Parametric Study of Flame Radiation Characteristics of a Tubular-Can Combustor

Francis M. Humenik, Russell W. Claus, and Geralyn M. Neely
Lewis Research Center
Cleveland, Ohio

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Francis M. Humenik
Russell W. Claus
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Geralyn M. Neely
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

A series of combustor tests were conducted with a tubular-can combustor to study flame radiation characteristics and effects with parametric variations in combustor operating conditions. Two alternate combustor assemblies using a different fuel nozzle were compared. Spectral and total radiation detectors were positioned at three stations along the length of the combustor can. Data were obtained for a range of pressures from 0.34 to 2.07 MPa (50 to 300 psia), inlet temperatures from 533 to 700K (500 to 800°F), for Jet A (13.9% hydrogen) and ENBS (12.9% hydrogen) fuels, and with fuel-air ratios nominally from 0.008 to 0.021. Spectral radiation data, total radiant heat flux data, and liner temperature data are presented to illustrate the flame radiation characteristics and effects in the primary, secondary, and tertiary combustion zones.

INTRODUCTION

Recent combustion experiments have emphasized the use of flame radiation measurements to determine effects of fuel quality variations on combustor emissions, flame temperature, and heat transfer characteristics (refs. 1, 2, 3). From analysis of the spectral flame radiation data, calculations of the flame temperature and soot concentration in each combustion zone yield some explanations for the effects observed (refs. 1, 4, 5). From analysis of total radiant heat flux data, some correlations with combustor liner temperatures have been demonstrated (ref. 2). Thus, combustor flame radiation measurements provide fundamental data that can be used to improve combustor inner thermal analysis and may help establish an analytical heat transfer model. These analytical efforts may yield improved liner durability in future designs by prescribing optimum adjustments to cooling airflow distribution. Also, liner development costs may be reduced by minimizing design iterations.

In order to expand the fundamental flame radiation data base, the series of combustor tests initiated with reference 1 were continued in order to provide a more complete mapping and parametric investigation of combustor operating variables on flame radiation. Three window-stations and three transducer-stations along the length of the combustor housing assembly provided access for spectral and total radiation sensors respectively. Thus, the flame radiation characteristics and effects in the three combustion zones could be compared.

The primary purpose of this report is to present an overall general description of the variation in spectral and total flame radiation characteristics in each combustion zone with variations in combustor operating conditions, reduction in fuel hydrogen content, and choice of fuel nozzle.

Data were obtained for a range of pressures from 0.34 to 2.07 MPa (50 to 300 psia), inlet temperatures from 533 to 700K (500 to 800°F) and for Jet A (13.9% hydrogen) and a research test fuel, ENBS (12.9% hydrogen, ref. 6). A single spectral radiance sensing system and three total radiance heat flux transducers provided measurements at the three locations along the length of the combustor can. Data from these sensors along with selected liner thermocouple data are presented to illustrate the flame radiation characteristics and effects in the primary, secondary, and tertiary combustion zones.

APPARATUS AND PROCEDURE

The flame radiation experiments were conducted with a single JT8D tubular combustor installed in a standard pipe section (25.4 cm, 10 inch, nominal diameter) modified to be a test housing assembly as shown in the schematic illustration of figure 1. Combustor inlet instrumentation consisted of two inlet static pressures and a five point inlet thermocouple rake (Chromel-Alumel) located in the inlet plenum section. The com-
bustor exit instrumentation (see figure 1) consisted of a set of eight-five point thermocouple racks (platinum - 13 percent rhodium/ platinum) for monitoring the exit temperature pattern and a set of four gas sample probes for routine exhaust gas analysis. Liner metal temperatures were measured with 24 thermocouples (Chromel-Alumel) of which 4 were located on the dome and the others divided along opposite sides of the combustor can to give 2 separate thermocouples on the outside of each cooling louver.

The flame radiation instrumentation consisted of three separate radiant heat flux transducers installed for continuous measurements at three stations along the combustor housing and a single spectral radiation detector unit positioned in line with one of the three window ports as illustrated in figure 2. The three radiant heat flux transducers were a Garden-type gauge that senses the radial transfer of heat to a sink by use of a differential thermoelectric circuit. Each transducer was water-cooled and required a continuous nitrogen purge to sweep the sensor tip. The stem of the transducer extended to the inner surface of the combustor liner through an existing air entry hole or a specially added clearance hole. The measurement locations nominally corresponded to primary (#1), secondary (#2), and tertiary (#3) combustion zones. Thus, a reading of total radiant heat flux in each combustion zone was obtained with each spectral scan of the flame radiation at a selected window port.

