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SUMMARY

Premixing-prevaporizing fuel systems were evaluated for use with a catalytic reactor for possible automotive gas turbine application. Spatial fuel-air distributions, degree of vaporization, pressure drop and air velocity profiles were measured. Three airblast injectors and an air-assist nozzle were tested. Air swirlers were used to improve the spatial fuel-air distribution. The work was done in a 12 cm tubular duct. Test conditions were: a pressure of 0.3 and 0.5 MPa, inlet air temperatures up to 800 K, air velocities of 10 and 20 m/s and fuel-air ratios up to 0.020. The fuel was Jet A. The best results were obtained with an air-blast configuration that used multiple cones to provide high velocity air for atomization and also straightened the inlet airflow. With this configuration, uniform spatial fuel-air distributions were obtained with mixing lengths greater than 17.8 cm. In this length, vaporization of the fuel was 98.5 percent complete at an inlet air temperature of 700 K. The total pressure loss was 1.0 percent with a reference velocity of 20 m/s and 0.25 percent at 10 m/s. The air velocity was uniform across the duct and no autoignition reactions were observed.

INTRODUCTION

The Lewis Research Center has been working in support of the ERDA (now DOE) automotive gas turbine program to advance the technology required to obtain an engine with high fuel economy and low emission levels. Catalytic combustors have shown the potential for low emission levels (refs. 1, 2, and 3) and are being evaluated for use in an automotive gas turbine. Catalyst evaluation work at Lewis utilizing vaporized propane is described in references 1 and 2. This paper describes the effort to develop a liquid fuel preparation system to be used in evaluation tests of a catalytic converter.

Requirements for a fuel preparation system for a catalytic converter should provide uniform fuel and velocity distributions, complete vaporization, no autoignition or flashback, and low pressure loss. Uniform fuel distribution and complete vaporization are necessary since catalytic substrates are currently limited to temperatures of 1800 K, thus rich zones or liquid drops burning off the substrate could damage it. A uniform velocity profile across the diameter of the duct is necessary since the effectiveness of the catalytic conversion is dependent on throughput across the duct. Autoignition or flashback must be prevented since this could damage the carburetor or the catalytic section and high levels of NO_x might result. For an automotive application it is desired to keep the combustor total pressure loss below 3 percent. A 2 percent loss for the catalyst section is practicable (ref. 2), so a 1 percent drop for the fuel injector would be acceptable.

With consideration of the above, the goals established (somewhat arbitrarily) for the fuel preparation system performance are:

1. Spatial fuel-air distribution within ±10 percent of the mean.
2. 90 percent of the fuel vaporized at an inlet air temperature of 800 K.
3. Velocity distribution across the duct within ±10 percent of the mean.
4. No autoignition or flashback.
5. Pressure drop less than 1 percent.

At the Workshop on Catalytic Combustion last year, data was presented (ref. 4) in which all the above goals were met with the exception that velocity distributions were not measured. However, cool flame reactions were observed at an inlet air temperature of 800 K. Thus it was felt that autoignition would be a problem at the higher inlet temperatures of 1030 K in present experimental automotive gas turbines, and even higher temperatures of proposed engines. To prevent autoignition the dwell time or length should be decreased. Also a shorter fuel preparation system would make a better automotive package (previous length was 35 cm). The effort described here was to investigate fuel preparation systems that would have a reduced length and dwell time and to measure velocity distributions for the best system.

APPARATUS

Test Rig

Figure 1 is a schematic of the test rig. The airflow rate was measured by a square-edged orifice. The air was heated to 800 K in a nonvitiating preheater. The fuel flow rate was measured by two turbine flowmeters in series. The duct diameter was 12 cm. A temperature and pressure measurement was taken upstream of the injector.

Two sample collecting probes, 90^{o} apart, were located downstream of the fuel injector to sample the fuel-air mixture. The fuel-air ratio was determined by passing the mixture sample over a catalyst heated in an oven to 1030 K and 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 hydrocarbon concentrations were measured on a Beckman Flame Ionization Detector. The amount of unburned hydrocarbons and carbon monoxide measured was negligible because mixture ratios were very lean. A temperature and pressure measurement was also taken at this station.

The sampling probes were used to make velocity measurements across the duct. With no flow through the probe, the total pressure at a point could be obtained and the velocity calculated using the wall static pressure measurement (since the wall static pressure was used instead of the local static pressure the velocity calculation is only approximately correct).

Twenty-five centimeters downstream of the probe station was a catalytic converter section. This section was used to simulate the pressure drop downstream of the fuel injector and to react the unburned fuel. Further downstream was an afterburner section in which the fuel-air mixture was enriched with hydrogen to complete the combustion at conditions where the catalytic converter was inefficient. Water was injected to cool the exhaust products and a back pressure valve was used to control the rig pressure.

Injectors

Four fuel injectors were evaluated and the results are discussed in this report. They were an air-assist atomizer, a splash-groove injector, a multiple-jet injector and a multiple conical tube injector. The air-assist atomizer was a Hartman whistle-type that depends on a high-velocity externally-supplied airstream for atomization. The other three injectors are airblast atomizers; that is, they rely on the relative velocity between fuel and air for atomization.

Sonicore nozzle. - The air-assist nozzle was a Hartman whistle-type that is produced commerically by Sonic Development Corporation. The particular nozzle used was a Sonicore P/N 125 M-A. This nozzle (see fig. 2(a)) uses an external air supply which provides a high velocity airstream for atomizing. As the airstream impinges upon the resonator cap, it produces strong local shock waves in the space between the nozzle and cap. Fuel is pumped or sucked into the airstream and the result is a cone shaped spray pattern of finely atomized droplets. The external airstream had a supply pressure of 0.55 MPa.

Splash-groove fuel injector. - This injector was developed by Ingebo (ref. 5) and the principal features of the injector are shown in figure 2(b). Fuel is injected through orifices onto three grooved portions of the nozzle. The fuel splashes over the lips of each of the three grooves and is atomized by the airflow.

Multiple-jet injector. - The multiple-jet injector is shown in figure 2(c). Sixty-one orifices of 0.25 mm diameter were located so that each of the 61 orifices injects fuel cross-stream into a space of approximately equal area. For some tests, a plate with drilled holes was placed upstream. This plate had some holes that were larger and some that were smaller than the rest of the holes in an effort to improve the fuel-air spatial distribution.

Multiple conical tube injector. - Photographs of this injector are shown in figure 2(d). Twenty-one conical tubes formed a tube bundle through which the air would flow. Each conical tube had an upstream diameter of 1.3 cm and a downstream diameter of 2.2 cm. The length of the conical tubes was 10.1 cm. Fuel was injected at the upstream end of the conical tube through a 0.5 mm inside diameter open ended fuel tube. Each fuel tube had a length of 25.4 cm.

Air swirlers. - With the Sonicore and Splash-Groove fuel injectors, air swirlers were used to improve the spatial fuel-air distribution. Typical swirlers are shown in figure 2(e). Two types of swirlers were used; a simple swirler in which there were 16 flat blades all at a constant angle to the flow and a compound swirler in which there were 8 blades in the inner swirler at a 30° angle to the flow and 16 blades in the outer swirler at a 60° angle to the flow.

RESULTS AND DISCUSSION

The spatial fuel-air distribution will be discussed for each of the four fuel injectors. Vaporization, pressure drop and air velocity distribution data will be presented for the conical tube fuel injector which had the best fuel-air distribution results. No autoignition problems occurred with any of the injectors at the conditions tested, although not all injectors were tested at the highest temperature or pressure.

