Experimental Examination of a Prevaporized Premixed Combustor

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An experimental prevaporizing/premixing combustor configuration was examined. Evaluation of the combustor configuration was accomplished by extracting gas samples at discrete locations from within the combustor and analyzing them for unburned hydrocarbons, CO, CO_2, and O_2. These data were used to calculate local combustion efficiency and temperature. Contour plots were developed to interpret the gaseous flowfield. Results indicate two distinct regions of combustion: one in the recirculation zone providing constant ignition of incoming air/fuel mixture, and another where vitiated air impinges on the burning air/fuel mixture downstream of the ignition source.

Introduction

THE experimental combustor geometry used in this investigation is identified as a shrouded tube and disk configuration. This configuration represents a compromise between the disk-in-duct configuration studied by Tuttle.[1] for the U. S. Environmental Protection Administration (EPA), the dump ramjet burner of Stull et al.,[2] and the prevaporizing/premixing fuel feed tube type of turbojet.

Flame stabilization is accomplished by a continuous ignition source of hot recirculating gases. The recirculation zone is established by the sudden area expansion.

The primary function of the tube and disk configuration is to allow control of the fuel/air equivalence ratio entering the combustion zone; however, influence on combustion appears to be the fuel preparation, i.e., fuel vaporization and mixing. A fuel such as propane flash-vaporizes under most conditions, but fuels such as jet-A require a finite time to vaporize.

Two fuels were selected for examination in this study: propane and jet-A. Propane was selected for its flash-vaporization characteristics at the temperature and pressure of this investigation. The examination of propane combustion is a study of near-homogeneous inlet condition. Jet-A represents a typical aviation fuel.

Experimental Apparatus and Results

The facility used in this investigation is one for the study of combustion processes similar to those found in actual gas turbine combustors. Air used for experimentation was heated by an indirect fired air preheater to temperatures typical of inlet conditions to practical combustors ($T \cong 800$ K). The operating conditions used in this investigation are summarized in Table 1.

The test section housed the shrouded tube and disk configuration. Gases were extracted from the test section using a water-cooled probe for locally discrete measurements. Samples passed through a filter immediately after exiting the probe. The filter removed soot at a rate of less than 1% of mass percent carbon.[3] The samples passed through a heated sampling line (550 K) until near the gas analysis instruments. The sampling grid and probe are shown in Fig. 1. Analysis of air entering the combustor, prior to fuel injection, was possible using a sampling rake located upstream of the test section. A temperature rake, also located in this vicinity, monitored inlet air temperature. Gas samples were analyzed for CO_2, CO, O_2, and unburned hydrocarbons (UHC). Thermocouples were located along the wall of the combustor (Fig. 1) to obtain boundary values for temperature.

Fuel was injected upstream of the combustion zone using a simplex pressure-atomizing nozzle. Fuel flowed directly into the fuel preparation tube along with a known fraction of inlet air. The fuel preparation tube allowed full or partial vaporization of the fuel, and mixing of the fuel and air prior to combustion. The fuel/air mixture passed out of the fuel preparation tube into the sudden area expansion where the flame was stabilized and combustion took place.

In the same plane in which fuel was injected, air not mixed with the fuel was split off and directed around the disk into an annular flow. This "fresh" air entered the combustion zone near the wall of the combustor and interacted with the flame.

The recirculation zone established by the disk provided the constant ignition source for the incoming fuel/air mixture by entraining hot combustion gases from the flame and returning them to the vicinity of the tube mouth.

The fuel/air mixture exiting the tube is designated by an equivalence ratio ϕ_t. This value was determined by knowledge of the amount of fuel injected into the tube and the quantity of air entering the tube. The airflow split between tube and annular flow was determined by pitot probe measurements in nonreacting airflow.

