RESEARCH MEMORANDUM

CORRELATION OF ISOHERMAL CONTOURS FORMED BY PENETRATION OF JET OF LIQUID AMMONIA DIRECTED NORMAL TO AN AIR STREAM

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SUMMARY

An investigation was conducted to correlate the isothermal contour lines formed downstream of a single jet of liquid ammonia directed normal to an air stream. Criteria are presented to facilitate the design of jet-engine thrust-augmentation systems utilizing the injection of liquid ammonia to cool the air at the compressor inlet. From the correlation presented, it is possible to construct an isothermal contour map for a single orifice operating within the following range of conditions: air velocity, 112 to 329 feet per second; air density, 0.024 to 0.070 pound per cubic foot; air temperature, 534° to 770° R; ammonia jet velocity, 63 to 244 feet per second; ammonia temperature, 433° to 470° R; mixing distance, 4 to 24 inches; orifice diameter, 0.018 to 0.053 inch. It was verified that the construction of the isothermal contours formed by a multiorifice injection system may be determined by simply adding the temperature drops of the overlapping single-orifice contour maps determined from the correlation.

INTRODUCTION

One method of augmenting the thrust of a turbojet engine is to cool the air entering or passing through the compressor. Water-alcohol mixtures have been extensively used as coolants because of their high latent heat of vaporization. The high boiling point of the water-alcohol mixtures, however, restricts their application to flight conditions for which the inlet-air temperature is relatively high, principally take-off. For low inlet-air temperatures, such as those encountered during high-altitude flight in the transonic speed range, liquid ammonia is an attractive coolant because of its low boiling point even though its latent heat of vaporization is only about one-half that of water. However, liquid ammonia would not be an effective coolant at low altitudes (ref. 1) where the atmosphere is relatively moist, because it combines exothermically with water to form ammonium hydroxide.
One of the basic requirements of an inlet coolant-injection system is that it distribute the coolant as evenly as possible in the inlet-air stream in order to provide a uniform temperature at the compressor inlet. It is evident that the penetration and cooling characteristics of the injected liquid must be known before an adequate injection system can be designed. In order to provide the needed information, an investigation was conducted at the NACA Lewis laboratory to measure and to correlate the isothermal contours formed by the penetration of a single jet of liquid ammonia directed normal to an air stream.

Data for this investigation were obtained at several distances downstream of the point of injection for several orifice diameters over ranges of ammonia-to-air velocity, density, and temperature ratios. A correlation of the temperature profile in a plane containing the axis of the ammonia jet is presented, together with a correlation of the maximum width of the isothermal contour map formed by the penetration of the jet of liquid ammonia into the air stream. The method of correlation employed in this investigation is similar to that used in references 2 and 3 to correlate the penetration characteristics of water and heated-air jets directed normal to an air stream.

From the correlations presented herein, it is possible (within the range of variables considered) to construct an isothermal contour map for a particular design application and to predict the temperature gradients formed by the injection system. In order to demonstrate a simple method of extending the single-orifice correlation to a multi-orifice injection system, a prediction of the isothermal contour map formed by a double-orifice system is made and compared with experimental results.

APPARATUS

Air System

The apparatus for this investigation was installed in a 21-inch-diameter duct which was connected to the laboratory dry-air system as schematically indicated in figure 1. Four combustor-type preheaters were used to obtain air temperatures from 80° to 300° F, and the desired stream velocity and density were established in the duct by regulating the air flow through the inlet and exhaust control valves. The quantity of air flowing through the system was measured by a calibrated A.S.M.E. type orifice located upstream of the inlet-air control valves.
Ammonia System

Liquid anhydrous ammonia was supplied at various temperatures and pressures to a single-orifice spray bar which injected the ammonia normal to the air flow in the 21-inch-diameter duct. In order to maintain the ammonia in its liquid state, the system was pressurized with helium from tanks connected to the ammonia storage tank (fig. 2). Liquid ammonia from the storage tank was passed through rotameters and a filter to the heat exchanger where it was cooled by the evaporation of ammonia surrounding the heat-exchanger coils. The temperature of the measured ammonia flow was controlled by varying the pressure and, hence, the evaporation rate of the surrounding ammonia in the heat exchanger. The pressurized ammonia from the heat exchanger was passed through the throttle to the spray bar shown in figure 3. In order to prevent heating of the ammonia as it flowed from the heat exchanger to the spray orifice, the connecting lines were insulated. The temperature of the liquid ammonia was measured by means of a thermocouple installed within the spray bar close to the orifice. The three single-orifice spray bars investigated had orifice diameters of 0.018, 0.029, and 0.053 inch. In addition, a two-orifice spray bar was used which was similar to the single-orifice bars except that it had two 0.031-inch-diameter orifices 1 inch apart.

