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RESEARCH MEMORANDUM

DETERMINATION OF RAM-JET COMBUSTION-CHAMBER TEMPERATURES BY MEANS OF TOTAL-PRESSURE SURVEYS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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RESEARCH MEMORANDUM

DETERMINATION OF RAM-JET COMBUSTION-CHAMBER TEMPERATURES BY MEANS OF TOTAL-PRESSURE SURVEYS

By I. Irving Pinkel

SUMMARY

A method is described by which the total temperature of the gases at the combustion-chamber outlet of a ram-jet engine may be determined from the loss in total pressure measured across the combustion chamber. A working chart is presented by means of which the ratio of the total temperature of the gases at the combustion-chamber outlet to the total temperature of the gases at the combustion-chamber inlet may be determined from the measured loss of total pressure across the combustion chamber and the known values of air flow, total pressure, and total temperature at the combustion-chamber inlet.

Values of total-temperature ratio across the combustion chamber of a 20-inch ram jet were obtained in the Cleveland altitude wind tunnel over a range of pressure altitudes from 6000 to 15,000 feet. The difference between the temperature ratio across the combustion chamber determined from the chart and that obtained from thermocouple measurement was within 6.2 percent of the thermocouple-temperature ratio and was within the accuracy of the thermocouple measurements.

INTRODUCTION

The evaluation of the performance of a jet-propulsion engine and its combustion chamber requires a knowledge of the temperature of the combustion-chamber outlet gases. The temperatures in a ram-jet combustion chamber, however, are often too high for thermocouple measurement and must be determined by other means. Because the total-pressure loss across the combustion chamber is dependent on the ratio of the total temperature of the outlet gases to the total temperature of the inlet gases (reference 1), the temperature ratio can be determined from the total-pressure measurements.

A chart is presented in reference 1 to estimate the pressure losses in jet-propulsion combustion chambers from the known values of total temperature, total pressure, and air flow at the combustion-chamber inlet and of the ratio of total temperature of the exit gas to total temperature of the inlet gas. It is based on the assumption that the pressure losses in a given combustion chamber can be matched by those of an equivalent combustion chamber of uniform cross-sectional area.

In order to determine the temperature of ram-jet combustion-chamber outlet gases from the pressure-loss chart, which is the application of the chart described in this report, the required known factors are the pressure loss across the combustion chamber, the air flow, and the total temperature and the total pressure of the air at the combustion-chamber inlet.

As an illustration of the use of the pressure-loss chart to obtain combustion-chamber temperature ratios, a comparison is made of the combustion-chamber temperature ratios computed from the pressure-loss chart with those determined by thermocouple measurement from wind-tunnel tests of a 20-inch ram jet taken over a range of pressure altitudes from 6000 to 15,000 feet. The combustion chamber of the 20-inch ram jet was considered to extend from the flame holder to the nozzle outlet because combustion continues in the nozzle. The range of temperature ratios compared was limited, however, to the values of combustion-chamber outlet-gas temperature for which thermocouple measurements could be made.

SYMBOLS

The terms involved in using the pressure-loss chart are defined in the following list of symbols: (The symbols on the pressure-loss chart in reference 1 have been modified in the present chart to conform to the corresponding ram-jet symbols that apply to the locations shown in fig. 1.)

A area of cross section of equivalent combustion chamber of constant cross section, square feet

K friction pressure-loss factor

M_2 Mach number of air flow at inlet of equivalent combustion chamber of constant cross section

M_B Mach number of air flow at inlet of combustion zone (fig. 2) of equivalent combustion chamber of constant cross section

P_2 total pressure of air at inlet of combustion chamber, pounds per square foot absolute

P_B total pressure of air at combustion-zone inlet, pounds per square foot absolute

P_4 total pressure of air at outlet of assumed combustion zone (nozzle outlet), pounds per square foot absolute

ΔP_F pressure loss due to friction, pounds per square foot

ΔP_M pressure loss due to addition of heat to the air stream by combustion, pounds per square foot

ΔP_T over-all pressure loss due to friction and heat addition, pounds per square foot

T_2 total temperature of air at inlet of combustion chamber, $^{\circ}R$

T_4 total temperature of gases at outlet of assumed combustion zone (nozzle outlet), $^{\circ}R$

W air mass flow through combustion chamber, pounds per second

DISCUSSION

The over-all total-pressure loss ΔP_T from the combustion-chamber inlet to the combustion-zone outlet is considered equal to the sum of two component pressure losses: the friction pressure loss ΔP_F and the momentum pressure loss ΔP_M. The friction pressure loss results from friction and turbulence in the flow produced by the flame holder and corresponds to the pressure loss in the section between stations 2 and B in the equivalent combustion chamber (fig. 2). The momentum pressure loss results from the addition of heat to the air flowing in the combustion zone. The momentum pressure loss corresponds to the pressure loss in the section between stations B and 4 in the equivalent combustion chamber.

