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FLOW CHARACTERISTICS OF VARIOUS SWIRL-CAN MODULE DESIGNS

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16. Abstract

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SUMMARY

Flow measurements were performed on each of six swirl-can combustor module designs under simulated combustor operating conditions to find the design which exhibited a small recirculation zone, intense air mixing, and good fuel distribution in its wake. These conditions are favorable for producing low oxides of nitrogen emissions and high combustion efficiency. The measurements were made using a three module array to simulate the multimodule array of a full combustor. The recirculation zones of the module wakes were found to vary both in size and strength among the designs at a test condition which simulated a combustor inlet pressure of 62 newtons per square centimeter (90 psia), an inlet air temperature of 589 K (600° F), and a reference velocity of 25.4 meters per second (83.5 ft/sec). At this same simulated operating condition, the turbulence intensities were 30 percent or greater in the wakes for all designs tested, indicating intense mixing taking place. A study of the fuel distribution indicated good fuel atomization for all designs at the aforementioned condition, but none of the designs exhibited a good fuel spray pattern under a simulated engine altitude relight condition. The swirl-can module design judged most promising as a result of the aforementioned measurements incorporated two air swirlers which discharged air in opposite directions (contraswirl), mixed fuel and air upstream of the inner swirler, and had a flow area blockage of 64.3 percent for the three module array.

INTRODUCTION

An experimental investigation was conducted to measure the recirculation zone, the turbulence intensity, and the fuel distribution patterns in the wake region of various swirl-can combustor module designs to provide design information for reducing combustor oxides of nitrogen emissions. Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by gas turbine engines. Two general areas of concern have been expressed: urban pollution in the vicinity of airports and pollution of the stratosphere. The principal urban pollutants are unburned hydrocarbons and carbon monoxide during idle and taxi, and oxides of nitrogen (NO_x) and smoke during takeoff and landing. Oxides of nitrogen are also considered to be a significant pollutant formed during high altitude cruise.

Altering gas turbine combustor designs to make substantial reductions in NO_x will be an extremely difficult task (ref. 1). Oxides of nitrogen are formed during any combustion process involving air. The amount formed is reaction rate controlled and is a function of flame temperature, dwell time of the combustion gases at high temperatures, concentrations of nitrogen and oxygen present, and the combustor pressure. Flame temperatures increase as the combustor inlet temperature increases and as the primary zone fuel-air ratio approaches stoichiometric values. Dwell time is affected by combustor primary zone length and reference velocity. Trends in combustor operating conditions indicate a steady increase in inlet temperature and pressure due to increasing compressor pressure ratios (ref. 2).

Lewis Research Center is engaged in research directed toward development of combustors with substantially reduced levels of NO_x emissions. Combustors consisting of arrays of combustor modules constitute one phase of this research. Past studies of these swirl-can modular combustors (refs. 3 to 8) indicate that this combustor type offers several inherent advantages for reducing NO_x. These advantages include:

(1) Short combustor lengths with accompanying short recirculation zones behind each module are realized for burning and mixing. Thus dwell time is reduced.

(2) Quick mixing of burning gases and diluent air occurs inasmuch as swirl-can combustors pass nearly all of the airflow through the primary combustion zone and large interfacial mixing areas exist between combustion gases and airflow around the swirl-cans.

(3) A more uniform mixture of fuel and air is produced by the large number of fuel entry points, thereby reducing localized intense burning.

The previous work was confined to burning tests of various swirl-can module designs in sector or full-annular combustors. No diagnostic work was performed to investigate the behavior of fuel and air in the primary zone or in the wake region of the modules.

The present investigation involves three different diagnostic measurements of the wake region of six different swirl-can module designs: a determination of the size and strength of the recirculation zone of the module wakes, a measure of the turbulence intensity in the module wakes, and a study of the fuel distribution from the swirl-can modules (using water instead of fuel). Measurements of the recirculation zone and turbulence intensity were obtained at an ambient pressure and temperature condition which simulated a combustor condition of 62-newton-per-square-centimeter (90-psia) inlet air pressure, 589 K (600° F) inlet air temperature, and a 25.4-meter-per-second (83.5-ft/sec) reference velocity. This condition is representative of the high power operation of previous swirl-can combustors. The fuel distribution study was conducted at the aforementioned condition as well as an ambient pressure and temperature condition which simulated an engine altitude relight condition with an inlet air pressure of 5.5 newtons per square centimeter (8.0 psia), an inlet air temperature of 311 K (100° F), and a reference velocity of 14.8 meters per second (49 ft/sec).

SYMBOLS

A	area
C_D	discharge coefficient
D	characteristic dimension of swirl-can module, 3.35 cm (1.32 in.)
N_R	Reynolds number
P_s	static pressure
P_t	total pressure
r	radial coordinate perpendicular to z-axis
T	temperature
V	velocity
V_{tot}	total air velocity vector
$\overline{V}_{xz}$	time averaged value of V_{xz}
v_{xz}	fluctuating component of V_{xz}
v'_{xz}	rms velocity, $\sqrt{\overline{(v_{xz})^2}}$
$\dot{w}$	airflow rate
$\dot{w}_{mod}$	airflow rate per swirl-can module, $\dot{w}_{ts}/4.37$
x, y, z	orthogonal coordinates
α	yaw angle of air velocity vector
β	pitch angle of air velocity vector
μ	viscosity
ρ	density

τ_1	turbulence intensity, $v'_{xz}/\overline{V}_{xz}$
τ_2	turbulence intensity, v'_{xz}/V_{ave}
ψ_n	normalized stream function

Subscripts:

ave	spatial average value
c	combustor condition
ts	simulation rig test section condition
xz	any quantity in x, z-plane

THEORY

The size and strength of the recirculation zone of the swirl-can module wake can influence the amount of NO_x formed. It is expected that a large recirculation zone results in a long dwell time of combustion gases and therefore produces relatively high levels of NO_x. On the other hand, a large amount of recirculated gas is beneficial from a combustion stability point of view. Therefore, a recirculation zone with good strength and minimum size would seem to provide low levels of NO_x but retain good combustion efficiency.

Mixing of the combustion gases and the air that bypasses the swirl-can modules also strongly affects the NO_x emissions of the combustor. The more intense the mixing, the quicker the temperature of the combustion gas is reduced below the level where NO_x formation occurs.

A good distribution of fuel in the combustor primary zone is very important from an emissions point of view. Large fuel droplets may result in poor vaporization and poor combustion efficiency which is reflected in high levels of carbon monoxide and unburned hydrocarbons. An uneven distribution of fuel may result in pockets of fuel and air which are close to the stoichiometric mixture ratio and result in very high temperature combustion and a high rate of NO_x formation. Also, it is important to have good fuel atomization at conditions that would exist during altitude relight of an engine. The swirl-can module is essentially an air-blast device (i. e., it relies mainly on combustion air flow to atomize fuel) and it is difficult to achieve good performance with air-blast fuel injectors at altitude relight conditions.

APPARATUS

Test Facility and Instrumentation System

The investigation was conducted in the test facility shown schematically in figure 1. Air at ambient temperature is remotely supplied to the facility at pressures up to 114 newtons per square centimeter (165 psia). The airflow is metered by a square-edged orifice installed with flange taps according to ASME standards. The air is then throttled to near atmospheric pressure by a flow control valve before entering an air filter and the test section. The air is discharged into the atmosphere through a noise absorbing duct. Water, used to simulate fuel, is supplied at high pressure from a nearby tank and is metered by a remote control valve. The water flow rate is measured by a turbine flowmeter using a frequency-to-voltage converter for readout and recording.

All test instrumentation was recorded by the Lewis Central Automatic Data Processing System (ref. 9). All pressures were measured by individual strain gage transducers or by using a Scanivalve system which has 48 ports, each ducting to a flush mounted ±1.72-newton-per-square-centimeter (±2.5-psid) strain gage transducer. The valve dwell time at each port was 0.2 second, three times the interval required to reach steady state. Continuous calibration of the Scanivalve system was provided by ducting known pressures to several ports. All data were remotely recorded on magnetic tape for subsequent processing with a digital computer data reduction program.

Test Section for Simulation Rig

The simulation tests of the swirl-can combustor were performed using a plexiglas rectangular pipe of inside dimensions 21.2 by 7.21 centimeters (8.34 by 2.84 in.) as shown in figure 2. Three swirl-can modules were mounted in a row as shown, and a small blockage strip was attached around the perimeter of the test section at a location alined with the downstream end of the modules. This strip adjusted the flow blockage to values equivalent to that of the swirl-can modules installed in the full annular combustor. The test section remained constant in cross section for 32 centimeters (12.5 in.) downstream of the swirl-can array before entering a converging transition section. Flow straightening screens and a tube bundle were mounted upstream of the test section. This arrangement resulted in a very flat air velocity profile ahead of the swirl-can module array. The orthogonal coordinate system used is shown in figure 2(a), and the origin of the system was taken to be at the center of the center swirl-can module at its downstream face.

A traverse mechanism was mounted on top of the test section for attachment of various probe devices. The traverse was mounted on a dove-tail slide for movement in the axial or z-direction. The traverse had a screw drive for movement of the probe in the x-direction. No motion was possible in the y-direction.

Swirl-Can Module Designs

A typical swirl-can module is shown schematically in figure 3. Each module consists of three components; a carburetor, an inner swirler, and a flame stabilizer. In operation, the module performs several functions. Each module mixes fuel with air, swirls the mixture, stabilizes combustion in its wake, and provides large interfacial mixing areas between the bypass air around the module and combustion gases in its wake.

Diagnostic measurements were made on six swirl-can module designs and a description of each design is presented in table I. The differences in the designs are in the projected flow area blockage, the degree of swirl, and the method of fuel injection. The blockage varied from 39.6 to 67 percent. In calculating the percent blockage, the swirler discharge coefficient was assumed equal to 1.

Swirl-can design 1 is essentially the baseline model. It incorporates a hexagonal flat-plate flame stabilizer and splashes a stream of fuel against the hub of the inner swirler; a mixture of fuel and air then passes through the inner swirler. The swirling fuel and air mixture creates a recirculation zone in the wake of the module inside of which stable combustion can occur.

Swirl-can design 2 is different from design 1 only in the flame stabilizer. A stamped swirler was installed in place of the hexagonal flat plate of design 1.

