RESEARCH MEMORANDUM

COOLING CHARACTERISTICS OF AN EXPERIMENTAL TAIL-PIPE BURNER WITH AN ANNULAR COOLING-AIR PASSAGE

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By authority of

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
WASHINGTON
February 26, 1952
The effects of tail-pipe fuel-air ratio (exhaust-gas temperatures from approximately 3060° to 3825° R), radial distribution of tail-pipe fuel flow, and mass flow of combustion gas on the temperature profiles of the combustion gas and on temperature profiles of the inside wall of the combustion chamber were determined for an experimental tail-pipe burner cooled by air flowing through an insulated cooling-air passage 1/2 inch in height. The effects on inside-wall temperature of varying the mass-flow ratio of cooling-air to combustion-gas mass flow from approximately 0.067 to 0.19, inlet cooling-air temperature from about 520° to 1587° R, and combustion-gas mass flow from 22.3 to 13.8 pounds per second were also determined.

Large circumferential variations existed in the combustion-gas temperature near the inside wall. These variations resulted in similar variations in the inside-wall temperature. The circumferential variations formed consistent patterns that were similar, although different in magnitude, for all configurations tested.

The two extremes in radial distribution of tail-pipe fuel flow, high fuel concentration toward the combustion-chamber wall and high fuel concentration in the center of the combustion chamber, changed the circumferential average inside-wall temperature 235° F at a station 48 inches downstream of the flame holder. The configuration having a high fuel concentration near the wall presented a more severe cooling problem as the circumferential variation was greatest for this configuration.

The spread of flame to the inside wall, as determined from measurements of combustion-gas temperature near the wall, was practically unaffected by fuel-air ratio. However, the flame spread to the wall was a function of radial fuel distribution. At no time did the flame impinge on the wall within 24 inches downstream of the flame holder. Radiant heat transfer to this section of the inside wall was insufficient to require wall cooling in the first 24 inches, if the tail-pipe materials could withstand nonafterburning operation without cooling.
With the most uniform distribution of tail-pipe fuel tested and an inlet cooling-air temperature of 520° R, an average inside-wall temperature of 1300° F at a station 48 inches downstream of the flame holder required mass-flow ratios of 0.12 and 0.09 with exhaust-gas temperatures of 3825° and 3435° R, respectively. When the distance was increased to 56 inches downstream of the flame holder, a mass-flow ratio of 0.115 was necessary with an exhaust-gas temperature of 3435° R.

At a mass-flow ratio of 0.145, the inside-wall temperature 48 inches downstream of the flame holder was increased about 4/10° per degree increase in inlet cooling-air temperature.

The temperature of the structural wall of an insulated tail-pipe burner having an inner liner would be practically the same with or without tail-pipe burning.

INTRODUCTION

The combustion-chamber walls of tail-pipe burners must either withstand high operating temperatures or be cooled to temperatures that give adequate strength and service life. The trend toward nonstrategic materials and improvements in performance and the operating range of tail-pipe burners have made cooling more critical. Many methods have been considered for cooling the walls of a tail-pipe combustion chamber including the flow of air through an annular passage surrounding the combustion chamber, the flow of turbine outlet gas through an annular passage formed by a concentric inner liner, the establishment of a cool-air film between the walls and the combustion gas by means of a porous wall or a series of annular nozzles, as well as ceramic coatings and fuel additives that coat the walls and reduce the radiant heat transfer to the walls or lower the wall temperature by their insulative properties. Many combinations of these methods have been and are being investigated at the NACA Lewis laboratory. Considerable attention has been given to the annular cooling-air shroud and to the inner liner and to their use in combination.

An analytical method was developed (reference 1) for calculating the maximum average wall temperature in tail-pipe combustion chambers cooled by the parallel flow of air through an annular cooling passage or cooled by turbine discharge gases flowing between an inner liner and the combustion-chamber wall. The method was based on the simplifying assumptions of a uniform transverse temperature profile, a linear rise in combustion-gas temperature from flame holder to exhaust-nozzle exit, and the fact that radiation from the combustion gas to the wall was twice the nonluminous radiation of a completely burned stoichiometric mixture of octane and air. Wall temperatures or cooling-air flows calculated by the method of reference 1 have checked well with values.
measured on experimental tail-pipe burners in which a uniform transverse temperature profile was approached. Agreement was poorer for burners producing nonuniform profiles. Some effects of changing the flame-holder design and tail-pipe fuel distribution, and consequently the transverse temperature profile, are given in reference 2.

The cooling and pumping characteristics of a tail-pipe burner having an inner liner and an external cooling-air shroud with an ejector nozzle are presented in reference 3, and an analytical method is developed in reference 4 for predicting the pressure drop through the cooling passages. These investigations on tail-pipe-burner cooling had limited ranges of cooling-air flows and inlet cooling-air temperature and no attempt was made to determine the combustion-gas temperature profiles as affected by changes in internal configuration and to relate them to the temperatures of the combustion-chamber walls.

This report includes some results of an experimental investigation on a tail-pipe burner which was extensively instrumented. Ranges of independent control of the cooling-air temperature, flow, and pressure, as well as the combustion-gas temperature and flow wider than those given in the references are presented herein. The data presented were obtained with a combustion chamber having a constant-flow area and an annular cooling passage of constant height. The effects of exhaust-gas temperature level, distribution of tail-pipe fuel across the turbine annulus, and mass flow of combustion gas on the temperature profiles of both the combustion gas and the inside wall are presented.

APPARATUS

Engine

A conventional and axial-flow turbojet engine was used in this investigation. The sea-level static thrust of the engine was approximately 3100 pounds at a rated engine speed of 12,500 rpm and a maximum turbine-outlet temperature of approximately 1200°F (1660° R). At this condition the air flow was slightly less than 60 pounds per second.

The fuel used in the engine and the tail-pipe burner was MIL-F-5572, grade 80, unleaded gasoline and had a lower heating value of 18,000 Btu per pound and a hydrogen-carbon ratio of 0.185.