The spatial fuel-air distributions were found by traversing the sample 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. The fuel-air ratio in the plots are normalized using the mean fuel-air ratio. The refererence velocity is the inlet velocity calculated using the inlet air temperature, inlet pressure, air massflow, and the area based on the 12 cm diameter.

Sonicore Fuel Injector

The spatial fuel-air distribution data obtained with the Sonicore fuel injector were not uniform.. With the use of a 30° vane angle air swirler the profile was very centered peaked (fig. 3). The fuel-air ratio in the center of the duct was over four times the mean value and there was very little fuel near the walls. With a 45° vane angle air swirler the profile improved so that the fuel-air ratio was 3.1 times greater than the mean in the center of the duct and about 0.5 of the mean at 0.5 cm from the wall. With a 60° vane angle air swirler the profile further improved but still was unacceptable. In the center the fuel-air ratio was 1.8 times the mean. The profile was not symmetrical with a local fuel-air ratio 1.1 times the mean at 1 cm from the wall and a value of 0.8 at 1 cm from the opposite wall. This nonsymmetry probably is the result of an interaction between the fuel tube, air assist tube and air swirler. A similar occurrence is reported in reference 6.

Adding a compound air swirler improved the profile as shown in figure 3(b). The fuel-air distribution was nearly uniform as one probe traversed horizontally across the duct but with the traverse perpendicular to this (vertical) nonsymmetry again was evident. The maximum fuel-air ratio (vertical profile) was 1.4 times the mean fuel-air ratio as compared to 1.3 for the 60° vane angle air swirler.

Splash-Groove Fuel Injector

The spatial fuel-air distribution obtained with the splash-groove fuel injector is presented in figure 4. With an inlet duct diameter of 12 cm and a 45° vane angle air swirler the profile is nonsymmetric with a fuel-air ratio of 0.65 of the mean at one side of the duct and 1.55 at the other side. The nonsymmetry is assumed to be caused by the interaction of the fuel tube and the air swirler as discussed with the Sonicore fuel injector.

In reference 4 uniform spatial fuel-air distributions were obtained with a 7.6 cm inlet diameter and 30° air swirler. Therefore, a reduction of inlet diameter from 12 to 10.2 cm with a 30° air swirler was tried to improve the distribution. A 15.2 cm long diffuser was used to expand from 10.2 to 12 cm. The distribution obtained was within ±20 percent of the mean at a mixing length of 24 cm. Decreasing the mixing length to 15.2 cm resulted in a poorer distribution. At 0.5 cm from the wall the fuel-air ratio ranged from 0.9 of the mean to 0.56 of the mean when the mixing length went from 24 to 15.2 cm.

Multiple-Jet Fuel Injector

The spatial fuel-air distribution obtained with the multiple-jet fuel injector was within ±40 percent of the mean after a mixing length of 25 cm (fig. 5). Calibration of the individual 61 orifices of the fuel injector showed the flow through each to be within ±10 percent of the mean. Thus the airflow distribution upstream of the fuel injector probably was not uniform. Another possibility is that the mixing-vaporizing process did not have sufficient time or length to be completed.

A drilled plate, shown in figure 2(c) was placed upstream of the fuel injector to improve the inlet air velocity profile. The drilled plate had larger holes in the center where the fuel-air ratio was high and smaller holes where the fuel-air ratio was low. The resulting profile was an improvement (see fig. 5) with the distribution within ±20 percent of the mean.

The pressure drop was negligible without the drilled plate but increased to 1.0 percent with the drilled plate at an inlet air temperature of 800 K, inlet pressure of 0.5 MPa and reference velocity of 20 m/s.

Mulitple Conical Tube Fuel Injector

To improve upon the spatial fuel-air distribution obtained with the multiple-jet fuel injector, the multiple conical tube fuel injector was designed. The reduced area at the inlet served three functions. First the pressure drop would help straighten out any airflow nonuniformities. Second, the increased air velocity (velocity at tube inlet was over 4 times the reference velocity) would improve the atomization of the fuel and thus improve vaporization and mixing. Third, the dwell time is reduced and thus any autoignition problems that might occur at higher temperatures and pressures would be reduced.

Nearly uniform spatial fuel-air distributions were obtained with the multiple conical tube fuel injector. With a mixing length of 22.9 cm (fig. 6(a)) the distribution was always within the design goal of ±10 percent of the mean at an inlet air temperature of 800 K, inlet air pressure of 0.3 MPa, reference velocities of 10 and 20 m/s and fuel-air ratios of 0.0065 and 0.0165. The distribution was slightly more uniform at 20 m/s than at 10 m/s.

Decreasing the mixing length to 17.8 cm resulted in a fuel-air distribution that generally is within ±10 percent of the mean with the largest deviation being 20 percent above the mean (fig. 6(b)). Further decreasing the mixing length to 12.7 cm resulted in profiles that were not nearly as uniform with the fuel-air ratio varying from 20 percent below the mean to 40 percent above (fig. 6(c)).

The pressure drop of the multiple conical tube fuel injector was approximately 1.0 percent at a reference velocity of 20 m/s (inlet air temperature of 800 K and pressure of 0.3 MPa). At 10 m/s the pressure drop was one-fourth of that at 20 m/s or 0.25 percent.

Vaporization data was taken with this fuel injector. The degree of vaporization was determined with the spillover technique as described in reference 4. Measurements were taken in the center of the duct. Since some vaporization data points were taken outside the efficient operating range of the catalytic converter this section was replaced with a hydrogen enriched burner. A drilled plate with 75 percent blockage was used as a flameholder. The drilled plate was 23.2 cm downstream of the gas sampling probe.

Nearly complete vaporization, 98.5 percent, of the fuel was obtained at an inlet air temperature of 700 K (reference velocity of 10 m/s, a fuel-air ratio of 0.020, pressure of 0.3 MPa and a vaporization length of 17.8 cm). As the inlet air temperature was decreased (see fig. 7), the degree of vaporization decreased. At an inlet air temperature of 600 K, about 88 percent of the fuel was vaporized and at 460 K only 66.7 percent of the fuel was vaporized.

Decreasing the fuel-air ratio from 0.020 to 0.010 did not change the degree of vaporization (within the scatter of the data) at 600 K and 10 m/s. The degree of vaporization for the 0.010 fuel-air ratio was 89 percent versus the value from the curve through the 0.020 fuel-air ratio points of 85.5 percent and the two 0.020 fuel-air ratio data points of 87.9 and 89.9 percent.

Increasing the reference velocity from 10 to 19 m/s increased the degree of vaporization from 88 to 96.6 percent at an inlet air temperature of 600 K. Increasing reference velocity has two opposing effects on vaporization. One effect is to improve atomization which would improve vaporization, while the other is to reduce dwell time which decreases vaporization. Since the vaporization increased with the increased velocity the effect of improved atomization was greater than the effect of reduced dwell time.

Air velocity measurements were taken with the traversing probes at mixing lengths of 17 and 25 cm. The profiles were within ±10 percent across the diameter of the duct.

SUMMARY OF RESULTS

Fuel preparations systems using a Sonicore, a splash-groove, a multiple-jet and a conical tube fuel injector were evaluated for use with a catalytic reactor. The following results were obtained:

1. The multiple conical tube fuel injector gave the best fuel-air distribution data. A distribution within ±10 percent of the mean was obtained at a 22.9 cm mixing length, within 20 percent at 17.8 cm mixing length and within 40 percent at a 12.7 cm mixing length.

