General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

EXPERIMENTAL EVALUATION OF TWO PREMIXING-PREVAPORIZING FUEL INJECTION CONCEPTS FOR A GAS TURBINE CATALYTIC COMBUSTOR

by Robert Tacina
Lewis Research Center
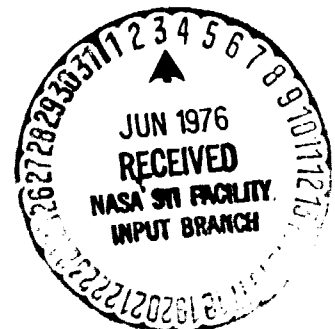Cleveland, Ohio 44135

EXPERIMENTAL EVALUATION OF TWO PREMIXING-PREVAPORIZING

FUEL INJECTION CONCEPTS FOR A GAS TURBINE

CATALYTIC COMBUSTOR

by Robert Tacina

Lewis Research Center

ABSTRACT

Experiments were performed to evolve and evaluate a premixing-prevaporizing fuel system to be used with a catalytic combustor for possible application in an automotive gas turbine. Spatial fuel distribution and degree of vaporization were measured using Jet A fuel. Two types of air blast injectors were tested, a splash-groove injector and a multiple-jet cross-stream injector. Air swirlers with vane angles of 15° and 30° were used to improve the spatial fuel distribution. The work was done in a 12-cm (4.75-in.) diameter tubular rig. Distribution and vaporization measurements were made 35.5 cm (14 in.) downstream of the injector. Test conditions were: a pressure of 0.5 MPa (5 atm), inlet air temperatures up to 800 K (980° F), velocity of 20 m/sec (66 ft/sec) and fuel-air ratios cf 0.01 and 0.025. The spatial fuel distribution was nearly uniform with the multiple-jet contrastream injector and the splash-groove injector with a 30° air swirler. The vaporization was nearly 100 percent at an inlet air temperature of 600 K (620° F) and at an 800 K (980° F) inlet air temperature fuel oxidation reactions were observed. The total pressure loss was less than 0.5 percent of the total pressure for the multiple-jet cross-stream injector and the splash-groove injector (without air swirler) and less than 1 percent for the splash-groove with a 30° air swirler for the above test conditions.

INTRODUCTION

Experiments were performed to evolve and evaluate a fuel preparation system to be used with a catalytic combustor for possible application in an automotive gas turbine. Catalytic combustors have been shown to be able to burn at lean fuel-air mixtures that are below the normal flammability limits with high efficiency and low NO_x emission levels (ref. 1). Uniform fuel distribution and complete fuel vaporization are necessary for catalytic combustors since the substrates are currently limited to temperatures below about 1800 K (2780° F), thus rich zones or liquid drops burning off the substrate could damage it.

Data on dropsize from various types of fuel injectors and data on single droplet vaporization rates are plentiful. But only limited data has been published on spatial fuel distribution and vaporization rates of sprays. Such information is necessary for the development of a premixing-prevaporizing system for a gas turbine combustor. Using a multiple-orifice contrastream injector, vaporization rates of JP-5 sprays were measured in reference 2 and using a simple orifice contrastream injector, vaporization rates of isooctane sprays were measured in reference 3. In reference 4 the spatial fuel distribution and degree of vaporization were measured from simplex pressure atomizers using isooctane and no. 2 oil as the fuel.

In this study spatial fuel distribution and vaporization data were taken with two types of air blast injectors, a splash-groove and a multiple-jet cross-stream injector. Air swirlers with vane angles of 15° and 30° were used to improve the spatial fuel distribution. Test conditions were: inlet pressure 0.5 MPa (5 atm), reference velocity 20 m/sec (66 ft/sec), fuel-air ratios of 0.01 and 0.025, and inlet air temperatures from 450 K (350° F) to 800 K (980° F). The fuel was Jet A.

APPARATUS

Test Rig

Figure 1 is a schematic of the test rig. The airflow rate was measured with a square edged orifice. The air was heated up to 800 K (980° F) in a nonvitiating preheater. The fuel flow was measured by two turbine flowmeters in series. A temperature and pressure measurement was taken upstream of the fuel injector. The duct diameter was 10.2 cm (4.0 in.) upstream of the injector and 12 cm (4.75 in.) downstream. A 7.6-cm (3.0-in.) diameter inlet section was inserted upstream of the injector to increase the air velocity which improves fuel atomization. A diffuser was then inserted downstream of the injector.