Test Section

The spray bar was located 5 inches from the bottom of the duct with the orifice directed upward on the vertical center line of the duct. In order to determine the isothermal contour lines formed by the ammonia jet, a twin-armed swinging rake equipped with aspirating thermocouples was installed in the duct (fig. 4). The thermocouple probes were pointed downstream to prevent droplets of liquid ammonia from contacting the thermocouple junctions, and the rake body was connected to the laboratory exhaust system to provide a continuous flow of gas through the thermocouple probes. A detailed sketch of the aspirating thermocouple probes is shown in figure 5. The mixing distance between the spray bar and the swinging survey rake was varied by altering the axial location of the spray bar in the duct.

Other instrumentation in the test section provided for the measurement of duct static pressure by means of three wall static taps 30 inches upstream of the survey rake (fig. 4) and the measurement of total air temperature with an 8-inch immersion thermocouple in the 8-foot straight section upstream of the survey rake.
CORRELATION PROCEDURE

Characteristics of Isothermal Contour Maps

From the temperature surveys made with the swinging rake described in the previous section, maps of constant temperature drop were constructed to define the penetration and cooling characteristics of the jet of liquid ammonia. Samples of these isothermal contour maps are presented in figure 6 for a range of air velocities. The slight displacement of all the contour maps from the vertical center line of the duct is attributed to some residual whirl of the air in the duct. It is believed that the experimental results obtained during this investigation were unaffected by the slight displacement of the isothermal maps.

In order to achieve a correlation of these isothermal contours, it was necessary to establish a method of defining the map in terms of its geometric dimensions. Accordingly, the maps were considered to be symmetrical about an axis containing both the maximum depth of penetration and the maximum temperature drop. It was decided that the isothermal contour map could be approximated if two temperature profiles, one along the axis of symmetry and one through the center of the map perpendicular to the axis of symmetry, were known. The axes of these temperature profiles are shown as dashed lines in figure 6.

A sketch of an isothermal contour map together with the temperature profiles existing along and perpendicular to the axis of symmetry is presented in figure 7. (The symbols used in figure 7 and elsewhere in this report are defined in appendix A.) The temperature profile along the axis of symmetry can be closely approximated by three straight lines as illustrated by figure 8, where typical temperature profiles are presented for a range of air velocities. The agreement between the tangents and the actual temperature profile along the axis of symmetry was particularly good on the upper portion of the profile. The center line of the spray bar was chosen as the datum line of this temperature profile, and the dimensions which will be correlated to define it are: $y_1$, $y_2$, $y_3$, $y_4$, and $\Delta T_m$ (fig. 7).

The temperature profile in a direction perpendicular to the axis of symmetry was obtained by cross-plotting from the isothermal contour map. These cross plots revealed that this temperature profile could be closely approximated by assuming a linear variation of temperature between the isotherm for a temperature drop of $5^\circ$ F and that for maximum temperature drop $\Delta T_m$. It was further observed that the isotherm of maximum temperature drop $\Delta T_m$ could be considered to be circular ($x_2 = y_3 - y_4$ in fig. 7). Therefore, the only dimension required to complete the correlation of the isothermal contour map is the distance between lines of $5^\circ$ F temperature drop ($x_1$).
Derivation of Correlation Equation