When the equivalence ratio of the tube flow is greater than one, all the fuel cannot be converted to CO_2 and H_2O in the premixed flame. Assuming a fully prevaporized/premixed fuel/air mixture exiting the fuel preparation tube, a diffusion flame would be present. This is the anticipated ideal situation if $\phi \geq 1.0$; however, in the study of jet-A, fuel droplets might be found exiting the fuel preparation tube as a result of incomplete vaporization. The type of fuel, injector size, residence time in the fuel preparation tube (a function of gas velocity in the tube and tube length), inlet temperature, and combustor pressure can vary the degree of prevaporization. Direct fuel impingement on the tube wall from the injector

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results in a film of fuel traveling down the wall of the tube subject to vaporization and thin sheet air blast atomization at the tube exit. Thus, at least three fuel inlet mechanisms must be considered: fuel as a vapor, fuel in droplets, and fuel droplets from wall shear at the tube mouth. Furthermore, the fuel vapor can have two sources: vaporization of droplets and vaporization from the fuel sheet on the tube wall. Discussion of such heterogeneous data will follow that of the homogeneous propane analysis.

Propane Flame

Research on the prevaporized/premixed propane flame utilized the equipment previously discussed with the run condition of Table 1. A 35-90 simplex hollow cone nozzle was used to inject liquid propane into the fuel preparation tube. Data were collected from sampled locations a minimum of three times. In regions of high fluctuating instrument readings, more data were taken.[4] To understand the flame structure and regions of important species production and consumption, the data are displayed in the form of contour plots, indicating concentration isopleths of the species presented, and as temperature and combustion efficiency contour plots.

Unburned hydrocarbon data are given in Fig. 2 as contours. The fuel/air mixture is not quite homogeneous across the fuel preparation tube mouth; it differs by about 20% from the centerline to the tube wall, with the greatest concentration of propane exiting near the tube wall.

Unburned fuel near the tube wall is swept quickly into the recirculation zone behind the disk, where a strong gradient in UHC concentration is seen in the outward radial direction. Strong gradients are seen between the disk and the high UHC concentration in the recirculation zone and radially inward along the face of the disk toward the fuel preparation tube. A strong jet persists axially from the tube wall containing fuel not entrained into the recirculation zone. Consumption of fuel is seen axially on and away from the centerline; rapidly decreasing UHC values are noted in the radial direction.

Oxygen contours (Fig. 3) reveal axial combustion occurring in a nearly uniform fashion along the centerline and radially outward to one tube diameter until far downstream from the plane of the disk. The fuel jet from the tube wall identified in the UHC contour plot manifests itself in this figure as a region of slightly diminished oxygen consumption. The 7% isopleth appears to represent an interface where flow from the centerline region interacts with gases from the counter-rotating vortices of those two regions. Since the oxygen contours do not indicate impingement of high O_2 concentration gases into this region, the combustion products in the outer vortex must be moving into the region. In such a case, these gases would be hot and possess available oxygen for continued combustion. The inlet annular flow appears to maintain a nearly uniform oxygen concentration along the wall of the combustor, with a mild gradient parallel to the wall.

Carbon monoxide formation (Fig. 4) displays the fuel jet identified in Fig. 2. As in the oxygen contours, this jet exhibits diminished combustion relative to the combustion occurring in the fuel/air flow from the tube. Reverse flow of CO toward the disk is identified by the 30,000-ppm CO contour. Vigorous combustion is occurring downstream as identified by the CO pool, >80,000 ppm CO. This region appears to be downstream of the disk-stabilized recirculation zone and in the region of annular/tube flow interactions noted in the oxygen analysis, where hot oxygen-rich gases are available. A steep gradient in CO exists radially outward from the reverse flow zone.

Carbon dioxide contours (Fig. 5) agree well with CO information in the fuel/air flow by indicating continued fuel oxidation in a nearly uniform manner axially in the flow region on the centerline to one tube radius. Again, the fuel jet from the tube wall manifests itself by diminished oxidation of the fuel. Intense CO_2 formation immediately downstream of the disk occurs in the region of the strong CO gradient in the reverse flow region nearest the annular air inlet. The momentary loss of CO_2 concentration between the <6.5% pool and the 6% isopleth results from dilution of combustion products by annular air. This flow then strongly interacts with the fuel/air tube flow, forming more CO_2 in the zone downstream of the disk and, as previously mentioned, produces vigorous combustion in the >80,000-ppm CO pool, which then oxidizes, producing the 7% CO_2 isopleth.

