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ANALYSIS OF JET-PROPULSION ENGINE COMBUSTION-CHAMBER PRESSURE LOSSES

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SUMMARY

The development and the use of a chart for estimating the pressure losses in jet-engine combustion chambers are described. By means of the chart, the pressure losses due to fluid friction and to momentum changes in the air flow accompanying combustion can be separately evaluated.

The pressure-loss chart is based on the assumption that the pressure losses in the actual combustion chamber can be matched by those of an equivalent combustion chamber of constant cross-sectional area. The concept of the equivalent combustion chamber serves as a convenient basis for comparing the pressure-loss characteristics of combustion chambers of a variety of designs. By means of the chart, the pressure losses of a combustion chamber can be specified by two numbers, one related to the friction pressure-loss characteristics and the other to the momentum pressure-loss characteristics of the combustion chamber.

The over-all pressure losses computed from the pressure-loss chart are within 7 percent of the experimental values for the three types of combustion chamber presented herein.

INTRODUCTION

The jet-propulsion engine, in common with other internal-combustion engines, utilizes fuel-air mixtures as the working substance in the engine cycle. For this reason, the manner of heat addition to the working substance and the flow characteristics of the combustion chamber have a marked effect on the performance of the jet-propulsion engine. In particular, combustion-chamber pressure losses result in reduced cycle efficiency and lowered mass air flow through the engine with a consequent reduction in engine thrust.

A chart has been developed to estimate combustion-chamber pressure losses in which the pressure losses due to fluid friction and the losses due to the addition of heat by combustion are separately
evaluated. The pressures considered are total or stagnation pressures unless otherwise specified. Pressure losses obtained with the chart are compared with the losses obtained from experiment for three current types of jet-propulsion engine combustion chamber.

DESCRIPTION OF SOME CURRENT TYPES OF COMBUSTION CHAMBER FOR JET-PROPULSION ENGINES

A cylindrical type of combustion chamber used in turbojet engines is shown in figure 1(a). The outside cylinder and the entrance section form a duct to carry the air from the compressor outlet to the turbine inlet. The inside cylinder, referred to as "the basket," surrounds the combustion zone. The basket is fitted with a dome having entrance slots for inducting part of the total air flow into the combustion chamber in a manner to provide good mixing with the fuel injected inside the dome. As combustion proceeds, the remainder of the air enters the combustion zone through holes arranged along the cylindrical surface of the basket. In this manner, the flow is split into primary and secondary streams to obtain fuel-air ratios in the combustion zone closer to stoichiometric than would be provided by mixing the fuel with the total air flow. The combustion rate and the ignition characteristics are thereby improved and the walls of the basket are cooled by the secondary air. This type of combustion chamber is usually installed in multiple units arranged in parallel.

The annular type of combustion chamber used in turbojet engines is shown in figure 1(b). The combustion-chamber annulus is formed by inside and outside walls that are coaxial with the drive shaft connecting the turbine and the compressor. This annular duct carries the total air flow from the compressor outlet to the turbine inlet. The toroidal basket is approximately triangular in section and is provided with slots and holes for splitting the flow into primary and secondary streams.

A form of combustion chamber for the ram-jet engine consists of a single cylindrical duct provided with a flame holder at the fuel-injection zone (fig. 1(c)). The combustion zone extends downstream of the flame holder. No basket is used in the ram jet in order to avoid the pressure losses involved in getting the air flow through the holes in a basket.

The three types of combustion chamber considered have in common an obstruction interposed between the combustion-chamber inlet and
the combustion zone. This obstruction to the air flow, which may be either a flame holder or a basket, causes a loss in total pressure between the combustion-chamber inlet and the combustion zone. The combustion zone is unobstructed in these three types of combustion chamber. No combustion chambers with structures in the combustion zone, such as fuel preheaters and vaporizers, catalytic surfaces, and heating elements, are considered.

**SYMBOLS**

The symbols in this report conform with those currently used for turbojet engines. Symbols used more than once are listed here for ready reference.