The dimensional analysis and experimental results of references 2 and 3 indicate that an equation of the form

$$\frac{y}{\sqrt{C \cdot D_j}} = K \left(\frac{V_j}{V_0}\right)^a \left(\frac{\rho_j}{\rho_0}\right)^b \left(\frac{S}{\sqrt{C \cdot D_j}}\right)^c \tag{1}$$

may be used to correlate the penetration characteristics of water and heated air jets directed normal to an air stream. The injection of liquid ammonia into an air stream, however, introduces an added complication in that the ammonia changes rapidly from the liquid to the gaseous state after injection. The evaporation rate of the liquid is dependent upon its vapor pressure and the conditions of pressure and temperature existing in the air stream. Because the vapor pressure of the liquid is a function of the liquid temperature $T_j$, and because the air temperature can be varied independently of the air density, an additional dimensionless ratio $T_j/T_0$ was added to equation (1). The resulting correlation equation was then written as follows:

$$\frac{y}{\sqrt{C \cdot D_j}} = K \left(\frac{V_j}{V_0}\right)^a \left(\frac{\rho_j}{\rho_0}\right)^b \left(\frac{T_j}{T_0}\right)^c \left(\frac{S}{\sqrt{C \cdot D_j}}\right)^d \tag{2}$$

Equation (2) was used to correlate the linear dimensions ($y_1, y_2, y_3, y_4$, and $x_1$) of the temperature profiles along and perpendicular to the axis of symmetry of the contour map (fig. 7). In order to correlate the maximum temperature drop $\Delta T_m$ occurring at the center of the contour map, the correlation equation was written in the following form:

$$\frac{\Delta T_m}{T_0 - T_j} = K_t \left(\frac{V_j}{V_0}\right)^e \left(\frac{\rho_j}{\rho_0}\right)^f \left(\frac{T_j}{T_0}\right)^g \left(\frac{S}{\sqrt{C \cdot D_j}}\right)^h \tag{3}$$

The general procedure followed in obtaining the data for this investigation was to hold three of the terms on the right side of the correlation equation constant and to determine the variation of the remaining term with the quantity being correlated. In this manner, the exponent of each term in the general correlation equation was evaluated for each of the dimensions correlated. The data obtained in this investigation are presented in table I and include the following range of variables:
EVALUATION OF EXPONENTS AND CONSTANTS

Correlation of Temperature Profile Along Axis of Symmetry

Boundary dimension $y_1$. - The distance between the spray-bar center line and the intersection of the upper bounding tangent of the temperature profile along the axis of symmetry of the isothermal contour map with the line of zero temperature drop was defined as $y_1$ (fig. 7).

The correlation equation for the bounding dimension $y_1$ was written as follows:

$$\frac{y_1}{\sqrt{C} D_j} = K_1 \left( \frac{V_J}{V_0} \right)^a \left( \frac{\rho_J}{\rho_0} \right)^b \left( \frac{T_J}{T_0} \right)^c \left( \frac{s}{\sqrt{C} D_j} \right)^d$$

(4)

The exponent of the velocity ratio $V_J/V_0$ was determined by holding the remaining terms of equation (4) constant and plotting the variation of the penetration parameter $y_1/\sqrt{C} D_j$ with the velocity ratio on logarithmic coordinates as shown in figure 9(a). Data are shown for two density ratios, each set of which may be represented by a straight line having a slope of 0.77. The exponent of the velocity ratio is therefore 0.77. The exponent of the density ratio $\rho_J/\rho_0$ was determined in a similar manner for two temperature ratios, and an exponent of 0.53 was obtained (fig. 9(b)). The effect of the temperature ratio on the penetration parameter $y_1/\sqrt{C} D_j$ is illustrated in figure 9(c) for two density ratios. In order to maintain the ammonia in its liquid state in the spray bar, the temperature of the ammonia was restricted in this investigation to a range of from 433° to 470° R. Although the range of $T_J$ is not large, it covers all cases of practical interest. The exponent of the temperature ratio was found to be 1.1 (fig. 9(c)).
The effect of the ratio of mixing distance to effective diameter was obtained by plotting the quantity 
\[ \frac{y_1/\sqrt{C} D_j}{(V_j/V_0)^{0.77} (p_j/p_0)^{0.53} (T_j/T_0)^{1.1}} \] as a function of 
\( S/\sqrt{C} D_j \) on figure 9(d). These data include three mixing distances and three orifice diameters and may be approximately represented by a line with a slope of 0.72.