2. With the multiple conical tube fuel injector 98.5 percent of the fuel was vaporized at an inlet air temperature of 700 K, pressure of 0.3 MPa, fuel-air ratio of 0.020, reference velocity of 10 m/s and mixing length of 17.8 cm. Increasing the reference velocity from 10 to 19 m/s increased the vaporization from 88 to 96.6 percent. The pressure drop was 0.25 percent at 10 m/s and 1.0 percent at 20 m/s. Uniform velocity profiles were obtained downstream of the injector. No autoignition reactions were observed at the conditions tested.

3. A spatial fuel-air ratio distribution that was within ±40 percent of the mean was obtained using the multiple-jet fuel injector and a mixing length of 25 cm. Placing a drilled plate upstream of the injector with large holes in rich zones and small holes in lean zones improved the distribution to within ±20 percent of the mean.

4. The splash-groove fuel injector with a 45^{o} vane angle air swirler had a maximum fuel-air ratio of 1.55 times the mean after a mixing length of 20.3 cm. Decreasing the inlet diameter from 12 to 10.2 cm and using a 30^{o} vane angle air swirler improved the distribution to within ±20 percent of the mean with a mixing length of 24 cm. Reducing the length to 15.2 cm resulted in a poorer profile which was lean at the wall.

5. The Sonicore fuel injector gave the poorest fuel-air distribution results. At a mixing length of 24.7 cm it had maximum values of local fuel-air ratio to mean fuel-air ratio of 4 with a 30^{o} vane angle air swirler, 3 with a 45^{o} swirler, 1.8 with a 60^{o} swirler and 1.5 with a compound 30^{o} to 60^{o} swirler.

REFERENCES

1. Anderson, D. N.: Emissions and Performance of Catalysts for Gas Turbine Catalytic Combustors. ASME Paper 77-GT-65, Mar. 1977.

2. Anderson, David N.; Tacina, Robert R.; and Mroz, Thaddeus S.: Catalytic Combustion for the Automotive Gas Turbine Engine. NASA TM X-73589, 1977.

3. De Corso, S. M. et al.: Catalysts for Gas Turbine Combustors - Experimental Test Results. ASME Paper 76-GT-4, Mar. 1976.

4. Tacina, Robert: Experimental Evaluation of Two Premixing-Prevaporizing Fuel Injection Concepts for a Gas Turbine Catalytic Combustor. NASA TM X-73422, 1976.

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.

6. Koltookian, Sarkis Aram: Experimental Measurements of Fuel-Air Mixing in a Laboratory Burner. B. S. Thesis, Massachusetts Instiute of Technology, 1977.

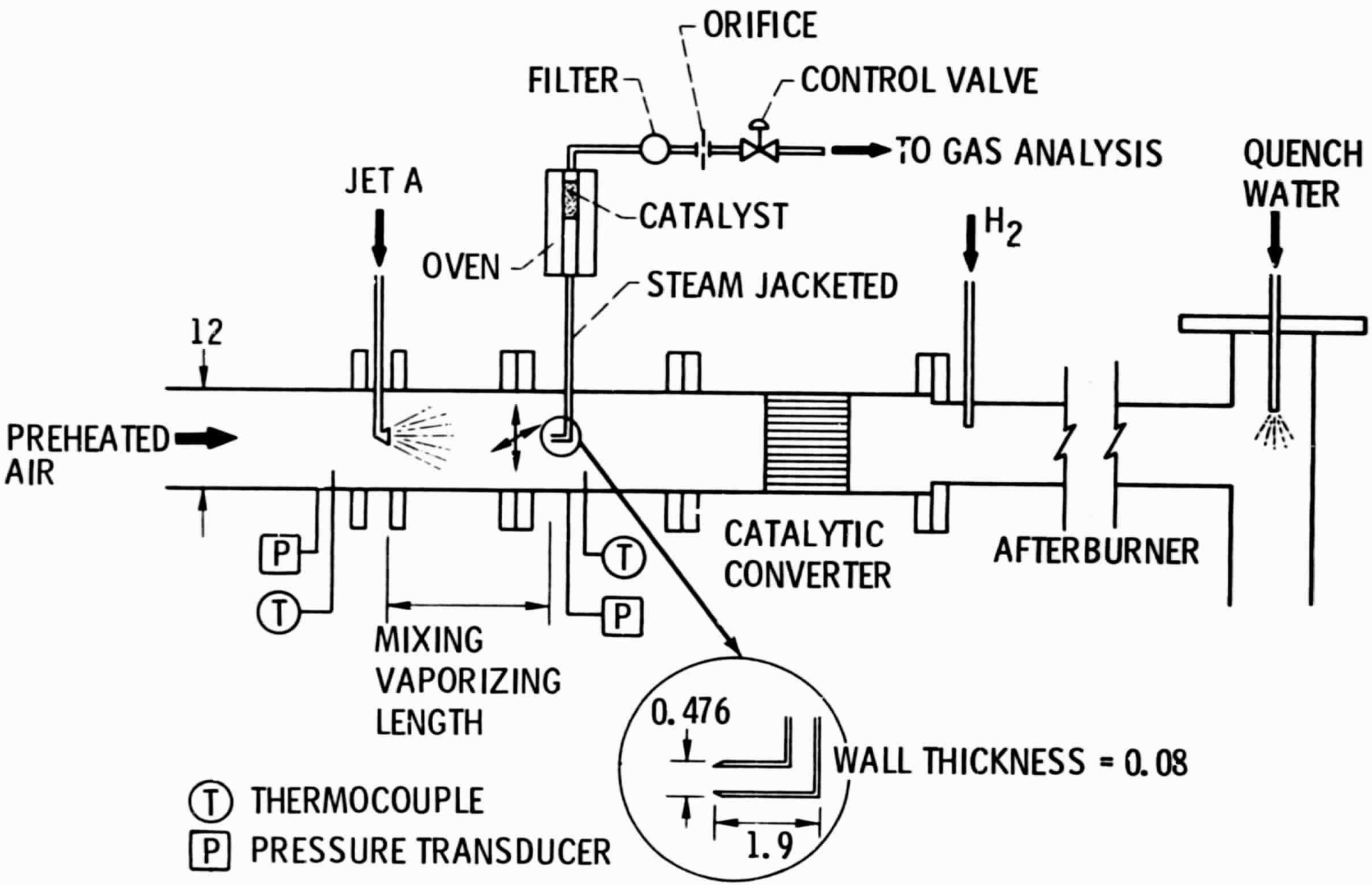
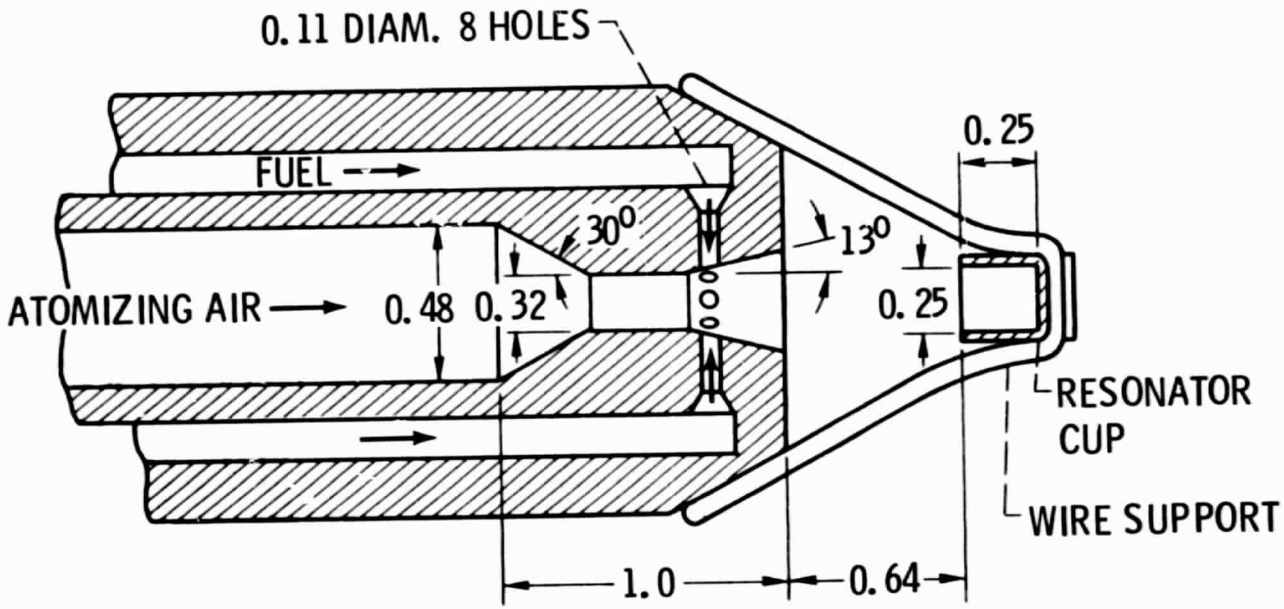
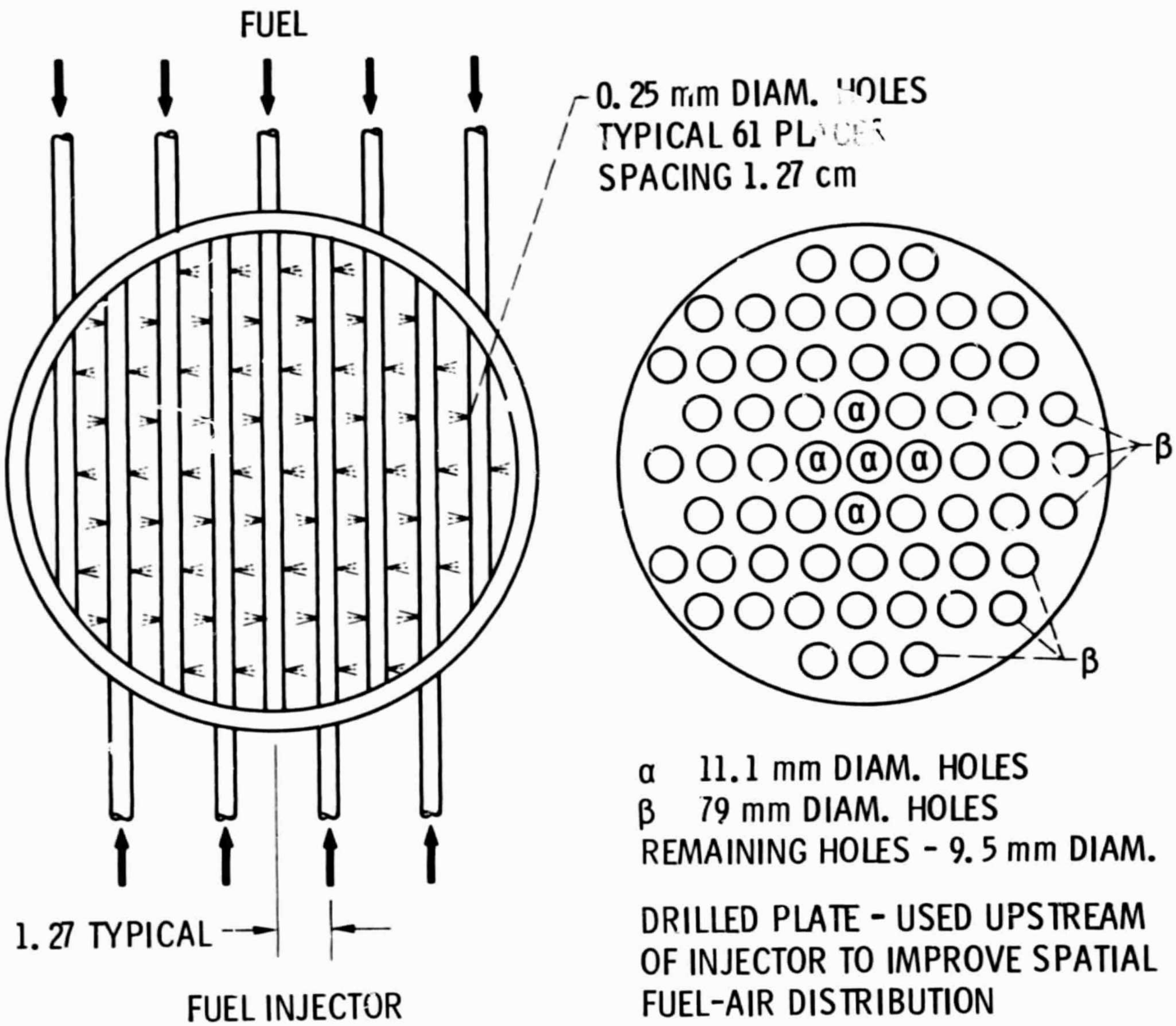