Two probes, 90° apart, were located 35.3 cm (14.0 in.) downstream of the fuel injector to sample the fuel-air mixture. Each could traverse across the diameter of the duct to obtain the spatial fuel distribution. The fuel-air ratio was determined by passing the mixture sample over a catalyst heated in an oven to 1030 K (1400° F) and then analyzing the products of combustion for carbon monoxide, carbon dioxide, and unburned hydrocarbons. Carbon monoxide and carbon dioxide concentrations were measured on Beckman nondispersive infrared analyzers and unburned hydrocarbons concentrations were measured on a Beckman Flame Ionization Detector. The amount of unburned hydrocarbons and carbon monoxide measured was negligible. These probes were also used to measure degree of vaporization by the spillover technique which is described in refer-

ence 2. A temperature and pressure measurement was also taken at this station. The fuel-air mixture was enriched with hydrogen and burned downstream of the sampling probes. Water was injected to cool the exhaust products and a back pressure valve was used to control the rig pressure.

Injectors

The two types of injectors discussed in this paper are both air blast atomizers. That is, they rely on the relative velocity between fuel and air for atomization. The first type discussed is a multiple-jet cross-stream injector, see figure 2. The location of the 28 orifices were chosen so that each of the 28 orifices injects fuel into a space of approximately equal area. The fuel was introduced in a plane 39.4 cm (15.5 in.) upstream of the probes.

The second injector was developed by Ingebo (ref. 5) and is designated a splash-groove injector (see fig. 3). Fuel is injected through orifices onto three grooved portions of the nozzle. The fuel splashes over the lip of each of the three grooves and is atomized by the airflow. In the experimental configuration the fuel was introduced in a plane 35.6 cm (14 in.) upstream of the probes. Air swirlers with vane angles of 15° and 30° could be inserted in the annular space around the injector.

Vaporization Data – Spillover Technique

The degree of vaporization was determined by the spillover technique (ref. 2). This technique consists of varying the velocity through the probe above and below the isokinetic velocity and determining the degree of vaporization by the change in fuel-air ratio through the probe. The following analysis was used (see symbol list in the appendix):

$$\left(\frac{f}{a}\right)_p = \left(\frac{f}{a}\right)_\ell + \left(\frac{f}{a}\right)_v = \frac{w_\ell}{w'_a} + \frac{w_v}{w'_a} = \frac{w_\ell}{w_a} \cdot \frac{w_a}{w'_a} + \frac{w_v}{w'_a} \tag{1}$$

if the degree of vaporization is uniform in the vicinity of the probe, then the vapor fuel-air ratio through the probe does not vary with velocity through the probe, that is

$$\frac{w_v}{w'_a} = \text{constant} - \left(\frac{f}{a}\right)_{iso} \cdot E \tag{2}$$

w_ℓ is assumed to be constant, that is, the streamlines of the liquid drops do not change with velocity through the probe

$$\frac{w_\ell}{w_a} = \left(\frac{f}{a}\right)_{\ell,\,iso} = (1 - E)\left(\frac{f}{a}\right)_{iso} = \text{constant} \tag{3}$$

$$\left(\frac{f}{a}\right)_p = (1 - E)\left(\frac{f}{a}\right)_{iso}\left(\frac{w_a}{w'_a}\right) + E\left(\frac{f}{a}\right)_{iso} \tag{4}$$

in terms of velocity

$$\frac{w_a}{w'_a} = \frac{V_{iso}}{V_p}, \quad V_{iso} = V_R \tag{5}$$

$$\frac{(f/a)_p}{(f/a)_{iso}} = (1 - E)\left(\frac{V_{iso}}{V_p}\right) + E \tag{6}$$

The fuel-air ratio through the probe was normalized by the fuel-air ratio determined by the inlet fuel flow divided by the inlet airflow.

$$\frac{(f/a)_p / (f/a)_{mean}}{(f/a)_{iso} / (f/a)_{mean}} = (1 - E)\left(\frac{V_{iso}}{V_p}\right) + E \tag{7}$$

$$E = \left[\frac{(f/a)_p / (f/a)_{mean}}{(f/a)_{iso} / (f/a)_{mean}} - \frac{V_{iso}}{V_p}\right] \bigg/ \left(1 - \frac{V_{iso}}{V_p}\right) \tag{8}$$

Figure 4 is a typical plot. The degree of vaporization is 0.81; that is, 81 percent of the fuel has vaporized.