Swirl-can design 3 is identical to design 1 with the hexagonal flat plate removed. The plate removal had the effect of reducing the blockage or pressure-drop across the module array. The recirculation zone in the wake of design 3 is then a result of the inner swirler alone and can be compared with the recirculation zone of design 1 where bluff body effects also contribute substantially to the wake.

Swirl-can designs 4 and 5 are similar to design 2 in that an additional swirler was used as the flame stabilizer. The difference is that these designs have a shroud around the tip of their outer swirlers to prevent the air from sliding off the swirler blades as well as for better structural integrity. The air is discharged in the same direction from both inner and outer swirlers (coswirl) in design 4, whereas the air is discharged in opposite directions from the inner and outer swirlers (contraswirl) in design 5. These differences in air swirl should influence the module wake characteristics.

Finally, swirl-can design 6 is similar to design 5 in that contraswirling air is discharged into the module wake; however, the inner swirler open area is greater for design 6 than for the other five designs. In addition, the fuel is sprayed into an air passage inside the inner swirler. The fuel mixes with the air as it travels through the conical passage and exits the module inside of the swirling air stream and into the recirculation zone. The purpose of the design was to better confine the fuel to the recirculation zone. A characteristic dimension was desired in presenting results and the tip diameter of the inner swirler for designs 1 to 5, D = 3.35 centimeters (1.32 in.), was chosen. This dimension was also used in design 6 for consistency, and was within 0.16 centimeter (0.06 in.) of its inner swirler tip diameter.

Measurement Systems

Air velocity measurement system for recirculation zone determination. - The air velocity vector was measured in the swirl-can array using a United Sensor and Control Corporation Model DC-125-12-CD probe. The probe has five pressure-sensing holes in its conical shaped head. The pressures were measured using the Scanivalve system described previously. The magnitude of the total velocity vector at any point was determined from the total pressure, the static pressure, and the air temperature; and its direction was determined from the yaw angle α and pitch angle β. The probe could be rotated 360° to determine the yaw angle α. The pitch angle β and total and static pressures, P_t and P_s, were determined from wind tunnel calibration curves. The air temperature was measured with an iron-constantan thermocouple.

Turbulence intensity measurement system. - The turbulence intensity of the swirl-can wake was measured with a Thermo-Systems, Inc. Model 1050 anemometer system with a hot-wire probe using a 0.0038-millimeter- (0.00015-in.-) diameter tungsten wire. The output of the anemometer was fed to a linearizing circuit, and the system was calibrated with a low turbulence air jet. The rms and average velocity signals from the system were recorded for each point in the module array wake and later analyzed by digital computer.

Photographic system for fuel distribution study. - For the fuel distribution study, water instead of fuel was supplied to only the center module and a camera, located below the test section as shown in figure 2(a), was focused to the wake region of the center swirl-can. A high intensity flash unit provided adequate light and also set the film exposure to approximately 15 microseconds.

ANALYSIS

Simulation of Combustor Operating Conditions

The diagnostic measurements were desired for the swirl-can combustor when it was operating at high inlet-air temperatures and pressures. However, the test facility for these measurements was limited to ambient temperature and pressure and, therefore, combustor operating conditions were simulated in the following way. The Reynold's number is related to airflow rate by

$$N_R = \frac{\rho VD}{\mu}$$

$$= \frac{\dot{w}D}{\mu A}$$

Equating the Reynolds number for the combustor operating condition and the test section operating condition gives

$$\frac{\dot{w}_c}{\mu_c A_c} = \frac{\dot{w}_{ts}}{\mu_{ts} A_{ts}}$$

where the characteristic swirl-can dimension D has been factored out since it is constant. The combustor annular open area at the axial location of the swirl-cans A_c is 0.420 square meter (4.52 ft^2) and the test section area A_{ts} is 0.0153 square meter (0.165 ft^2). The airflow rate for the simulation tests can then be related to the actual combustor airflow rate by

$$\dot{w}_{ts} = (0.0364)\dot{w}_c \frac{\mu_{ts}}{\mu_c} \tag{1}$$

The viscosity is only dependent on temperature for moderate pressures and can be approximated by the expression

$$\mu = [175 + 0.388(T - 278)] \times 10^{-7} \quad \text{kg/(sec)(m)} \tag{2}$$

where the temperature T is in K. Equations (1) and (2) can be used to determine the proper airflow rate for the test section to simulate any combustor operating condition. The high power combustor operating condition of an inlet air pressure of 62 newtons per square centimeter (90 psia), an inlet air temperature of 589 K (600° F), and an airflow rate of 50 kilograms per second (110.3 lb/sec) corresponding to a reference velocity of 25.4 meters per second (83.5 ft/sec) (reference area = 0.535 m^2 (5.76 ft^2)), for example, results in a test section airflow rate for the swirl-can simulation rig of

$$\dot{w}_{ts} = (0.0364)(50)\,\frac{180\times10^{-7}}{296\times10^{-7}}\ \text{kg/sec} = 1.11\ \text{kg/sec}$$

when the test section air temperature is 292 K. Other combustor operating conditions could be simulated in the test section in the same way.

Recirculation Zone Mapping

The recirculation zone in the wake of a swirl-can combustor module was determined by construction of a contour map of stream function. The air velocity vector V_{tot} was determined as a function of radius r for various axial positions (z) downstream of the center swirl-can module using the five-point pressure probe described previously. The probe was confined to the centerline of the module array and axisymmetry around the center module was assumed within the center module's wake. At each of a number of axial positions, curves of the axial velocity V_z against r were then constructed from the relation

$$V_z = V_{tot} \cos \beta \cos \alpha$$

where the yaw angle α and pitch angle β are explained in figure 4. Normalized stream function ψ_n as a function of r are then computed from the relation

$$\psi_n(r) = 2\pi \int_0^r \frac{\rho V_z R\, dR}{\dot{w}_{mod}}$$

where $\dot{w}_{mod}$ is the airflow rate per swirl-can module and is related to the test section airflow rate by

$$\dot{w}_{mod} = \frac{\dot{w}_{ts}}{4.37}$$

(There are the equivalent of 4.37 swirl-can modules in the test section when the perimeter blockage strip is accounted for.) Finally, the contour map of normalized stream function is generated from computer using the previous data of stream function as input. The contour mapping is confined to the region immediately downstream of the center swirl-can module where the assumption of axisymmetry has been made.

Turbulence Intensity

A single wire probe for the hot-wire anemometer system was confined to the centerline of the module array and was of fixed orientation as shown in figure 5. The probe was, therefore, sensitive to the velocity component in the x, z-direction. This velocity component may be written as

$$V_{xz} = \overline{V}_{xz} + v_{xz}$$

where $\overline{V}_{xz}$ is the time average value at any position and v_{xz} is the fluctuating component of V_{xz}. The rms value of v_{xz} is expressed as

$$v'_{xz} = \sqrt{\overline{v^2_{xz}}}$$

where the symbol ($\overline{\ }$) again denotes time averaged. The turbulence intensities measured by the hot-wire probe are then defined as

$$\tau_1 = \frac{v'_{xz}}{\overline{V}_{xz}}$$

$$\tau_2 = \frac{v'_{xz}}{V_{ave}}$$

where V_{ave} is the spatial average air velocity of the entire test section

$$V_{ave} = \frac{\dot{w}_{ts}}{0.0153\ \rho_{ts}} \qquad \text{m/sec}$$

The turbulence intensity τ_1, may be thought of as a comparison of the mixing velocity with the local steady velocity, whereas τ_2 is the mixing velocity normalized to the spatial average velocity of the test section. Both turbulence intensities measure the amount of mixing that is taking place.

Units

The U. S. customary system of units was used for primary measurements and calculations. Conversion to SI units (Systems International d' Unites) is done for reporting purposes only. In making the conversion, consideration is given to implied accuracy and may result in rounding off the values expressed in SI units.

RESULTS

Recirculation Zone Mapping

The wakes of the center swirl-can of the three module array for six different swirl-can module designs are shown in figure 6. The actual test conditions simulated a high power combustor operating condition of an inlet air pressure of 62 newtons per square centimeter (90 psia), an inlet air temperature of 589 K (600° F), and a reference velocity of 25.4 meters per second (83.5 ft/sec). Stream function contours were confined to the center swirl-can wake region where the axisymmetry assumption was valid and where wall effects were minimal. The stream function lines are normalized with respect to the inlet airflow rate per swirl-can module. Probing could not be done inside a z/D value of 0.28 due to probe design. The recirculation zone is that region where the stream function is negative, and the size of this region varied a great deal among module designs, the smallest being design 1 and the largest being design 4. The strength of the recirculation zone is related to the maximum negative value of the stream function and varied from a value of 0.054 for design 2 to 0.12 for design 4. In other words, 12 percent of the incoming air was recirculated in the wake of design 4 and only 5.4 percent in design 2.

The wakes of the six designs have a number of interesting points. Using design 1 as a baseline model, the chief effect of removing the hexagonal flame stabilizer (design 3) was to move the center of the recirculation zone downstream. The size and strength of the recirculation zone changed only by a small amount. The addition of an outer swirler on the flame stabilizer (designs 4 and 5) greatly increased both the size and the strength of the recirculation zone over that of design 1. The contraswirl arrangement of design 5 (air discharged through swirlers in opposite directions) greatly shortened the recirculation zone over the coswirl arrangement of design 4 with very little reduction in strength. The contraswirl arrangement of design 2 on the other hand resulted in a much lower recirculation strength, probably due to interference of the adjacent cans. This reduced recirculation could have been a result of the outer swirlers not being shrouded, allowing the air to slip off the outer swirler blades. Finally, design 6 had recirculation zone elongated over that of design 5, probably because of the additional axial airflow from the conical annulus inside of the inner swirler. From a combustion stability and combustion efficiency point of view, a large recirculation zone strength is desirable. On the other hand, since NO_x formation is residence time dependent, a minimum recirculation zone region is desirable. Based on these criteria, the most promising designs are 1 and 5. Design 1 and design 5 have recirculation zone strengths of 0.095 and 0.107, respectively, and have relatively small recirculation zone volume. However, the center of the recirculation zone appears quite close to the flame stabilizer of design 1 and flame stabilizer high temperatures may result during severe operating conditions.

