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PERFORMANCE OF A TURBOJET COMBUSTOR USING NATURAL GAS FUEL HEATED TO 1200° F (922 K)

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16. Abstract

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SUMMARY

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INTRODUCTION

Liquefied natural gas is an attractive fuel for high-performance turbojet engines because of its higher heat of combustion and higher heat-sink capacity relative to conventional kerosene-type JP fuels (ref. 1). If the heat capacity of the liquefied natural gas is used to its full potential, fuel temperatures up to 1200° F (922 K) entering the combustor may be encountered. The effect of such high fuel temperatures on combustor performance could be significant. If the improvement were great enough, it would make possible the use of higher reference velocities, simpler flameholder geometries with low pressure loss, and shorter, smaller combustors.

A rectangular combustor segment with simple U-gutter flameholders was tested over a range of fuel temperatures from ambient to 1200° F (922 K). The combustor envelope shape and the test conditions were typical of short-length primary combustors. The particular flameholder design makes the results of interest for afterburner applications as well as for low-pressure-loss primary combustors.

TEST INSTALLATION

The combustor was installed in a test facility connected to the laboratory air supply and exhausted through a quenching station and a noise supporessor to the atmosphere (fig. 1). Combustion air at near-atmospheric pressure was directed through a vitiating preheater where it was heated to 600° F (589 K) prior to entering the test combustor. A set of screens was installed downstream of the preheater to provide a uniform velocity profile entering the test combustor.

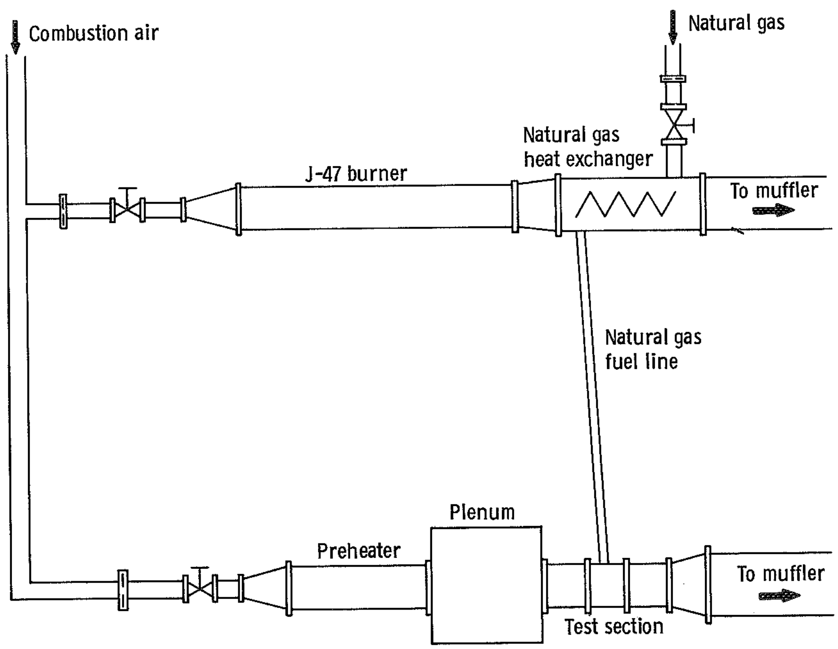

Figure 1. - Combustor installation and methane heat exchanger.

The natural gas heat exchanger used a single J-47 can burner to supply the required heat to a double-coil arrangement through which the fuel ran from a supply trailer to the test combustor. This heater had fuel and combustion air measurements which were independent of those of the test preheater and combustor.

The 10- by 15-inch (25.4- by 38.1-cm) test section (fig. 2) contained three U-gutter flameholders (fig. 3). Fuel was injected from two rows of 0.064-inch (0.163-cm) holes, 30° on either side of the fuel tube horizontal centerline. All the combustion air, except for combustor liner film-cooling air, was brought through the burning zone. There was

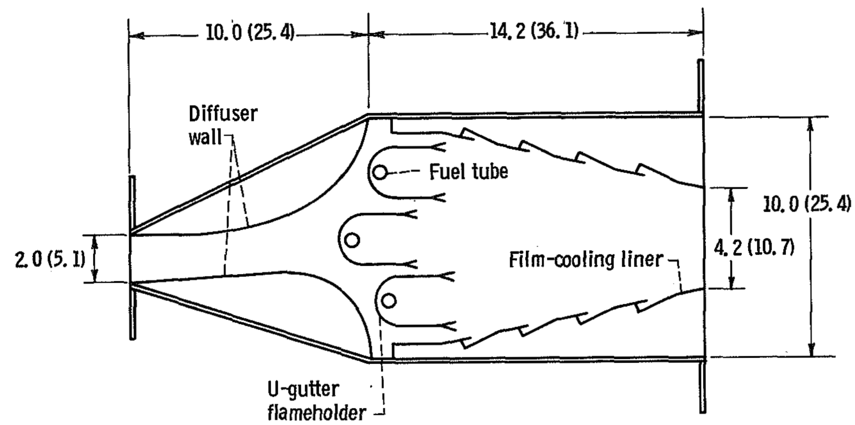

Figure 2. - Combustor installation in 10- by 15-inch (25.4- by 38.1-cm) rectangular test section. (Dimensions are in inches (cm).)