Installation

The standard tail pipe was replaced by an experimental tail-pipe-burner assembly attached to the turbine flange. The engine and the tail-pipe burner were mounted on a wing section in the 20-foot-diameter
test section of the altitude wind tunnel. Refrigerated air was supplied to the compressor inlet through a duct from the tunnel make-up air system. This duct was connected to the engine with a labyrinth seal, which made possible measurement of thrust with the tunnel balance system. Air was throttled from approximately sea-level pressure to the desired pressure at the compressor inlet; while pressure in the tunnel test section was maintained at the desired altitude. Cowlings and fairings were omitted from the engine and the tail-pipe burner in order to simplify the installation and to facilitate inspection and servicing of engine, tail-pipe burner, and instrumentation.

Tail-Pipe-Burner Assembly

The entire tail-pipe-burner assembly was fabricated of 1/16-inch Inconel. The over-all length of the engine and tail-pipe burner was approximately 16.1 feet, of which the tail-pipe diffuser, the combustion chamber, and the nozzle were 2, 5, and 1 feet, respectively. Figure 1 is a schematic drawing of the installation showing the fuel-spray bars in the annular diffuser, the cylindrical combustion chamber with insulated cooling passage, and the fixed-conical exhaust nozzle. The flame holder had a single V-gutter with sinusoidal corrugations on the trailing edges. The V-gutter had a mean diameter of 18 inches, a mean width across the corrugations of 1 3/4 inches, and an included angle of 35°. The blockage at the downstream face of the flame holder was about 23 percent and the velocity at the flame holder under the conditions of this investigation was approximately 480 feet per second. The cooling passage had a constant height of 1/2 inch and was insulated with 1 inch of refractory cement.

Fuel-spray bars. - Twelve radial fuel-spray bars were equally spaced 8.75 inches downstream of the turbine flange and 15.25 inches upstream of the flame-holder center line. Each bar had seven holes (number 76 drill) that sprayed fuel normal to the gas flow. Three different sets (twelve bars per set) of spray bars were used to vary the fuel distribution across the turbine discharge annulus. The first set (fig. 2(a)) produced a nearly uniform fuel distribution with a slightly higher fuel concentration at the very center for flame stability and piloting action. The second set (fig. 2(b)) increased the fuel concentration toward the combustion-chamber wall and decreased the fuel flow in the center of the combustion chamber. The third set of spray bars (fig. 2(c)) concentrated more fuel at the center and decreased the fuel concentration near the combustion-chamber walls.

Configurations. - The three sets of fuel-spray bars were used in combination with four different exhaust nozzles to form essentially three configurations as follows:
Because it was recognized that the combustion pattern would be irregular and the temperatures to be measured were severe on thermocouples, as many thermocouples as practicable were used in order to obtain representative average temperatures and to provide sufficient thermocouples if some thermocouples should fail. Six instrumentation stations, B to G (fig. 3), were provided along the length of the cylindrical combustion chamber. Thermocouples were installed at station B for measurement of the inlet cooling-air temperature. Stations C to F had six groups of instrumentation, equally spaced around the circumference, for measuring the temperatures of the inside and outside walls of the tail-pipe burner and of the cooling air as well as the static and total pressures of the cooling air. The temperatures of the inside and outside walls were also measured at four points around the circumference at station G, and the cooling-air temperatures and pressures at station G were measured in the discharge ducts on the downstream plenum chamber. The locations of the instrumentation at each of these stations, at the exhaust nozzle, the cooling-air metering nozzle, and the upstream plenum chamber are shown in figure 4. The cross section of a typical group of instrumentation at stations C through F is shown in figure 5.

The means of providing for longitudinal movement due to thermal expansion can be seen in figure 5. The platinum-rhodium - platinum thermocouple probes extended through sliding seals in the outside wall and the sliding channels connecting the inside and outside walls permitted longitudinal movement of the walls.

The usual pressure and temperature instrumentation was installed at several measuring stations through the engine. Fuel flows to the engine and tail-pipe burner were measured with calibrated rotameters.

Wall-temperature measurement. - The temperature of the inside wall of the tail-pipe burner was measured with chromel-alumel thermocouples spot-welded to the outer surface of the wall (fig. 5). Conductive
cooling of the junction was reduced by strapping the leads to the wall for 3/4 inch downstream of the junction before extending the leads across the cooling passage. The temperature of the outside wall was measured by a chromel-alumel thermocouple welded into the head of a hollow oval-headed screw (fig. 5). Conductive cooling of the junction was negligible because the stem of the screw was buried under the cooling-passage insulation.

Cooling-air temperature measurement. - The cooling-air temperatures were measured by means of National Bureau of Standards type (fig. 6) shielded thermocouples (reference 5). The -radiation shield consisted of a 1/4-inch length of 1/8-inch silver tubing which was slid over the bare junction and compressed to a biconvex airfoil section.

Combustion-gas temperature measurement. - Combustion-gas temperatures near the inside wall were measured by means of the platinum-rhodium - platinum thermocouples shown in figure 7. Each thermocouple probe had a water-cooled supporting stem and two thermocouples in parallel having a common hot junction. The leads from the junction were arranged in a cross to give mechanical support at high temperatures. Negligible conduction error was obtained by means of the high length-diameter ratio of the leads between the junction and the cooled supporting stem. No radiation shield was used because of the low emissivity and absorptivity of the platinum and platinum-rhodium wires.

Gas temperature profiles at station F were obtained by means of a rake having seven sonic-flow orifice temperature probes (fig. 8). The temperature of a gas sample flowing into one of these probes is obtained from a thermodynamic equation and is theoretically independent of radiation effects (see reference 6).

The exhaust-gas temperature was computed (as given in appendix A) from rake measurements of total pressure at the exhaust-nozzle exit and the measured gas flow.