The spectral radiation system components included an optical sensing head unit, a programmable controller, and a printer as shown in figure 3. The sensing head consists of an optical radiation telescope system, a variable spectral filter system, and an indium antimonide radiation detector which required high pressure gaseous nitrogen for cooling. The programmable controller provided a choice of step-scanning cycle for sensing at the desired wavelength increments. Further details and description of the spectral radiometer apparatus are given in reference 1. The location of the window ports for spectral measurements and the location of the three total radiant heat flux transducers are included with the photographs of the JTBD tubular can combustor in figure 4.

The arrangement of the apparatus in the test facility is shown in the photograph of figure 5. The exit instrumentation racks and gas sample probes are on the left. The flow direction is right to left. The spectral viewing ports contained sapphire windows whose transmittance bandwidth and high temperature capability are suited to this application. For safety reasons, local focusing of the spectral detector optics and optimizing the output signal was conducted only at low pressure (0.34 MPa, 50 psia). Spectral data scanning and recording was initiated from an adjacent control room.

Two candidate fuel nozzles, FNH1 and FNH2, were selected for comparison in this test program. FNH1 was a standard type fuel nozzle for a conventional JTBD assembly configuration; FNH2 was a commercial substitute offered for experimental comparison. Both fuel nozzles, FNH1 and FNH2, were the dual orifice pressure atomizing type. From flow calibration with each fuel nozzle, FNH2 produced a higher flow rate than FNH1 (by about 10-15%) at representative primary and secondary test pressures but no other significant differences were apparent. Testing was initiated with fuel nozzle FNH1 to obtain a representative set of data; then with fuel nozzle FNH2, a more complete data set was obtained which included data with both Jet A (13.9% hydrogen) and ERBS (12.9% hydrogen) fuels.

Figure 1. - Schematic of tubular combustor installation. Nominal flow capabilities of test facility: inlet pressure, 25 atm; inlet air temperature, 870 K; inlet airflow rate, 10 kg/sec.
Figure 2. Assembly of tubular combustor for flame radiation studies.

Figure 3. Spectral radiometer system components: programmable controller with printer, and sensing head.
RADIANT HEAT FLUX

<table>
<thead>
<tr>
<th>ZONE</th>
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<th>( \theta ), LOC.</th>
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<td></td>
<td>cm</td>
<td>in.</td>
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<tr>
<td>1</td>
<td>12.7</td>
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<tr>
<td>2</td>
<td>18.5</td>
<td>7.3</td>
</tr>
<tr>
<td>3</td>
<td>28.7</td>
<td>11.3</td>
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SPECTRAL RADIANCE

<table>
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<td>7.4</td>
<td>2.9</td>
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<tr>
<td>2</td>
<td>22.1</td>
<td>8.7</td>
</tr>
<tr>
<td>3</td>
<td>34.0</td>
<td>13.4</td>
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Figure 4. - Photographs of tubular-can combustor with flame radiation zone locations.

Figure 5. - Photograph of JT8D combustor housing assembly during experiments. Installation of radiant heat flux transducers, location of window-stations and spectral radiometer sensing head are shown.
Test conditions (see Table 1) were selected to cover the normal range of combustor operation while maintaining a constant mass flow parameter for the parametric variations. Test conditions include combustor pressures of 0.34 MPa (50 psia), 0.69 MPa (100 psia), 1.38 MPa (200 psia), and 2.07 MPa (300 psia); combustor inlet temperatures of 533K (500°F), 616K (650°F) and 700K (800°F); with fuel-air ratios nominally from 0.008 to 0.021.

Test fuels (see Table II) included the conventional Jet A and the experimental ERBS fuel (ref. 6). Many recent combustion experiments have included tests with ERBS fuel because it is representative of a possible future fuel that has potential for use if another fuel crisis occurs or fuel supplies are disrupted. The data obtained with this fuel indicate combustion performance trends with reductions in fuel hydrogen content.