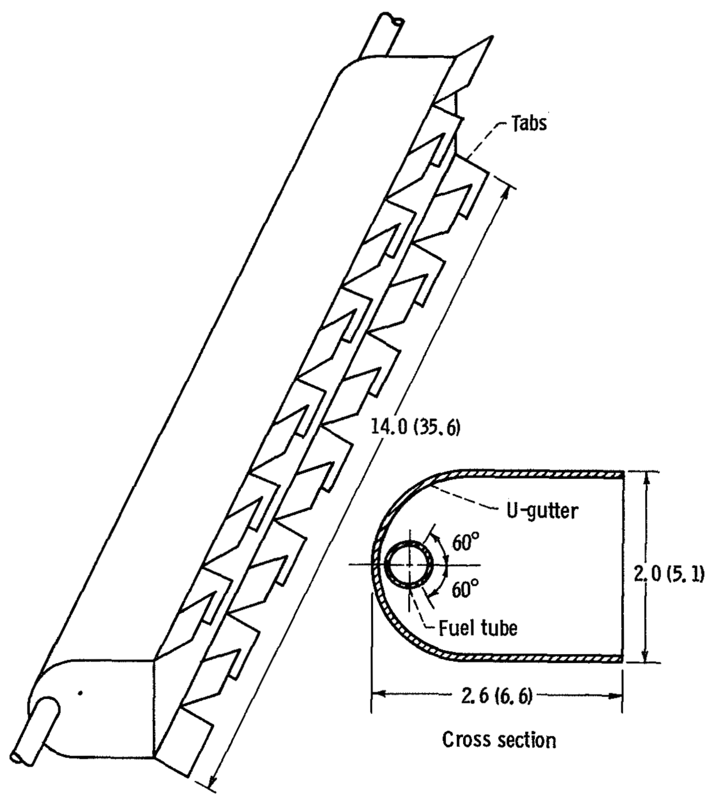

Figure 3. - U-gutter flameholder and fuel tube. (Dimensions are in inches (cm).)

no diluent air entering downstream of the primary zone, as would be found in conventional combustors.

FUEL COMPOSITION AND TEST CONDITIONS

The fuel was natural gas containing approximately 94 percent methane by volume. The composition of a typical sample of this natural gas is given in table I.

TABLE I. - COMPOSITION OF TYPICAL NATURAL GAS SAMPLE

Component	Volumetric percentage
Methane	94.2
Nitrogen	1.06
Helium	.042
Carbon dioxide	.93
Ethane	3.1
Propane	.43
Butane, Pentane	.34

The maximum fuel temperature of 1200° F (922 K) is typical of the compressor outlet temperature of a Mach 3 engine. In such an engine, compressor-discharge bleed air might be routed through a fuel-air heat exchanger and used for turbine-blade cooling, while heating the fuel to the desired temperature. The temperature limitation imposed by thermal cracking and the accompanying formation of deposits in the fuel system is also near 1200° F (922 K). For an arbitrary limit of 0.01 percent cracking in 10 seconds fuel residence time (ref. 2), methane can be heated to 1245° F (947 K).

The maximum fuel residence time was estimated to be 7 seconds; therefore, it was not unexpected that the fuel system showed no evidence of deposits. It must be noted, however, that low fuel pressures of the order of 10 to 13 psig (69 000 to 103 000 N/m^2) in the U-gutter fuel tubes were used. Decomposition at higher fuel system pressures and increased residence times requires further investigation.

INSTRUMENTATION

Airflow rates and natural gas fuel flow rates were measured by square-edged orifices installed in accordance with ASME specifications. ASTM A-1 fuel flow rates to the combustion air preheater and to the natural gas heater were measured by turbine flowmeters.