The remaining unknown required to complete the correlation of the penetration parameter \( y_1/\sqrt{C} D_j \) is the coefficient \( K_1 \). In evaluating this coefficient, the penetration parameter was plotted as a function of the quantity 
\[ (V_j/V_0)^{0.77} (p_j/p_0)^{0.53} (T_j/T_0)^{1.1} (S/\sqrt{C} D_j)^{0.72} \] (fig. 9(e)). Substitution of coordinate values into the correlation equation yielded a value of \( K_1 \) equal to 0.214. The working equation for the boundary dimension \( y_1 \) is then

\[ \frac{y_1}{\sqrt{C} D_j} = 0.214 \left( \frac{V_j}{V_0} \right)^{0.77} \left( \frac{p_j}{p_0} \right)^{0.53} \left( \frac{T_j}{T_0} \right)^{1.1} \left( \frac{S}{\sqrt{C} D_j} \right)^{0.72} \]  (5)

Boundary dimension \( y_2 \). - The distance between the spray-bar center line and the intersection of the lower-boundary tangent of the temperature profile along the axis of symmetry with a line of zero temperature drop was defined as \( y_2 \) (fig. 7). However, because the dimension \( y_2 \) becomes negative under certain conditions, the quantity \( (y_1 - y_2)/\sqrt{C} D_j \) was chosen as the lower-boundary defining parameter. By a process similar to that used to correlate the penetration parameter \( y_1/\sqrt{C} D_j \), the following equation was developed:

\[ \frac{y_1 - y_2}{\sqrt{C} D_j} = K_2 \left( \frac{V_j}{V_0} \right)^{0.60} \left( \frac{p_j}{p_0} \right)^{0.45} \left( \frac{T_j}{T_0} \right)^{1.1} \left( \frac{S}{\sqrt{C} D_j} \right)^{0.72} \]  (6)

The lower-boundary parameter \( (y_1 - y_2)/\sqrt{C} D_j \) is presented as a function of the right side of equation (6) in figure 10. Substitution of coordinate values from figure 10 into equation (6) yields a value of \( K_2 \) equal to 0.317, and equation (6) becomes

\[ \frac{y_1 - y_2}{\sqrt{C} D_j} = 0.317 \left( \frac{V_j}{V_0} \right)^{0.6} \left( \frac{p_j}{p_0} \right)^{0.45} \left( \frac{T_j}{T_0} \right)^{1.1} \left( \frac{S}{\sqrt{C} D_j} \right)^{0.72} \]  (7)
Maximum temperature drop $\Delta T_m$. - The maximum temperature drop occurring at the center of the isothermal contour map must be known before a temperature profile along the axis of symmetry (fig. 7) can be constructed. The dimensionless parameter selected for this correlation was $\Delta T_m/(T_0 - T_j)$, and by a process similar to that previously described the following correlation equation was developed:

$$\frac{\Delta T_m}{T_0 - T_j} = K_t \left( \frac{v_j}{V_0} \right)^{0.6} \left( \frac{p_j}{p_0} \right)^{1.0} \left( \frac{T_j}{T_0} \right)^{4.0} \left( \frac{s}{\sqrt{c}D_j} \right)^{-0.9}$$

(8)

The maximum-temperature-drop parameter $\Delta T_m/(T_0 - T_j)$ is presented as a function of the right side of equation (8) in figure 11 to determine the value of $K_t$. The value of $K_t$ as determined from figure 11 is 0.838, and equation (8) may be written as

$$\frac{\Delta T_m}{T_0 - T_j} = 0.838 \left( \frac{v_j}{V_0} \right)^{0.6} \left( \frac{p_j}{p_0} \right)^{1.0} \left( \frac{T_j}{T_0} \right)^{4.0} \left( \frac{s}{\sqrt{c}D_j} \right)^{-0.9}$$

(9)

Boundary dimensions $y_3$ and $y_4$. - The distances between the spray-bar center line and the intersections of the upper and lower tangents of the temperature profile along the axis of symmetry with the tangent to the point of maximum temperature drop were defined as $y_3$ and $y_4$, respectively (fig. 7). It was found that $y_3$ and $y_4$ could be correlated with $y_1$ as illustrated in figure 12. Although these correlations are not rigorous, they afford a simple determination of these dimensions when $y_1$ has been found from the general equation.