Figure 1. - Rig schematic, dimensions in cm.



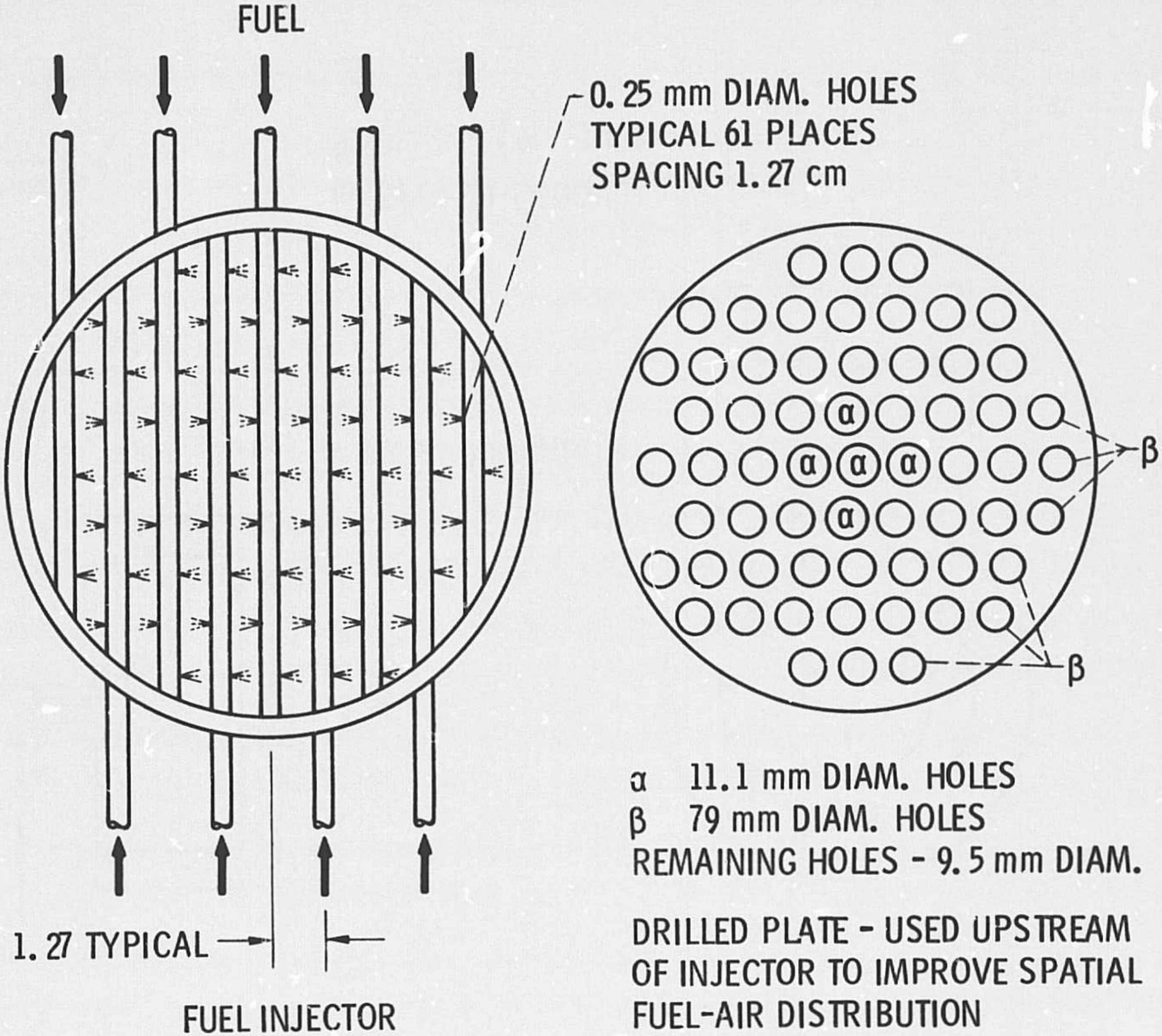
(a) SONICORE.