Locations of the combustor inlet and exit instrumentation planes are indicated in figure 4. The positions of the temperature and pressure probes in these planes are shown in

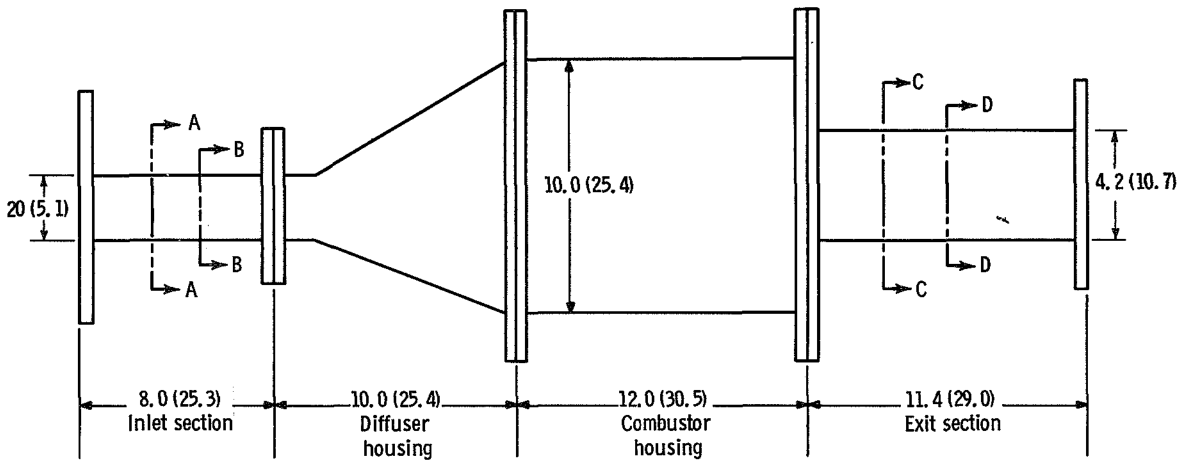

Figure 4. - Test section assembly and instrumentation. (Dimensions are in inches (cm).)

figure 5. Combustor inlet temperatures were measured by two iron-constantan thermocouples (section A-A, fig. 5). Inlet pressures were measured by seven three-point total-pressure rakes and by 10 wall static-pressure taps (section B-B, fig. 5). Combustor exit temperatures were measured by means of eight five-point total-temperature rakes (section C-C, fig. 5). The temperature probes were constructed of platinum/platinum-13-percent-rhodium wires, 0.020 inch (0.51 cm) in diameter, and were of the bare-wire wedge type. Exit pressures were measured by seven five-point total-pressure rakes and by two wall static-pressure taps (section D-D, fig. 5).

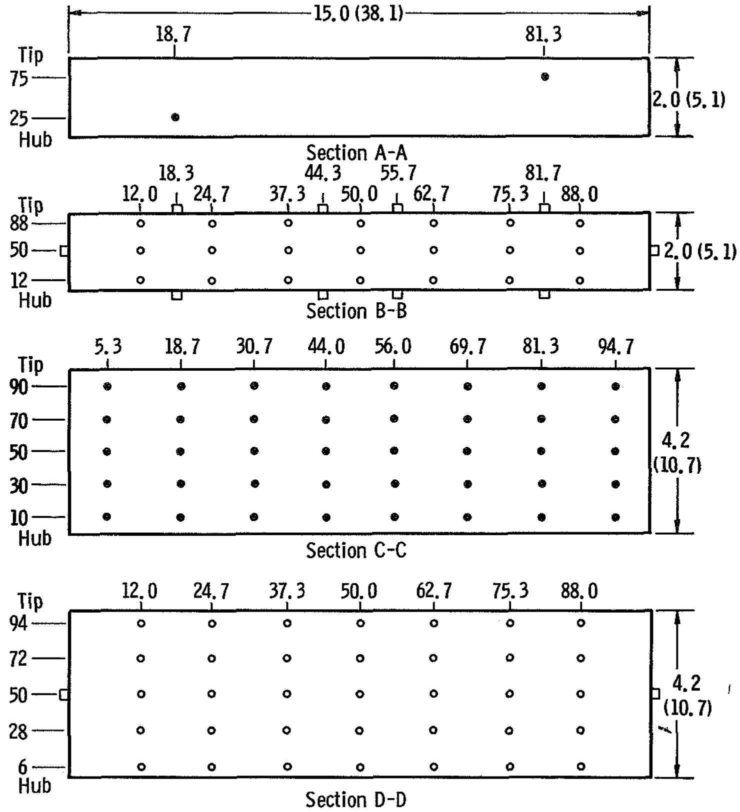

Figure 5. - Location of temperature and pressure probes in percentage of duct height and width. (Dimensions are in inches (cm). See fig. 4 for location of sections A-A to D-D.)

CALCULATIONS

Radiation Correction to Combustor Exit Temperature

The exit temperatures of the test combustor were measured by unshielded wedge-type platinum/platinum-13-percent-rhodium thermocouples. The walls of the combustor housing were cooled by a water spray, and were cool relative to the indicated thermocouple temperature. The thermocouple rakes were water-jacketed. Since the thermocouples radiate heat to these cold surfaces, a correction was made to the indicated temperatures:

$$\text{Radiation correction} = \frac{36\epsilon_w \sqrt{d}}{\sqrt{Mp}} \left(\frac{T_w}{1000}\right)^{3.82}$$

where

ϵ_w	emissivity of thermocouple wire
d	wire diameter, in.
T_w	measured wire temperature, ^oR
M	Mach number at thermocouple plane
p	pressure, atm

Values of radiation correction against T_w at several Mach numbers for the thermocouples used in this investigation are plotted in figure 6. The derivation of the radiation correction equation is given in appendix A.