Correlation of Temperature Profile Perpendicular to Axis of Symmetry

The temperature profile along a line through the center of the isothermal contour map perpendicular to the axis of symmetry may be approximated if the dimensions $x_1$, $x_2$, and $\Delta T_m$ are known (fig. 7). A correlation of the maximum temperature drop $\Delta T_m$ is presented in the previous section. The dimension $x_2$ can be assumed to be equal to $y_3 - y_4$ as discussed in the section CORRELATION PROCEDURE. The distance $x_1$ perpendicular to the axis of symmetry between lines of 50°F temperature drop is therefore the only additional dimension required to complete the correlation of this temperature profile. The
Isothermal contour maps possess a similarity of shape which permitted a correlation of the maximum horizontal width parameter \( x_1/D_j \) as a function of the previously correlated parameter \( (y_1 - y_2)/D_j \). This correlation, which is presented in figure 13, affords a simple approach to the solution of design problems.

**APPLICATION OF CORRELATION**

The correlation presented provides a means of predicting the isothermal contour map formed by a single jet of liquid ammonia directed normal to an air stream. In order to design a multiorifice injection system from this correlation, two assumptions can be made: (1) The temperature drop at any point within the ammonia spray field is proportional to the quantity of ammonia present, and (2) the effects of droplet impingement are negligible. Naturally, the assumption that the temperature drop is proportional to the quantity of ammonia present fails when the air becomes saturated with ammonia. Figure 14 shows the limiting temperature drop obtainable by saturating dry air with ammonia; the temperature drops indicated cannot be exceeded.

To substantiate the two assumptions, data were obtained from a double-orifice spray bar, and a prediction of the resulting isothermal contour map is made from the single-orifice correlation. For the conditions under which the two-orifice data were obtained, temperature profiles along and perpendicular to the axis of symmetry for a single orifice were constructed from the correlation and are presented in figures 15(a) and (b). An isothermal contour map for the single orifice was then constructed by fairing the isotherms between points of known temperature along and perpendicular to the axis of symmetry. The two such single-orifice contour maps presented in figure 15(c) are displaced from each other by a distance equal to the spacing of the orifices on the double-orifice spray bar. The contour map for the double-orifice system was then constructed by adding the temperature drops of the overlapping single-orifice maps. As an aid to the combining of the overlapping maps, a composite temperature profile perpendicular to the axis of symmetry was constructed (fig. 15(d)) by adding the temperature drops \( (\Delta T) \) of two single-orifice temperature profiles displaced from each other by the distance between orifices. The isothermal contour map predicted in this manner for the double-orifice injection system is represented in figure 15(e) by solid lines, which are in good agreement with the experimentally measured contour map represented by dashed lines. To compensate for the slight whirl present in the duct, the experimental contour map was rotated so that its axis would coincide with that of the predicted contour map. It is believed that with the assumptions made to predict the isothermal contours formed by a multiorifice injection system sufficiently accurate results for most engineering designs can be obtained.
CONCLUDING REMARKS

An empirical correlation was developed by means of which the isothermal contour lines formed downstream of a single jet of liquid ammonia directed normal to an air stream can be predicted. From this correlation, the isothermal contour lines formed by a multiplicity of ammonia jets can be approximated with sufficient accuracy for most engineering applications.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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SYMBOLS

The following symbols are used in this report:

A  area, sq ft
C  coefficient of discharge
D  diameter, in.
g  acceleration due to gravity, 32.16 ft/sec²
K  coefficient
p  static pressure, lb/sq ft abs
R  gas constant for air, 53.4 ft-lb/(lb)²
S  mixing distance between spray bar and swinging survey rake, in.
T  indicated temperature, °R
ΔT  difference between air-stream temperature and temperature at some point within the ammonia spray field, °F
V  velocity, ft/sec
w  weight flow, lb/sec
x  dimension normal to axis of symmetry of isothermal contour map, in.
y  dimension along axis of symmetry of isothermal contour map, in.
ρ  density, lb/cu ft
a, b, c, d, e, f, g  exponents
Subscripts:

i  ideal conditions
j  conditions in ammonia jet
m  maximum condition
t  temperature correlation
0  conditions in air stream
1,2,3,4  linear correlations (see fig. 7)
Methods of Calculation

Air density was calculated from the equation of state:

\[ \rho_0 = \frac{P_0}{R_0 T_0} \text{ lb/cu ft} \]

where the value of \( R_0 \) was taken as 53.4 ft-lb/(lb)\(^0\)R.