RESULTS AND DISCUSSION

Spatial Fuel Distribution

The spatial fuel distribution was found by traversing the sampling probes across the diameter of the duct. The fuel-air ratio was sampled isokinetically at seven points across the diameter of the duct with each probe. In figures 5 and 6, only one representative profile of the two is presented. The fuel-air ratio in the plot is normalized using the fuel-air ratio determined from the

inlet fuel flow divided by the inlet airflow.

The spatial fuel distribution of the multiple-jet cross-stream injector was nearly uniform for all conditions tested; in figure 5 the results with an 800 K (980° F) inlet air temperature are shown. Note no air swirler was used. The integrated values over the duct cross section of the normalized fuel-air ratio is less than 1 in figure 5, but the difference from 1 is within the accuracy of the instrumentation.

For the splash-groove fuel injector there are two sets of spatial fuel distribution curves shown in figure 6. In figure 6(a) the fuel distribution is shown without the use of an air swirler and in figure 6(b) the fuel distribution is shown with the addition of a 30° air swirler. Without an air swirler the profile was very center peaked, but with the addition of the 30° air swirler the profile became uniform. Results using a 15° air swirler instead of a 30° air swirler were nearly the same.

Vaporization Data

The degree of vaporization was determined with the spillover probe technique. The measurements were taken with the probe in the center of the duct. The vaporization data are presented in Table I.

Using a correlation developed in reference 2 for a multiple-orifice contra-stream injector, only about 50 percent of the fuel would be expected to vaporize at the above conditions. However, the test conditions were outside the range of conditions for which the correlation in reference 2 was developed. The reason for the higher degree of vaporization may be a result of smaller drop sizes being formed than occurred in reference 2.

Autoignition

At the 800 K (980° F) inlet air temperature condition with a fuel-air ratio of 0.025, a reference velocity of 20 m/sec (66 ft/sec), and a rig pressure of 0.5 MPa (5 atm), there was a 10 K (18° F) temperature rise from the injection point to the downstream thermocouple for the multiple-jet cross-stream injector and a 40 K (70° F) rise for the splash-groove injector, indicating oxidation reactions had begun. The difference in temperature rise may be due to the splash-groove injector having higher local values of fuel-air ratio near the injector. At the above conditions and a fuel-air ratio of 0.01 there was no temperature rise. Autoignition occurred at temperatures below 800 K (980° F) for configurations that had nonuniform fuel distributions.

Pressure Drop

The pressure drop from the injector to the sample probes was less than 0.5 percent of the inlet total pressure for the multiple-jet cross-stream injector and the splash-groove injector without an air swirler, at the conditions tested. With a 30° air swirler the pressure drop of the splash-groove was approximately 1 percent.

CONCLUDING REMARKS

The multiple-jet cross-stream injector and the splash-groove injector with a 30° air swirler had a uniform fuel distribution and a high degree of vaporization with little total pressure drop at the conditions tested. At the 800 K (980° F) inlet air temperature condition, fuel oxidation reactions were observed. For the automotive gas turbine application, higher inlet air temperatures would be encountered, and therefore the dwell time would probably have to be reduced to prevent autoignition. Reducing dwell time will affect the vaporization and possibly the fuel distribution and therefore an approach different from that investigated may be required for a higher inlet air temperature application.