The radiation correction is an estimate, affected by radiation form factors for the particular geometries involved, and by other factors. Since the combustor wall temperature was considered to be very low relative to the indicated thermocouple wire temperature, the calculated correction must be considered as a maximum correction. If the combustor wall temperature had an appreciable value, the radiation correction would be lower than the maximum value calculated.

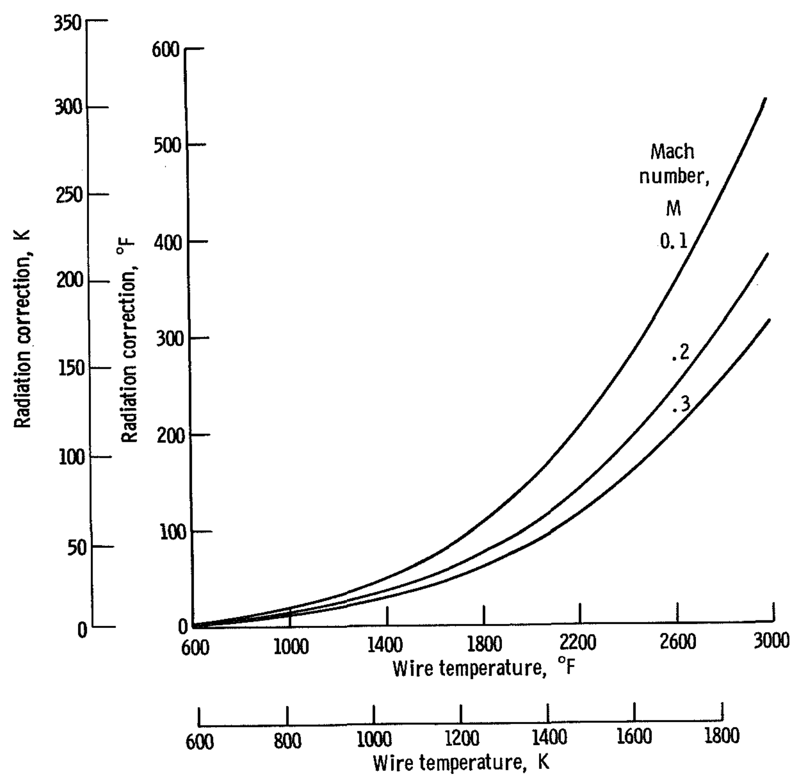

Figure 6. - Radiation correction as function of measured wire temperature at 1 atmosphere for various Mach numbers.

Combustion Efficiency Calculation

Combustion efficiency was defined as the ratio of the actual enthalpy rise through the test combustor to the theoretical enthalpy rise. The equation used, which recognizes the enthalpy contribution of the heated fuel and the vitiating effect of the combustion air preheater, is as follows:

$$\text{Combustion efficiency} = \frac{\left[\left(h_a\right)_{T_{ex}} - \left(h_a\right)_{T_{ph}}\right] + \left[f_{ph}\left(\frac{Am + B}{m + 1}\right)_{ph}\right]_{T_{ph}}^{T_{ex}} + \left[f_{ts}\left(\frac{Am + B}{m + 1}\right)_{ts}\right]_{T_r}^{T_{ex}}}{f_{ts}\left\{H_{lv,ts} + \left[h_{f,ts}\right]_{T_r}^{T_{f,ts}}\right\}}$$

The derivation of this equation and explanation of symbols is given in appendix B.

Combustor Reference Velocity Calculation

The combustor reference velocity is based on the combustor inlet conditions of static pressure, total temperature, and combustion air flow rate, and the maximum combustor cross-sectional area.

RESULTS AND DISCUSSION

The combustor inlet air temperature was held constant at 600° F (589 K), and the natural gas fuel temperature was varied from approximately 80° to 1200° F (300 to 922 K). The fuel-air ratio was held near to 0.020. Pressure was near atmospheric. Data were obtained at five reference velocities; 46, 71, 92, 100, and 107 feet per second (14.0, 21.6, 28.0, 30.5, and 32.6 m/sec). At a fixed reference velocity of 72 feet per second (21.9 m/sec), data were obtained over a range of fuel-air ratios from 0.0100 to 0.0297. Combustor performance data are presented in table II.

Effect of Natural Gas Temperature on Combustion Efficiency

Figure 7 shows the effect of natural gas temperature on combustion efficiency at the five reference velocities. It is evident that an increase in combustion efficiency is achieved through the use of heated fuel. The amount of the increase depends on the se-

TABLE II. - COMBUSTOR PERFORMANCE DATA

[Combustor pressure nominally atmospheric.]