Accuracy

Four flight recorders were used because of the large number of thermocouples and in order to reduce the recording time while maintaining equilibrium conditions. The estimated over-all accuracy of the temperature measurements are as follows:

Wall temperature, °F ........................................ +15
Cooling air, °F .................................................. ±10
Gas temperatures near the wall, °F .......................... ±20
Sonic-flow orifice probe, °F ................................. ±150
Exhaust gas temperature, °F ................................ ±50
The geometry of the tail-pipe diffuser and the flame holder in combination with the fuel-spray bars producing approximately uniform distribution of fuel across the turbine annulus (configuration A) was shown, in preliminary tests on a similar burner, to give good performance and operating characteristics over a wide range of altitudes and fuel-air ratios. Cooling characteristics of the experimental tail-pipe burner were obtained with the seven combinations of exhaust-nozzle exit area and fuel-spray bars, at pressure altitudes of 30,000 and 40,000 feet, a flight Mach number of 0.52, and an engine speed of 12,500 rpm. It was impossible to run the tests at lower pressure altitudes because the flow of dry cooling air, at approximately atmospheric pressure from outside the tunnel, was dependent on the difference in the atmospheric pressure and the pressure in the tunnel test section. Dry refrigerated air was supplied to the engine at 50°F. The total pressure at the engine inlet was regulated to correspond to the desired pressure at each altitude with complete free-stream total-pressure recovery.

Most of the data were obtained by adjusting the tail-pipe fuel flow to maintain an average turbine-outlet temperature of 1633°±12° R; an approximately constant exhaust-gas temperature was thus obtained for each nozzle-exit area and mass flow. The remainder of the data were taken at lower turbine-outlet temperatures.

The cooling-air flow and the cooling-air temperature were systematically varied while holding all other quantities constant.

The approximate range of variables investigated with a limiting turbine-outlet temperature of 1633° are given in the following table:
<table>
<thead>
<tr>
<th>Configuration</th>
<th>Altitude (ft)</th>
<th>Exhaust-gas temperature $T_g$ ($^\circ$R)</th>
<th>Combustion-gas flow $W_g$ (lb/sec)</th>
<th>Mass ratio $W_a/W_g$</th>
<th>Cooling-air inlet temperature $T_a$ ($^\circ$R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30,000</td>
<td>3060</td>
<td>22.1</td>
<td>0.0672 to 0.1872</td>
<td>500 to 1587</td>
</tr>
<tr>
<td></td>
<td>30,000</td>
<td>3240</td>
<td>22.2</td>
<td>0.1002 to 0.1917</td>
<td>500 to 1222</td>
</tr>
<tr>
<td></td>
<td>30,000</td>
<td>3435</td>
<td>22.3</td>
<td>0.0953 to 0.1796</td>
<td>502 to 1408</td>
</tr>
<tr>
<td></td>
<td>40,000</td>
<td>3265</td>
<td>13.8</td>
<td>0.1440 to 0.1906</td>
<td>528 to 1340</td>
</tr>
<tr>
<td></td>
<td>30,000</td>
<td>3825</td>
<td>22.8</td>
<td>0.1374 to 0.1906</td>
<td>515</td>
</tr>
<tr>
<td>B</td>
<td>30,000</td>
<td>3215</td>
<td>22.2</td>
<td>0.0985 to 0.1891</td>
<td>495 to 1223</td>
</tr>
<tr>
<td>C</td>
<td>30,000</td>
<td>3235</td>
<td>22.3</td>
<td>0.1420 to 0.1912</td>
<td>524 to 1450</td>
</tr>
<tr>
<td></td>
<td>30,000</td>
<td>3764</td>
<td>22.4</td>
<td>0.1912</td>
<td>524</td>
</tr>
</tbody>
</table>

The cooling-air mass flow was controlled by flap valves on the outlet ducts of the downstream plenum chamber. The static pressure in the cooling passage was balanced against the static pressure of the combustion gas at station F by means of pressure-regulating valves upstream of the air-metering nozzle in conjunction with the flap valves. When the pressures were balanced, large pressure forces were transferred from the hot, and consequently weaker, inside wall to the cooler outside wall. This transfer tended to minimize any changes in cooling-passage height. The cooling-air temperature was varied by means of a turbojet can-type combustor in the cooling-air supply duct downstream of the air-metering nozzle.

**RESULTS AND DISCUSSION**

Typical results of this cooling investigation are presented graphically and the performance of the three configurations are tabulated in
tables I and II. The effects of exhaust-gas temperature level, radial distribution of tail-pipe fuel flow, and combustion-gas mass flow on the temperature profiles of the combustion gas are presented first because of the influence these profiles have on the temperatures of the inside wall.

Reproducibility of Combustion-Gas Temperature Profiles

Circumferential profiles. - The combustion-gas temperatures near the inside wall, the temperature of the inside and outside walls of the cooling passage and the cooling-air temperature are plotted against the group positions around the circumference at station F in figure 9. The reproducibility of the data is indicated in figures 9(a) to 9(c) for a check point having an exhaust-gas temperature of approximately 3060° R, mass-flow ratio of 0.098, and an inlet cooling-air temperature of 530° R. The profiles are similar as the accumulated afterburner time increased from 32 minutes to 9 hours and 22 minutes. The profiles with an exhaust-gas temperature of 3484° R (fig. 9(d)) are similar although the temperature levels are higher. The profiles shown in figure 9 were obtained with the first set of fuel bars, which produced the most uniform fuel distribution. The reproducibility shown is typical of data obtained with the other configurations. The large variations in gas temperatures around the circumference are reflected in the inside-wall temperature. The difference between the highest and the lowest gas temperatures around the circumference, as measured by the platinum thermocouples at station F, was approximately 500° to 900° F, and the difference for the inside-wall temperatures was about 400° to 600° F. The larger circumferential variations in gas temperature are believed to be caused by asymmetrical distributions in the engine fuel-air ratio and in turbine-discharge gas flows because daily inspections disclosed no plugging of the fuel-spray bars in the tail-pipe burner.