The velocity of the air stream \( V_0 \) was computed from the air density \( \rho_0 \) and the measured air flow by the continuity equation

\[ V_0 = \frac{W_0}{\rho_0 A_0} \text{ ft/sec} \]

Properties of liquid ammonia were obtained from reference 4 and the jet velocity was calculated from Bernoulli's equation

\[ V_j = \sqrt{2g \frac{P_j - P_0}{\rho_j}} \]

where \( V_j \) is the ideal velocity of a liquid jet issuing from an orifice.

The coefficient of discharge of the orifices was defined as the ratio of the measured to the ideal ammonia flow. Ideal ammonia flow was calculated from the following equation:

\[ W_1 = \rho_j A_j \sqrt{2g \frac{P_j - P_0}{\rho_j}} \]

where \( A_j \) is the physical area of the orifice. Measured values of the coefficient of discharge are presented in table I.
REFERENCES


### TABLE I - AMMONIA INJECTION DATA

| Ammonia jet velocity, \( V_j \) | Air velocity, \( V_a \) | Ammonia density, \( \rho_j \) | Air density, \( \rho_a \) | Ammonia temperature, \( T_j \) | Air temperature, \( T_a \) | Temperature ratio, \( \frac{T_j}{T_a} \) | Density ratio, \( \frac{\rho_j}{\rho_a} \) | Mixing parameter, \( \sqrt{\frac{\rho_j}{\rho_a}} \) | jets | percent | jets | percent | jets | percent | jets | percent | jets | percent | jets | percent | jets | percent | jets | percent | jets | percent | jets | percent | jets | percent | jets | percent |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 108                             | 396             | 41.0            | 0.0844          | 444             | 546             | 1.004           | 761             | 0.554           | 974             | 0.841           | 570             | 0.350           | 10.6            | 104             | 0.298           |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |            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Figure 1. - Schematic diagram of air system.
Figure 2. - Schematic diagram of ammonia system.
Figure 3. - Schematic diagram of ammonia spray-bar.

Figure 4. - Schematic diagram of swinging temperature-survey rake.
Figure 5. - Schematic diagram of aspirating-type thermocouple used on swinging temperature survey rake.
(a) Air velocity, 112 feet per second.

Figure 6. - Typical isothermal contour maps determined for range of air velocities. Ammonia velocity, 82.7 feet per second; air density, 0.054 pound per cubic foot; ammonia density, 41.2 pounds per cubic foot; air temperature, 544°F; ammonia temperature, 464°F; mixing distance, 14 inches; and orifice diameter, 0.029 inch.
(b) Air velocity, 183 feet per second.

Figure 6. - Continued. Typical isothermal contour maps determined for range of air velocities. Ammonia velocity, 82.7 feet per second; air density, 0.054 pound per cubic foot; ammonia density, 41.2 pounds per cubic foot; air temperature, 544° R; ammonia temperature, 464° R; mixing distance, 14 inches; and orifice diameter, 0.029 inch.
Air velocity, 324 feet per second.

Figure 6. - Concluded. Typical isothermal contour maps determined for range of air velocities. Ammonia velocity, 82.7 feet per second; air density, 0.054 pound per cubic foot; ammonia density, 41.2 pounds per cubic foot; air temperature, 544° R; ammonia temperature, 464° R; mixing distance, 14 inches; and orifice diameter, 0.029 inch.
Figure 7. - Dimensions selected for correlation of isothermal contour map formed by injection of liquid ammonia normal to air stream.
Figure 8. - Typical temperature profiles along axis of symmetry together with respective bounding tangents for range of air velocities. Ammonia velocity 82.7 feet per second; air density, 0.054 pound per cubic foot; ammonia density, 41.2 pound per cubic foot; air temperature, of 544° R; ammonia temperature, 464° R; mixing distance, 14 inches; and orifice diameter, 0.029 inch.
(a) Effect of velocity ratio on penetration parameter for two density ratios. Orifice diameter, 0.029 inch; mixing distance, 14 inches.