Turbulence Measurements

Air velocity and turbulence intensities along the centerline of the center module are shown in figure 7 for five swirl-can module designs. The measurements were made using the single hot-wire probe described previously and, therefore, the probe was only sensitive to the x, z-component of velocity. The test conditions were identical to those for the recirculation zone measurements. The turbulence was not measured for design 1. However, the results from the other five designs were quite similar and there is no reason to suspect that the turbulence of design 1 is very different.

The velocity curves all show the same trend, peaking near the middle of the recirculation zone, and displaying a minimum at the tail end of the recirculation zone. Since the probe responds equally to forward or reverse directions of airflow, the absolute value of velocity is indicated. The velocity is of course in the negative z-direction in the recirculation zone.

The turbulence intensity τ_1 reflects the large changes in the local velocity for each design; therefore, little comment can be made except to say that the intensities were very high at all points. High measured turbulence intensities measured by a hot-wire probe are subject to error due to unaccounted for nonlinear effects (ref. 10) and the data, therefore, will be limited to qualitative analysis.

The turbulence intensity τ_2 demonstrated a fairly constant high level for all five designs of about 30 percent. Also, the turbulence intensity did not show any sign of decay with downstream distance even up to 5.5 inner swirler diameters. This indicates that mixing is very intense in the near wake region as well as downstream of the recirculation zone. This behavior is beneficial for minimum NO_x production since the hot combustion gases would quickly be cooled by the diluent air below temperatures where NO_x is formed.

Air velocity profiles and turbulence intensity profiles across the swirl-can array for three different positions downstream of the array are shown in figure 8 for swirl-can design 5. The results of the other designs were similar. The velocity is peaked between swirl-cans as expected, and the turbulence intensities are again very high. The high velocity air jetting between cans has a proportionately larger degree of turbulence as evidenced both by the peaked τ_2 profiles and the fairly flat τ_1 profiles. This large level of turbulence again indicates a high level of mixing between the bypass air and the combustion gas from the swirl-can module wakes and is favorable to low NO_x emissions.

Fuel Distribution

Photographs were taken of the fuel distribution from the center swirl-can module for all six designs at test conditions which simulated high power combustor operation, low power combustor operation (idle), and various altitude relight conditions. Examples of these photographs are shown in figure 9 for designs 1, 2, 5, and 6 for two simulated test conditions: the high power combustor operating condition used in the recirculation zone mapping and previous turbulence intensity measurements, and an altitude relight condition of a combustor inlet air pressure of 5.5 newtons per square centimeter (8.0 psia), a combustor inlet air temperature of 311 K (100° F), and a reference velocity of 14.8 meters per second (49 ft/sec). Water was used to represent fuel for all the tests. At all conditions, the fuel distribution was independent of the fuel-air ratio or fuel-flow rate. The photographic system used in these tests was limited in resolution, and a more sophisticated system is necessary to better define the fuel spray pattern. However, this study did produce the following conclusions. Good fuel distribution around the swirl-can was exhibited by all six designs at the high power combustor operating condition, but designs 2 and 5 seemed to emit a finer droplet size than the other designs. All designs except design 6 had a tendency to eject the fuel out of the recirculation zone as can be seen in the photographs of figure 9. At the altitude relight condition, all designs emitted large fuel droplets. Designs 2 and 5 exhibited the best fuel droplet distributions. The fuel was poorly distributed for all other designs being confined to the lower portion of the swirl-can module wake. Therefore, none of the designs seemed to show promising results for altitude relight although designs 2 and 5 seemed to perform better than the rest.

Discussion of Results

All six swirl-can designs exhibited intense mixing in the wakes of the modules which is favorable in reducing NO_x formation. However, the size of the recirculation zone of the wakes is also important in NO_x formation, and swirl-can designs 1 and 5 had minimum recirculation zone size while maintaining good recirculation strength for good combustion stability. Good fuel distribution is also necessary from an emissions point of view, not only for minimum NO_x formation but also for low carbon monoxide and unburned hydrocarbon emissions. Swirl-can designs 2 and 5 displayed the best fuel spray distribution.

From these observations, swirl-can design 5 seems to be most promising, both for high combustion efficiency as well as for minimum NO_x formation. This swirl-can design has had initial tests in a single module combustor rig (model 8 of ref. 11) and exhibited low gaseous emissions as shown in figure 10. In addition, because of the tendency of the fuel to be ejected out of the module wake, a modification of this design was also tested which was similar to swirl-can design 6 in that the fuel was injected directly into the wake region without passing through the inner swirler (model 9 of ref. 11). These test results are also presented in figure 10 and show a considerable decrease in unburned hydrocarbon and carbon monoxide levels indicating higher combustion efficiency as well as a small drop in NO_x emissions. These results reflect the results of the fuel distribution photographs. In addition, the combustion efficiency was greater than 99 percent for both designs at all conditions tested as evidenced by the unburned hydrocarbons and carbon monoxide emissions. An emission index value of 10 for unburned hydrocarbons, and 42.5 for carbon monoxide each reflect a 1-percent combustion inefficiency. Thus, these initial burning tests confirm the results of the diagnostics study.

SUMMARY OF RESULTS

Six swirl-can module designs underwent a series of flow measurements at simulated combustor operating conditions to determine the most promising design in terms of conditions which are favorable to produce low NO_x emissions and high combustion efficiency. The tests led to the following results:

1. The recirculation zones of the module wakes varied both in size and strength. Designs 1 and 5 were judged most promising in terms of minimum recirculation zone size and high recirculation zone strength. The recirculation zone strength is related to the maximum negative stream function in the recirculation zone and was 0.095 and 0.107 for designs 1 and 5, respectively.

2. Turbulence intensities were very high for all designs tested. Measured values were 30 percent or greater. These results indicate that intense mixing takes place in the module wake as well as between combustion gases and the air that passes between the swirl-can modules.

3. Fuel distribution photographs show good fuel atomization at simulated high

power combustor operation for all designs; however, none of the designs exhibited a good fuel spray pattern under simulated altitude relight conditions. The fuel spray had a tendency to be ejected out of the module wake for all designs except design 6.

Based on the previous results, swirl-can design 5 is considered most promising and initial combustor burning tests confirm the prediction of low NO_x emissions (NASA TM X-3167) with good combustion efficiency. In addition a modification of this design to better confine the fuel to the module wake resulted in even lower emissions.

Lewis Research Center,
National Aeronautics and Space Administration,
and
U.S. Army Air Mobility R&D Laboratory,
Cleveland, Ohio, January 22, 1975,
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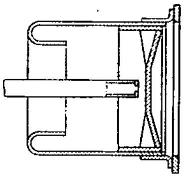
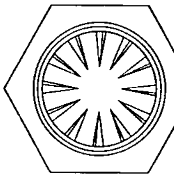
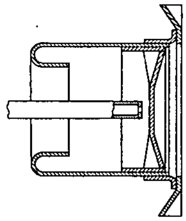
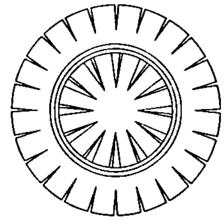
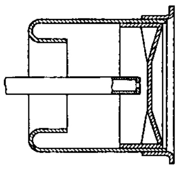
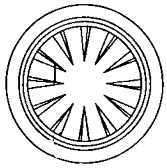
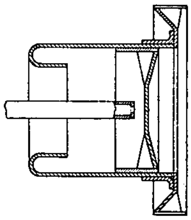
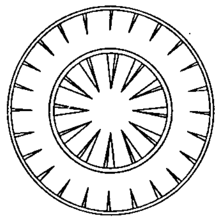
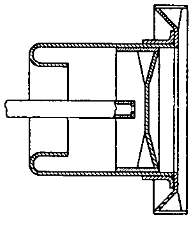
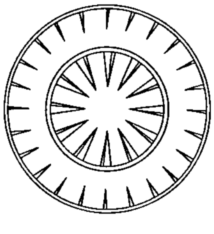
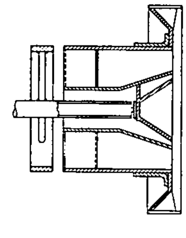
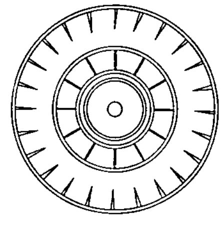
7. Niedzwiecki, Richard W.; Juhasz, A. J.; and Anderson, D. N.: Performance of a Swirl-Can Primary Combustor to Outlet Temperature of 3600° F (2256 K). NASA TM X-52902, 1970.
8. Niedzwiecki, Richard W.: Preliminary Tests of a Simplified Modular Turbojet Combustor. NASA TN D-5688, 1970.

9. Central Automatic Data Processing System. NACA TN 4212, 1958.

10. Hinze, J. O.: Turbulence. McGraw-Hill 1959, pp. 96-100.

11. Mularz, Edward J.; Wear, Jerrold D.; and Verbulecz, Peter W.: Pollution Emissions from Single Swirl-Can Combustor Modules at Parametric Test Conditions. NASA TM X-3167, 1974.