- **A**  area of cross section of equivalent combustion chamber of constant cross section, square feet
- **g**  factor for converting slugs to pounds mass, 32.2
- **K**  combustion-chamber pressure-loss factor
- **M**  Mach number, ratio of airspeed to local speed of sound
- **N**  engine rotational speed, rpm
- **P**  absolute total (stagnation) pressure, pounds per square foot
- **ΔP_f**  loss in total pressure due to friction (friction pressure loss), pounds per square foot
- **ΔP_m**  loss in total pressure due to heat addition to the air flow by combustion (momentum pressure loss), pounds per square foot
- **ΔP_T**  over-all loss in total pressure due to friction and heat addition, pounds per square foot
- **p**  absolute static pressure, pounds per square foot
- **R**  gas constant for air, 53.3 foot-pounds per pound °R
- **T**  total (stagnation) temperature, °R
- **t**  static temperature, °R
$v$ speed of gas flow, feet per second

$W$ air mass flow, pounds per second

$\gamma$ ratio of specific heat at constant pressure to specific heat at constant volume

$\theta_2$ ratio of total temperature of compressor inlet air to static temperature of standard NACA air at sea level

$\rho$ air density, pounds per cubic foot

$\rho_T$ air density measured under total (stagnation) conditions, pounds per cubic foot

Subscripts:

2 compressor inlet

4 combustion-chamber inlet, also compressor outlet of turbojet engine or diffuser outlet of ram-jet engine

5 combustion-chamber outlet, also turbine inlet of turbojet engine or nozzle inlet of ram-jet engine

B entrance to combustion zone of equivalent combustion chamber

DEVELOPMENT OF THE PRESSURE-LOSS CHART

Assumption. - The development of the combustion-chamber pressure-loss chart is based on the assumption that the pressure-loss characteristics of the actual combustion chamber can be matched by those of an equivalent combustion chamber of constant cross-sectional area having the form shown in figure 2. The air enters the combustion chamber from the left and experiences a loss in total pressure due to friction in the zone from station 4 to station B. This friction pressure loss $\Delta P_f$ corresponds to the pressure loss in the actual combustion chamber involved in bringing both the primary and secondary air from the compressor outlet, or the diffuser outlet for the ram-jet engine, through the basket, or the flame holder, into the combustion zone. This loss is the pressure loss measured across the actual combustion chamber with the air flowing but no combustion taking place. It is assumed that all the pressure loss due to friction takes place before the air becomes involved in
the combustion. The losses in the combustion-chamber entrance section and those involved in getting the air through the basket, or the flame holder, are considered to account for most of the fluid-friction pressure losses in the combustion chamber. The use of the pressure-loss chart is therefore restricted to combustion chambers having an unobstructed combustion zone. Pressure losses, designated as momentum pressure losses $\Delta P_M$, also occur in the combustion zone with the addition of heat to the flowing gas. The over-all loss in total pressure $\Delta P_T$ in the combustion chamber is the sum of the friction and the momentum pressure losses.

$$\Delta P_T = \Delta P_F + \Delta P_M$$ (1)

No account is taken of the effect of fuel injection on the mass flow and the gas velocity through the combustion zone. For the turbojet engine, in which the fuel-air ratio is low because of the temperature limitation imposed by the turbine material, the error involved in neglecting the fuel addition in the expression for the computed combustion-chamber pressure losses is small.

Theoretical considerations - The theoretical considerations involved in developing the combustion-chamber pressure-loss chart use the equivalent combustion chamber of constant cross-sectional area (fig. 2) as the model. The analysis is made in three steps: An expression is obtained for the friction pressure loss in terms of the combustion-chamber entrance-air conditions. The conditions at the entrance to the combustion zone are evaluated to account for the effect of friction pressure loss on the air flow. The equations required for computing the momentum pressure loss are then obtained, based on the combustion-zone entrance conditions and the total temperature ratio across the combustion chamber.

General laws for fluid-friction pressure losses indicate the following relation among $\Delta P_F$, $W$, and $\rho_T$.

$$\Delta P_F = \frac{KW^2}{\rho_T} = \frac{KW^2RT}{P_4}$$ (2)

Equation (2) is in agreement with experimental data obtained with the combustion chambers of the turbojet and the ram-jet engines. For convenience in setting up the pressure-loss chart, the friction pressure loss is related to the Mach number of flow at the entrance to the equivalent combustion chamber. From the expression for the Mach number
\[ M^2 = \frac{v^2}{\gamma g A^2 (pRt)} \]

and the relation satisfying the law of conservation of mass for steady flow in the combustion chamber

\[ W = \rho A v \]

the following equation is obtained:

\[ M^2 = \frac{\rho A^2 v^2 (Rt)}{\gamma g A^2 (pRt)} = \frac{W^2 R t}{\gamma g A^2 p^2} = \frac{W^2 R t}{\gamma g A^2 p^2} \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{\gamma - 1} \]  