Temperature calculations based on a carbon balance assuming chemical equilibrium at the local temperature at which gas extraction occurred[4] from gas analysis data are presented in Fig. 6. Since no experimental data for H_2 and H_2O were collected, temperature computations assumed $H_2 \ll H_2O$.

Obvious from Fig. 6 is the complex interaction of flowfield and combustion. The fuel jet emanating from the tube wall is immediately evident. The fuel/air mixture temperature exiting the fuel preparation tube is below the in-

Table 1 Combustor operating conditions

Airflow rate = 1.0 kg/s, inlet air temperature = 800 K

Fuel	Liquid Propane (C_3H_8)	Jet-A
Overall equivalence ratio	0.23	0.30
Tube equivalence ratio	0.88	1.15
Combustor pressure	808 kPa	404 kPa
Initial spray Sauter mean diameter	Flash vaporization	87 μm

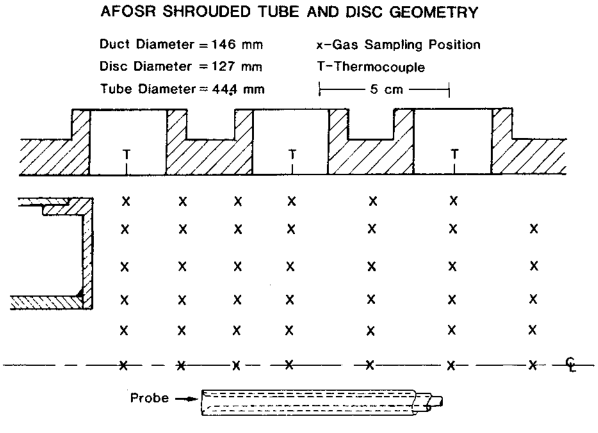

Fig. 1 Gas sampling grid and probe.

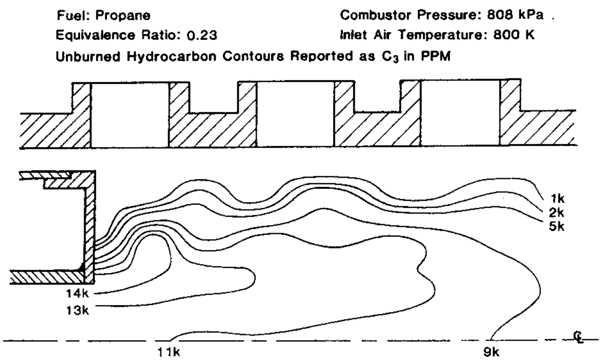

Fig. 2 Propane flame unburned-hydrocarbon contour plot.

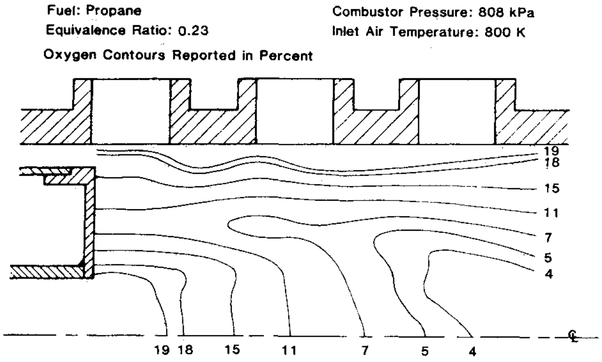

Fig. 3 Propane flame oxygen contour plot.

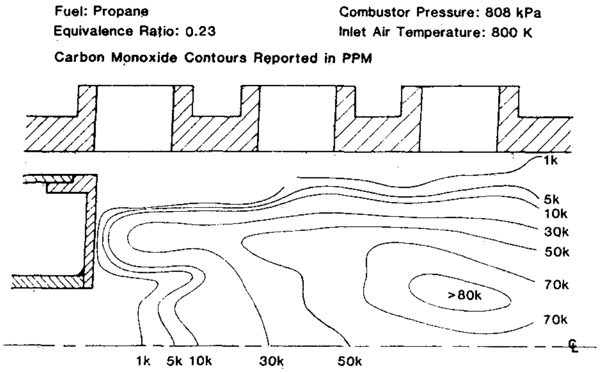

Fig. 4 Propane flame carbon monoxide contour plot.