Longitudinal profiles. - Typical longitudinal profiles of the combustion-gas temperature measured by the platinum-rhodium - platinum thermocouples 1/2 inch from the inside wall are shown in figure 10. The general reproducibility of the combustion pattern for a given set of fuel-spray bars can be seen by comparing the relative positions of the temperature profiles for each circumferential group as the exhaust-gas temperature is increased (fig. 10). Similar reproducibility of the relative positions of each group was observed in the longitudinal profiles for the combustion-gas temperature measured 1/4 inch from the inside wall and for the temperature of the inside wall.

Inasmuch as the longitudinal temperature profiles for various circumferential positions reproduced in a consistent manner in spite of large circumferential temperature variations, the effects of exhaust-gas temperature, of fuel distributions, and of combustion-gas mass flow are based on circumferential average temperatures. (The temperatures in table II are circumferential averages.)
Effect of Variables on Average Longitudinal Profiles of Combustion-Gas Temperature

Exhaust-gas temperature. - The effect of increased exhaust-gas temperature (or tail-pipe fuel-air ratio) and the spread of the flame toward the inside wall are shown in figure 11. The combustion-gas temperature within 1/4 inch of the wall (fig. 11(a)) remains at approximately turbine-discharge temperature as far downstream as station D indicating that, for the same fuel distribution, the spread of the flame toward the inside wall is practically unaffected by fuel-air ratio (exhaust-gas temperature level) although the transverse temperature gradients between stations C and D increase with fuel-air ratio as can be seen from figure 11(b). Consequently, no cooling would be required for configuration A in the first 24 inches downstream of the flame holder if the burner walls could withstand the nonafterburning operation without cooling. Downstream of this point, the cooling requirements increase as the transverse gas temperature gradients near the wall increase with both distance from the flame holder and with exhaust-gas temperature level.

Fuel distribution. - The effects of marked changes in tail-pipe fuel distribution across the turbine-discharge annulus on the gas temperatures near the inside wall are shown in figure 12. Figure 12(a) shows that the flame spreads out to the wall between 24 and 36 inches downstream of the flame holder depending on the radial distribution of fuel. The flame intercepted the wall first with configuration B, which had a high fuel-air ratio near the wall, and last with configuration C, which had a high fuel-air ratio in the center of the burner. The cooling problem apparently can be altered by changes in fuel distribution at a given exhaust-gas temperature level. It is not, however, always possible to alleviate the cooling problem by altering the radial distribution of fuel because of possible adverse effects on performance and operational characteristics of the tail-pipe burner. For example, configuration C produced low inside-wall temperatures with the third set of fuel-spray bars, and had very smooth combustion and the exhaust nozzle was colder than for configuration A at the same exhaust-gas temperature, but it was impossible to obtain a turbine-outlet gas temperature of 1633° R with these fuel-spray bars when the exhaust-nozzle exit area was 2.160 square feet. On the other hand, configuration B, which produced high inside-wall temperatures, was difficult to ignite, burned roughly, and blow-out whenever the turbine-outlet gas temperature dropped below 1615° R.

The corresponding changes in transverse temperature profiles with changes in fuel distribution will be discussed in the section Fuel Distribution.

Combustion-gas mass flow. - The effect of decreasing the combustion-gas mass flow on the gas temperatures near the inside wall is shown in
The decrease in mass flow of combustion gas from 22.29 to 13.85 pounds per second, resulting from increasing the altitude from 30,000 to 40,000 feet, lowered the combustion-gas temperatures between stations E and F, about 400° and 200° F at distances from the inside wall of 1/4 and 1/2 inch, respectively. These temperature reductions, however, would be about one-half as great if cross-plotted data from figure 11 were used to estimate the longitudinal temperature profile at the same exhaust-gas temperature as with the lower mass flow. The decrease in exhaust-gas temperature occurred because the tail-pipe fuel flow was adjusted for a constant indicated turbine-outlet gas temperature, but the mean turbine-outlet gas temperature decreased because of a change in the radial temperature profile as altitude was changed.

Variation of Gas Temperatures Near the Wall with Cooling-Air Flow and Temperature

The temperature of the combustion gas near the wall was affected slightly by the inside-wall temperature, and consequently, by the mass flow and the temperature of the cooling air. The influence of cooling-air flow and the inlet cooling-air temperature on the gas temperature measured 1/4 inch from the inside wall was found to be negligible at stations C and D. The effect of cooling-air flow at stations E and F is given by the approximate equation

\[ \Delta T_{g,1/4} = 1000 \Delta \left( \frac{W_a}{W_g} \right) \]  

and the effect of inlet cooling-air temperature is about 1/100 per degree rise in inlet cooling-air temperature. (The symbols used are defined in appendix B.)

Effects of Variables on Transverse Gas-Temperature Profile at Station F

Some of the more representative transverse profiles of the combustion-gas temperature at station F were selected for presentation. The temperatures in the combustion zone were obtained by means of the sonic-flow orifice rake and the temperatures near the wall were measured by the platinum-rhodium - platinum thermocouples 1/4 inch from the inside wall.

Exhaust-gas temperature. - Transverse temperature profiles are shown for configuration A in figure 14. Temperature peaks in figure 14(a) corresponding to the wake of the single-V flame holder tend to disappear and the profile to become more uniform as the exhaust-gas temperature is increased (figs. 14(b) and (c)).
The gas temperatures 1/4 inch from the inside wall and in the center of the combustion zone increased 600° to 700° R as the average exhaust-gas temperature increased approximately 440° R.