(3)

In the derivation of equation (3), use is made of the perfect gas law and the reversible adiabatic relations

\[ \frac{T}{t} = 1 + \frac{\gamma - 1}{2} M^2 \]

and

\[ \frac{P}{p} = \left( \frac{T}{t} \right)^{\gamma - 1} \]

Equations (2) and (3) applied to station 4 yield the desired relation

\[ \frac{\Delta P_F}{P_4} = \frac{KW^2 RT_4}{P_4^2} = \frac{\gamma_4 g A^2 M_4^2}{\gamma_4 + 1} \left( 1 + \frac{\gamma_4 - 1}{2} M_4^2 \right)^{\gamma_4 - 1} \]  

(4)

The second term in equation (4) \( \frac{KW^2 RT_4}{P_4^2} \) shows that the friction pressure-loss ratio \( \frac{\Delta P_F}{P_4} \) depends only on the air mass flow and the total temperature and pressure at the entrance to the combustion chamber. No choice of the cross-sectional area \( A \) of the equivalent combustion chamber need be made at this stage of development but a value will later be chosen to give the correct value of \( \Delta P_M \).
The Mach number of the flow at the entrance to the combustion zone $M_B$ differs from the Mach number of the combustion-chamber inlet $M_4$ because of the friction pressure loss experienced by the flow. The expression relating these quantities is obtained by means of equation (3), as applied to stations 4 and B. Inasmuch as the total temperature of the gases at stations 4 and B are the same

\[
W \sqrt{T_4} = W \sqrt{T_B} = \frac{\sqrt{\gamma_4^2 R M_4 P_4}}{\gamma_4 + 1} = \frac{\sqrt{\gamma_B^2 R M_B P_B}}{\gamma_B + 1}
\]

\[
\left(1 + \frac{\gamma_4 - 1}{2} M_4^2 \right)^2 (\gamma_4 + 1) = \left(1 + \frac{\gamma_B - 1}{2} M_B^2 \right)^2 (\gamma_B + 1)
\]

The value of $\gamma_4$ may be assumed equal to $\gamma_B$ because $t_4$ is not appreciably different from $t_B$. The equation used to correct $M_4$ to $M_B$ is

\[
1 - \frac{P_B}{P_4} = \frac{P_4 - P_B}{P_4} = 1 - \frac{M_4}{M_B} \left(1 + \frac{1}{2} \frac{M_B^2}{M_4^2} \right)
\]

The expression for momentum pressure-loss ratio $\frac{\Delta P_M}{P_B}$ for an unobstructed-combustion chamber of uniform cross-sectional area is developed in the appendix.

\[
\frac{\Delta P_M}{P_B} = 1 - \frac{\left(1 + \gamma_B M_B^2 \right) \left(1 + \frac{\gamma_5 - 1}{2} M_5^2 \right)}{\gamma_5 \gamma_B \left(1 + \gamma_5 M_5^2 \right) \left(1 + \frac{\gamma_B - 1}{2} M_B^2 \right)}
\]
In order to use equation (6) a relation is required among $M_5$, the known value of $M_B$, and the temperature ratio across the combustion chamber $T_5/T_4$. This relation is obtained by writing equation (3) as applied to stations B and 5 successively.

\[
\frac{\gamma_5}{\gamma_4} = \left(1 + \frac{\gamma_B - 1}{2} M_B^2 \right)^{-1}
\]

By division of these equations and from the fact that the total temperatures at the combustion-chamber inlet and at the entrance to the combustion zone are equal, that is, $T_4 = T_B$, there is obtained

\[
\frac{T_5}{T_4} = \left(1 + \frac{\gamma_B - 1}{2} M_B^2 \right)^{-1}
\]
The final expression is

\[
\frac{P_B}{P_5} = \left(1 + \frac{\gamma_5M_5^2}{2}\right)\left(1 + \frac{\gamma_5 - 1}{2}M_5^2\right)\frac{\gamma_B}{\gamma_B - 1}
\]

\[
\left(1 + \frac{\gamma_5M_5^2}{2}\right)\left(1 + \frac{\gamma_5 - 1}{2}M_5^2\right)
\]

Equations (6) and (7) are used to compute \( \Delta P_M / P_B \) from the known values of \( M_B \) and the temperature ratio \( T_5 / T_4 \).