Figure 2. - Fuel injectors, dimensions in cm.



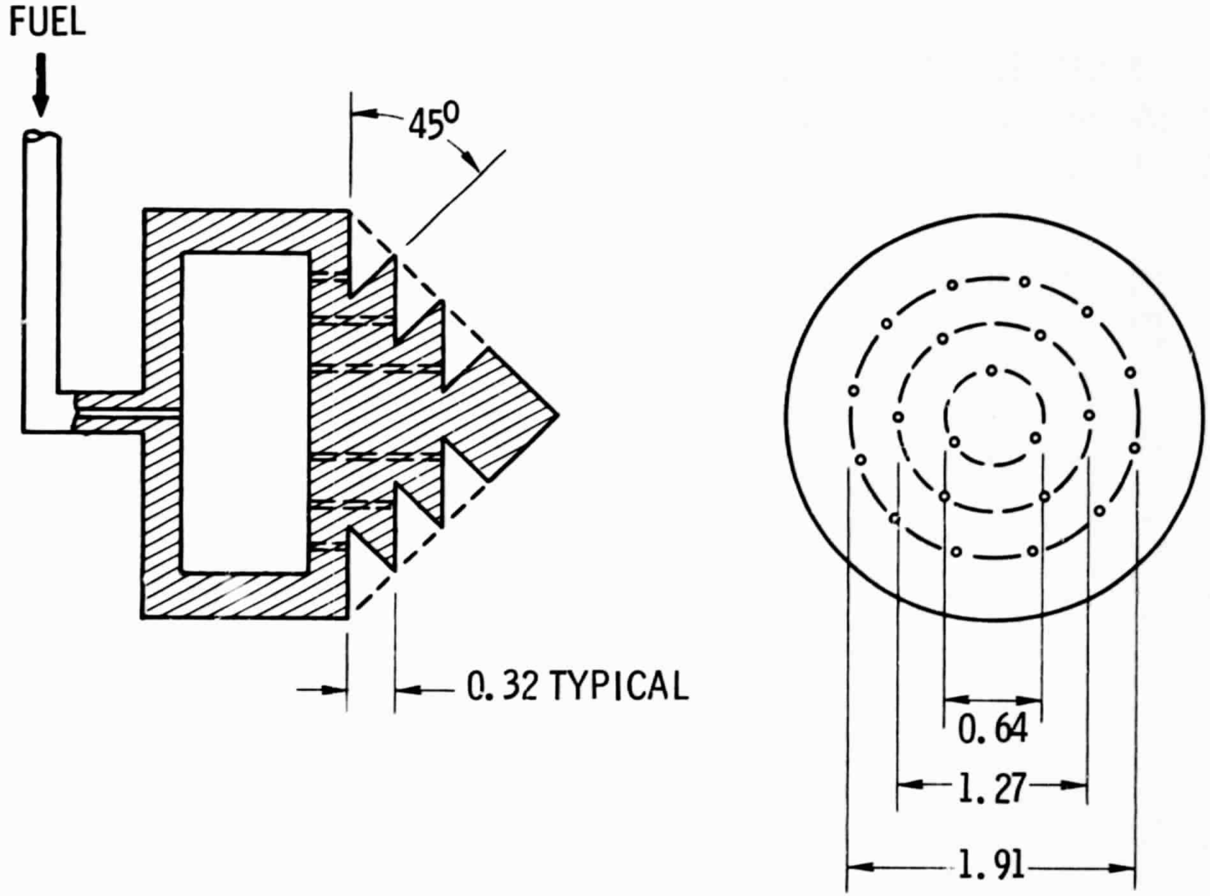
(c) MULTIPLE JET.

Figure 2. - Continued.