Fuel distribution. - The effects of changing the radial distribution of fuel across the turbine annulus on the transverse profile of combustion-gas temperature are shown in figure 15. Figure 15(a) shows that the transverse temperature profile of configuration A at an exhaust-gas temperature of 3266° R had a temperature peak in the wake of the flame-holder gutter similar to the peaks existing at an exhaust-gas temperature of approximately 2926° R (fig. 14(a)). The high fuel concentrations near the inside wall in configuration B (fig. 15(b)) resulted in much higher gas temperatures near the inside wall at the bottom of the burner and the gas temperature at the center of the burner was greatly reduced because the tail-pipe fuel-air ratio and exhaust-gas temperatures were practically constant. The average gas temperatures 1/4 inch from the inside wall were approximately 400° R higher for configuration B than for configuration A at a mass-flow ratio of 0.143 and an exhaust-gas temperature of approximately 3240° R. The fuel distribution of configuration C moved the peak temperatures toward the center of the burner and the average gas temperature 1/4 inch from the inside wall was about 350° R lower than for configuration A at a mass-flow ratio of 0.143. For the three radial fuel distributions tested, the increase in fuel concentration in the center of the burner produced a slightly smaller effect on the gas temperatures near the inside wall than did the increase in the fuel concentration toward the walls. This fuel distribution also aggravated the circumferential temperature variations. The relation of these profiles to the average inside-wall temperature will be discussed in the next section.

Effect of Variables on Longitudinal Profiles of Average Inside-Wall Temperatures

Because the variations in longitudinal and circumferential temperature profiles of the inside-wall temperature were consistent, circumferential average temperatures are used in the following comparisons.

Exhaust-gas temperature. - The variations in the longitudinal profile of the average inside-wall temperature with exhaust-gas temperature level is shown in figure 16. The inside-wall temperature increases from the flame holder to the exhaust-nozzle inlet with exhaust-gas temperature level. The variation of wall temperature with exhaust-gas temperature level is slight at stations C and D because the flame has not spread to the wall. The wall temperatures at these stations are influenced more by the mass flow and inlet temperature of the cooling air than by the exhaust-gas temperature level. Downstream of station D, the wall temperature
increases because the temperature gradients near the wall and the radiant heat transfer increase as exhaust-gas temperature level increases. The profiles shown were obtained with a mass-flow ratio of approximately 0.145. The effect of mass-flow ratio on the wall temperature will be shown in the Combustion-Gas Mass Flow section.

Fuel distribution. - The effect of fuel distribution on the inside-wall temperatures is shown in figure 17 for an average exhaust-gas temperature of 3290° R and a mass-flow ratio of 0.145. The curves have been extrapolated linearly to station G, as indicated by the data of figures 16 and 18, because only two thermocouples were functioning during these readings and the temperatures at these positions were usually higher than the circumferential average temperature. Configuration B had the highest average inside-wall temperature as a result of the very high gas temperatures at the bottom of the burner; the average inside-wall temperatures of configuration A are intermediate, whereas configuration C had the lowest wall temperatures as a result of the lower gas-temperature gradients near the walls of the burner. For the two extremes in fuel distribution tested, the spread in average inside-wall temperatures at station F was 239° F, but the circumferential variations in wall temperature were greatest with configuration B.

Combustion-gas mass flow. - With an average mass-flow ratio of 0.144, the average inside-wall temperature was lowered 40° to 100° at stations F and G when the mass flow of combustion gas was decreased from 22.29 to 13.85 pounds per second (fig. 18). Comparison of the wall temperatures at the lower mass flow with wall temperatures interpolated from figure 16 indicates, however, that these reductions resulted primarily from the decrease in exhaust-gas temperature level.

Effect of Mass-Flow Ratio and Cooling-Air Temperature on Average Inside-Wall Temperatures

Mass-flow ratio. - The effect of cooling-air mass-flow ratio on the average inside-wall temperature is shown in figure 19. The limiting values of the average inside-wall temperature at stations C, D, and E with no cooling-air flow were assumed to coincide with their respective average gas temperatures 1/4 inch from the inside wall with no cooling-air flow.

As previously discussed, the inside-wall temperatures at stations C and D are nearly independent of the exhaust-gas temperature level and vary inversely with mass-flow ratio. The higher wall temperatures at station D result from increased radiant heat transfer from the combustion zone. Both radiant and convective heat transfer became important downstream of station D as a result of the higher gas-temperature level and
the flame impingement on the walls. Thus, from station D on downstream, a distinct curve results for each tail-pipe fuel-air ratio (exhaust-gas temperature level) as shown in figure 19. Figure 19(a) shows that no cooling air is required in the first 24 inches downstream of the flame holder (station D) if the tail-pipe materials can withstand nonafter-burning operation without cooling.

A mass-flow ratio of 0.12 is required in order to maintain an average inside-wall temperature of 1300° F, 48 inches downstream of the flame holder (station F) with an exhaust-gas temperature of 3825° R, and the mass-flow ratio is about 0.09 with an exhaust-gas temperature of 3435° R. An average inside-wall temperature of 1300° F, 56 inches downstream of the flame holder (station G), requires a mass-flow ratio of approximately 0.115 at 3435° R. An average inside-wall temperature of 1300° F was selected as representative in order to allow for possible hot spots as high as 1600° F.

Cooling-air temperatures. - The variation of inside-wall temperature with inlet cooling-air temperature (fig. 20) is similar for all exhaust-gas temperatures but differs in temperature level. The wall temperature increased with a slightly increasing rate as the cooling-air temperature was increased. When the inlet cooling-air temperature was increased 1000° F, the inside-wall temperatures increased at stations F and G about 400° F at a mass-flow ratio of 0.145. The inside-wall temperatures at station G (fig. 20(b)) were about 100° F higher than at station F (fig. 20(a)) with an exhaust-gas temperature of approximately 3060° R, and about 150° F higher with an exhaust-gas temperature of 3435° R.

Interrelation of Temperatures

The interrelation of the exhaust-gas temperature, gas temperatures near the wall, inside-wall temperature, and cooling-air temperatures are shown in figure 21 for station F. The cooling-air temperature rise to station F is the vertical distance between the cooling-air temperature curve and the diagonal dashed line. This rise in cooling-air temperature becomes small as the inlet cooling air is raised to temperatures of 1500° to 1700° R, indicating that a combustion chamber with an inner liner maintains a layer of gas at approximately turbine-outlet temperature next to the outside structural wall. Consequently, the temperature of the structural wall of an insulated tail-pipe burner having an inner liner would be practically the same with or without tail-pipe burning.