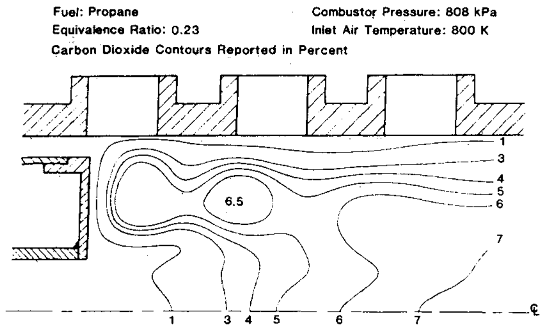

Fig. 5 Propane flame carbon dioxide contour plot.

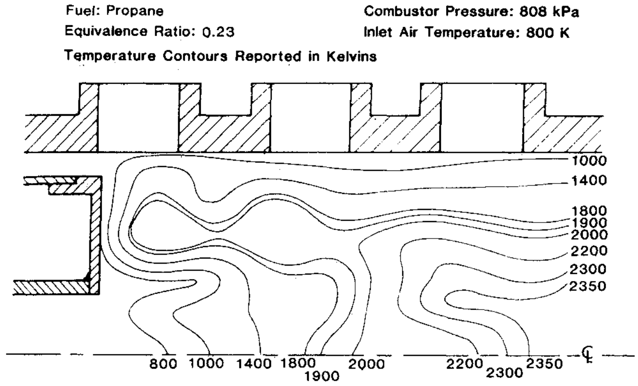

Fig. 6 Propane flame temperature contour plot.

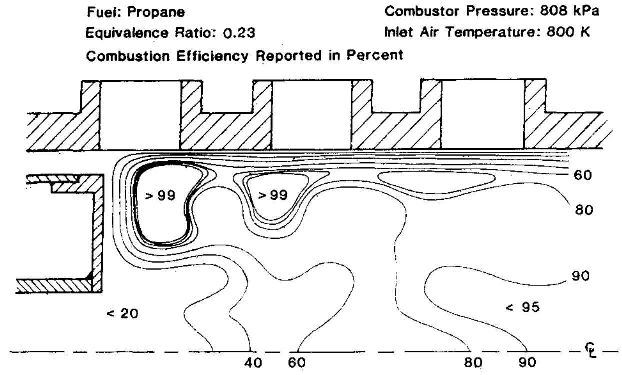

Fig. 7 Propane flame combustion efficiency contour plot.

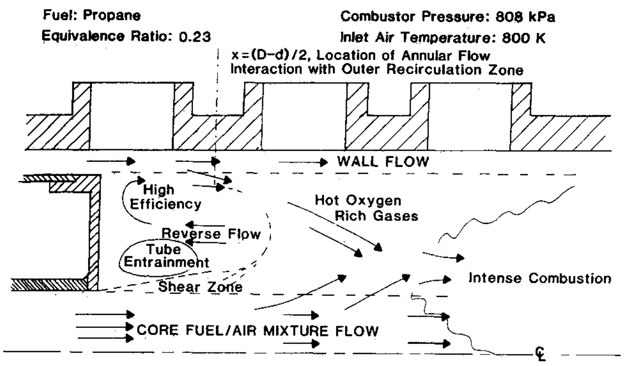

Fig. 8 Interpretation of propane flame.

let air temperature 800 K contour due to fuel evaporation in the fuel preparation tube. The combustion process occurring directly downstream of the fuel preparation tube near the centerline proceeds relatively uniformly until the region of intense combustion is reached. Here, enhanced combustion results from high-temperature oxygen-rich combustion products interacting with the fuel/air mixture. Another high-temperature region is near the disk. This region corresponds to the location where CO is oxidizing to CO_2. The necking of this region results from annular air impingement; consequently, consumption of fuel is slower (see Fig. 2) and heat release is less. This is more obvious in the combustion efficiency contour plot (Fig. 7).