$$\Delta P_T = \Delta P_F + \Delta P_M \tag{1}$$

or

$$\frac{\Delta P_T}{P_2} = \frac{\Delta P_F}{P_2} + \frac{\Delta P_M}{P_2} \cong \frac{\Delta P_F}{P_2} + \frac{\Delta P_M}{P_B} \tag{2}$$

The pressure-loss chart in reference 1 is arranged to provide values of friction and momentum pressure-loss ratios, $\frac{\Delta P_F}{P_2}$ and $\frac{\Delta P_M}{P_B}$, for known combustion-chamber-inlet conditions and temperature ratio T_4/T_2, once the values of friction pressure-loss factor K and cross-sectional area of the equivalent combustion chamber A are known. The construction for obtaining the pressure losses from the chart (reproduced with changed notation as fig. 3) starts with the known value of the entrance parameter $W\sqrt{T_2}/P_2$ on the ordinate of quadrant IV. The Mach number M_2 is obtained from the proper A curve in quadrant IV and $\Delta P_F/P_2$ is obtained from the curve in quadrant I with the value of KA^2 for the combustion chamber. From this value of $\Delta P_F/P_2$ and the curve in quadrant II having the value of M_2 previously obtained, M_B is evaluated. The momentum pressure-loss ratio $\Delta P_M/P_B$ is obtained from this value of M_B and the known value of T_4/T_2. The over-all total-pressure-loss ratio $\Delta P_T/P_2$ is then the sum of $\Delta P_F/P_2$ and $\Delta P_M/P_B$ (equation (2)).

The values of K and A for a given combustion chamber are obtained from the pressure-loss chart with a measured value of ΔP_T and ΔP_F taken for the same known value of the entrance parameter $W\sqrt{T_2}/P_2$. The value of ΔP_T is obtained by measuring the pressure loss across the combustion chamber with combustion taking place at some measurable value of the temperature ratio T_4/T_2. The friction pressure loss ΔP_F is measured across the combustion chamber with air flowing at the same value of the inlet parameter $W\sqrt{T_2}/P_2$ without combustion. The difference between ΔP_T and ΔP_F is equal to ΔP_M (equation (1)). The values of K and A are obtained using this information on pressure losses and temperature ratio across the combustion chamber by means of the construction Y shown on figure 3. Line a-b is drawn parallel to the abscissa through the known value of $\Delta P_M/P_B$ ending on the curve having the value of T_4/T_2 used when ΔP_T was measured. Line c-d is drawn parallel to the abscissa through the known value of $\Delta P_F/P_2$. Line e-f is drawn parallel to the abscissa through the value of the inlet parameter $W\sqrt{T_2}/P_2$ used in determining ΔP_T and ΔP_F. The line a-g drawn parallel to the ordinate intersects line c-d on a curve in quadrant II having some value of M_2. Line h-j is drawn parallel to the ordinate through this value of M_2 on the abscissa of quadrant I. The intersection of line h-j with line c-d determines the value of KA^2. The intersection of line h-j with line e-f gives the value of A. The values of K and A are reasonably constant for all conditions of ram-jet operation for which the flame is steady and originates at the flame holder.

The use of the pressure-loss chart with which this report is concerned is the evaluation of the temperature of the outlet gases of the combustion chamber from pressure-loss measurements once the values of K and A have been established. By means of total-pressure probes located at the combustion-chamber outlet, a value of the loss in total pressure ΔP_T across the combustion chamber is obtained in the subsonic case. The construction X shown on the pressure-loss chart (fig. 3) gives the value of T_4/T_2 from the known value of the entrance parameter $W\sqrt{T_2}/P_2$ and the measured value of ΔP_T. The value of $\Delta P_F/P_2$ is obtained from the known value of $W\sqrt{T_2}/P_2$ and the proper A and KA^2 curves. The value of $\Delta P_F/P_2$ is subtracted from the measured value of $\Delta P_T/P_2$ to give $\Delta P_M/P_B$ (equation (2)). Line l-m is drawn parallel to the abscissa through the value of $\Delta P_M/P_B$. Line n-p is drawn through the known value of $\Delta P_F/P_2$ ending on the curve in quadrant II having the value of M_2 obtained at the abscissa of quadrant I when $\Delta P_F/P_2$ was evaluated. Line r-s, drawn parallel to the ordinate, intersects line l-m on a curve in quadrant III having the value of the temperature ratio T_4/T_2. Inasmuch as the total temperature of the gases at the inlet of the combustion chamber T_2 is known, the total temperature of the gases at the outlet of the combustion chamber T_4 can be obtained.