Run	Inlet natural gas temperature		Inlet air temperature		Airflow		Nominal reference velocity		Fuel-air ratio	Average outlet temperature		Combustion efficiency, percent
	°F	K	°F	K	lb/sec	kg/sec	ft/sec	m/sec		°F	K	
1	70	294	620	600	1.81	0.82	46	14.0	0.0203	1777	1243	91.5
2	380	467	591	584					.0200	1791	1251	93.7
3	595	586	588	582					.0200	1799	1255	93.2
4	880	744	607	593					.0199	1860	1289	97.7
5	1200	922	600	589					.0200	1879	1299	98.3
6	90	306	615	597	2.98	1.35	71	21.6	.0196	1644	1169	81.3
7	580	578	613	596					.0195	1772	1240	90.8
8	900	756	606	592					.0195	1820	1267	94.3
9	1210	928	601	589					.0194	1851	1289	96.3
10	70	294	593	585	3.88	1.76	92	28.0	.0204	1327	993	53.7
11	580	578	589	583	3.93	1.78			.0204	1651	1173	78.3
12	900	756	593	585	3.93	1.78			.0201	1745	1225	84.9
13	1190	917	598	587	3.92	1.78			.0200	1894	1308	96.3
14	900	756	592	584	4.36	1.98	100	30.5	.0211	1734	1219	81.0
15	1205	925	596	587	4.42	2.01	100	30.5	.0210	1897	1309	92.3
16	910	761	601	589	4.83	2.19	107	32.6	.0209	1511	1095	64.3
17	1200	928	589	583	4.81	2.18	107	32.6	.0209	1763	1236	82.6
18	75	297	603	591	2.90	1.32	72	21.9	.0133	1114	874	54.4
19			602	590	2.93	1.33			.0140	1134	886	55.5
20			610	594	2.93	1.33			.0154	1241	945	60.3
21			587	582	2.91	1.32			.0189	1565	1125	78.3
22			588	582	2.92	1.33			.0216	1749	1227	83.8
23			603	591	2.92	1.33			.0246	1962	1346	89.4
24			576	576	2.95	1.34			.0271	2105	1425	92.4
25			570	572	2.95	1.34			.0297	2246	1503	94.8
26	990	806	605	592	2.91	1.32			.0100	1142	890	71.6
27	990	806	603	591	2.92	1.33			.0117	1282	968	78.2
28	990	806	607	593	2.87	1.30			.0131	1383	1024	80.3
29	980	800	601	589	2.92	1.33			.0138	1430	1050	81.2
30	1010	817	597	587	2.92	1.33			.0152	1541	1112	85.2
31	1010	817	599	588	2.91	1.32			.0186	1810	1261	91.2
32	1000	811	594	586	2.92	1.33			.0212	2036	1387	96.7
33	990	806	612	596	2.92	1.33			.0241	2234	1497	98.4

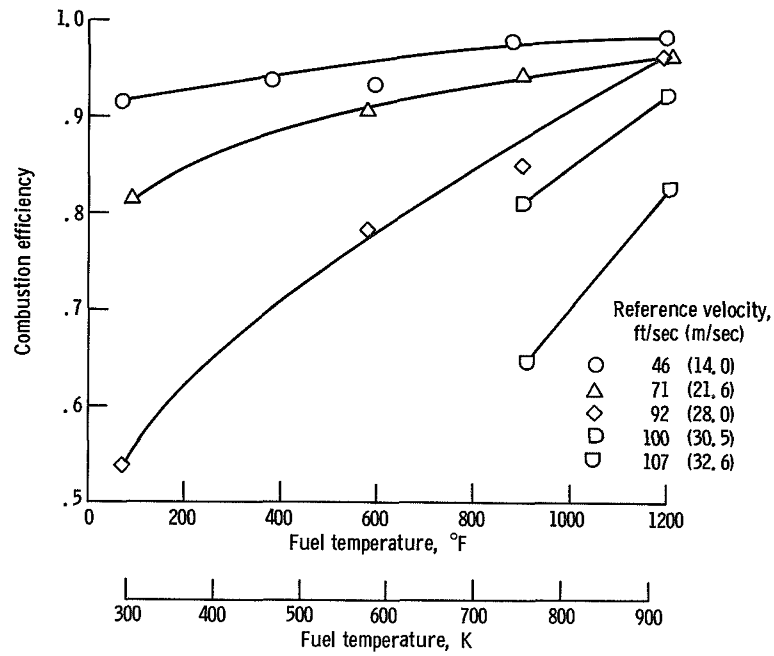

Figure 7. - Effect of fuel temperature on combustion efficiency for various reference velocities. Fuel-air ratio, 0.020; inlet air temperature, 600° F (589 K).

verity of the operating conditions. For example, at a reference velocity of 46 feet per second (14.0 m/sec), heating the methane fuel from 70° to 1200° F (294 to 922 K) increased combustion efficiency from 0.915 to 0.983, while this same increase of methane fuel temperature at a reference velocity of 92 feet per second (28.0 m/sec) increased combustion efficiency from 0.537 to 0.963. Thus, higher reference velocities could be used in this type combustor if advantage were taken of the improvement due to fuel heating.