Measurement of airflow rates were obtained from a conventional ASME orifice station; measurement of fuel flow rates were obtained from conventional turbine type flowmeters. The NASA Lewis ESCORT automatic data acquisition system provided on-line instantaneous monitoring of data with formal data recording and batch processing using the laboratory IBM 370/3033 system.

**TABLE I. - TEST CONDITIONS**

<table>
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<tr>
<th>Combustor pressure</th>
<th>Combustor inlet temperature</th>
<th>Airflow rate</th>
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<tr>
<td>MPa</td>
<td>psia</td>
<td>K</td>
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<tr>
<td>0.34</td>
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<td>533</td>
</tr>
<tr>
<td>0.69</td>
<td>100</td>
<td>616</td>
</tr>
<tr>
<td>1.38</td>
<td>200</td>
<td>700</td>
</tr>
<tr>
<td>2.07</td>
<td>300</td>
<td>800</td>
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**TABLE II. - FUEL CHARACTERISTICS**

<table>
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<tr>
<th>Specifications</th>
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<th>ERBS</th>
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<tr>
<td>Initial boiling point</td>
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<td>10 percent evaporated</td>
<td>451</td>
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<td>50 percent evaporated</td>
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<td>488</td>
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<td>90 percent evaporated</td>
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<td>Freezing point, K</td>
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<td>Net heat of combustion, J/g</td>
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<td>52,000</td>
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<td>Hydrogen, percent by weight</td>
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<td>12.9</td>
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<tr>
<td>Aromatics, percent by volume</td>
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<tr>
<td>Sulfur (total), percent by weight</td>
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<td>0.065</td>
</tr>
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</table>

**RESULTS AND DISCUSSION**

Fundamental flame radiation data were obtained with an experimental tubular combustor configuration to determine variations in flame radiation characteristics for a range of parametric test conditions. Data are presented in figures 6 to 9 to illustrate some fundamental flame radiation characteristics which are useful for comparing performance trends, examining correlations, and explaining variations in each combustion zone. Specific results discussed are as follows:

1. comparison of two candidate fuel nozzles, figure 6;
2. spectral flame radiation variation, figure 7;
3. total radiant heat flux variation, figure 8;
4. comparison of radiant heat flux with liner temperature, figure 9.

**Comparison of Fuel Nozzles**

The variations in radiant heat flux distributions with variations in fuel-air ratio produced by fuel nozzles FN1 and FN2 with Jet A fuel are shown in figure 6. These data are grouped to compare the results in each combustor zone at the low combustor pressure of 0.69 MPa (100 psia) with the high combustor pressure of 2.07 MPa (300 psia). In general, significantly different rates of radiant heat flux variations are apparent in each zone along with an overall increase in radiant heat flux levels with combustor pressure increase.

The specific characteristics for combustion zone #1 (primary, see figure 6(a) and (b) only) show that FN2 produced higher radiant heat flux than FN1 at both the low and high combustor pressure levels for fuel-air ratios from 0.012 and greater. Since soot is a major contributor to total flame radiation, increased levels of radiant heat flux are usually an indicator of higher soot concentrations. However, other data (higher local liner temperatures and higher exhaust NOX levels) indicate that primary zone flame temperatures may also have been higher with FN2. For instance, at the low pressure condition with f/a = 0.018, local liner temperatures were 50K (89°F) higher in this zone with FN2 whereas at the high pressure condition with f/a = 0.016, local liner temperatures were 34K (60°F) higher with FN2. Similarly, exhaust NOX levels were 12 ppm higher (82 ppm vs 94 ppm) at the low pressure condition (f/a = 0.018) with FN2 and 45 ppm higher (186 ppm vs 211 ppm) at the high pressure condition (f/a = 0.016) with FN2. These data are indicators that FN2 produced higher flame temperatures resulting in substantially increased NOX levels and higher local liner temperatures. Thus, a combination of higher flame temperatures and increased soot concentration may have produced the higher radiant heat flux in this zone with FN2.

The characteristics in combustion zone #2 (secondary, see figure 6(c) and (d) only) show rapidly changing combustion reaction conditions occurring in this zone with increase in fuel-air ratio. With FN2, there was a very steep increase in radiant heat flux at the high combustor pressure condition ranging from 16 W/cm² (f/a = 0.0089) to a peak of 80 W/cm² (f/a = 0.0159). With FN1, the peak radiant heat flux level was 77 W/cm² (f/a = 0.0130). Thus, at the high pres-
sure condition, relatively high radiant heat flux levels are evident in the secondary zone with either fuel nozzle.