In order for the measured value of the total pressure in the combustion zone to be representative of the flow at the measuring station, the total pressures obtained from the survey rakes should be weighted according to the local mass flow in the neighborhood of each pressure probe. As a first approximation the mass-flow distribution in the combustion zone can be considered to be the same as that upstream of the flame holder. This assumption takes no account of the effect of the flame holder, fuel-spray distribution, and boundary-layer growth on the mass-flow distribution in the combustion zone. A better approximation to the mass-flow distribution could be obtained by correlating the mass-flow distribution upstream of the flame holder with that in the combustion zone. This correlation is carried out for several combustion-zone temperatures low enough for the necessary measurements to be made over the range of combustion-chamber inlet conditions of interest. The mass-flow distribution at the high combustion-chamber temperatures is obtained by extrapolating the mass-flow distribution measured at the low combustion-chamber temperatures. The uncertainty regarding the mass-flow distribution in the combustion zone represents one of the approximations involved in using the method of this report to obtain combustion-chamber total temperatures.

Altitude-wind-tunnel data taken on a 20-inch ram jet, which was instrumented with temperature and pressure survey rakes in front of and behind the combustion chamber and nozzle outlet, were used in making the comparison between experimental and calculated values of T_4/T_2 in table I. The operational pressure altitude ranged from 6000 to 15,000 feet. The difference between the experimental and the calculated values of T_4/T_2 for the range of pressure altitudes tested is less than 6.2 percent of the experimental value. This difference in the temperature ratios obtained from thermocouple readings and pressure-loss measurements were within the accuracy of the thermocouple-temperature measurements.

The temperatures obtained from the pressure-loss chart are not subject to the errors involved in measuring temperature with thermocouples. These errors in the thermocouple temperatures include the absence of correction for conduction and radiation effects and uncertainties in the values of the thermocouple impact-recovery factor required to compute the total temperature from the indicated temperature. The temperatures obtained from the pressure-loss chart are the total temperatures representative of the stations.

Values of KA^2 and A used to obtain the calculated temperature ratios are tabulated in figure 3. The range of values of $W\sqrt{T_2}/P_2$ for the complete combustion chamber exceeded the limit of the ordinate scale of quadrant IV. For this reason the calculations were made for a 60° segment of the combustion chamber for which W and A are one-sixth as large as the corresponding quantities for the complete combustion chamber and KA^2 is the same for the segment and complete combustion chamber. The value of A was 0.36 square foot for the 60° segment and 2.16 square feet for the complete combustion chamber. The geometrical area of the cross section of a 20-inch-diameter combustion chamber is 2.18 square feet. From these data, the actual cross-sectional area of the cylindrical ram-jet combustion chamber can be used as a first approximation for the value of the cross-sectional area of the equivalent-combustion chamber A.

Temperature T_4 has been considered to represent the combustion-chamber-outlet total temperature. If the total-pressure probes were located at a station within the combustion zone, however, the value of T_4 obtained from the pressure-loss chart would represent an estimate of the total temperature at that station. A survey could thus be made of the longitudinal temperature distribution in the combustion chamber. In general, a separate value of K and A should be determined for each station in the combustion zone. The values of K and A probably require little adjustment except for stations close to the flame holder.

Experimental and calculated temperature ratios at station 3 (fig. 1) are also compared in table I. The divergence between the experimental and calculated values of T_3/T_2 is attributed to heterogeneity of the flame at station 3. Most of the thermocouples at station 3 appear to be located in flame zones of higher than average temperatures.

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REFERENCE

1. Pinkel, I. Irving, and Shames, Harold: Analysis of Jet-Propulsion Engine Combustion-Chamber Pressure Losses. NACA TN No. 1180, 1947.

TABLE I - COMPARISON OF EXPERIMENTAL AND COMPUTED TOTAL-TEMPERATURE RATIOS FOR 20-INCH-DIAMETER COMBUSTION CHAMBER OF RAM JET

Altitude (ft)	$\frac{W\sqrt{T_2}}{P_2}$	$\frac{T_4}{T_2}$ Calculated (a)	$\frac{T_4}{T_2}$ Experimental (b)	$\frac{T_4}{T_2}$ Difference (percent)	$\frac{T_3}{T_2}$ Calculated (a)	$\frac{T_3}{T_2}$ Experimental (b)
6,000	0.1820	2.08	2.14	-2.8	1.42	2.06
6,000	.3560	2.29	2.39	-4.2	1.43	1.84
10,000	.2164	3.40	3.28	3.7	1.50	2.55
10,000	.2671	3.75	3.64	3.0	1.67	2.62
10,000	.3842	1.44	1.49	-3.3	1.23	1.47
15,000	.2155	3.54	3.77	-6.1	------	------
15,000	.2360	1.82	1.92	-5.2	1.33	1.77
15,000	.3282	1.60	1.68	-4.8	1.20	1.64

[a]From chart of figure 3.