Combustion efficiency in the region of CO oxidation is better than 99%, as expected for such an occurrence. The necking of the 2000 K isotherm mentioned above appears as a region of lowered efficiency between two pools of >99% combustion efficiency. Even though the efficiency is high, the temperature is significantly less than the adiabatic flame temperature for the inlet fuel/air mixture $\phi=0.88$. Thus, this is a dilute mixture, as would be expected in the outer recirculation zone where annular air entrainment could occur. The fuel/air mixture near the centerline is steadily oxidized. The zone of vigorous combustion results in efficiencies near 99%. Temperatures here are more exemplary of combustion mixtures with equivalence ratios near $\phi_t\,[T(\phi=0.88)_{\mathrm{abiabatic}}=2500\ \mathrm{K}]$. The fuel jet from the tube wall is evidenced by the 20% combustion efficiency isopleth.

The flowfield interpretation of the preceding analysis indicates a relatively uniform core flow along the combustor centerline from the fuel preparation tube (Fig. 8). The shear layer between this core flow and the inner recirculation zone starts near the tube wall and deviates from the core flow at approximately a 10-deg angle, as indicated by the fuel jet. The radial limit of fuel entrained into the lower recirculation zone, the reverse flow location of CO, and the very high combustion efficiency region (>99%) relate the interface between inner and outer recirculation zones.

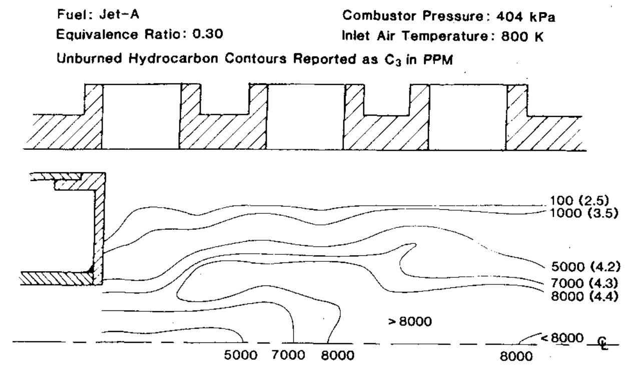

Fig. 9 Jet-A flame unburned hydrocarbon contour plot reported as C_3 in ppm. Log_{10} values of ppm C_3 are reported in parentheses.

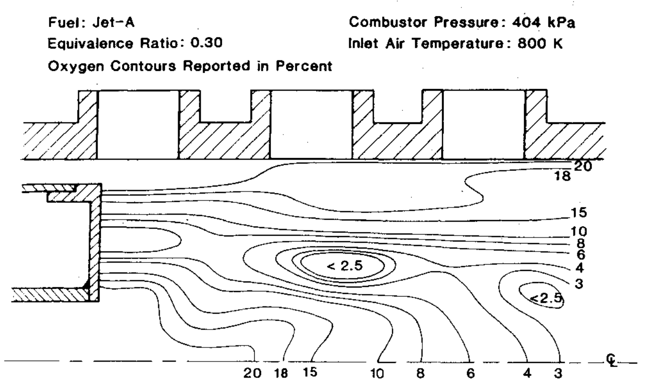

Fig. 10 Jet-A flame oxygen contour plot.

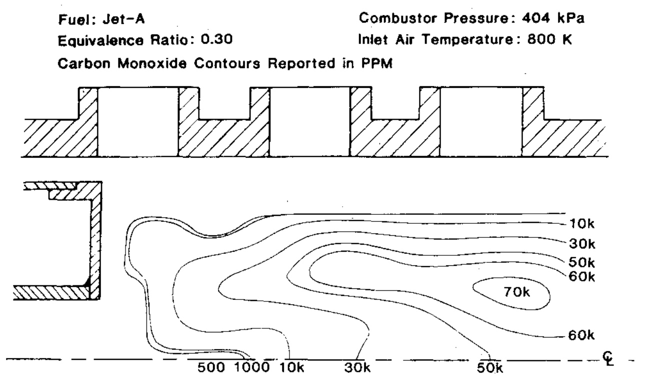

Fig. 11 Jet-A flame carbon monoxide contour plot.