The mechanism which brings about an improvement in combustion efficiency with heated fuel appears to be the ability of the heated fuel to stabilize combustion. Even with an over-stoichiometric fuel-air ratio within the flameholder, the mass flow rate of the fuel is so small relative to that of the combustion air that the mixture temperature is not significantly increased over the inlet temperature of the combustion air, except in a very localized area at the fuel-air mixing interface. It is evidently in this area that the additional heat input is effective in promoting stability. If the same heat input were added to the combustion air, the increase in combustion air temperature would be, at most, about 70° F (39 K). Such an increase in air temperature would be expected to have no appreciable effect on the combustion efficiency.

Heated fuel allowed stable operation at reference velocities of 100 and 107 feet per second (30.5 and 32.6 m/sec), conditions at which burning could not be maintained with low-temperature natural gas. For the case of 100-foot-per-second (30.5-m/sec) reference velocity, burning became unstable at a fuel temperature of approximately 600° F (589 K), and blowout occurred at fuel temperatures below 420° F (489 K); while at 1200° F (922 K), combustion efficiency was about 92.3 percent.

Effect of Reference Velocity on Combustion Efficiency

The data of figure 7 are crossplotted in figure 8 to show the effect of reference ve-

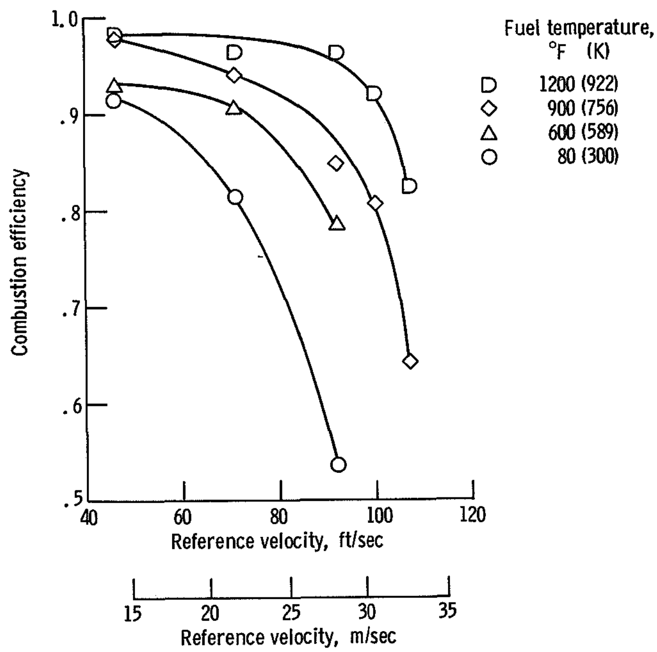

Figure 8. - Effect of reference velocity on combustion efficiency for various fuel temperatures. Fuel-air ratio, 0.020; inlet air temperature, 600° F (589 K).

locity on combustion efficiency at several fuel temperatures. Combustion efficiency decreases with increasing reference velocity at all fuel temperatures. However, for a given efficiency level, higher reference velocities can be obtained with heated fuel.

Reference 3 describes a detrimental effect of vitiated inlet air on the combustion efficiency of a natural-gas combustor. The loss of combustion efficiency because of vitiation increases with increasing combustor reference velocity and, at a low combustor reference velocity, with decreasing fuel-air ratio. The effect, if any, of vitiated inlet air on combustion efficiency in the present investigation could not be evaluated.

Effect of Fuel-Air Ratio on Combustion Efficiency

The effect of fuel-air ratio on combustion efficiency is shown in figure 9, with results at two fuel temperatures. The combustor inlet air temperature was 600° F (589 K), and inlet pressure was near atmospheric. Reference velocity was 72 feet per second (21.9 m/sec). Combustion efficiency was higher with heated natural gas over the entire range of fuel-air ratios. The minimum fuel-air ratio at which satisfactory combustion efficiency was achieved was lowered considerably when heated fuel was used.