TABLE I. - DESCRIPTION OF THE SIX SWIRL

Design	Sketch of swirl-can: Cross section	Sketch of swirl-can: View looking upstream	Perc… block… in 153-… (23.8-i… test sec…
1			50.
2			67.
3			39.6
4			64.3
5			64.3
6			53.0

[a]Includes small blockage strip of appropriate size around perimeter of test sectior

MBUSTOR MODULES TESTED IN SIMULATION RIG COMBUSTOR

Flame stabilizer description	Inner swirler description	Fuel injection description
Hexagon of side L = 2.8 cm (1.1 in.); full area, 20.2 cm^2 (3.14 $in.^2$)	Stamping, 12 blades, 45° angle at tips; tip diameter, 3.35 cm (1.32 in.); hub diameter, 1.90 cm (0.75 in.); open area, 2.30 cm^2 (0.357 $in.^2$)	Fuel tube centered in can; 0.13-cm- (0.050-in.-) diameter orifice at end of tube, 0.32 cm (0.125 in.) upstream of inner swirler; fuel sprayed through inner swirler
Stamped swirler, 24 blades, 30° angle at tips; no shroud at swirler tip; swirler blades of opposite rotation from inner swirler; tip diameter, 6.10 cm (2.40 in.); hub diameter 4.57 cm (1.80 in.); open area, 2.93 cm^2 (0.454 $in.^2$)	Stamping, 12 blades, 45° angle at tips; tip diameter, 3.35 cm (1.32 in.); hub diameter, 1.90 cm (0.75 in.); open area, 2.30 cm^2 (0.357 $in.^2$)	Fuel tube centered in can; 0.13-cm- (0.050-in.-) diameter orifice at end of tube, 0.32 cm (0.125 in.) upstream of inner swirler; fuel sprayed through inner swirler
Circular sleeve; outer diameter, 4.44 cm (1.75 in.); full area, 15.5 cm^2 (2.40 $in.^2$)	Stamping, 12 blades, 45° angle at tips; tip diameter, 3.35 cm (1.32 in.); hub diameter, 1.90 cm (0.75 in.); open area, 2.30 cm^2 (0.357 $in.^2$)	Fuel tube centered in can; 0.13-cm- (0.050-in.-) diameter orifice at end of tube, 0.32 cm (0.125 in.) upstream of inner swirler; fuel sprayed through inner swirler
Stamped swirler, 24 blades, 45° angle at tips; swirler blades of same rotation as inner swirler; tip diameter, 5.79 cm (2.25 in.); hub diameter, 4.57 cm (1.80 in.); open area, 2.90 cm^2 (0.450 $in.^2$); swirler shroud diameter, 5.94 cm (2.34 in.)	Stamping, 12 blades, 45° angle at tips; tip diameter, 3.35 cm (1.32 in.); hub diameter, 1.90 cm (0.75 in.); open area, 2.30 cm^2 (0.357 $in.^2$)	Fuel tube centered in can; 0.13-cm- (0.050-in.-) diameter orifice at end of tube, 0.32 cm (0.125 in.) upstream of inner swirler; fuel sprayed through inner swirler
Stamped swirler, 24 blades, 45° angle at tips; swirler blades of opposite rotation from inner swirler; tip diameter, 5.79 cm (2.25 in.); hub diameter, 4.57 cm (1.80 in.); open area, 2.90 cm^2 (0.450 $in.^2$); swirler shroud diameter, 5.94 cm (2.34 in.)	Stamping, 12 blades, 45° angle at tips; tip diameter, 3.35 cm (1.32 in.); hub diameter, 1.90 cm (0.75 in.); open area, 2.30 cm^2 (0.357 $in.^2$)	Fuel tube centered in can; 0.13-cm- (0.050-in.-) diameter orifice at end of tube, 0.32 cm (0.125 in.) upstream of inner swirler; fuel sprayed through inner swirler
Stamped swirler, 24 blades 45° angle at tips; swirler blades of opposite rotation from inner swirler; tip diameter, 5.79 cm (2.25 in.); hub diameter, 4.57 cm (1.80 in.); open area, 2.90 cm^2 (0.450 $in.^2$); swirler shroud diameter, 5.94 cm (2.34 in.)	Full-bladed swirler mounted at upstream end of can; 12 blades, 45° angle blades; tip diameter, 3.51 cm (1.38 in.); hub diameter, 1.27 cm (0.50 in.); open area, 5.06 cm^2 (0.784 $in.^2$)	Fuel tube centered in can; 0.051-cm (0.020-in.) circumferential slot at end of tube; fuel sprayed through slot into airstream; fuel-air mixture exits can through annular slot of open area, 0.70 cm^2 (0.11 $in.^2$)

ssumes C_D = 1 for all swirlers.

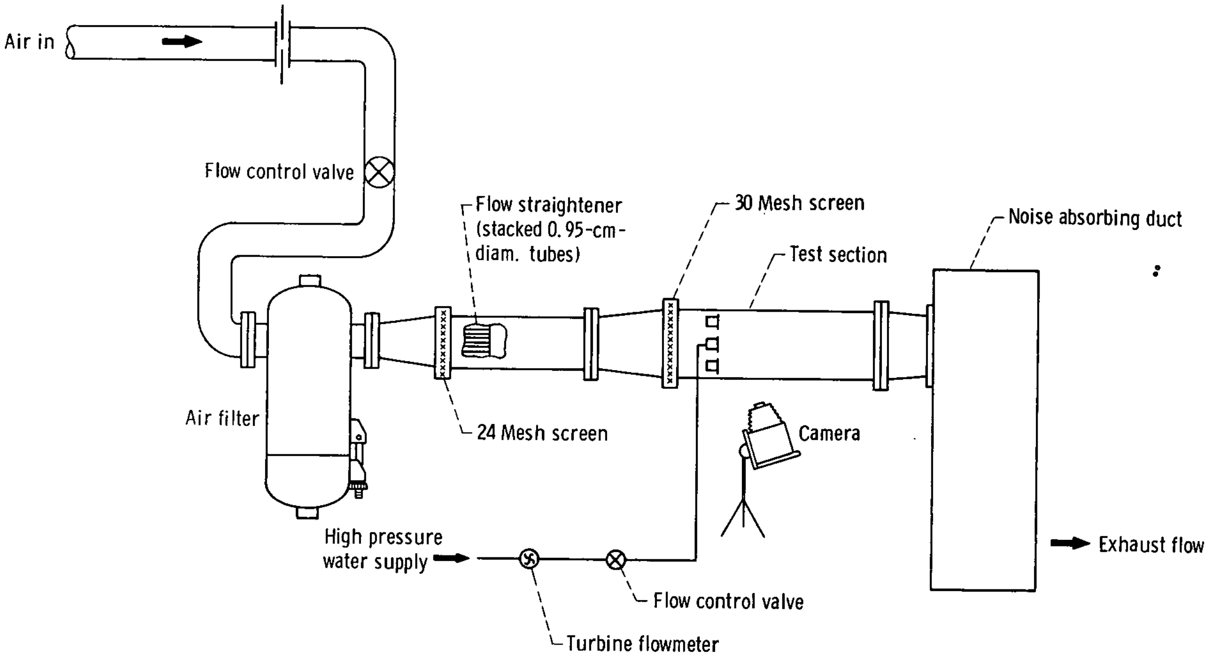
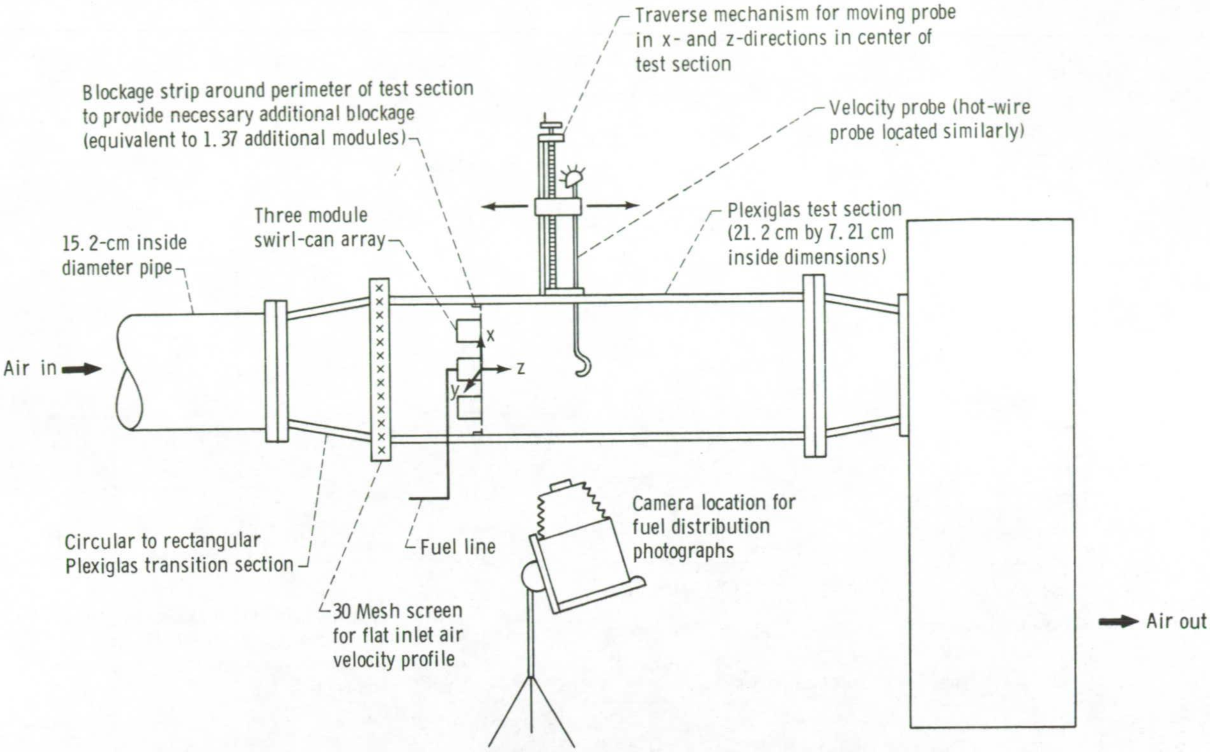
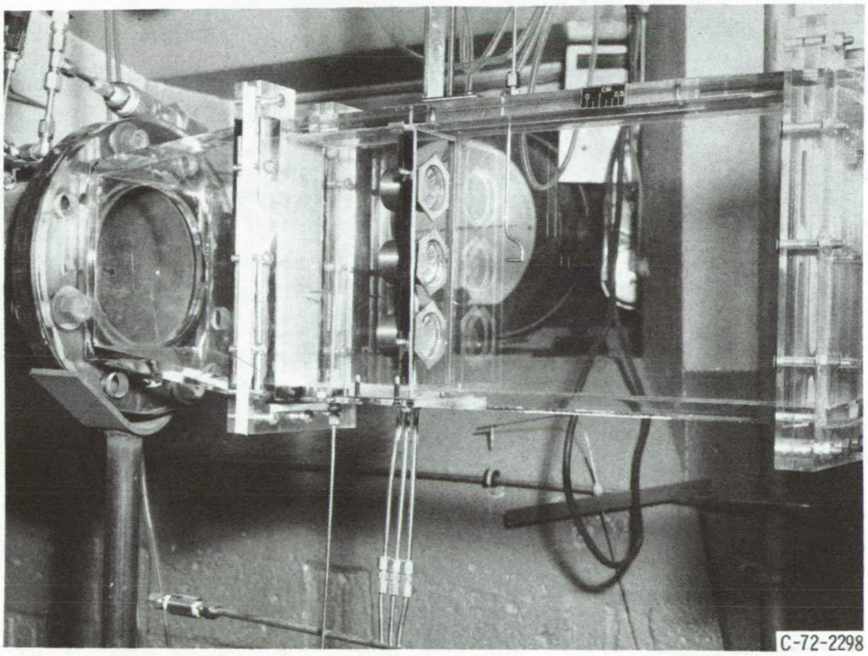


Figure 1. - Test facility for swirl-can combustor simulation rig.