The annular flow exhibits only a slight influence on the recirculation zone. This air is quickly mixed with hot combustion products and produces another region of high efficiency. These gases then move toward the radial plane of the recirculation zone interface, where they strongly interact with the combustion fuel/air mixture of the core flow, producing intense combustion in a region of high turbulence and mixing. The thermocouples located on the wall of the combustor revealed only slight combustion product mixing into the annular wall flow. The thermocouple located farthest downstream indicated a temperature rise of about 100 K from the 800 K inlet condition. This flowfield interpretation is summarized in Fig. 8.

Jet-A Flame

The effects of heterogeneous, i.e., two-phase (gas/liquid) combustion were examined, using jet-A as the test fuel. A 16–90 hollow cone simplex atomizing nozzle was used to inject the fuel into the fuel preparation tube. Again, data were collected from sampled locations at least three times. Regions of extreme fluctuation in meter readings were often encountered, requiring as many as four or five samplings at a location.[4]

Due to liquid droplets existing near the fuel preparation tube mouth, the UHC data obtained do not allow a hydrocrabon balance to be made; they do, however, provide a quantitative interpretation of droplet vaporization during combustion within the flame. Unburned hydrocarbon data are presented in Fig. 9 as C_3 to allow direct comparison to the UHC propane data (Fig. 2). Immediately, the low-inlet UHC values are obvious. Even though the tube equivalence ratio of the jet-A flame is 1.15 and the propane is 0.88, the jet-A UHC values are half those of the propane data. Jet-A is still in liquid phase at the fuel preparation tube mouth. As in the propane case, the greatest UHC concentration in the plane of the disk is at the tube wall. Although the obvious entrainment of fuel into the recirculation zone present in the propane UHC data is absent here, relatively high values do exist where the recirculation zone was identified in the homogeneous investigation. Vaporization of fuel as it travels downstream is seen in the 8000-ppm contour. Due to slower gas velocities in the shear zone, droplets emanating from the tube wall, elevated gas temperatures nearer the recirculation zone, or a combination thereof, fuel vaporization occurs earlier in the radial plane of the tube wall than on the centerline. Very low fuel concentrations exist on the centerline to an axial distance of about one tube diameter. Combustion appears to be the driving force in fuel vaporization, as evidenced by the oxygen (Fig. 10) and CO (Fig. 11) contour plots, i.e., UHC concentrations increase in regions where oxygen is being consumed and CO is being formed. As in the propane case, no unburned hydrocarbon impinges on the combustor wall.

Oxygen data (Fig. 10) show combustion initiating near the tube mouth in the shear zone enveloping the lower recirculation zone. Two zones of intense combustion exist ($<2.5\%$). The first zone at $r=D-d$ results from injection of hot gases from the outer recirculation zone enriched with annular air oxygen. Fuel is provided by UHC produced in the shear layer of the lower recirculation zone. More entrainment of annular air occurs, and these hot gases move on to react with the fuel/air mixture nearer the centerline and produce another region of intense combustion at $r=d$.

The CO data of Fig. 11 correspond with the scenario presented above. Delayed combustion exists on the centerline, with primary initiation of combustion in the shear layer of the lower recirculation zone. The 1000-ppm contour defines the lower recirculation zone and indicates minimal combustion occurring there. The regions of intense combustion are defined by the 60,000-ppm CO isopleth.

Oxidation to CO_2 occurs predominantly in the upper recirculation zone (Fig. 12). The hot gases created here entrain annular air, which dilutes the CO_2 concentration, but further oxidation of CO rapidly occurs, forming more CO_2. The heat release encourages fuel vaporization and continued combustion. These gases move into the region of intense combustion. The gap between the 9% contours downstream results from dilution as fuel changes from the liquid to vapor phase and rapid CO_2 production occurs. Oxidation of CO_2 again occurs near the exit plane of the combustor, evidenced by the downstream 9% contour.

The techniques used to calculate both local temperature and combustion efficiency[4] require complete unburned hydrocarbon information (i.e., total vapor and liquid phase UHC data at every location probed). Since liquid fuel data were not collected, computation of local temperature and combustion efficiency was not possible; that is why local temperature and combustion efficiency contour plots are absent for jet-A data.