APPENDIX - SYMBOLS

E degree of vaporization $= \dfrac{(f/a)_v}{(f/a)_v + (f/a)_\ell}$

f/a fuel-air ratio

$(f/a)_{mean}$ fuel-air ratio determined by inlet fuel flow divided by inlet airflow

P_3 inlet pressure

T_3 inlet air temperature

V probe velocity at inlet

V_R reference velocity, velocity based on inlet pressure, inlet temperature, and the area of the 12-cm (4.75-in.) diameter duct

w fuel flow through probe

w_a airflow through the probe at isokinetic velocity

w'_a airflow through the probe

Subscripts:

iso   isokinetic

ℓ liquid

p   probe

v   vapor

REFERENCES

1. Anderson, David N.; Tacina, Robert R.; and Mroz, Thaddeus S.: Performance of a Catalytic Reactor at Simulated Gas Turbine Combustor Operating Conditions. NASA TM X-71747, 1975.

2. Foster, Hampton, H.; and Ingebo, Robert D.: Evaporation of JP-5 Fuel Sprays in Air Streams. NACA RME55K02, 1956.

3. Bahr, Donald W.: Evaporation and Spreading of Isooctane Sprays in High Velocity Air Streams. NACA RME53I14, 1953.

4. Kennedy, J. B.; and McVey, J. B.: An Experimental Study of Fuel Spray Vaporization Rates. APL The 11th JANNAF Combustion Meetings, Vol. 2, 1974, pp. 387-406.

5. Ingebo, Robert D.; and Norgren, Carl T.: Combustor Exhaust Emissions with Air Atomizing Splash-Groove Fuel Injectors Burning Jet A and Diesel Number 2 Fuels. NASA TM X-3255, 1975.

TABLE I. -- VAPORIZATION DATA

[Fuel-air ratio of 0.01, reference velocity of 20 m/sec
(66 ft/sec) and rig pressure of 0.5 MPa (5 atm).]

Type of injector	Inlet air temperature, K (^{o}F)		
	450 (350)	500 (440)	600 (620)
	Fraction vaporized		
Multiple-jet cross-stream	0.81	0.94	1.00
Splash-groove	----	.93	1.00
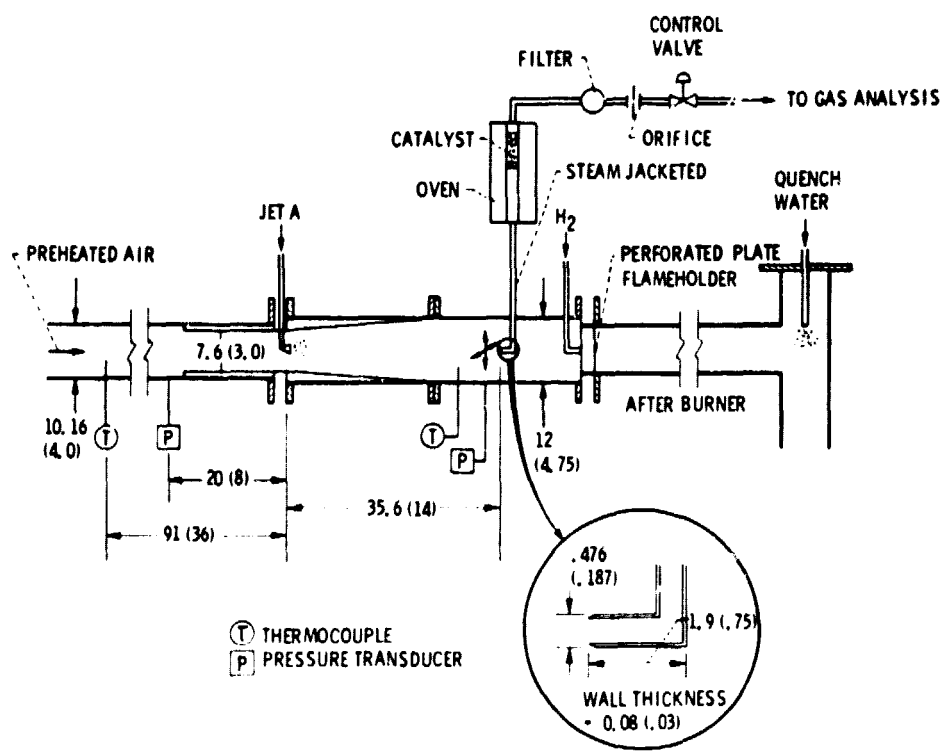
Figure 1. - Rig schematic. (Dimensions in cm (in.).)