(a) Test section schematic.



(b) Photograph of test section of swirl-can combustor simulation rig.

Figure 2. - Test section of swirl-can combustor simulation rig.

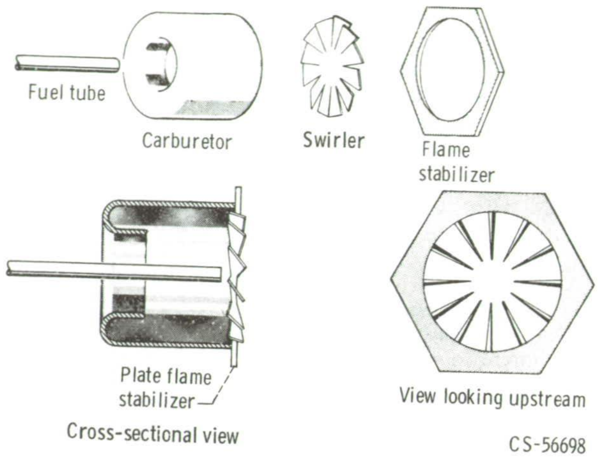


Figure 3. - Typical swirl-can module details.

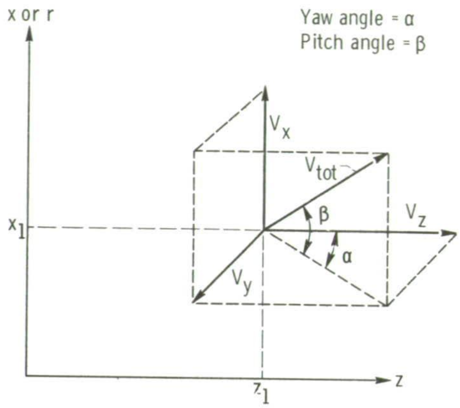


Figure 4. - Schematic of the orthogonal coordinate system and the total velocity vector for any point (x_1, z_1), showing the location of the yaw angle α and the pitch angle β.

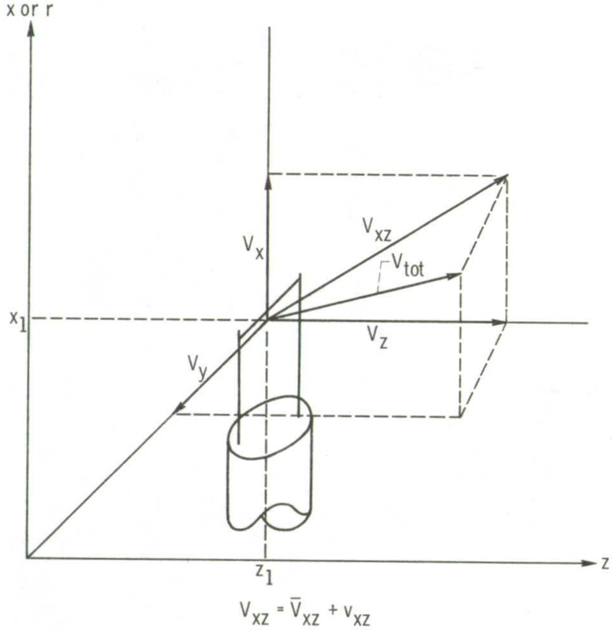
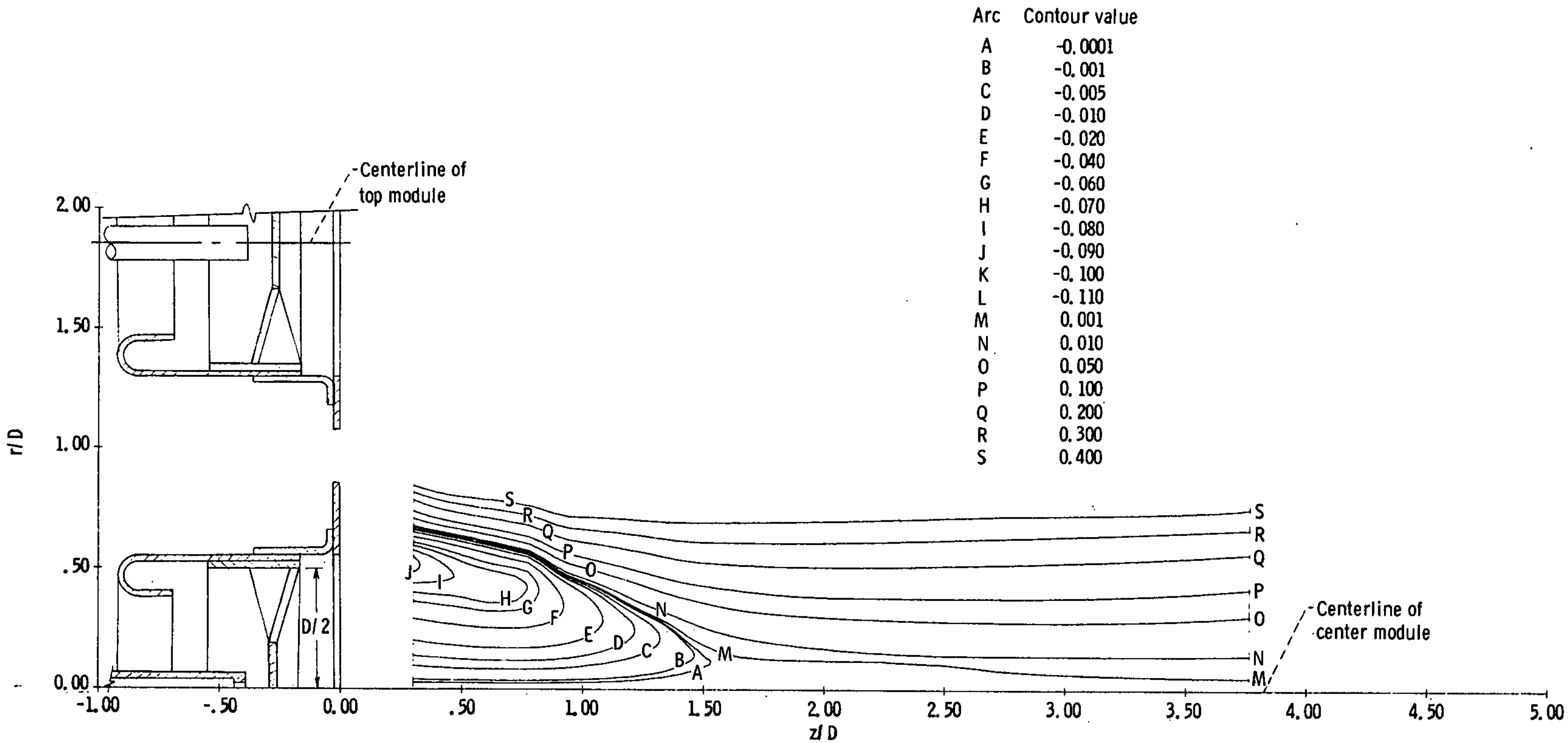
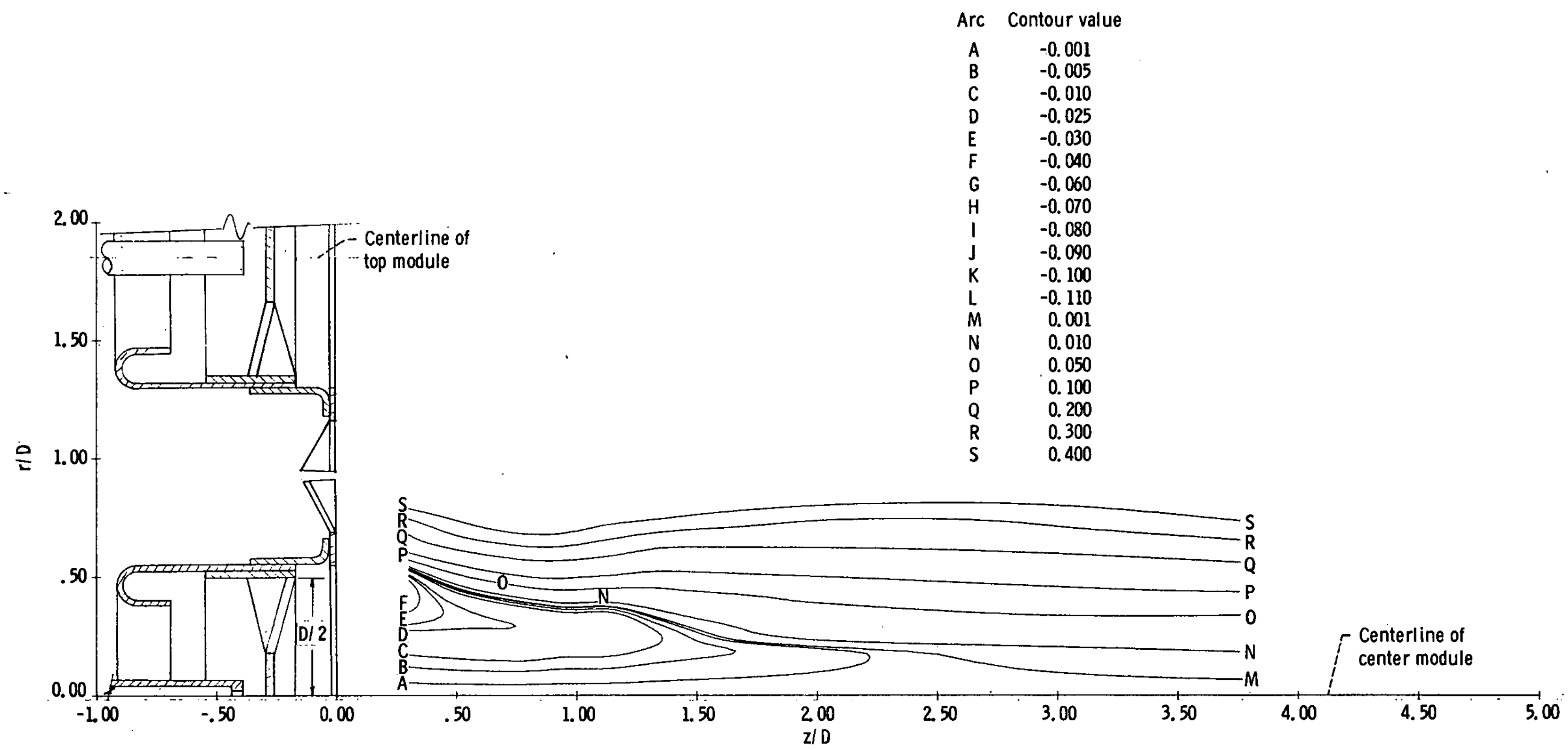


Figure 5. - Relation between instantaneous total velocity vector V_{tot} and velocity component measured by hot-wire probe V_{xz}.