Construction of pressure-loss chart. - From the pressure-loss chart shown as figure 3, \( \Delta P_F \), \( \Delta P_M \), and \( \Delta P_T \) can be obtained from known values of the combustion-chamber-inlet parameter \( W_\sqrt{T_4/P_4} \) and the temperature ratio across the combustion chamber. The chart is set up in the following manner: Quadrant IV gives a plot of \( W_\sqrt{T_4/P_4} \) against \( M_4 \) according to equation (3), modified as

\[
\frac{W_\sqrt{T_4}}{P_4} = \sqrt{\frac{\gamma_4}{\gamma_4 - 1} AM_4} \left(1 + \frac{\gamma_4 - 1}{2}M_4^2\right)^{\frac{2}{2\gamma_4 - 1}}
\]

for several values of the parameter A. The variation of \( \Delta P_P / P_4 \) with \( M_4 \) according to equation (4) is given in quadrant I for
several values of the parameter $KA^2$, where $K$ is defined by equation (2). The curves in quadrant II correct $M_4$ to $M_B$ to account for the change in Mach number accompanying the friction pressure loss $\Delta P_F$. This correction is made by means of equation (5). In quadrant II, $\Delta P_F/P_4$ is plotted against $M_B$ for various values of $M_4$. In quadrant III, $\Delta P_M/P_B$ is plotted against $M_B$ according to equations (6) and (7) for various values of the temperature ratio $T_5/T_4$. The value of $\gamma_5$ used in equations (6) and (7) to obtain the curves of quadrant III are average values for the temperature range corresponding to the temperature ratio $T_5/T_4$ and the required fuel-air ratio with an assumed 95-percent combustion efficiency. In order to obtain the temperature range, it was assumed that $T_4$ was 600° R for values of $T_5/T_4$ less than 3.8 and 400° R for $T_5/T_4$ greater than 3.8. These values of $T_4$ approximate those of the turbojet and ram-jet engines, respectively. The over-all pressure-loss ratio $\Delta P_T/P_4$ is obtained from the values of $\Delta P_F/P_4$ and $\Delta P_M/P_B$ given by the chart by means of the expression

$$\frac{\Delta P_T}{P_4} = \left(\frac{\Delta P_F}{P_4} + \frac{\Delta P_M}{P_B}\right) \left(1 - \frac{\Delta P_F}{P_4}\right) + \left(\frac{\Delta P_F}{P_4}\right)^2$$

(6)

derived from equation (1) and the relation

$$P_B = P_4 - \Delta P_F$$

For most applications of the chart, little error is made if $P_B$ is assumed equal to $P_4$ in the denominator of the pressure-loss-ratio terms and equation (6) is expressed simply as

$$\frac{\Delta P_T}{P_4} = \frac{\Delta P_F}{P_4} + \frac{\Delta P_M}{P_4} = \frac{\Delta P_F}{P_4} + \frac{\Delta P_M}{P_B}$$

(6a)

Use of the pressure-loss chart. - The chart is used in the following manner to obtain the various pressure losses: Assume, temporarily, that the value of $K$ is 1.0 and $A$ is 0.20 square feet for the combustion chamber. For a known value of $W\sqrt{\frac{T_4}{P_4}}$ equal to 0.0230 and the temperature ratio $T_5/T_4$ of 3.40, the
pressure losses due to friction and momentum are evaluated in four steps around the chart. Start with the known value of $W\sqrt{T_4/P_4}$ on the ordinate of quadrant IV. From the curve having the value of $A$, equal to 0.20, $M_4$ is determined to be 0.126 on the abscissa of quadrant IV and the corresponding value of 0.0278 for $\Delta P_F/P_4$ is obtained by means of the curve in quadrant I having the value of 0.04 for $KA^2$ for the combustion chamber. Proceed parallel to the abscissa through this value of $\Delta P_F/P_4$ to the curve in quadrant II having the value of $M_4$ previously established; the value of 0.130 for $M_B$ is determined on the abscissa of quadrant II. From the $T_5/T_4$ curve having the value of 3.40 in quadrant III, $\Delta P_M/P_B$ is determined to be 0.0276 on the ordinate of quadrant III. The overall pressure-loss ratio $\Delta P_T/P_4$ is then computed to be 0.0554 by adding $\Delta P_M/P_B$ to $\Delta P_F/P_4$.