CONTROL VALVE

FILTER

TO GAS ANALYSIS

ORIFICE

CATALYST

STEAM JACKETED

OVEN

QUENCH WATER

JET A

H₂

PREHEATED AIR

PERFORATED PLATE FLAMEHOLDER

7.6 (3.0)

10.16 (4.0)

12 (4.75)

AFTER BURNER

20 (8)

35.6 (14)

91 (36)

T THERMOCOUPLE
P PRESSURE TRANSDUCER

.476 (.187)

1.9 (.75)

WALL THICKNESS
0.08 (.03)

TWENTY-EIGHT
0.37 mm (.0145 IN.)
ORIFICES

2a

a

a = 0.64 CM (0.25 IN.)

SECTION AA,
SCALE 3x

GAS
SAMPLE

A

FUEL

7.6 CM (3.0 IN.)

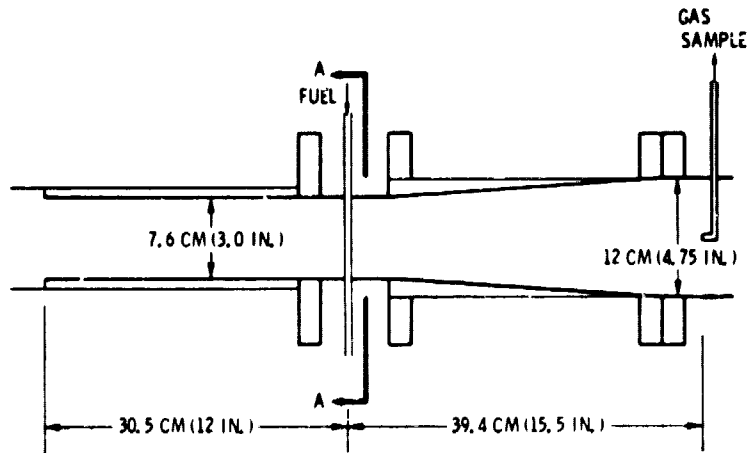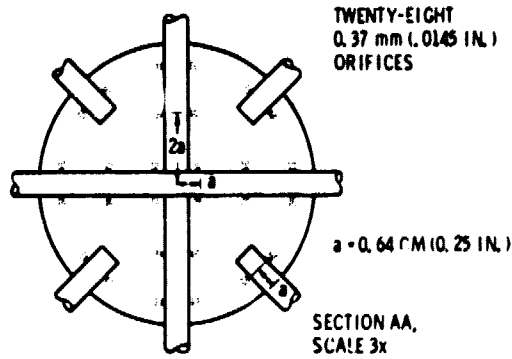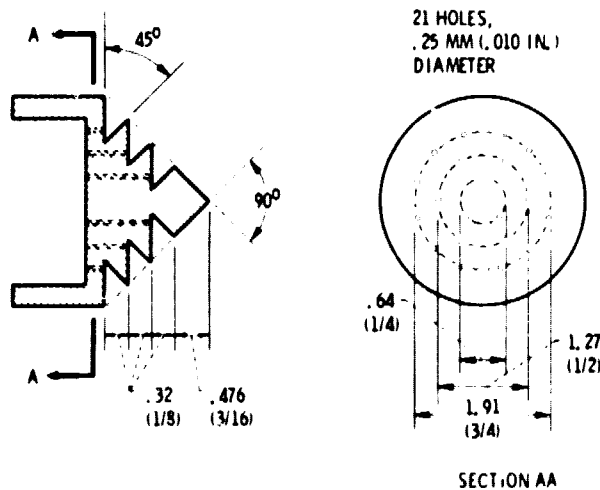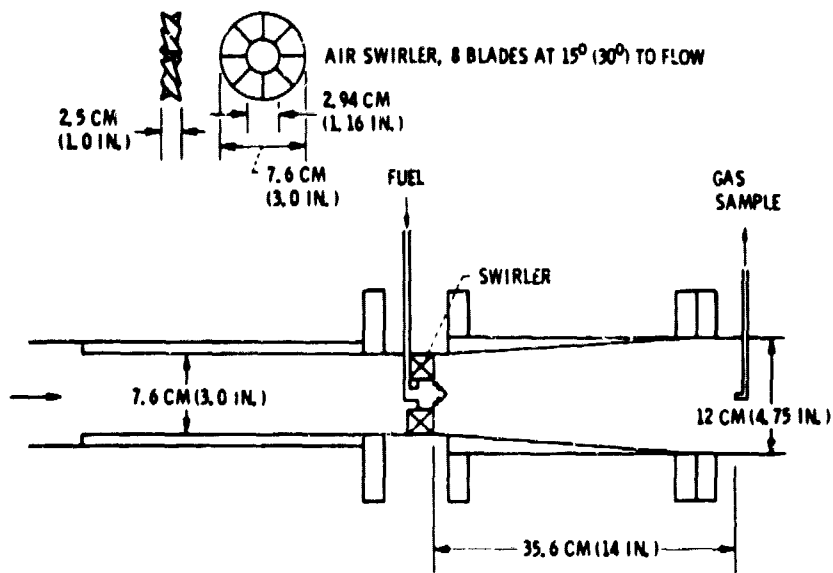12 CM (4.75 IN.)