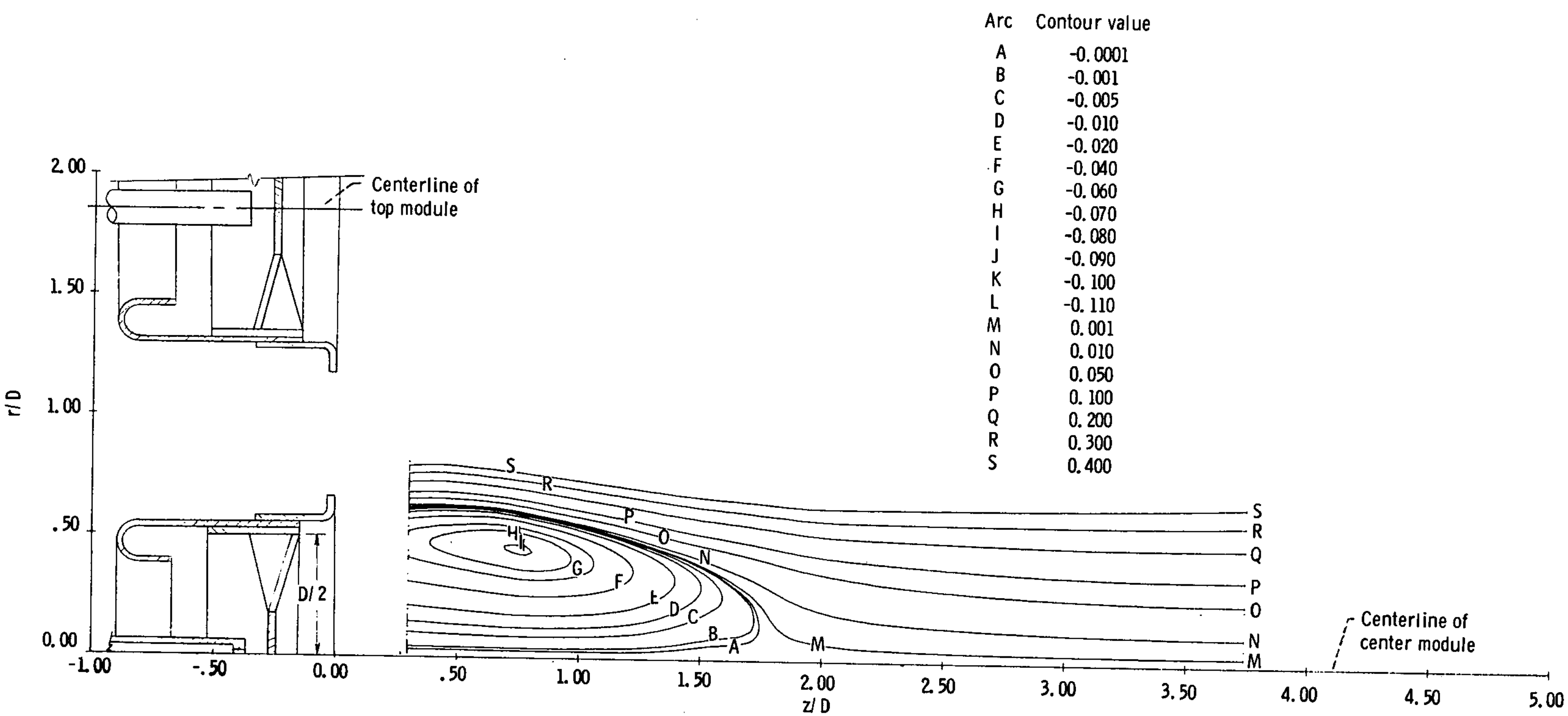
(a) Swirl-can design 1.

Figure 6. - Recirculation zone of center module for six swirl-can designs using lines of constant stream function normalized with respect to inlet airflow rate of one module. Simulated for combustor inlet air pressure of 62 newtons per square centimeter (90 psia), inlet air temperature of 589 K (600^0 F), and reference velocity of 25.4 meters per second (83.5 ft/sec). Characteristic dimension of swirl-can module D = 3.35 centimeters (1.32 in.).



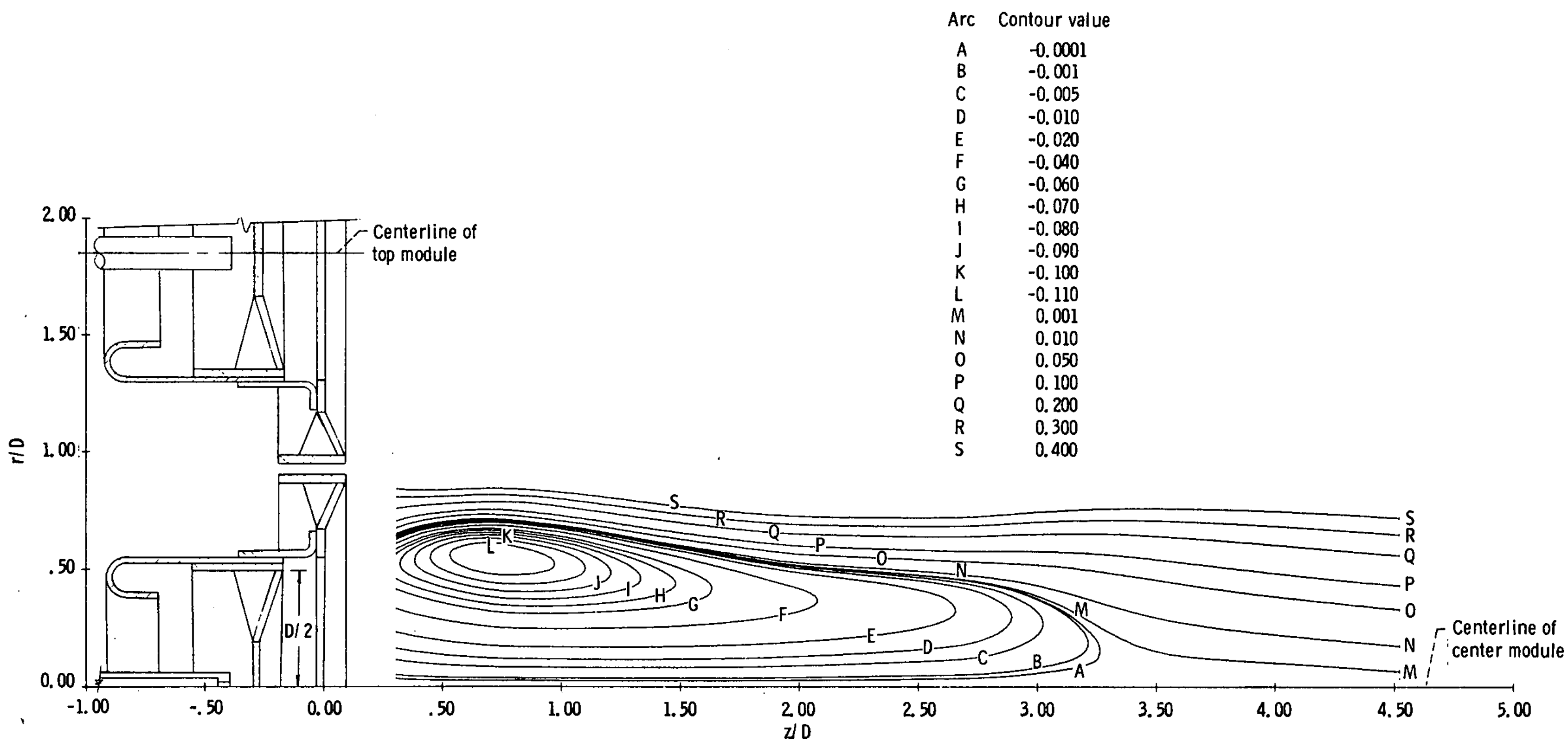
(b) Swirl-can design 2.

Figure 6. - Continued.