Determination of $K$ and $A$. - The value of $K$ and $A$ for a given combustion chamber can be determined by means of the pressure-loss chart if $\Delta P_T/P_4$ and $\Delta P_F/P_4$ are known from experiment for the same value of $W\sqrt{T_4/P_4}$. The pressure loss due to friction $\Delta P_F$ is measured by total-pressure tubes located at the combustion-chamber inlet and exit with air flowing through the combustion chamber without combustion taking place. The over-all pressure loss is obtained with these pressure tubes with the air flowing at the same value of $W\sqrt{T_4/P_4}$ and combustion taking place at a known value of $T_5/T_4$.

In figure 4, a reduced print of figure 3, there is demonstrated a construction in which the values of $A$ and $KA^2$ were established for a cylindrical-type combustion chamber by means of the following experimentally determined data:

$$\frac{W\sqrt{T_4}}{P_4} = 0.0346$$

$$\frac{\Delta P_T}{P_4} = 0.0420$$
\[
\frac{\Delta P_F}{P_4} = 0.0280 \text{ (from engine windmilling data)}
\]

\[
\frac{\Delta P_M}{P_B} = \frac{\Delta P_T}{P_4} - \frac{\Delta P_F}{P_4} = 0.0140 \text{ (according to equation (8a))}
\]

\[
\frac{T_5}{T_4} = 1.78
\]

Line B-A, quadrant III, was drawn parallel to the abscissa through the known value of \(\Delta P_M/P_B\) and ends on the proper \(T_5/T_4\) curve. Line C-D was drawn parallel to the abscissa through the value of \(\Delta P_F/P_4\); line E-F was drawn parallel to the abscissa through the value of \(W\sqrt{T_4/P_4}\); line A-G was drawn parallel to the ordinate. The intersection of lines A-G and C-D determined a value of \(M_4\). The line H-J was taken parallel to the ordinate through \(M_4\) on the abscissa of quadrant I. The intersection of line H-J with line C-D determined the value of \(K\) for the cylindrical type combustion chamber. The intersection of lines E-F and H-J similarly determined the value of \(A\) in quadrant IV.

If \(\Delta P_F\) is known for a different value of \(W\sqrt{T_4/P_4}\) than corresponds to \(\Delta P_T\), the required value of \(\Delta P_F\) corresponding to \(\Delta P_T\) can be obtained by evaluating \(K\) in equation (2) with the known values of \(\Delta P_T\) and corresponding value of \(W\sqrt{T_4/P_4}\). The required value of \(\Delta P_F\) may then be obtained by using this value of \(K\) and the value of \(W\sqrt{T_4/P_4}\) corresponding to \(\Delta P_T\).

A method of obtaining \(KA^2\) and \(A\) for a combustion chamber when only the over-all loss in total pressure \(\Delta P_T\) can be obtained is shown in figure 5, a reduced print of figure 3. It is assumed that, for a known value of \(W\sqrt{T_4/P_4}\), two values of \(\Delta P_T/P_4\) can be measured that correspond to two different known values of the combustion-chamber temperature ratio \(T_5/T_4\). The value of \(\Delta P_F/P_4\) is the same for both cases because \(W\sqrt{T_4/P_4}\) is the same (equation (4)). The difference in the measured values of \(\Delta P_T/P_4\) represents the difference in the values of \(\Delta P_M/P_B\) (equation (8a)).
This difference is set on a divider according to the scale of the ordinate of quadrant III (fig. 5). With the line joining the divider points held parallel to the ordinate, one leg of the divider is moved along one of the curves in quadrant III having one of the values of $T_5/T_4$ used in the tests until the other leg of the divider intercepts the curve having the other value of $T_5/T_4$. The values of $\Delta P_M/P_B$ are thus determined for both engine conditions and the value of $\Delta P_T/P_4$ is obtained by subtracting $\Delta P_M/P_B$ from the corresponding value of $\Delta P_T/P_4$ (equation (8a)). A construction similar to that described in the previous paragraph can now be made to obtain $A$ and $KA^2$, as shown in figure 5 for the experimental data given in the insert.