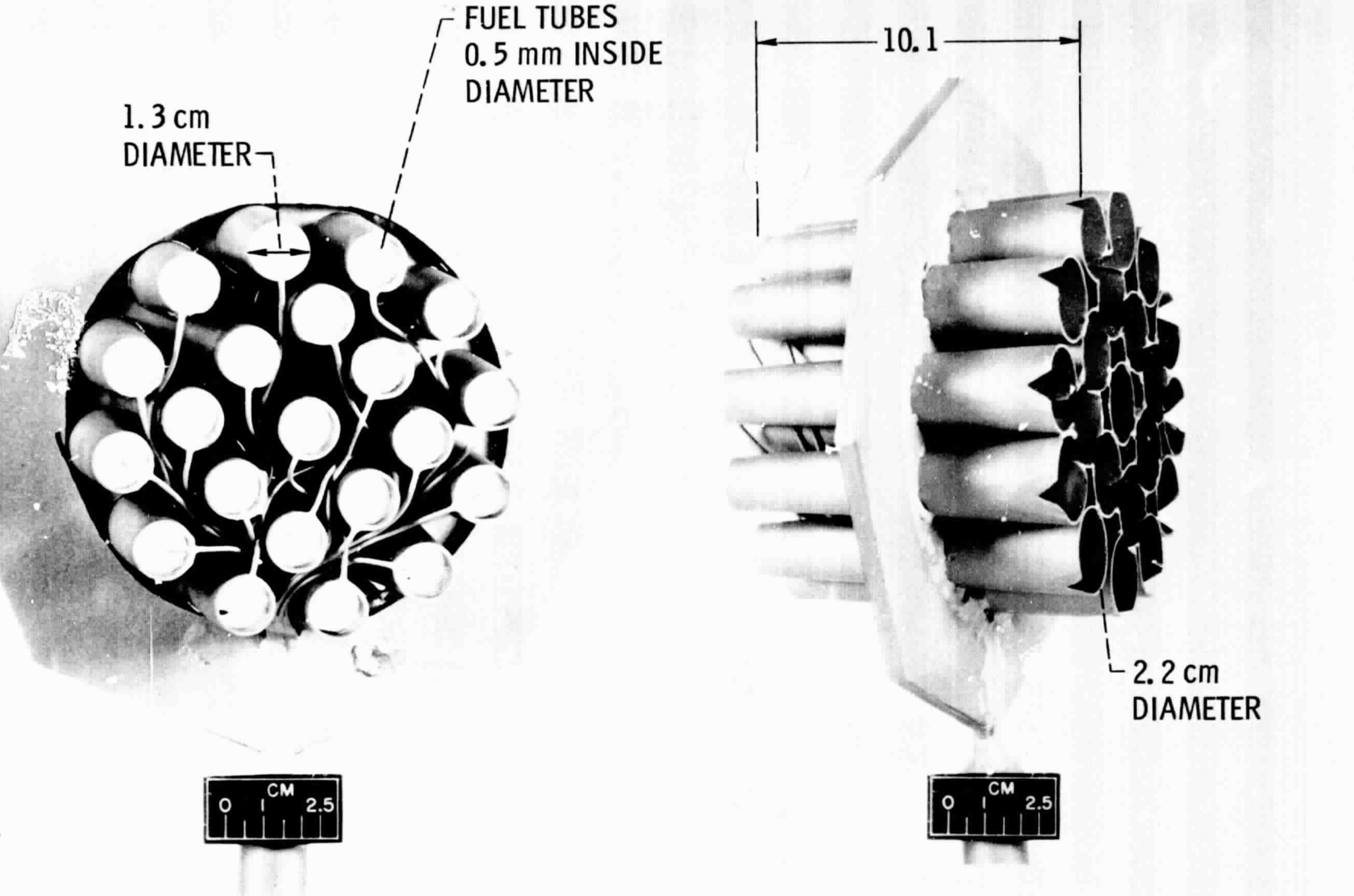


(c) MULTIPLE JET.

Figure 2. - Continued.

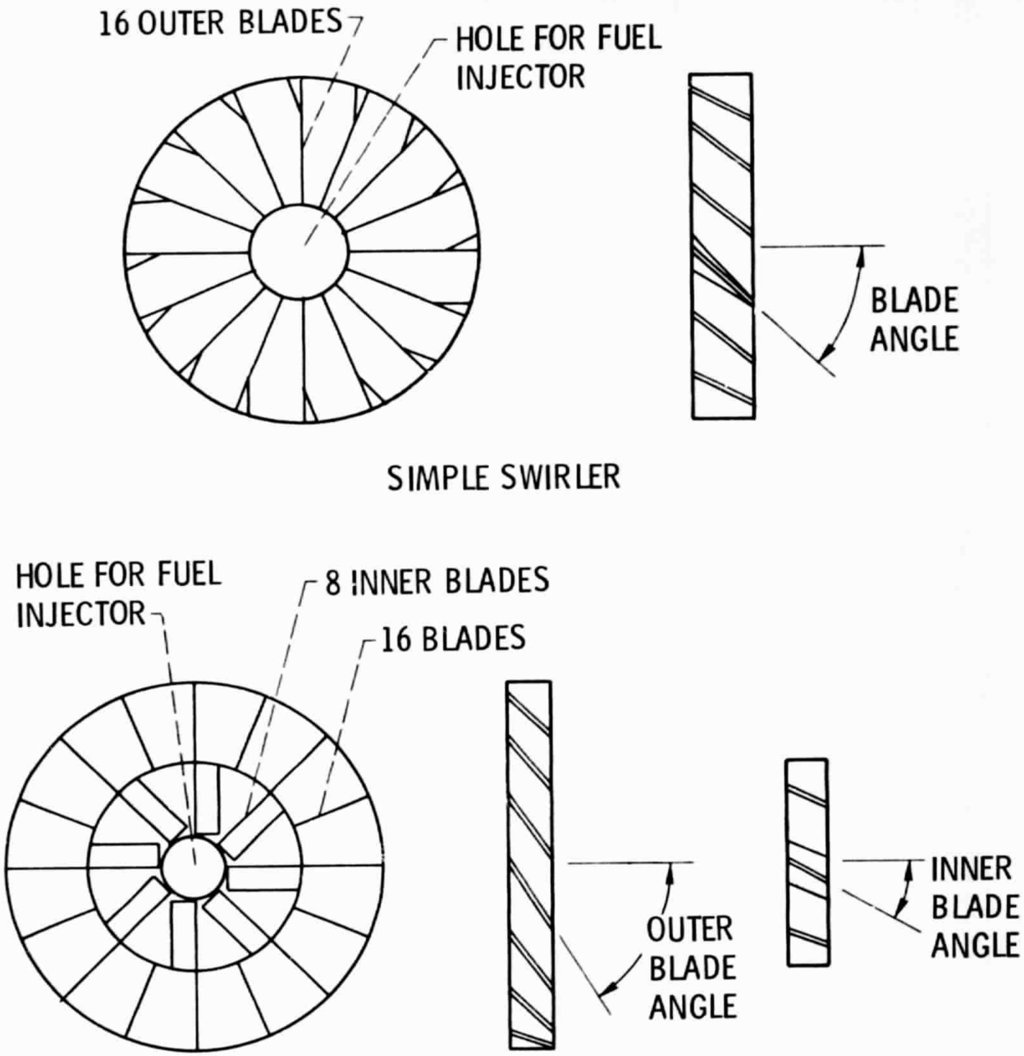


(b) SPLASH-GROOVE.
Figure 2. - Continued.



(d) MULTIPLE CONICAL TUBES.

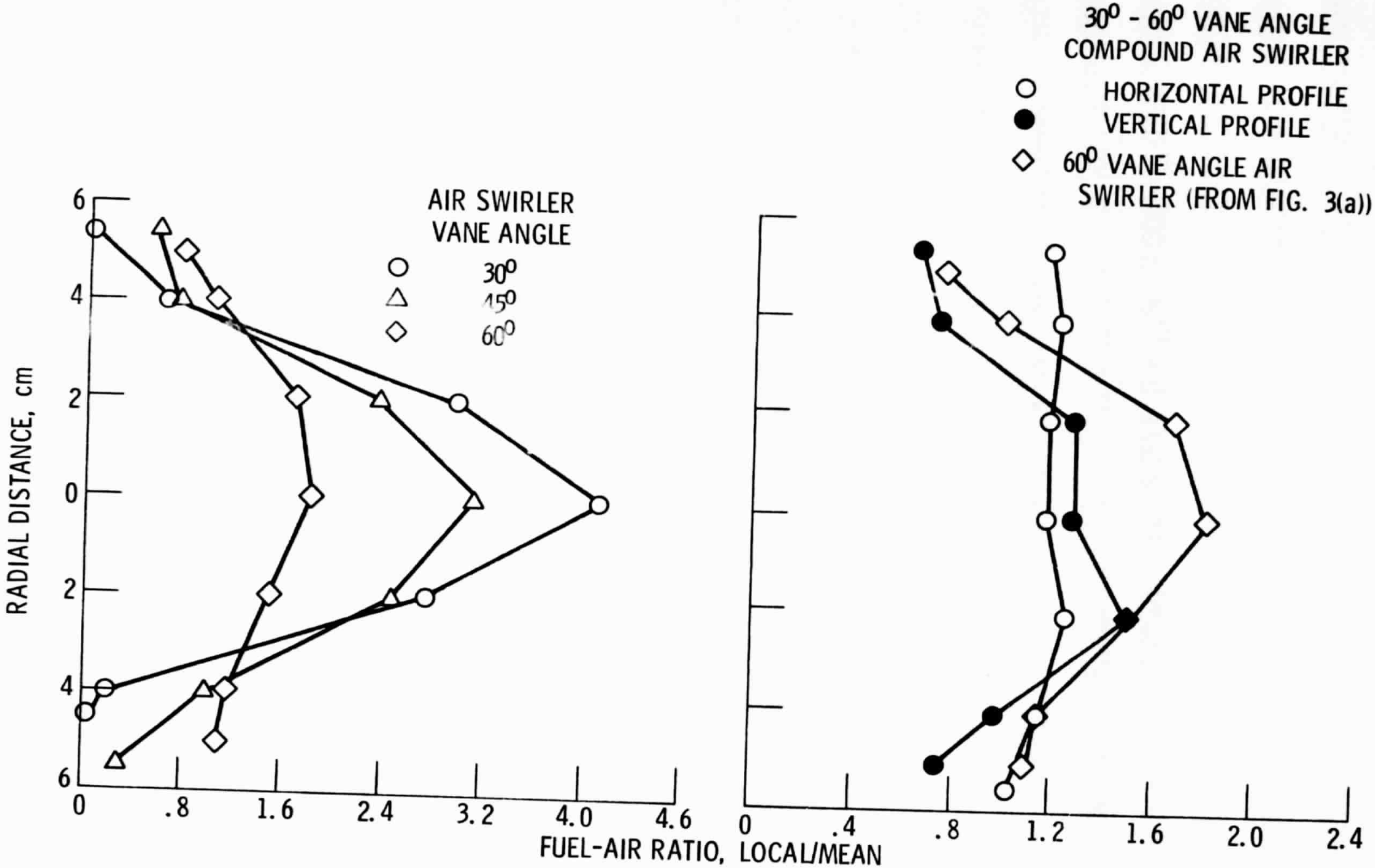
Figure 2. - Continued.