(b) Effect of density ratio on penetration parameter for two temperature ratios. Orifice diameter, 0.029 inch; mixing distance, 14 inches.

Figure 9. - Correlation of boundary dimension $y_1$. 
Temperature ratio, $T_J/T_0$

(c) Effect of temperature ratio on penetration parameter for two density ratios. Orifice diameter, 0.029 inch; mixing distance, 14 inches.

Figure 9. - Continued. Correlation of boundary dimension $y_1$. 

Temperature drop, $\Delta T$

Temperature profile along axis of symmetry
Figure 9. - Concluded. Correlation of boundary dimension $y_1$. 

(a) Final correlation of penetration parameter

$$
\left( \frac{y_1}{y_0} \right)^{0.77} \left( \frac{\rho_j}{\rho_0} \right)^{0.53} \left( \frac{T_j}{T_0} \right)^{1.1} \left( \frac{S}{\sqrt{C} D_j} \right)^{0.72}
$$

Temperature drop, $\Delta T$
Along axis of symmetry
Figure 10. - Correlation of lower-boundary defining parameter of temperature profile along axis of symmetry.
Figure 11. Correlation of maximum-temperature-drop parameter.
Figure 12. - Correlation of boundary dimensions in terms of boundary dimension $y_1$. 

Temperature drop, $\Delta T$ 
Temperature profile 
along axis of symmetry.
Variable Orifice Mixing diameter, distance, 
\[ D, \quad S, \]
\[ \text{in.}, \quad \text{in.} \]

- \( \frac{v_0}{V_0} \): 0.029, 14
- \( \frac{\rho_j}{\rho_0} \): 0.029, 14
- \( \frac{T_j}{T_0} \): 0.029, 14
- \( \frac{s_j}{c D} \): 0.029, 14
- \( \frac{V_j}{V_0} \): 0.018, 14
- \( \frac{V_j}{V_0} \): 0.033, 14

Temperature drop, \( \Delta T \)
Temperature profile along axis of symmetry

**Figure 12.** Concluded. Correlation of boundary dimensions in terms of boundary dimension \( y_1 \).
Figure 15. - Correlation of width parameter with lower-boundary parameter.
Figure 14. - Limiting temperature drop obtainable by saturating dry air with ammonia vapor. Constant-pressure process in which all cooling is accomplished by latent heat of vaporization of liquid ammonia is assumed.
(a) Temperature profile along axis of symmetry constructed from correlation.

Figure 15. - Prediction of isothermal contour map for double-orifice injection system. Velocity ratio, 0.52; density ratio, 741; temperature ratio, 0.82; mixing distance to diameter ratio, 560.
Figure 15. - Continued. Prediction of isothermal contour map for double-orifice injection system. Velocity ratio, 0.52; density ratio, 741; temperature ratio, 0.82; mixing distance to diameter ratio, 560.
(c) Two predicted single-orifice isothermal contour maps superimposed to represent double-orifice system.

Figure 15. - Continued. Prediction of isothermal contour map for double-orifice injection system. Velocity ratio, 0.52; density ratio, 741; temperature ratio, 0.82; mixing distance to diameter ratio, 560.
(a) Construction of temperature profile normal to axis of symmetry of double-orifice isothermal contour map.

Figure 15. - Continued. Prediction of isothermal contour map for double-orifice injection system. Velocity ratio, 0.52; density ratio, 741; temperature ratio, 0.82; mixing distance to diameter ratio, 560.
(e) Comparison of predicted and experimental isothermal contour maps
double-orifice injection system.

Figure 15. - Concluded. Prediction of isothermal contour map for double-
orifice injection system. Velocity ratio, 0.52; density ratio, 741;
temperature ratio, 0.82; mixing distance to diameter ratio, 560.