Remarks concerning the use of the chart. - The values of $W\sqrt{\frac{T_4}{P_4}}$ for turbojet engines may be obtained from the compressor performance data. The operating line for a compressor is often given as a plot of the pressure ratio across the compressor $P_4/P_2$ against corrected engine speed $N/\sqrt{\rho_2}$ and corrected air-weight flow $\frac{2116}{\sqrt{519}} W\sqrt{\frac{T_2}{P_2}}$. For each corrected engine speed there corresponds a value of $P_4/P_2$ and $W\sqrt{\frac{T_2}{P_2}}$ for a given flight speed and altitude. The factor $W\sqrt{\frac{T_4}{P_4}}$ is computed from these data by dividing $W\sqrt{\frac{T_2}{P_2}}$ by $P_4/P_2$ and evaluating $T_4$ from the relation

$$T_4 = T_2 \left[ \frac{\gamma - 1}{\gamma} \left( \frac{P_4}{P_2} \right)^{\gamma - 1} + \frac{1}{\eta_c} \right]$$

where $\eta_c$ is the compressor efficiency. The compressor efficiency is obtained from compressor performance data.

For combustion chambers having air-flow rates $W$ large enough to make the value of the entrance parameter $W\sqrt{\frac{T_4}{P_4}}$ exceed the limits on the chart, only a segment of the combustion chamber is considered. Assume, for example, that a $35^\circ$ segment of the combustion chamber, which carried one-twelfth the total air flow, gives
values of \( W \sqrt{\frac{T_4}{P_4}} \) that fit the scale of the chart. The value of \( A \) is then one-twelfth that for the complete combustion chamber. The value of \( K \) is 144 times that for the complete combustion chamber (equation (2)). The value of \( K A^2 \) is the same for the segment and the complete combustion chamber. This property of the parameter \( K A^2 \) led to the choice of the pressure-loss chart arrangement given in figure 3, where \( K A^2 \) rather than \( K \) is taken as the parameter in quadrant I. The various pressure losses for the segment are the same as those of the complete combustion chamber. The construction for obtaining \( K \) and \( A \) for the segment is the same as that described for the complete combustion chamber. The values of pressure losses and temperature ratio obtained by experiment with the complete combustion chamber are used and the value of \( W \) corresponds to the air flow through the segment.

A variety of forms of the pressure-loss chart is possible. The form presented in figures 3, 4, and 5 is considered to have the most general utility. For special application, several of the quadrants can be combined for ease of manipulation.

RESULTS AND DISCUSSION

Comparison of experimental and computed pressure losses. - A comparison of experimental with computed combustion-chamber pressure losses is given for the cylindrical, annular, and ram-jet types of combustion chamber illustrated in figure 1.

The data for the pressure losses of the cylindrical combustion chamber were obtained from tests of a complete jet-propulsion engine in the Cleveland altitude wind tunnel. Figure 6 shows experimental and computed over-all pressure-loss ratios for two cylindrical combustion chambers installed in the same engine. These combustion chambers differ only in the primary entrance arrangements on the dome of the basket and in the relative proportion of primary and secondary air. For combustion chamber I, \( A \) is computed to be 0.300 square foot and \( K \) is computed to be 0.667. For combustion chamber II, \( A \) is computed to be 0.240 square foot and \( K \) is computed to be 0.347. Type I has the higher value of \( K \) and therefore the higher values of friction pressure-loss ratio (fig. 7(a)); type II has the lower value of \( A \) and therefore the higher momentum pressure-loss ratio (fig. 7(b)). The actual area of cross section of the combustion zone was approximately 0.29 square foot. These data serve to
illustrate how the values of $K$ and $A$ are influenced by the relative proportions and manner of induction of primary and secondary air as well as the gross geometry of the combustion chamber.

Comparisons of computed and experimental values of the pressure losses in an annular combustion chamber and a combustion chamber for a ram jet are given in tables I and II, respectively. The data for the annular combustion chamber were obtained with the combustion chamber directly connected to an air source of variable temperature and an exhaust system capable of reproducing altitude pressures. The data for the combustion chamber of a ram jet were taken from tests of a complete 20-inch ram jet operating in the Cleveland altitude wind tunnel. For both combustion chambers, the pressure-loss ratios computed from the chart are within 7 percent of the experimental values.

Significance of $K$ and $A$. - The concept of the equivalent combustion chamber of constant cross section can serve as a convenient basis for comparing the pressure-loss characteristics of combustion chambers of a variety of designs. The values of $KA_c^2$ and $A/A_c$, where $A_c$ is the maximum area of cross section of the combustion chamber, can be taken as figures of merit along with other criteria for comparing the excellence of combustion chambers. Good combustion chambers should have low values of $KA_c^2$ and high values of $A/A_c$.