COMPOUND SWIRLER

(e) AIR SWIRLERS.

Figure 2. - Concluded.



(a) CONSTANT VANE ANGLE AIR SWIRLERS.

(b) COMPOUND AIR SWIRLER, 30° INSIDE VANE ANGLE AND 60° OUTSIDE VANE ANGLE.

Figure 3. - Spatial fuel distribution, Sonicore fuel injector, 24.7 cm mixing length. T_{in} = 600 K, P_{in} = 0.5 MPa, V_R = 20 M/S, f/a = 0.010.

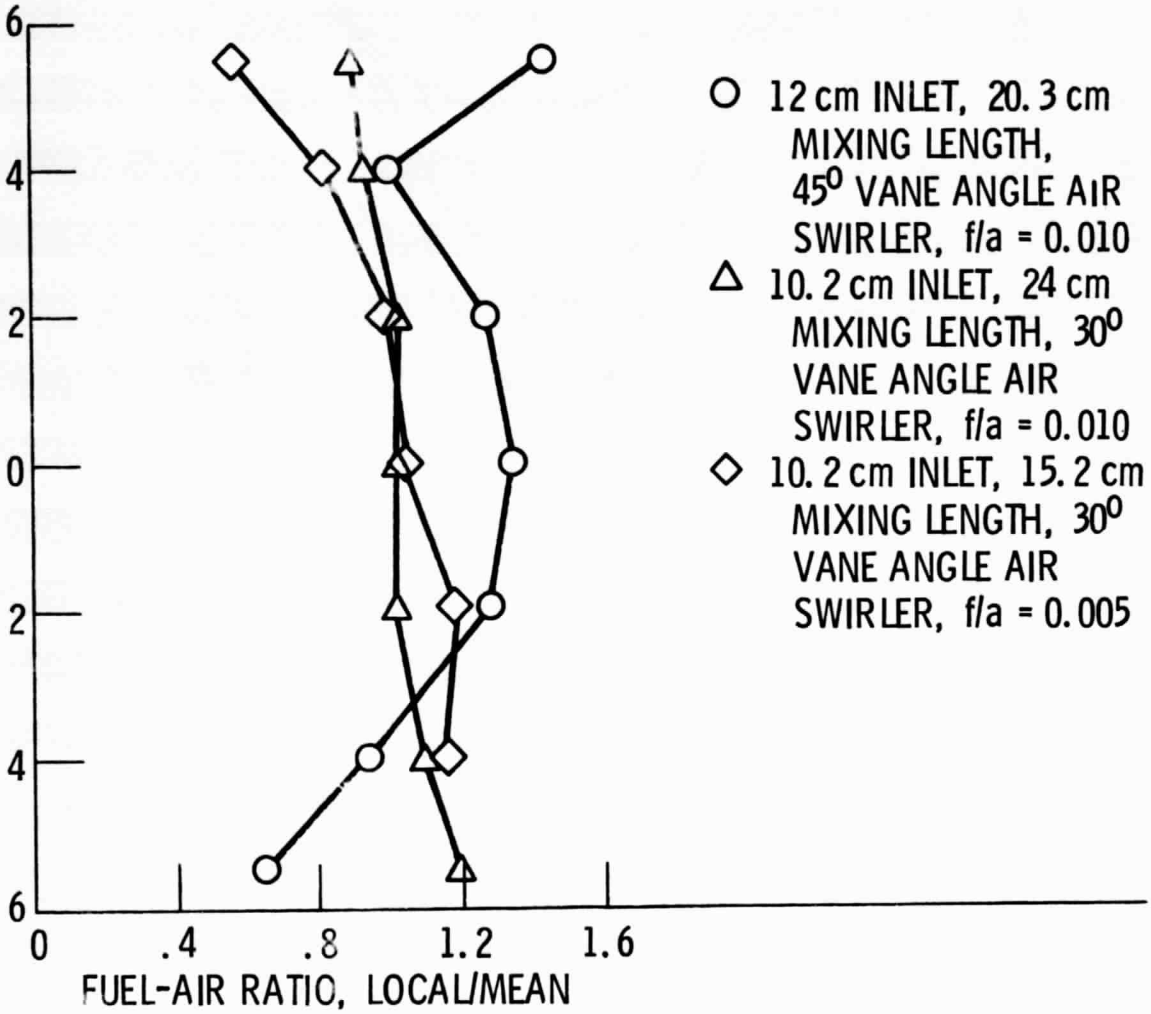


Figure 4. - Spatial fuel distribution, splash-groove fuel injector. T_{in} = 800 K, P_{in} = 0.3 MPa, V_R = 20 M/S.