The data of figure 22 can be shown to better advantage by means of the parameter \( \frac{T_{g,F} - T_{w,F}}{T_{w,F} - T_{a,F}} \) which is obtained from a heat balance across the inside wall at station F. This parameter is the ratio of the over-
all heat-transfer coefficients on the cooling-air and combustion-gas sides of the inside wall $H_a/H_g$. The ratio $H_a/H_g$ is a function of the inlet cooling-air temperature, exhaust-gas temperature, turbine-discharge gas temperature, and mass-flow ratio for a given fuel distribution and burner geometry. This parameter can be plotted against the ratio of the inlet cooling-air temperature to the exhaust-gas temperature $T_{a,B}/T_g$ for given mass-flow ratios, turbine-discharge gas temperatures, and radial fuel distributions. Inasmuch as the cooling-air temperature $T_{a,F}$ and the effective-gas temperature $T_{g,F}$ are not generally known, and because these temperatures are functions of the same variable as the ratio $H_a/H_g$, the more convenient parameter $\frac{T_g - T_{w,F}}{T_{w,F} - T_{a,B}}$ is plotted in figure 22 against $\frac{T_{a,B}}{T_g}$. The parameter $\frac{T_g - T_{w,F}}{T_{w,F} - T_{a,B}}$ varies approximately linearly with $\frac{T_{a,B}}{T_g}$ but varies in level and slope with the radial fuel distribution and mass-flow ratio. The upper curve is for configuration C with a mass-flow ratio of 0.143. The second curve from the top is the mean line through the data of configuration A with mass flows of combustion gas of 22.5 and 13.8 pounds per second at a mass-flow ratio of approximately 0.143. The effect of exhaust-gas temperature level from $3064^\circ$ to $3845^\circ$ R is not apparent within the scatter of the data. The large discrepancy between the data points and the curve for configuration A at $\frac{T_{a,B}}{T_g} = 0.54$ amounts to only $41^\circ$ R in $T_{w,F}$. The parameter $\frac{T_g - T_{w,F}}{T_{w,F} - T_{a,B}}$ is very sensitive to small changes in $T_{w,F}$ for values of $\frac{T_{a,B}}{T_g}$ greater than approximately 0.50.

The third curve is for configuration A at a mass-flow ratio of 0.098. The data of configuration C fall along the lowest curve at a mass-flow ratio of 0.143.

COOLING-AIR PRESSURE DROP

The pressure drop through the cooling passage is shown in figure 23 against the cooling-air flow. The use of $\sigma$ based on inlet temperature and pressure satisfactorily correlated the data. The pressure drop increases with exhaust-gas temperature because of increased momentum pressure drop accompanying higher heat transfer to the cooling air.
The isothermal friction factor for the instrumented cooling passages is shown in figure 24. The turbulence created by the instrumentation and the interlocking stringers was great enough to make the friction factor practically independent of Reynolds number. The value was about 0.009 for a Reynolds number range of $1.6 \times 10^4$ to $1.3 \times 10^5$. Without the instrumentation the friction factor should lie closer to the line for commercial pipe.

**SUMMARY OF RESULTS**

The effects of tail-pipe fuel-air ratio (exhaust-gas temperature level), radial distribution of tail-pipe fuel, and mass flow of combustion gas on the temperature profiles of the combustion gas and inside wall of the combustion chamber were determined for an experimental tail-pipe burner cooled by air flowing through an insulated cooling-air passage 1/2 inch in height.

Large circumferential variations existed in the combustion-gas temperature near the inside wall. These variations in combustion-gas temperature resulted in similar variations in the inside-wall temperature. The difference between the highest and the lowest gas temperatures around the circumference 1/4 inch from the inside wall was approximately 500°F to 900°F, whereas the corresponding difference in the inside-wall temperatures was 400°F to 600°F. These circumferential variations formed consistent patterns that were similar, although different in magnitude, for all configurations tested.

The two extremes in radial distribution of tail-pipe fuel flow, high fuel concentration toward the combustion-chamber wall and high fuel concentration in the center of the combustion chamber, produced a spread in circumferential average inside-wall temperatures of 235°F at a station 48 inches downstream of the flame holder. The configuration having a high fuel concentration toward the wall presented more of a cooling problem than is indicated by the difference in average inside-wall temperatures because the circumferential variation in temperature was greatest for this configuration.

The distance downstream of flame holders at which the flame spread to the inside wall, as determined from measurements of combustion-gas temperature near the wall, was practically unaffected by tail-pipe fuel-air ratio. However, the spread of the flame toward the wall was a function of radial fuel distribution. At no time did the flame impinge on the inside wall closer than 24 inches downstream of the flame holder. Radiant heat transfer to this section of the inside wall was insufficient as to require wall cooling in the first 24 inches if the tail-pipe materials could withstand nonafterburning operation without cooling.
With the most uniform distribution of tail-pipe fuel tested and an inlet cooling-air temperature of $520^\circ R$, an average inside-wall temperature of $1300^\circ F$ at a station 48 inches downstream of the flame holder required mass-flow ratios of 0.12 and 0.09 at exhaust-gas temperatures of $3825^\circ$ and $3435^\circ R$, respectively. Increasing the distance to 56 inches downstream of the flame holder necessitated a mass-flow ratio of 0.115 with an exhaust-gas temperature of $3435^\circ R$.

At a mass-flow ratio of 0.145, the inside-wall temperatures at a station 48 inches downstream of the flame holder were increased approximately $4/10^\circ$ per degree increase in inlet cooling-air temperature.

It was shown that the temperature of the structural wall of an insulated tail-pipe burner having an inner liner would be practically the same with or without tail-pipe burning.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio.
APPENDIX A

CALCULATION OF EXHAUST-GAS TEMPERATURE

The exhaust-gas temperature was calculated from the following equation when the nozzle was choked:

\[
T_g = \gamma g \left( \frac{\gamma g + 1}{2} \right) g \frac{\gamma g}{R} \left( \frac{p_n C_n C_T A_n}{w} \right)^2
\]  

(B1)

where \( C_n = 0.965 \).