The values of $K$ and $A$ obtained from the pressure-loss chart indicate how a combustion chamber should be modified to reduce the pressure losses. If pressure losses are high because of large values of $K$, improvement is obtained by opening the air-flow passages, particularly in the basket. If pressure losses are high because of low values of $A$, improvement is obtained by devoting more of the combustion-chamber cross section to the combustion zone. The combustion-chamber pressure losses can also be reduced by altering the relative proportions of primary and secondary air and the manner of induction of the air into the combustion zone.

The assumption that the value of $A$ for a given combustion chamber is fixed for all conditions of engine operation applies only if the flame is always seated at the same location in the combustion zone. Preliminary evidence shows that, for some combustion chambers, the value of $A$ decreases with values of $W \sqrt{T_4/P_4}$ above a critical value, which is characteristic of the
combustion chamber. This decrease in the value of $A$ is believed to be associated with the movement of the flame seat or the zone of maximum combustion rate downstream. If this supposition is correct, a rapid rate of decrease of $A$ with increasing values of $W\sqrt{T_4/P_4}$ may serve as an indication that blow-out conditions in the combustion chamber are being approached.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, July 31, 1946.
APPENDIX - DEVELOPMENT OF EXPRESSION FOR MOMENTUM PRESSURE LOSS

The momentum pressure loss in a chamber of constant cross section, neglecting friction, is developed. A similar development is given in reference 1 for the static-pressure drop accompanying the addition of heat to a flowing gas. The expression is required in terms of the loss in total pressure.

The drop in static pressure required to accelerate the gas flow at any section in the combustion chamber is

$$dp = -\frac{\rho v}{g} \, dv$$  \hspace{1cm} (9)

For steady flow in a combustion chamber of constant cross section

$$W = \rho A v$$

or

$$\rho v = C$$  \hspace{1cm} (10)

where \( C \) is a constant.

$$\int_{p_B}^{p_5} dp = -\frac{C}{g} \int_{v_B}^{v_5} dv$$

$$p_5 - p_B = \frac{\rho_B v_B^2 - \rho_5 v_5^2}{g}$$  \hspace{1cm} (11)

From the relations

$$\mu^2 = \frac{v^2}{\gamma \rho_0 R_t}$$

and

$$\rho \frac{p}{\rho} = R_t$$
\[ \rho \frac{v^2}{g} = \gamma \rho M^2 \]

\[ p_5 - p_B = \gamma_B p_B M_B^2 - \gamma_5 p_5 M_5^2 \] (12)

or

\[ p_5 \left( 1 + \gamma_5 M_5^2 \right) = p_B \left( 1 + \gamma_B M_B^2 \right) \]

\[ \frac{p_5}{p_B} = \frac{1 + \gamma_B M_B^2}{1 + \gamma_5 M_5^2} \] (13)

From the relation between static pressure and total pressure,

\[ \frac{p}{p} = \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}} \]

\[ \frac{p_5}{p_B} = \frac{\left( 1 + \gamma_B M_B^2 \right)^{\frac{\gamma}{\gamma - 1}}}{\left( 1 + \gamma_5 M_5^2 \right)^{\frac{\gamma}{\gamma - 1}}} \] (14)
\[
1 - \frac{P_5}{P_B} = \frac{P_B - P_5}{P_B} = \frac{\Delta P_N}{P_B} = 1 - \left( 1 + \frac{\gamma_B M_B^2}{2} \right) \frac{\gamma_5 - 1}{\gamma_5} \frac{M_5^2}{\gamma_B - 1}
\]

which is the desired equation and is equation (6) of the text.

REFERENCES

TABLE I

COMPARISON OF EXPERIMENTAL AND COMPUTED PRESSURE-LOSS RATIO S IN AN ANNULAR COMBUSTION CHAMBER

\[ \frac{K}{A} = 0.0132 \text{ for entire combustion chamber;} \]
\[ A = 1.58 \text{ sq ft for entire combustion chamber;} \]
\[ KA^2 = 0.0330 \text{ for entire combustion chamber or one-fourth segment} \]