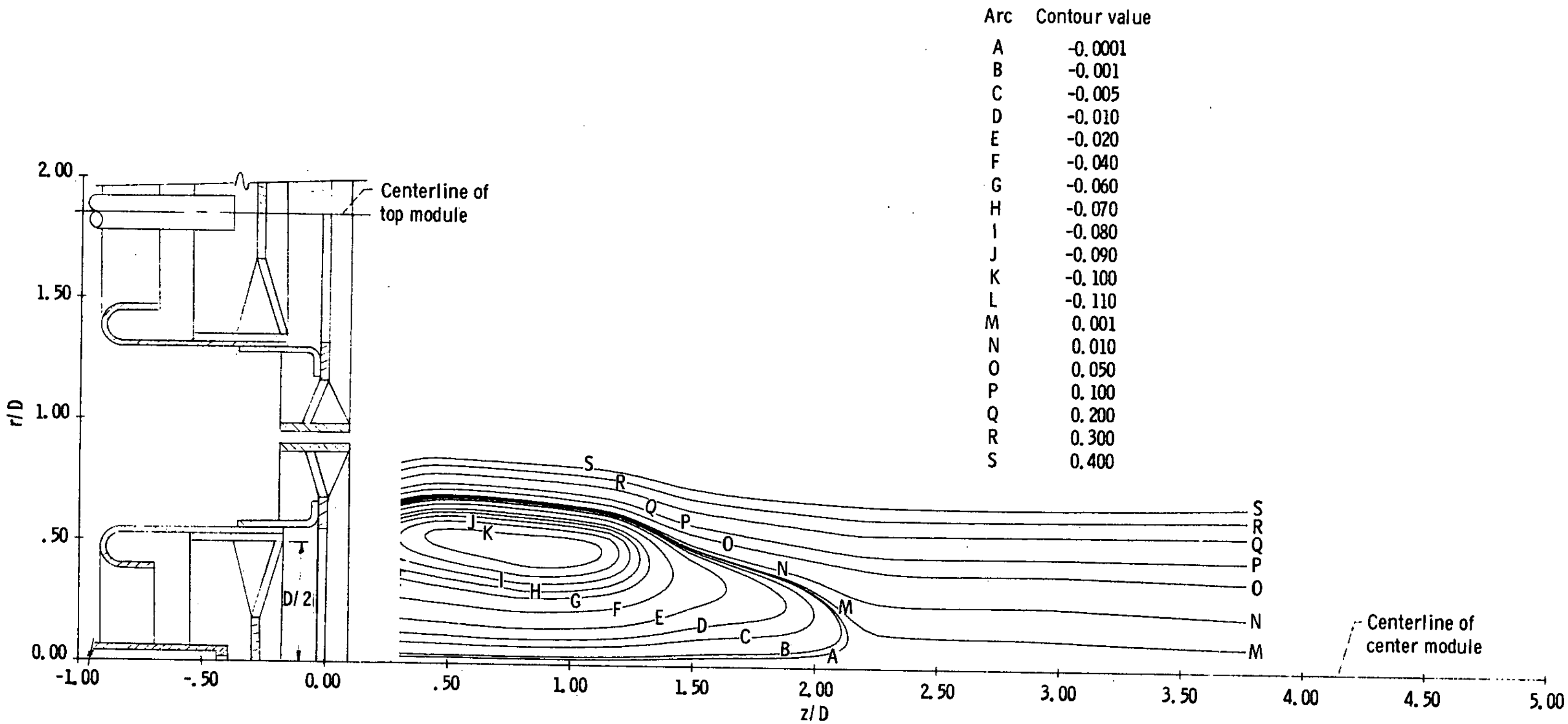
(c) Swirl-can design 3.

Figure 6. - Continued.



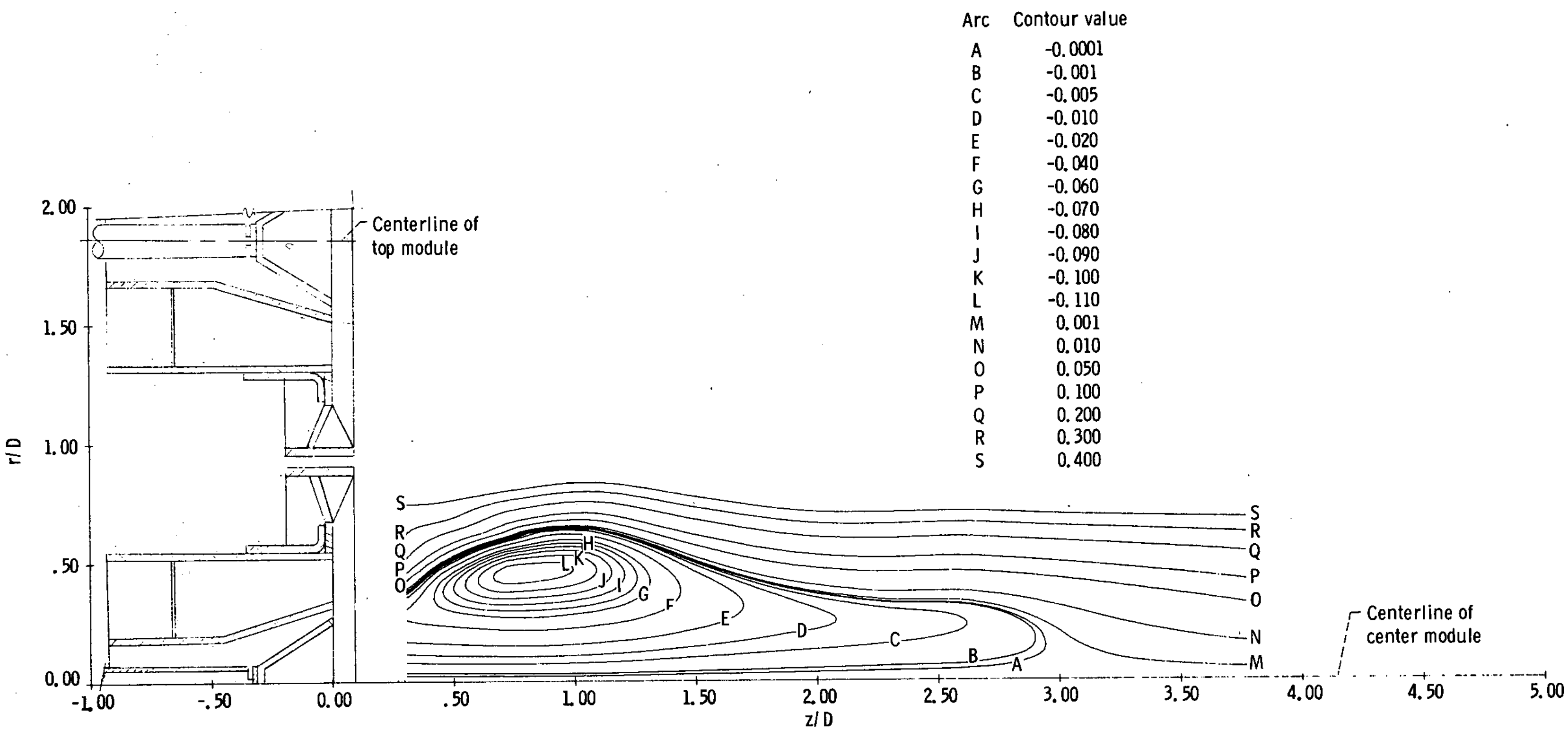
(d) Swirl-can design 4.

Figure 6. - Continued.



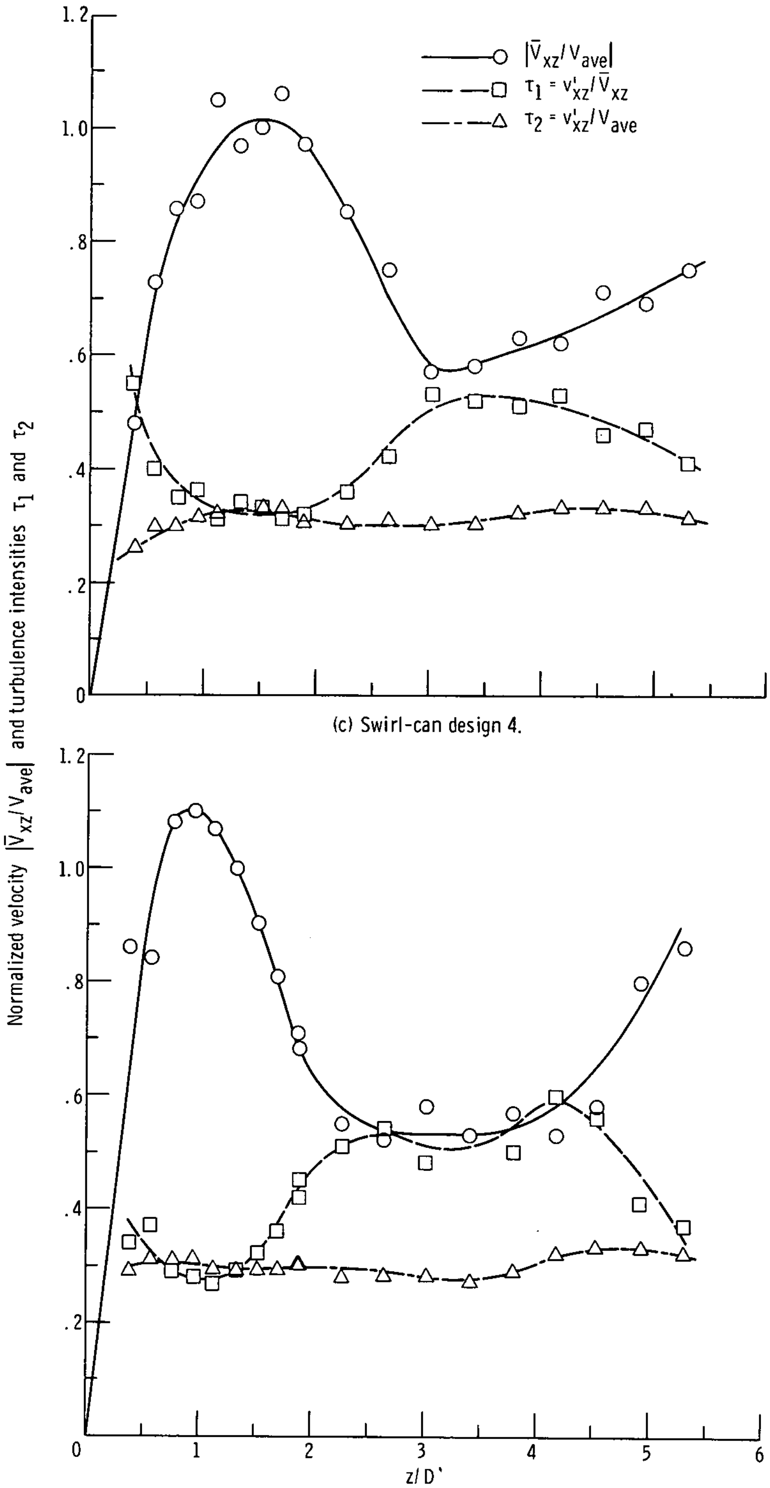
(e) Swirl-can design 5.

Figure 6. - Continued.



(f) Swirl-can design 6.

Figure 6. - Concluded.



(c) Swirl-can design 4.

(d) Swirl-can design 5.

Figure 7. - Continued.