\( C_T = \left[ 1 + 9 \times 10^{-6} (t_n - 70) \right]^2 \)

and \( p_n \) was obtained from the critical pressure ratio corresponding to \( \gamma g \)

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

When the nozzle was unchoked

\[
T_g = \frac{\gamma g - 1}{\gamma g w_g^2} \frac{g}{2R} \left[ 1 - \left( \frac{p_0}{p_n} \right)^{\frac{\gamma g - 1}{\gamma g}} \left( \frac{F_1}{C_j} \right) \right]
\]  

(B2)

where \( C_j = 0.97 \).
APPENDIX B

SYMBOLS

\( A_n \) area of exhaust-nozzle throat at 70° F, sq ft

\( C_j \) ratio of scale jet thrust to ideal jet thrust

\( C_n \) exhaust-nozzle flow coefficient

\( C_T \) area thermal expansion coefficient

\( D_h \) hydraulic diameter of cooling passage (twice cooling passage height), ft

\( F_j \) scale jet thrust, lb

\( f \) isothermal friction factor

\( f/a \) fuel-air ratio

\( (f/a)_t \) tail-pipe fuel-air ratio

\( g \) acceleration due to gravity, ft/sec²

\( H_a \) combined coefficient of heat transfer on the cooling-air side, Btu/(hr)(sq ft)(°R)

\( H_g \) combined coefficient of heat transfer on combustion-gas side, Btu/(hr)(sq ft)(°R)

\( l \) flow distance between stations B and F, ft

\( P_n \) total pressure at exhaust-nozzle throat, lb/sq ft abs.

\( P_5 \) turbine-outlet total pressure, lb/sq ft abs.

\( P_8 \) exhaust-nozzle total pressure, lb/sq ft abs.

\( P_0 \) static pressure in tunnel test section, lb/sq ft abs.

\( P_n \) static pressure at exhaust-nozzle throat, lb/sq ft abs.

\( \bar{u} \) average dynamic pressure between stations B and F, lb/sq ft

\( R \) gas constant, ft-lb/(lb)(°R)

\( Re \) Reynolds number
cooling-air temperature, °R or °F
exhaust-gas temperature at nozzle exit, °R
combustion-gas temperature measured 1/4 inch from inside wall, °R or °F
combustion-gas temperature measured 1/2 inch from inside wall, °R or °F
outside-wall temperature, °F
turbine-outlet total temperature, °R
inside-wall temperature, °R or °F
engine-inlet total temperature, °R
average temperature of exhaust nozzle lip, °F
cooling-air flow, lb/sec
gine fuel flow, lb/hr
tail-pipe fuel flow, lb/hr
combustion gas flow, lb/sec
mass-flow ratio
ratio of specific heats of exhaust gas corresponding to total fuel-air ratio and exhaust-gas temperature
tail-pipe combustion efficiency
ratio of density at prevailing temperature and pressure to density at standard temperature and pressure

Subscripts:
B to G longitudinal stations

REFERENCES


| 50,000 | 1.990 | 0.315 | 592 | 471 | 503 | 546 | 688 | 1411 | 12,15 | 0.0397 | 0.0286 | 0.1425 | 0.2021 | 1427 | 1527 | 1528 | 3128 | 92 |
| 51 | 0.315 | 592 | 471 | 503 | 546 | 688 | 1411 | 12,15 | 0.0397 | 0.0286 | 0.1425 | 0.2021 | 1427 | 1527 | 1528 | 3128 | 92 |
| 52 | 0.315 | 592 | 471 | 503 | 546 | 688 | 1411 | 12,15 | 0.0397 | 0.0286 | 0.1425 | 0.2021 | 1427 | 1527 | 1528 | 3128 | 92 |
| 53 | 0.315 | 592 | 471 | 503 | 546 | 688 | 1411 | 12,15 | 0.0397 | 0.0286 | 0.1425 | 0.2021 | 1427 | 1527 | 1528 | 3128 | 92 |
| 54 | 0.315 | 592 | 471 | 503 | 546 | 688 | 1411 | 12,15 | 0.0397 | 0.0286 | 0.1425 | 0.2021 | 1427 | 1527 | 1528 | 3128 | 92 |
| 55 | 0.315 | 592 | 471 | 503 | 546 | 688 | 1411 | 12,15 | 0.0397 | 0.0286 | 0.1425 | 0.2021 | 1427 | 1527 | 1528 | 3128 | 92 |
| 56 | 0.315 | 592 | 471 | 503 | 546 | 688 | 1411 | 12,15 | 0.0397 | 0.0286 | 0.1425 | 0.2021 | 1427 | 1527 | 1528 | 3128 | 92 |
| 57 | 0.315 | 592 | 471 | 503 | 546 | 688 | 1411 | 12,15 | 0.0397 | 0.0286 | 0.1425 | 0.2021 | 1427 | 1527 | 1528 | 3128 | 92 |

*Based on average Wg*

*Approximately 0.315.
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[Table content continues with more parameters and data]
| Run | Combustion A | Inside wall | Outside wall | Cooling air | Combustion A | Inside wall | Outside wall | Cooling air | Combustion A | Inside wall | Outside wall | Cooling air | Combustion A | Inside wall | Outside wall | Cooling air | Combustion A | Inside wall | Outside wall | Cooling air |
|-----|-------------|-------------|--------------|-------------|-------------|-------------|--------------|-------------|-------------|-------------|-------------|--------------|-------------|-------------|-------------|-------------|-------------|--------------|-------------|-------------|-------------|
| 1   | 1068        | 1068        | 1068         | 1068        | 1068        | 1068        | 1068         | 1068        | 1068        | 1068        | 1068        | 1068         | 1068        | 1068        | 1068        | 1068        | 1068        | 1068        | 1068        | 1068        |
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| 10  | 1077        | 1077        | 1077         | 1077        | 1077        | 1077        | 1077         | 1077        | 1077        | 1077        | 1077        | 1077         | 1077        | 1077        | 1077        | 1077        | 1077        | 1077        | 1077        | 1077        |

**TABLE IX - CIRCUMFERENTIAL AVERAGE TEMPERATURES, °C**

**NACA FARM 51125**
<table>
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<tr>
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<th>Station E</th>
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<td>1152</td>
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Figure 1. - Tail-pipe burner assembly.
(a) Nearly uniform fuel distribution.