The characteristics in combustion zone #3 (tertiary, see figure 6 (e) and (f) only), show that FN1 yields higher radiant heat flux than FN2 at both low and high combustor pressure levels. In this zone, combustor temperatures have been reduced, combustion reactions are completed, and therefore, the radiant heat flux levels are attributed solely to soot concentration. Thus, with the substantial difference in radiant heat flux levels between the two fuel nozzles, it is evident that FN1 results in higher exhaust smoke levels than FN2. Since FN2 produced much higher exhaust NOx levels, a trade-off between exhaust smoke and exhaust NOx was obtained by the choice of fuel nozzle alone.

In summary, the substitute experimental fuel nozzle, FN2, produced a significant re-distribution of total radiant heat flux between combustion zones. It is also apparent that radiant heat flux levels in each zone increased with increase in combustor pressure. Finally, the combustor assembly with FN2 produced less exhaust smoke than FN1, but higher exhaust NOx levels. The combustor assembly with FN2 was utilized for all subsequent testing.

Spectral Flame Radiance Variation

The variations in spectral flame radiance for nominal fuel/air ratios of 0.016 obtained with fuel nozzle FN2, and with Jet A and ERBS fuels are shown in figure 7. Data at 0.34 MPA (50 psia) and 0.69 MPA (100 psia) are presented in order to focus on the comparison of differences between the two fuels. Data at higher pressures up to 2.7 MPA (300 psia) were also obtained but did not reveal any significant fuel differences.

In combustion zone #1 (primary, see fig. 7(a) and (b)), spectral flame radiance levels at a nominal reference wavelength near 1.5 µm and combustor pressure of 0.34 MPA (50 psia) was about 1.3 W/cm² sr µm with Jet A fuel and increased to about 2.7 W/cm² sr µm with ERBS fuel. With combustor pressure of 0.69 MPA (100 psia), spectral flame radiance levels increased substantially to 4.2 W/cm² sr µm with Jet A fuel and to 4.5 W/cm² sr µm with ERBS fuel. The peaks at about 4.5 µm wavelength are due to CO₂ band radiation and are an indicator of flame temperature (ref. 1). Comparing the peaks indicates only slightly reduced flame temperature with combustor pressure increase but substantial flame radiance increase which is attributed to substantial increase in soot concentration. The increase in flame radiance with ERBS fuel (12.9% hydrogen) was most evident at the lower combustor pressure and tends to be less distinct at high combustor pressures.

In combustion zone #2 (secondary, see figure 7(c) and (d)), spectral flame radiance levels at 1.5 µm wavelength and combustor pressure of 0.3 MPA (50 psia) was about 1.2 W/cm² sr µm with Jet A fuel and increased to about 2.4 W/cm² sr µm with ERBS fuel. With combustor pressure of 0.69 MPA (100 psia), spectral flame radiance levels increased substantially to about 5.7 W/cm² sr µm with both Jet A and ERBS fuels. The similarity in CO₂ band radiance peaks at 4.5 µm wavelength indicates very little difference in flame temperature at both combustor pressures and with either fuel. Thus, only a small increase in soot concentration was evident at the lower combustor pressure with the ERBS fuel. The peaks at 2.7 µm wavelength are the contribution to the flame radiance due to water vapor which is most evident at low combustor pressure.

In combustion zone #3 (tertiary, see figure 7(e) and (f)), spectral flame radiance levels were generally below 0.6 W/cm² sr µm with both combustor pressures and with both fuels. The CO₂ band radiance peaks are very similar and indicate the lowering of combustor temperature in this zone. It thus appears that soot concentration levels are practically identical with either fuel and greatly reduced compared to zones #1 and #2. Thus, despite higher soot levels produced in the primary zone with ERBS fuel, the additional soot was burned up before it reached the combustor exit. This indicates that with either fuel there was no discernible difference in exhaust smoke levels.

