required to reduce metal temperatures to an acceptable level for infrared suppression at the high flight speeds.

Adequate cooling was not attained at lower flight speeds for the constraints imposed by this study. A wide variety of geometries can be investigated to optimize the design and to further reduce the duct temperature. The concept of external fins could also be used to augment other types of suppressors and thus allow them to use less coolant and less power from the engine.

Lewis Research Center,
National Aeronautics and Space Administration,
and
U. S. Army Air Mobility R&D Laboratory,
Cleveland, Ohio, March 12, 1975,
505-04.

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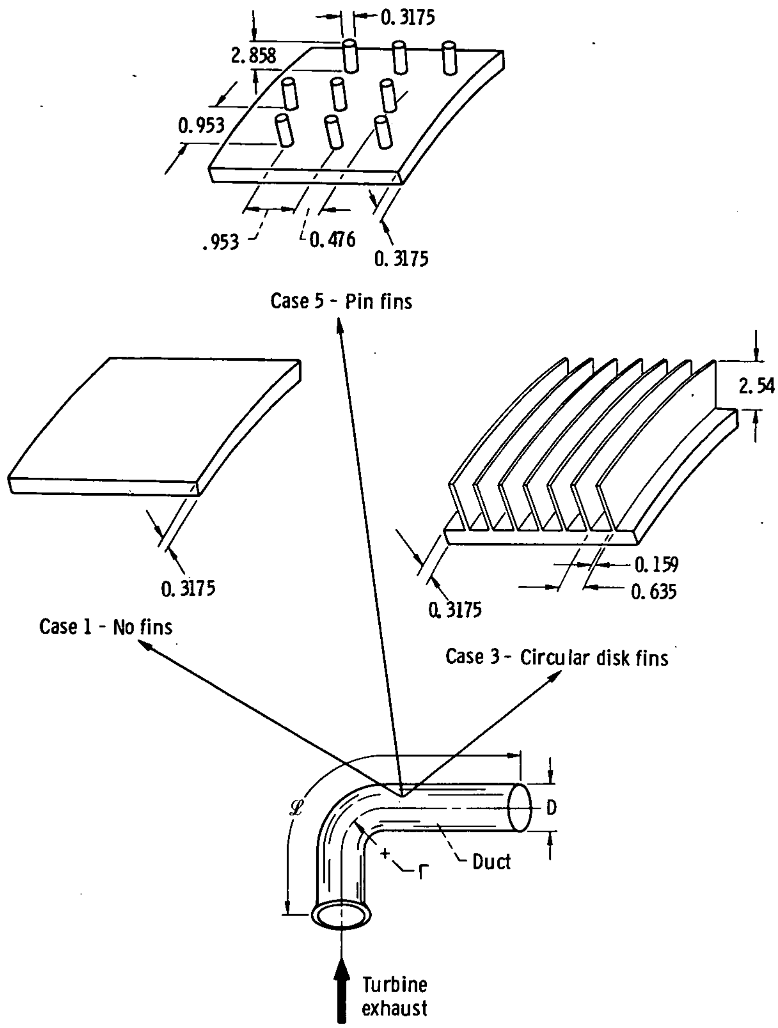
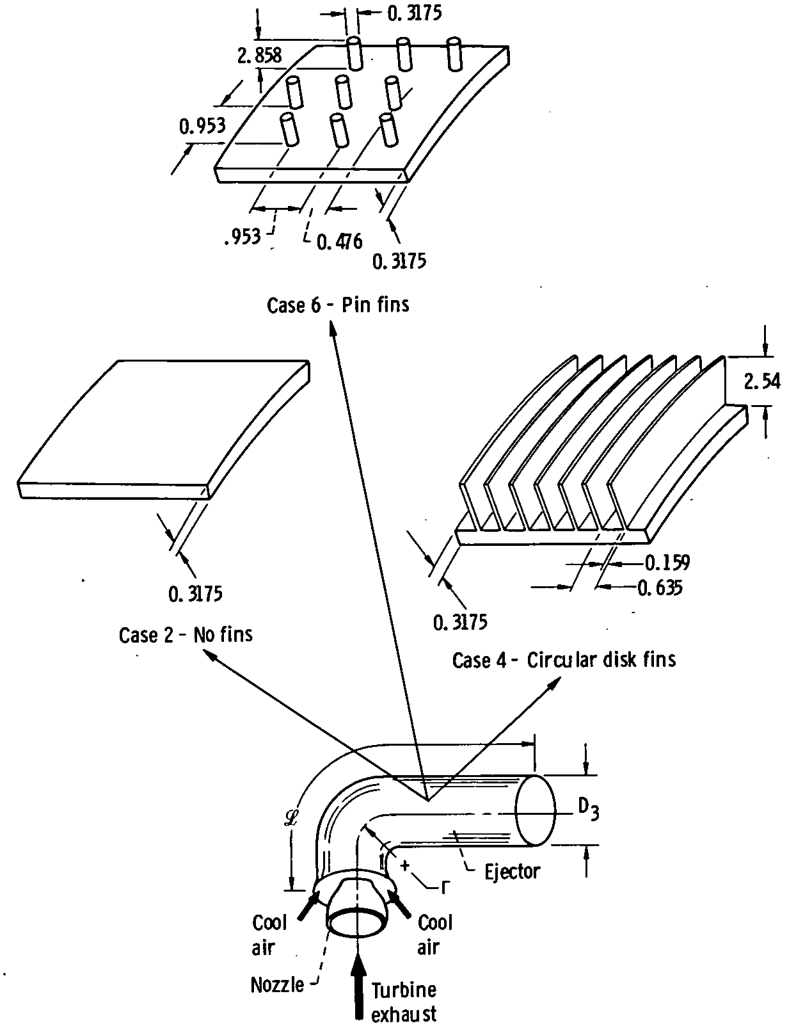