(b) Fuel distribution concentrated toward outside of burner.

(c) Fuel distribution concentrated toward center of burner.

Figure 2. - Fuel-spray bars.
Figure 3. - Instrumentation stations on the tail-pipe burner.
(a) Station B, cooling-passage inlet, looking downstream.

Figure 4. Location of instrumentation.
(b) Stations C through E, looking downstream.

Figure 4. - Continued. Location of instrumentation.
Figure 4. - Continued. Location of instrumentation.

(c) Station F, looking downstream.
(d) Station G.

Figure 4. - Continued. Location of instrumentation.
(e) Exhaust-nozzle exit, looking downstream.

Figure 4. - Continued. Location of instrumentation.
(f) Throat of cooling-air metering nozzle.

Figure 4. - Continued. Location of instrumentation.
Figure 4. Concluded. Location of instrumentation.

(g) Cooling-air inlet plenum chamber, looking downstream.
Figure 5. - Typical instrumentation group for stations 3 to F.
Figure 6. - National Bureau of Standards type shielded thermocouple for cooling-air temperature measurement.
Figure 7. - Platinum-rhodium - platinum thermocouple probes.
Figure 8. - Interior view of combustion chamber showing installation of sonic-flow orifice rake and platinum-rhodium - platinum thermocouples.
(a) Accumulated afterburner time, 32 minutes; exhaust-gas total temperature, 2993° R; mass-flow ratio, 0.1006; inlet cooling-air temperature, 526° R.

Figure 9. - Circumferential temperature variations at station F, configuration A.
Figure 9. Continued. Circumferential temperature variations at station F, configuration A.

(b) Accumulated afterburner time, 3 hours and 36 minutes; exhaust-gas total temperature, approximately 3060°F; mass-flow ratio, 0.0399; inlet cooling-air temperature, 53°F.

Combustion gas 1/2 in. from inside wall; cooling air cooling air from inside wall 1/4 in. from inside wall.
(c) Accumulated afterburner time, 9 hours and 22 minutes; exhaust-gas total temperature, 3105° R; mass-flow ratio, 0.0985; inlet cooling-air temperature, 529° R.

Figure 9. - Continued. Circumferential temperature variations at station F, configuration A.
Figure 9. Concluded. Circumferential temperature variations at station F, configuration A.

(d) Accumulated afterburner time, 3 hours and 48 minutes; exhaust-gas total temperature, 3484° R; mass-flow ratio, 0.1050; inlet cooling-air temperature, 550° R.
Figure 10. - Longitudinal gas-temperature profiles 1/2 inch from inside wall, configuration A.
(c) Exhaust-gas total temperature, 3611° R; mass-flow ratio, 0.1374; inlet cooling-air temperature, 536° R.

Figure 10. - Concluded. Longitudinal gas-temperature profiles 1/2 inch from inside wall, configuration A.
Figure 11. - Variation of longitudinal profile of exhaust-gas temperature near inside wall with exhaust-gas temperature for configuration A. Approximate inlet cooling-air temperature, 520° R.
Figure 11. - Concluded. Variation of longitudinal profile of exhaust-gas temperature near inside wall with exhaust-gas temperature for configuration A. Approximate inlet cooling-air temperature, 520\(^\circ\) R.
Figure 12. - Effect of fuel distribution on gas temperatures near inside wall.

Exhaust-gas total temperature, approximately 3230° R; mass-flow ratio, 0.145;
cooling-air inlet temperature, 510° R.
<table>
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<td>$W_b/W_g$</td>
<td>$T_{a,b}$ ($^\circ$R)</td>
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(a) Temperatures 1/4 inch from inside wall.

(b) Temperatures 1/2 inch from inside wall.

Figure 13: Effect of combustion-gas mass flow on gas temperatures near inside wall for configuration A.
Figure 14. - Transverse profiles of combustion-gas temperature at station P, configuration A.
Figure 15. Effect of fuel distribution on transverse profiles of combustion-gas temperature at station F.
Figure 16. - Effect of exhaust-gas temperature on longitudinal profiles of average inside-wall temperature for configuration A.

Figure 17. - Effect of fuel distribution on longitudinal profile of average inside-wall temperature.

Figure 18. - Effect of combustion-gas mass flow on longitudinal profile of inside-wall temperature for configuration A.
Figure 19. - Variation of average inside-wall temperature with mass-flow ratio of cooling air to combustion gas for configuration A. Approximate inlet cooling-air temperature, 520°F.
Figure 20. Variation of inside-wall temperature with inlet cooling-air temperature for configuration A. Mass-flow ratio, 0.145.
(b) Configuration A; exhaust-gas temperature, 3064°F; combustion-gas flow, 22.3 pounds per second; mass-flow ratio, 0.098.

Figure 21. - Relation of temperatures at station B.
Figure 21. - Continued. Relation of temperatures at station F.
(e) Configuration A; exhaust-gas temperature, 3265°F; combustion-gas flow, 13.8 pounds per second; mass-flow ratio, 0.143.

(f) Configuration B; exhaust-gas temperature, 3225°F; combustion-gas flow, 22.3 pounds per second; mass-flow ratio, 0.144.

Figure 21. - Continued. Relation of temperatures at station F.
(g) Configuration C; exhaust-gas temperature, 3250° F; combustion-gas flow, 22.3 pounds per second; mass-flow ratio, 0.143.

Figure 21. - Concluded. Relation of temperatures at station F.
Figure 22. - Comparison of effects of exhaust-gas temperature level, radial distribution of tailpipe fuel flow, and mass-flow ratio on cooling characteristics.

Figure 23. - Correlation of cooling-air pressure drop.
Figure 24. - Isothermal friction factor for instrumented cooling passages.