Total Radiant Heat Flux Variation

The variations in total radiant heat flux with increase in combustor pressure for each combustion zone are shown in figure 8. These data were obtained with FN2 for a nominal fuel-air ratio of 0.016, inlet temperatures of 533K (500°F) and 615K (650°F), with Jet A and ERBS fuels. There is a fast rate of increase in radiant heat flux in combustion zones #1 and #2 at the low combustor pressure levels and a slow rate of increase in radiant heat flux at the high combustor pressure levels. This generally corresponds to the expected increase in flame emissivity with increase in combustor pressure. Combustor zones #1 (primary) and #2 (secondary) produced very similar levels of radiant heat flux ranging from about 16 W/cm² at low combustor pressures to about 78 W/cm² at a combustor pressure of 2.07 MPA (300 psia) with Jet A fuel (see figure 8(a)); whereas, combustor zone #3 (tertiary) was much lower and ranged only from about 7 to 29 W/cm² for this range of test conditions. There was a small increase of up to 10 W/cm² in radiant heat flux intensity in each zone with ERBS fuel compared to Jet A fuel. The effect of increasing the combustor inlet temperature by 22K (128°F) did not produce a notable variation in the intensity of the radiant heat flux (see figure 8 (a) and (b)).

Comparison of Radiant Heat Flux with Linner Temperatures

The total radiant heat flux data in each combustion zone for two combustor pressures of 0.69 MPA (100 psia) and 2.07 MPA (300 psia); nominal fuel-air ratio of 0.016; for Jet A and ERBS fuels are shown in figure 9(a) for an inlet temperature of 533K (500°F) and in figure 9(b) for an inlet temperature of 700K (800°F). The corresponding local liner temperature data are shown in figure 9(c) and (d) respectively. These data illustrate that although the radiant heat flux increased as expected with combustor pressure increase, the liner temperatures for a combustor pressure of 2.07 MPA (300 psia) were substantially lower than those for a combustor pressure of 0.69 MPA (100 psia). This is attributed to a large increase in convective cooling at high pressures sufficient to offset the increased flame radiation and still reduce liner temperatures. There was also an increase in radiant heat flux and liner temperatures...
with the increase in combustor inlet temperature from 533K (500°F) to 700K (800°F). This is an indicator that flame temperatures increased proportionately and that the film cooling effectiveness is also reduced with the higher inlet temperature condition. The ERBS fuel data consistently indicated an additional increase in radiant heat flux and liner temperatures in each combustion zone compared to the Jet A fuel data. A large increase of 33K (59°F) in local liner temperature with the ERBS fuel was especially evident in combustion zone 2 with combustor pressure of 0.69 MPa (100 psia) and combustor inlet temperature of 533K (500°F). The highest radiant heat flux occurred in combustion zone 1 (primary) with a combustor pressure of 2.07 MPa (300 psia) and combustor inlet temperature of 700K (800°F); whereas, the highest differential liner temperatures also occurred in combustion zone 1 but at the lower combustor pressure of 0.69 MPa (100 psia) with combustor inlet temperature of 700K (800°F).

SUMMARY OF RESULTS

Spectral flame radiance characteristics and total radiant heat flux measurements were obtained with a tubular can combustor for a range of pressures from 0.34 to 2.07 MPa (50 to 300 psia), inlet air temperatures from 533 to 700K (500 to 800°F), and for Jet A and ERBS (12.9% hydrogen) fuels.

A comparison of two fuel nozzles over a range of fuel-air ratios from 0.0087 to 0.0222 was illustrated with Jet A fuel. A substitute experimental fuel nozzle produced a redistribution of total radiant heat flux between combustion zones, substantially higher total radiant heat flux levels in the primary zone, a steep increase in secondary zone heat flux from 16 W/cm² (f/a = 0.0089) to a peak of 80 W/cm² (f/a = 0.0159) with a combustor pressure of 2.07 MPa (300 psia), and lower total radiant heat flux levels in the tertiary zone.

The other significant flame radiation characteristics and effects for the tubular-can combustor with the substitute fuel nozzle are as follows:

1. For a fuel-air ratio of 0.016, and inlet air temperature of 533K (500°F), the spectral flame radiance (nominal wavelength near 1.5 μm) substantially increased from a level of about 1.3 to 4.2 W/cm² μm in the primary zone, from 1.2 to 5.7 W/cm² μm in the secondary zone, and from 0.15 to 0.6 W/cm² μm in the tertiary zone with a combustor pressure increase from 0.34 MPa (50 psia) to 0.69 MPa (100 psia) using Jet A fuel.