(a) Plain duct configuration.

Figure 1. - Configurations used for helicopter exhaust duct cooling study. All dimensions are in centimeters.



(b) Ejector configuration.

Figure 1. - Concluded.

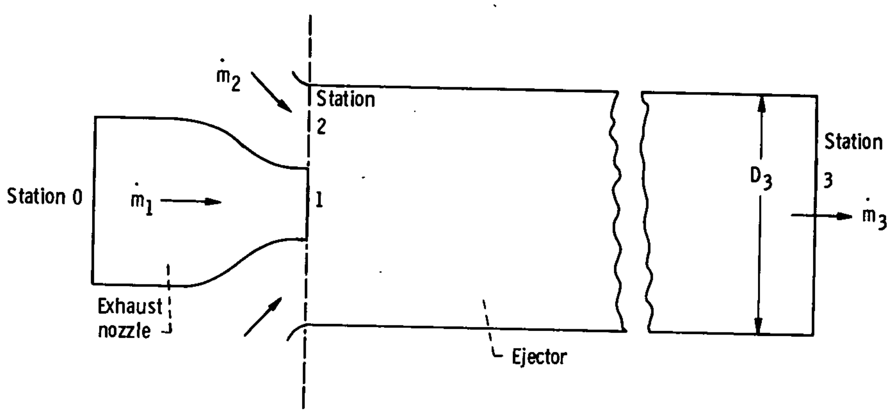
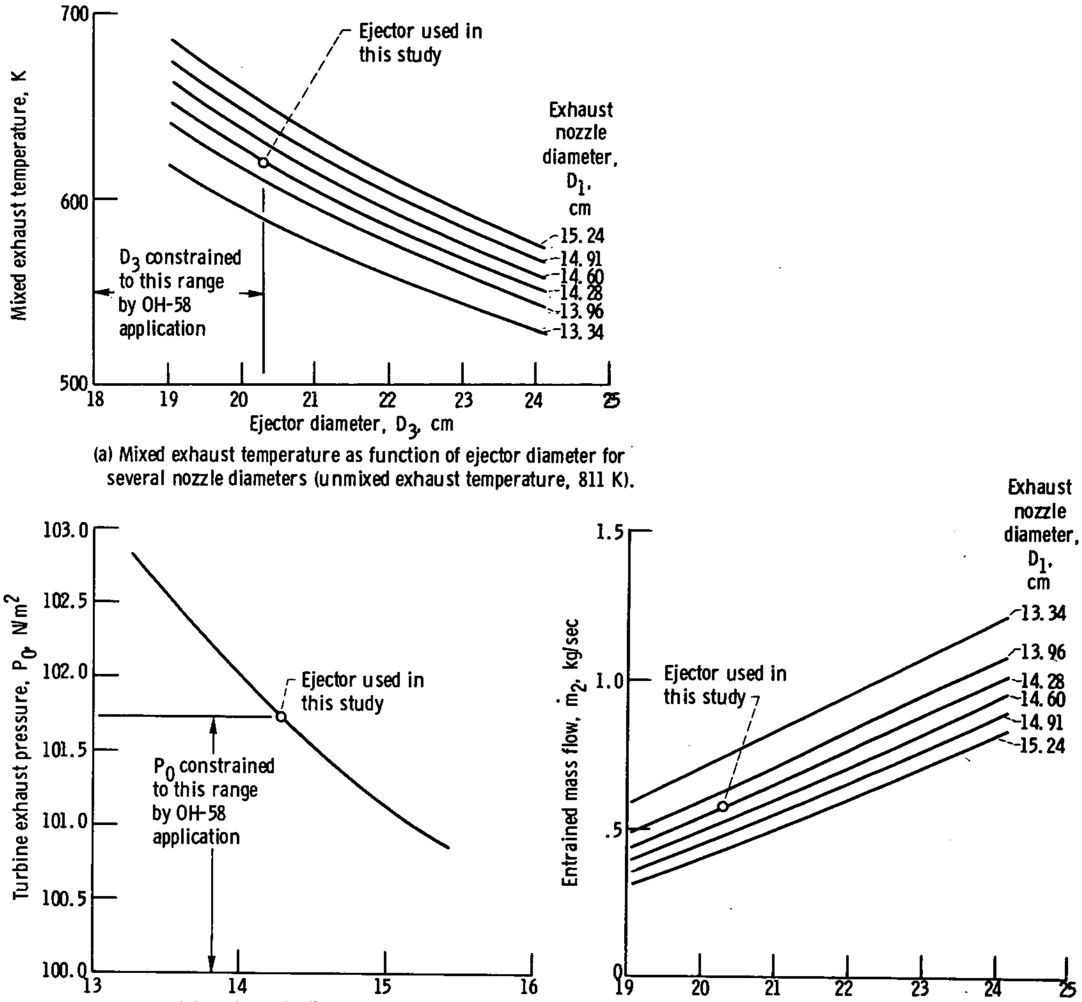


Figure 2. - Ejector model.



(a) Mixed exhaust temperature as function of ejector diameter for several nozzle diameters (unmixed exhaust temperature, 811 K).

(b) Turbine exhaust pressure as function of exhaust nozzle diameter.

(c) Entrained mass flow as function of ejector diameter for several nozzle diameters (primary exhaust flow, 0.907 kg/sec).

Figure 3. - Ejector flow characteristics.

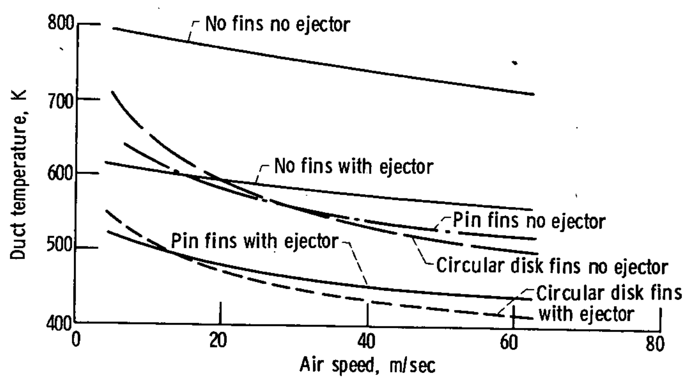


Figure 4. - Variation in exhaust duct temperature with air speed for all six cases.

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