A

30.5 CM (12 IN.)

39.4 CM (15.5 IN.)

Figure 2. - Multiple-jet cross-stream injector, twenty-eight 0.37 mm (.014 in.)
holes, 7.6 cm (3.0 in.) inlet.

A

45°

90°

.32
(1/8)

.476
(3/16)

A

21 HOLES,
.25 MM (.010 IN.)
DIAMETER

.64
(1/4)

1.27
(1/2)

1.91
(3/4)

SECTION AA

(a) INJECTOR.

Figure 3. - Splash-groove fuel injector.

AIR SWIRLER, 8 BLADES AT 15° (30°) TO FLOW

2.5 CM
(1.0 IN.)

2.94 CM
(1.16 IN.)

7.6 CM
(3.0 IN.)

FUEL

SWIRLER

GAS
SAMPLE

7.6 CM (3.0 IN.)

12 CM (4.75 IN.)

35.6 CM (14 IN.)

(b) ASSEMBLY, 7.6 CM (3.0 IN.) INLET, 35.6 CM (14 IN.) VAPORIZATION LENGTH, SWIRLER
INSERTED.

Figure 3. - Concluded.

VAPORIZATION = 0.81

$T_3 = 450$ K (350° F)
$P_3 = 0.5$ MPa (5 ATM)
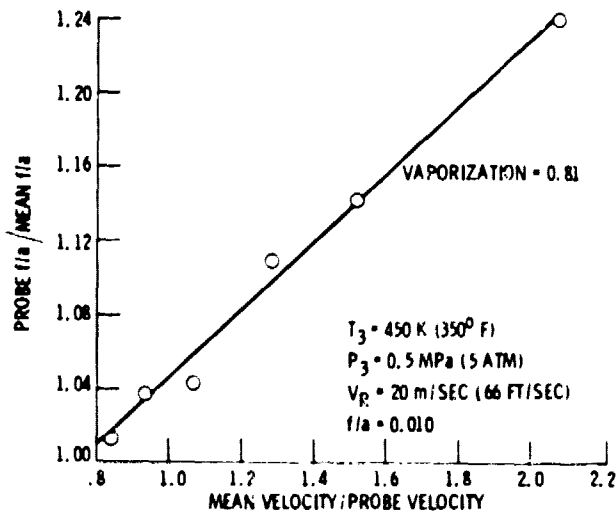$V_R = 20$ m/SEC (66 FT/SEC)
f/a = 0.010