2. For a fuel-air ratio of 0.016, and inlet air temperature of 533K (500°F), the total radiant heat flux substantially increased from a level of about 16 W/cm² to 66 W/cm² in the primary zone, from 16 to 78 W/cm² in the secondary zone, and from 7 to 29 W/cm² in the tertiary zone with a combustor pressure increase from 0.34 MPa (50 psia) to 2.07 MPa (300 psia) using Jet A fuel.

3. A comparison of total radiant heat flux variation and differential local liner temperature variation by combustion zone for a fuel-air ratio of 0.016 revealed that with a combustor inlet air temperature of 700K (800°F), the highest radiant heat flux occurs in the primary zone with a combustor pressure of 2.07 MPa (300 psia); whereas, the highest differential liner temperatures occur with a combustor pressure of 0.69 MPa (100 psia), and also in the primary zone.

4. There was an increase in local liner temperatures with ERBS fuel which ranged up to 33K (59°F) higher than those obtained with Jet A fuel in combustion zone 2 at low power conditions of 0.69 MPa (100 psia), 533K (500°F), f/a = 0.016.

CONCLUDING REMARKS

Flame radiation data are a necessary input to the fundamental data base required for advanced liner thermal analysis and to establish an analytical heat transfer model. The data which have been presented indicate the general flame radiation characteristics and effects produced with variations in operating conditions and choice of fuel nozzles. More detailed heat transfer analysis and other auxiliary calculations using the data from this test program are continuing and undergoing evaluation. The preliminary interpretations of this data are based on the previous experiments which are referenced as applied to this data set.

ACKNOWLEDGEMENTS

This series of tubular-can combustor tests required the support of several individuals and organizational elements at the NASA Lewis Research Center. The authors wish to express their appreciation to the following groups and individuals: Computer Services Division; Test Installations Division; and, in particular, Robert C. Ehlers, Thomas F. Nietsgo, and Osvaldo Rivera, members of the Research Experiments Branch, who were responsible for test operations.

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**Figure 6.** Comparison of standard (FN-1) and substitute (FN-2) fuel nozzles: variation in total radiant heat flux with variation in fuel-air ratio; Jet A fuel; inlet air temperature, 533 K (900°F).

- (a) Zone #1 (primary); combustor pressure, 0.65 MPa (100 psia).
- (b) Zone #1 (primary); combustor pressure, 2.07 MPa (300 psia).
- (c) Zone #2 (secondary); combustor pressure, 0.65 MPa (100 psia).
- (d) Zone #2 (secondary); combustor pressure, 2.07 MPa (300 psia).
- (e) Zone #3 (tertiary); combustor pressure, 0.65 MPa (100 psia).
- (f) Zone #3 (tertiary); combustor pressure, 2.07 MPa (300 psia).

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**ORIGINAL PAGE IS OF POOR QUALITY**
Figure 7. - Variation in spectral flame radiance with spectral wavelength; fuel air ratio, 0.016; Jet A and ERBS fuels; inlet air temperature, 533 K (950°F); fuel nozzle, PN #2.

(a) Zone #1 (primary); combustor pressure, 0.34 MPa (50 psia).
(b) Zone #1 (primary); combustor pressure, 0.69 MPa (100 psia).
(c) Zone #1 (secondary); combustor pressure, 0.34 MPa (50 psia).
(d) Zone #2 (secondary); combustor pressure, 0.69 MPa (100 psia).

Figure 7. - Continued.
Figure 7. - Concluded.

(e) Zone 4 (tertiary); combustor pressure, 0.34 MPa (50 psia).
(f) Zone 3 (tertiary); combustor pressure, 0.69 MPa (100 psia).

Figure 8. - Variation in total radiant heat flux by combustion zone with increase in combustor pressure; fuel-air ratio, 0.016; Jet A and ERBS fuels; fuel nozzle, FN #2.

(a) Inlet air temperature, 533 K (900°F).
(b) Inlet air temperature, 616 K (1100°F).
Figure 9. - Comparison of radiant heat flux variation and liner temperature variation by combustion zone; fuel-air ratio, 0.016; Jet A and ERBS fuels; combustor pressures, 0.69 MPa (100 psia) and 2.07 MPa (300 psia); fuel nozzle, FN #2.