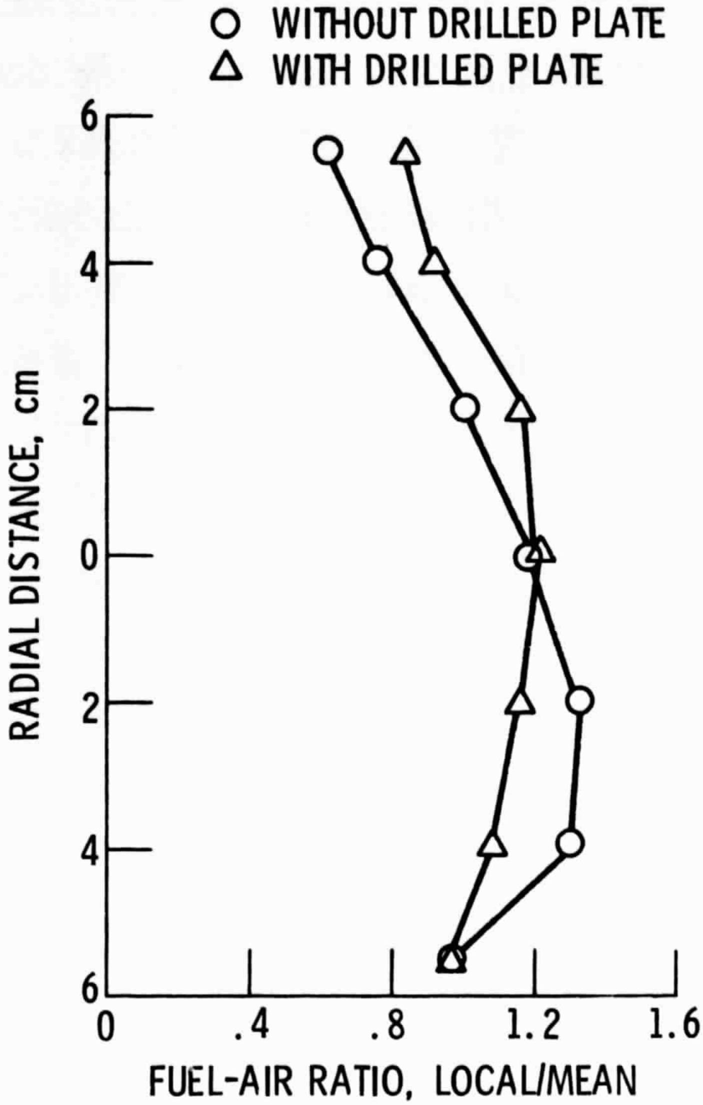


Figure 5. - Spatial fuel distribution, multiple-jet fuel injector, 25 cm mixing length. T_{in} = 800 K, P_{in} = 0.5 MPa, V_R = 20 M/S, f/a = 0.010.

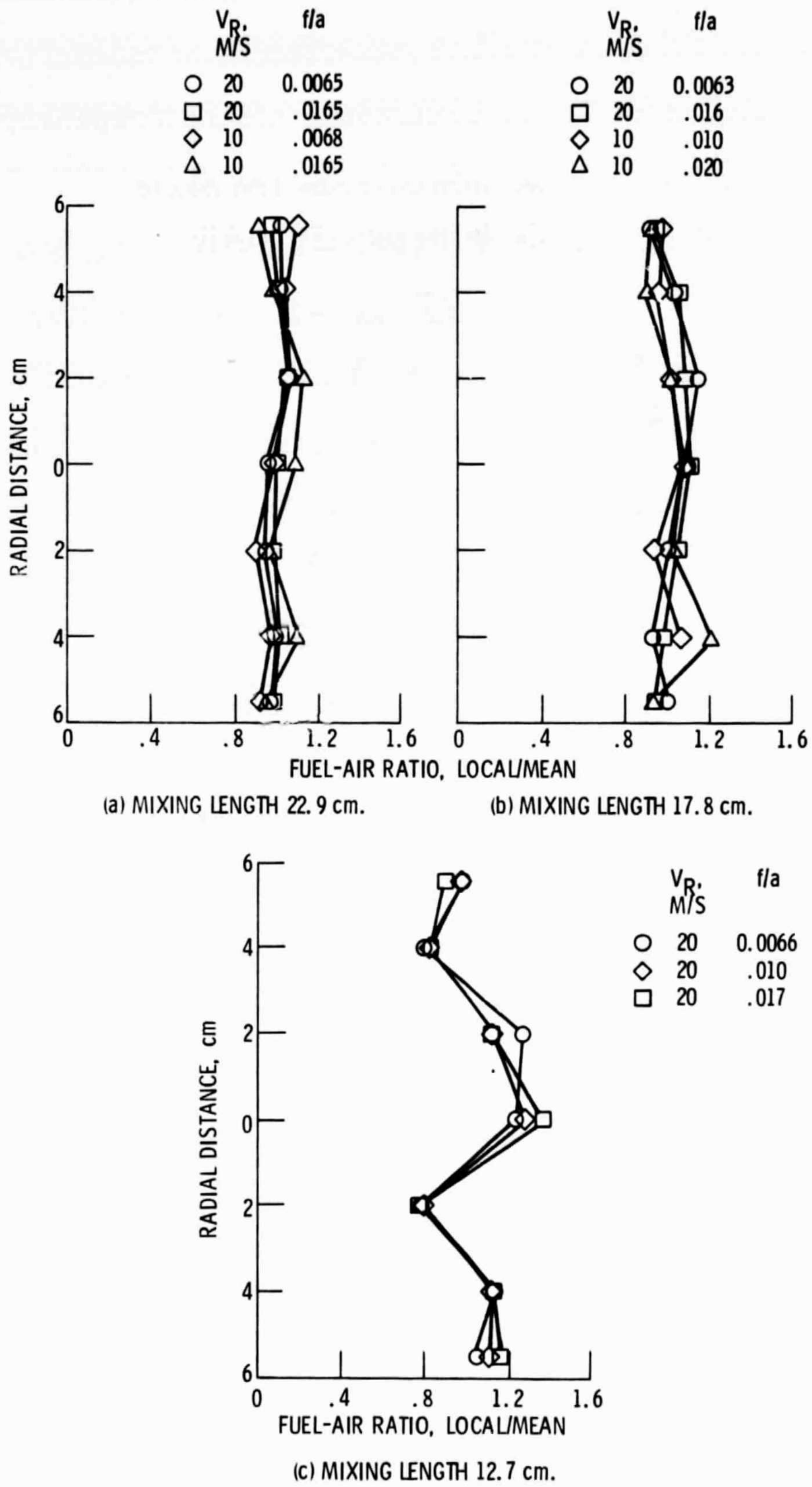


Figure 6. - Spatial fuel distribution, multiple conical tube fuel injector. T_{in} = 800 K, P_{in} = 0.3 MPa.

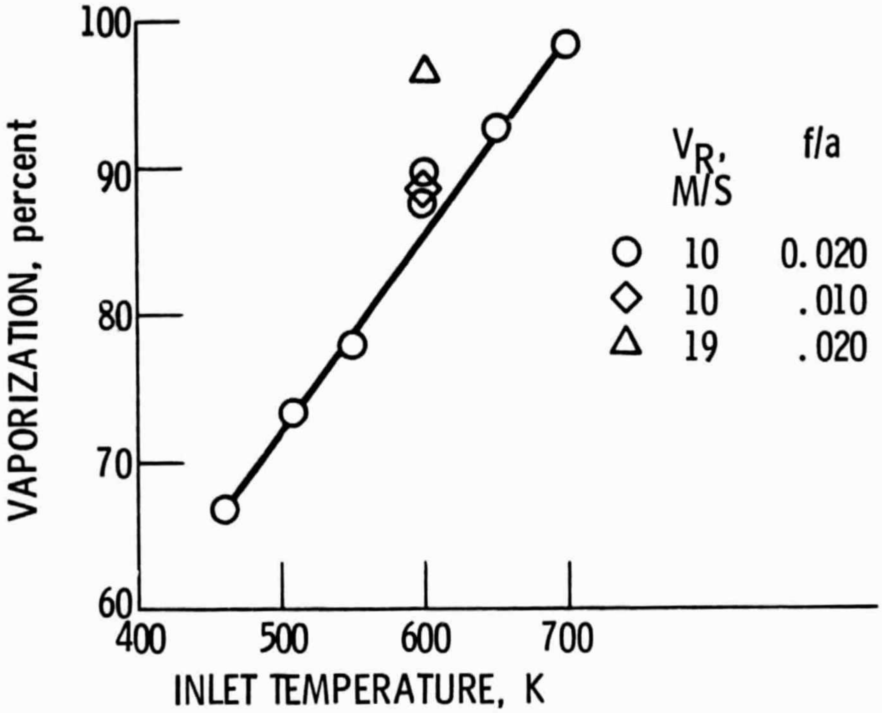


Figure 7. - Effect of inlet air temperature on degree of vaporization using multiple conical tube fuel injector. P_{in} = 0.3 MPa, vaporization length = 17.8 cm.