[b]From wind-tunnel data.

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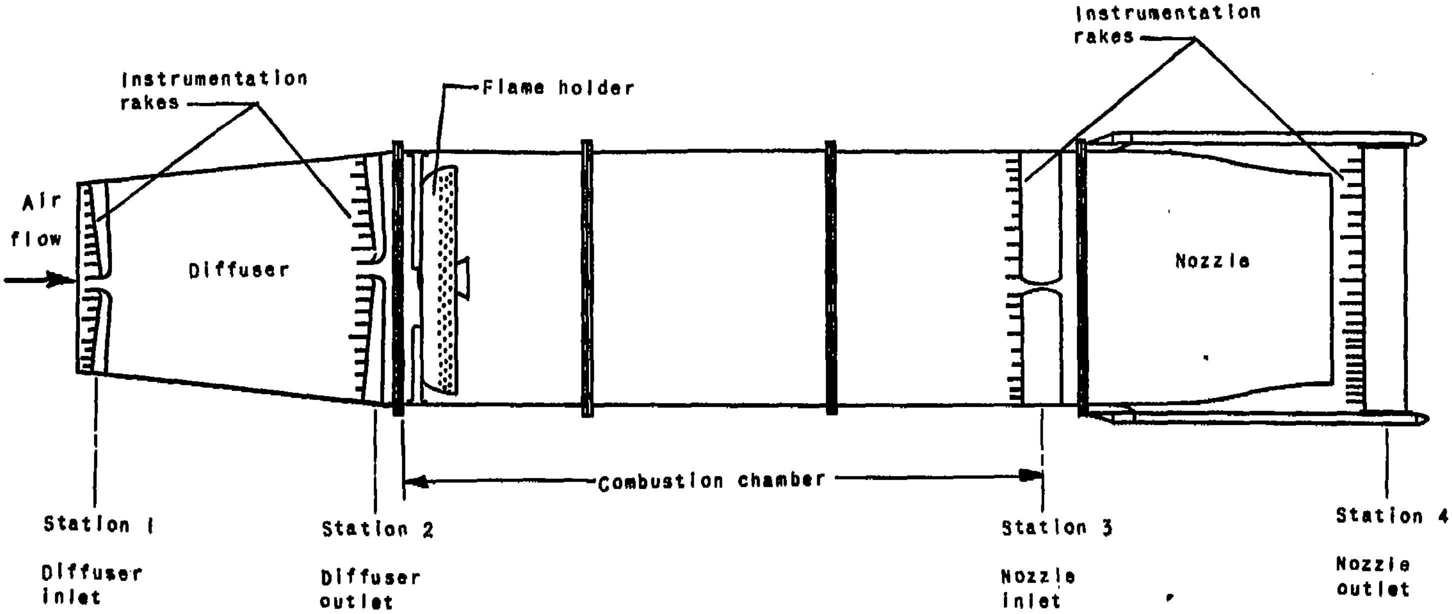

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Figure 1. - Diagram of 20-inch ram-jet engine.

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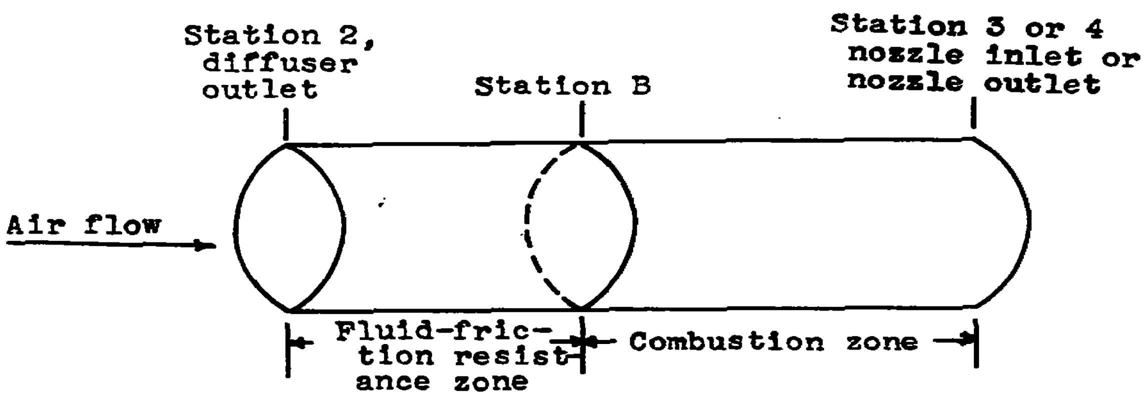

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Figure 2.- Station locations on equivalent combustion chamber of constant cross-sectional area.