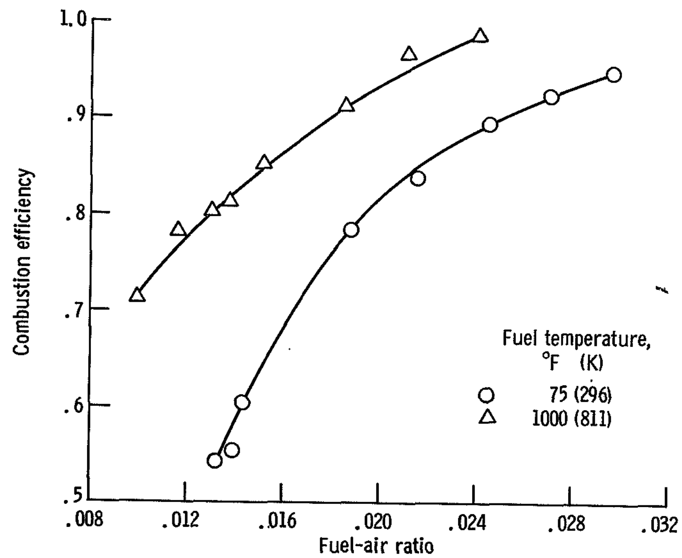

Figure 9. - Effect of fuel-air ratio on combustion efficiency at various fuel temperatures. Reference velocity, 72 feet per second (21.9 m/sec); inlet air temperature, 600° F (689 K).

SUMMARY OF RESULTS

Combustion efficiency was substantially improved by increasing the temperature of the natural gas fuel. The maximum value of reference velocity at which a given level of efficiency could be attained was increased. A high level of combustion efficiency was achieved at some reference velocities at which no burning was possible with unheated fuel. The minimum fuel-air ratio at which stable burning was possible was lowered by heating the fuel. The fuel system was free of deposits caused by thermal cracking.

These data were obtained with a single combustor and a single fuel injector design. The quantitative effects of fuel heating would be expected to be different for other combustor configurations; however, the performance trends with fuel heating should be similar. It appears probable that advantage can be taken of fuel heating to permit the use of simpler and smaller-size combustors.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 28, 1969,
126-15.

APPENDIX A

DERIVATION OF RADIATION CORRECTION EQUATION

Reference 4 gives the analytically determined radiation correction to the indicated thermocouple junction temperature as

$$\text{Radiation correction} = \frac{K^*_{rad}}{\sqrt{Mp}}\left(\frac{T_w}{1000}\right)^{-0.18}\left[\left(\frac{T_w}{1000}\right)^4 - \left(\frac{T_d}{1000}\right)^4\right]$$

where

K^*_{rad} radiation correction coefficient

M Mach number at thermocouple plane

p pressure, atm

T_w measured wire temperature, ^oR

T_d duct temperature, ^oR

This equation can be written as

$$\text{Radiation correction} = \frac{K^*_{rad}}{\sqrt{Mp}}\left(\frac{T_w}{1000}\right)^{3.82}\left[1 - \left(\frac{T_d}{T_w}\right)^4\right]$$

If it is assumed that $T_d << T_w$, the term $\left[1 - \left(T_d/T_w\right)^4\right]$ may be neglected.

Reference 4 gives $K^*_{rad} \approx 27\epsilon_w\sqrt{d}$ for a bare wire in crossflow, as shown in figure 2(d) of reference 4, where

ϵ_w emissivity of thermocouple wire

d wire diameter, in.

This expression was obtained analytically. For a 20-gage Chromel-Alumel thermocouple with emissivity of 0.7 to 0.8, K^*_{rad} has a theoretical value of 3.4 to 3.9. This value was checked experimentally in reference 4. The bare-wire-in-crossflow thermocouple was compared in a high-temperature tunnel with a sonic-aspirated probe which was virtually free from radiation errors. The experimental value of K^*_{rad} obtained for the bare-wire-in-crossflow thermocouple was 3.6±0.4, which was consistent with the theoretical value. Thus, the analytically determined expression for K^*_{rad} was considered valid. It was postulated that expressions for other probe designs would be similar in algebraic form. The experimentally determined value of K^*_{rad} for a 20-gage unshielded wedge Chromel-Alumel thermocouple, as shown in figure 2(e) of reference 4, was 4.8±0.4. This leads to the expression

$$K^*_{rad} \approx 36\epsilon_w\sqrt{d}$$

for the unshielded wedge thermocouple. Since it is postulated in reference 4 that the constant of proportionality in the radiation correction equation is a function of the geometry of the thermocouple, it is assumed that the expression for K^*_{rad} obtained for Chromel-Alumel thermocouples can be applied to the platinum/platinum-13-percent-rhodium thermocouples used in the present investigation. Then the radiation correction equation becomes

$$\text{Radiation correction} = \frac{36\epsilon_w\sqrt{d}}{\sqrt{Mp}}\left(\frac{T_w}{1000}\right)^{3.82}$$

APPENDIX B

DERIVATION OF COMBUSTION EFFICIENCY EQUATION

Combustion efficiency was defined as the ratio of the actual enthalpy rise through the test combustor to the theoretical rise. The actual enthalpy rise is calculated as described in detail in reference 5 and summarized as follows:

The first law of thermodynamics applied to ideal constant-pressure combustion for leaner-than-stoichiometric mixtures leads to

$$\Big[h_a\Big]_{T_r}^{T_a} - fh_c = \Big[(1 + f)h_b\Big]_{T_r}^{T_b}$$

where, for example, $\Big[h_a\Big]_{T_r}^{T_a}$ is used to mean "the value of h_a at T_a minus the value of h_a at T_r," and T_r is a reference temperature taken as 540° R, and where

h_a enthalpy of air, Btu/lb

T_a total air temperature, °R

f fuel-air ratio

h_c lower enthalpy of combustion, Btu/lb

h_b enthalpy of leaner-than-stoichiometric burned mixture of fuel and air, Btu/lb

T_b total temperature of burned mixture, °R

The lower enthalpy of combustion of a fuel at constant pressure h_c is defined as the heat $-h_c$ removed during the combustion at constant pressure of a mixture of fuel and oxygen when the initial and final temperatures are equal and the products of combustion are in the gaseous phase. The fuel is assumed to enter the system at 540° R.

For leaner-than-stoichiometric mixtures, the term $(1 + f)h_b$ is given by

$$(1 + f)h_b = h_a + f\,\frac{Am + B}{m + 1}$$

where

$$A = \frac{H_{H_2O} - \frac{1}{2}H_{O_2}}{2.016}$$

$$B = \frac{H_{CO_2} - H_{O_2}}{12.010}$$

and where

H molal enthalpy, Btu/lb-mole

m hydrogen-carbon ratio of fuel, lb/lb

The term (Am + B)/(m + 1) accounts for the difference between the enthalpy of the carbon dioxide and water vapor in the burned mixture and the enthalpy of the oxygen removed from the air by their formation.

For combustion in the vitiating preheater, the enthalpy balance is

$$\Big[h_a\Big]_{T_r}^{T_{in}} + \Big[f_{ph}h_{f,ph}\Big]_{T_r}^{T_{f,ph}} + f_{ph}H_{lv,ph} = \left[h_a + f_{ph}\left(\frac{Am + B}{m + 1}\right)_{ph}\right]_{T_r}^{T_{ph}}$$

where

T_{ph} preheater outlet total temperature, ^{o}R

$T_{f,ph}$ fuel temperature entering preheater, ^{o}R

T_{in} air total temperature entering preheater, ^{o}R

$h_{f,ph}$ enthalpy of fuel entering preheater, Btu/lb

f_{ph} preheater fuel-air ratio

$H_{lv,ph}$ lower heating value of preheater fuel at T_r, Btu/lb

For the test section combustion, the enthalpy balance is

$$\left[h_a + f_{ph}\left(\frac{Am + B}{m + 1}\right)_{ph}\right]_{T_r}^{T_{ph}} + \Big[f_{ts}h_{f,ts}\Big]_{T_r}^{T_{f,ts}} + f_{ts}H_{lv,ts}$$

$$= \left[h_a + f_{ph}\left(\frac{Am + B}{m + 1}\right)_{ph} + f_{ts}\left(\frac{Am + B}{m + 1}\right)_{ts}\right]_{T_r}^{T_{ex}}$$

where

T_{ex}	test section exit total temperature, ^{o}R
$T_{f,ts}$	fuel temperature entering test section, ^{o}R
$H_{lv,ts}$	lower heating value of test section fuel at T_r, Btu/lb
$h_{f,ts}$	enthalpy of fuel entering test section, Btu/lb
f_{ts}	test section fuel-air ratio

Then, if the enthalpy leaving the preheater is subtracted from the enthalpy leaving the test section, the actual enthalpy rise across the combustor is obtained

$$\Delta h_{act} = \left[\left(h_a\right)_{T_{ex}} - \left(h_a\right)_{T_{ph}}\right] + \left[f_{ph}\left(\frac{Am + B}{m + 1}\right)_{ph}\right]_{T_{ph}}^{T_{ex}} + \left[f_{ts}\left(\frac{Am + B}{m + 1}\right)_{ts}\right]_{T_r}^{T_{ex}}$$

The ideal enthalpy rise across the combustor is

$$\Delta h_{id} = f_{ts}\left\{H_{lv,ts} + \left[h_{f,ts}\right]_{T_r}^{T_{f,ts}}\right\}$$

Then, the combustion efficiency equation, considering both vitiation in the preheater and fuel entering the test section at a temperature other than T_r, is

$$\text{Combustion efficiency} = \frac{\left[\left(h_a\right)_{T_{ex}} - \left(h_a\right)_{T_{ph}}\right] + \left[f_{ph}\left(\frac{Am + B}{m + 1}\right)_{ph}\right]_{T_{ph}}^{T_{ex}} + \left[f_{ts}\left(\frac{Am + B}{m + 1}\right)_{ts}\right]_{T_r}^{T_{ex}}}{f_{ts}\left\{H_{lv,ts} + \left[h_{f,ts}\right]_{T_r}^{T_{f,ts}}\right\}}$$

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