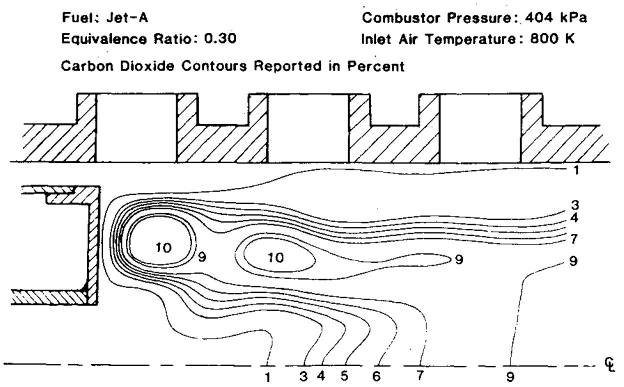

Fig. 12 Jet-A flame carbon dioxide contour plot.

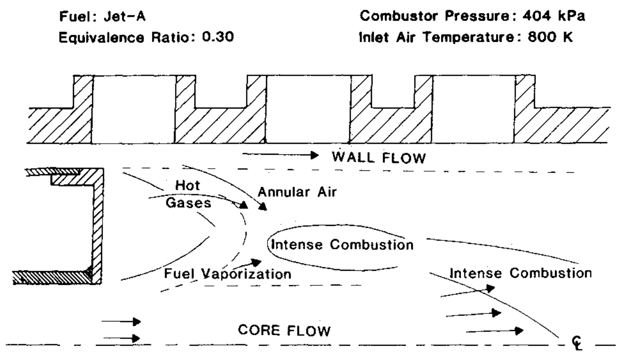

Fig. 13 Interpretation of jet-A flame.

Figure 13 presents a summary of the flowfield determined from jet-A data. The general characteristics of the jet-A flowfield are similar to those of the propane (Fig. 8). The deviations produced by the heterogeneous character of the jet-A flame result from fuel droplets acting as fuel sources within the combustor. For the propane flame, a well-defined fuel inlet boundary condition existed. Because the fuel spray from the tube wall produced droplets more difficult to entrain into the lower recirculation zone, less UHC is seen as a well-defined region within the lower recirculation zone when compared to the propane flame (Fig. 9). Since fuel that would ordinarily be entrained by the lower recirculation zone in a homogeneous flame sweeps past it in the jet-A case, fuel directly reaches the region where hot oxygen-rich gases exist. This produces a region of intense combustion farther from the plane of the disk than is observed in the propane flame.

The jet-A flame is primarily influenced by fuel droplet motion and vaporization, whereas the propane flame follows the gas flowfield of the shrouded tube and disk geometry. Even though combustion does occur differently in the two flames (propane combustion initiates from well-defined inlet conditions, and jet-A combustion acts as if fuel vapor sources are present within the combustor), the gross flowfield characteristics are similar: core flow along the centerline from the fuel preparation tube, a shear layer between the core flow and the lower recirculation zone, counter-rotating vortices within the recirculation zone envelope, strong wall flow from annular air inlet, location of the recirculation-zone envelope, and the interaction region of fuel/air tube flow with hot combustion products from the outer recirculation zone enriched with oxygen from annular air.

Summary

For this investigation, neither the combustor operating conditions nor the type of combustion occurring (homogeneous or heterogeneous) significantly affected the flowfield of the combustor. Variations in local species concentration occurred as a result of the type of flame and therefore the fuel type and the operating conditions. (Combustor operating conditions, such as inlet air temperature and combustor pressure, can affect initial fuel spray size, fuel vaporization, reaction kinetics, turbulence, etc.) Fundamental flowfield characteristics, however, were very similar. Thus, the flowfield for a given geometry or configuration provides a firm foundation on which to interpret the effects of fuel property variations due to different fuels and operating conditions. Residence times in a particular region of the flowfield can assist in determining the extent of fuel vaporization or reaction. Velocity field information can also provide insight into potential deviations in fuel spray trajectory. The differences in the combustion process within the flame, however, do not appear to change significantly the general flow characteristics of the combustor.

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