PROBE f/a / MEAN f/a

MEAN VELOCITY / PROBE VELOCITY

Figure 4. - Degree of vaporization, multiple-jet cross-stream
injector.
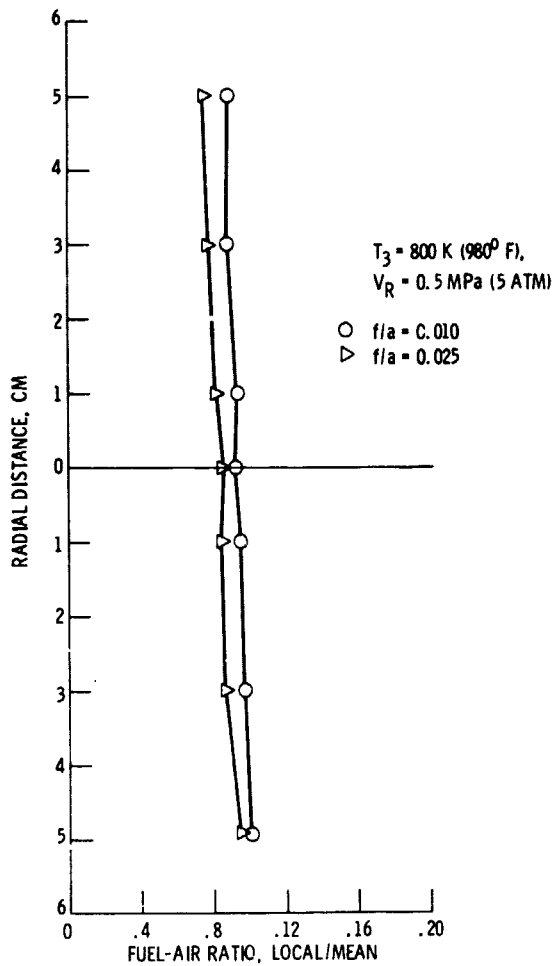
Figure 5. – Spatial fuel distribution, multiple-jet cross-
stream injector, twenty-eight 0. 37 mm (0.014 in.) holes.

$T_3 = 600$ K (620^0 F)
$V_R = 20$ m/SEC (66 FT/SEC)

○ f/a = 0.010
▷ f/a = 0.025

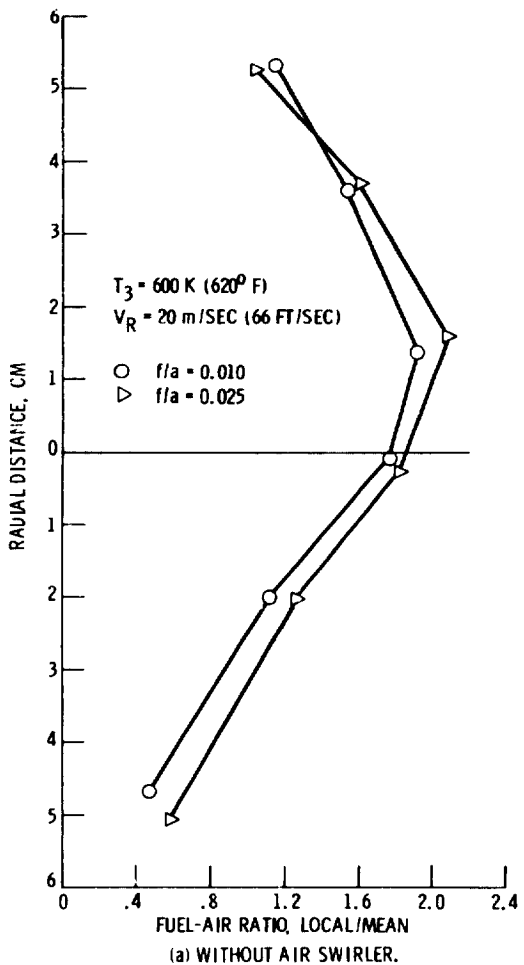RADIAL DISTANCE, CM

FUEL-AIR RATIO, LOCAL/MEAN

(a) WITHOUT AIR SWIRLER.

Figure 6. - Spatial fuel distribution, splash-groove fuel injector.

$V_R = 20$ m/SEC (66 FT/SEC)
$P_3 = 0.5$ MPa (5 ATM)

○ $T_3 = 600$ K (620^0 F), f/a = 0.010
▷ = 600 K (620^0 F), f/a = 0.025
◇ $T_3 = 800$ K (930^0 F), f/a = 0.010

RADIAL DISTANCE, CM

FUEL-AIR RATIO, LOCAL/MEAN

(b) WITH 30^0 AIR SWIRLER.

Figure 6. - Concluded.