<table>
<thead>
<tr>
<th>( \frac{W \sqrt{T_4}}{P_4} ) (a)</th>
<th>( \frac{T_5}{T_4} )</th>
<th>Total pressure-loss ratio, ( \frac{\Delta P_T}{P_4} )</th>
<th>Difference (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Computed (a)</td>
<td>Experimental</td>
</tr>
<tr>
<td>0.0339</td>
<td>2.93</td>
<td>0.0243</td>
<td>0.0229</td>
</tr>
<tr>
<td>0.0393</td>
<td>2.73</td>
<td>0.0315</td>
<td>0.0315</td>
</tr>
<tr>
<td>0.0451</td>
<td>2.02</td>
<td>0.0335</td>
<td>0.0317</td>
</tr>
<tr>
<td>0.0480</td>
<td>2.60</td>
<td>0.0459</td>
<td>0.0430</td>
</tr>
<tr>
<td>0.0497</td>
<td>2.49</td>
<td>0.0484</td>
<td>0.0478</td>
</tr>
</tbody>
</table>

*These values were computed by using a one-fourth segment of the combustion chamber; that is, values of \( \frac{W \sqrt{T_4}}{P_4} \) used on the chart are one-fourth the value for the entire combustion chamber.*

National Advisory Committee for Aeronautics
TABLE II

COMPARISON OF EXPERIMENTAL AND COMPUTED PRESSURE-LOSS RATIOS IN A COMBUSTION CHAMBER OF A RAM JET

\[ K = 0.00364 \text{ for entire combustion chamber; } A = 2.16 \text{ sq ft for entire combustion chamber; } KA^2 = 0.0170 \text{ for entire combustion chamber or } 60^\circ \text{ segment; actual area of combustion chamber, 2.18 sq ft} \]

<table>
<thead>
<tr>
<th>Altitude (ft)</th>
<th>( \frac{W \sqrt{T_4}}{P_4} )</th>
<th>( \frac{T_5}{T_4} )</th>
<th>Total pressure-loss ratio, ( \frac{\Delta P_T}{P_4} )</th>
<th>Difference (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Computed</td>
<td>Experimental</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6,000</td>
<td>0.0303</td>
<td>2.14</td>
<td>0.0155</td>
<td>0.0127</td>
</tr>
<tr>
<td>6,000</td>
<td>0.0303</td>
<td>2.39</td>
<td>0.0595</td>
<td>0.0558</td>
</tr>
<tr>
<td>10,000</td>
<td>0.0341</td>
<td>2.36</td>
<td>0.0179</td>
<td>0.0180</td>
</tr>
<tr>
<td>10,000</td>
<td>0.0543</td>
<td>2.39</td>
<td>0.0492</td>
<td>0.0480</td>
</tr>
<tr>
<td>10,000</td>
<td>0.0708</td>
<td>1.33</td>
<td>0.0463</td>
<td>0.0458</td>
</tr>
<tr>
<td>15,000</td>
<td>0.0359</td>
<td>3.77</td>
<td>0.0276</td>
<td>0.0290</td>
</tr>
<tr>
<td>15,000</td>
<td>0.0393</td>
<td>1.92</td>
<td>0.0198</td>
<td>0.0186</td>
</tr>
<tr>
<td>15,000</td>
<td>0.0547</td>
<td>1.68</td>
<td>0.0345</td>
<td>0.0327</td>
</tr>
</tbody>
</table>

\(^a\)These values are for a 60° segment of the combustion chamber.

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Figure 1a - Schematic views of various combustion chambers for jet-propulsion engines.

(a) Cylindrical type, turbojet engine.

Station 5, turbine inlet
Station 4, compressor outlet
Air flow
Figure 1b - NACA TN NO. 1160

(b) Annular type, turbojet engine.

Figure 1. - Continued. Schematic views of various combustion chambers for jet-propulsion engines.
Figure 2. - Equivalent combustion chamber of constant cross-sectional area.
Figure 3. - Combustion-chamber pressure-loss chart. (A 19-by-20-in. copy of this chart can be obtained upon request from the NACA).
Figure 4. - Determination of $K A^2$ and $A$ from measured values of $\Delta P_F$ and $\Delta P_T$. 
Figure 5. - Determination of $KA^2$ and $A'$ from two measured values of $\Delta P_T$. 
Figure 6.- Comparison of experimental and computed over-all pressure-loss ratios for two cylindrical-type combustion chambers.
Figure 7. Comparison of computed friction and momentum pressure-loss ratios for two types of combustion chamber.

(a) Friction pressure loss.

(b) Momentum pressure loss.