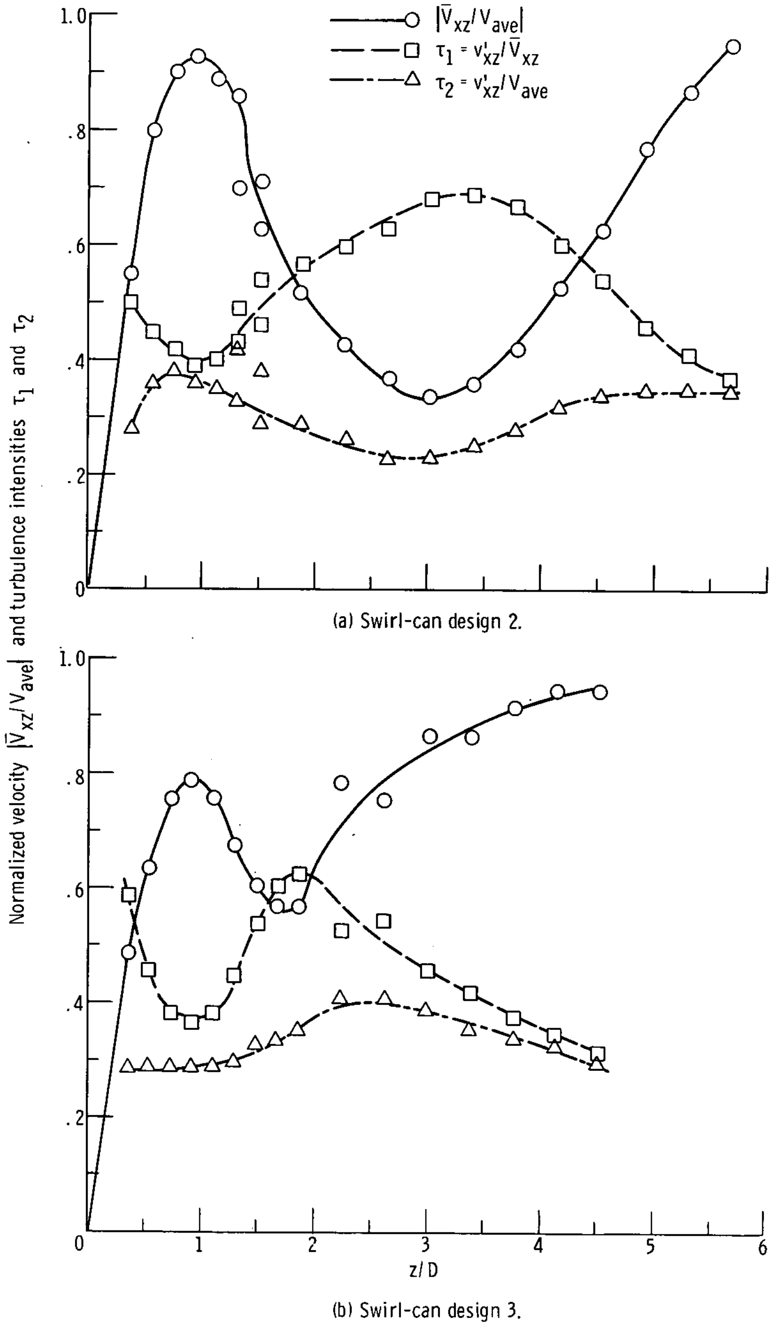
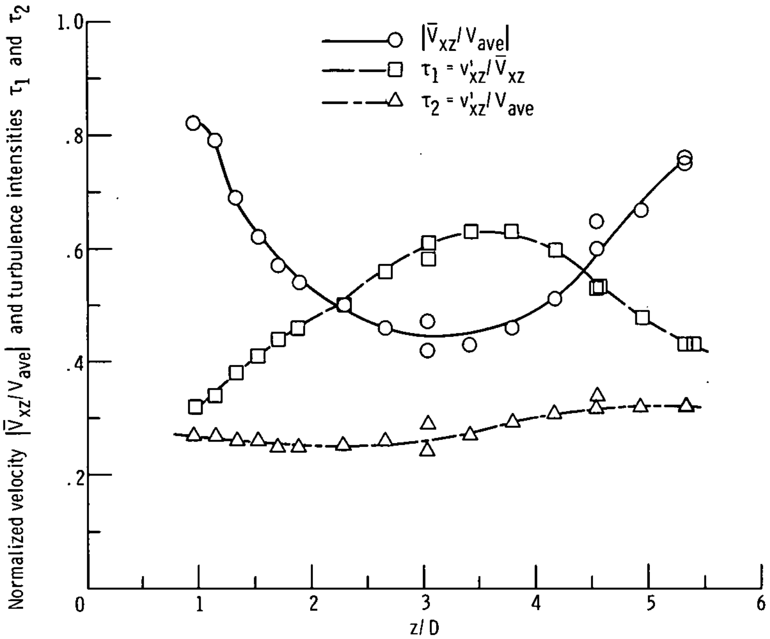
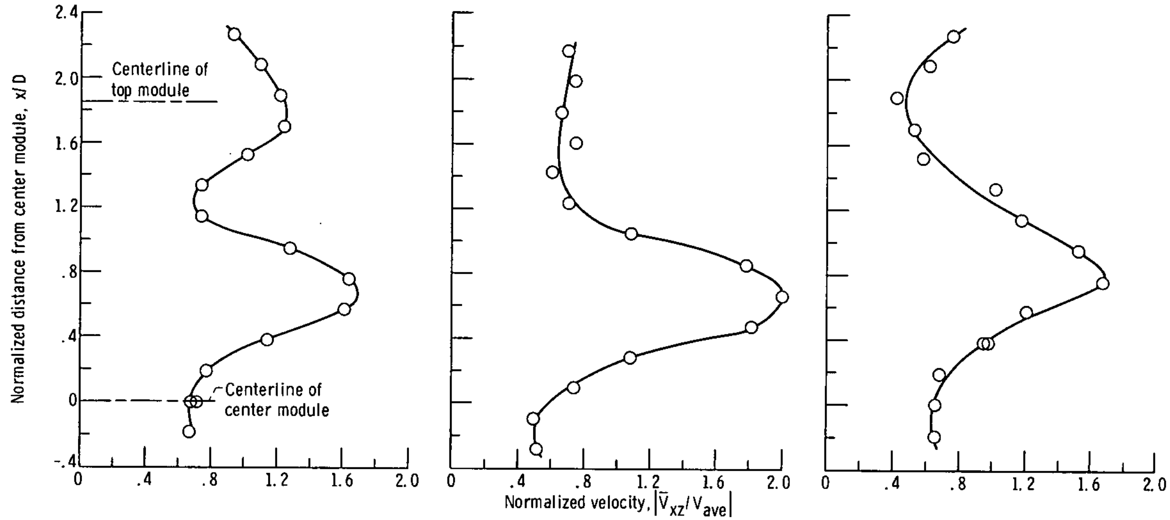


Figure 7. - Air velocity and turbulence intensity profiles along centerline of center module designs 2 to 6 at operating condition simulating combustor inlet air pressure of 62 newtons per square centimeter (90 psia), inlet air temperature of 589 K (600° F), and reference velocity of 25.4 meters per second (83.5 ft/sec). Characteristic dimension of swirl-can module D = 3.35 centimeters (1.32 in.); average velocity V_{ave} = 58 meters per second (190 ft/sec).



(e) Swirl-can design 6.

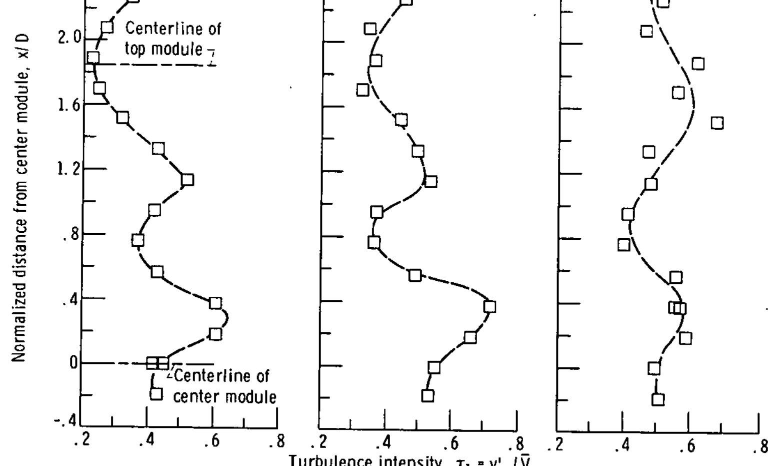
Figure 7. - Concluded.



(a-1) At z/D = 1.89.

(a-2) At z/D = 3.03.

(a-3) At z/D = 4.54.

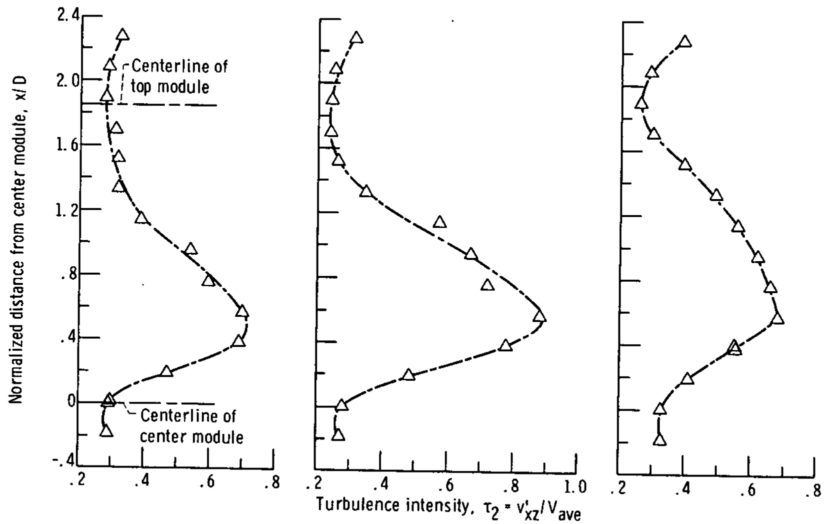


(b-1) At z/D = 1.89.

(b-2) At z/D = 3.03.

(b-3) At z/D = 4.54.

(b) Profiles of τ_1 for three positions downstream of array.



(c-1) At z/D = 1.89.

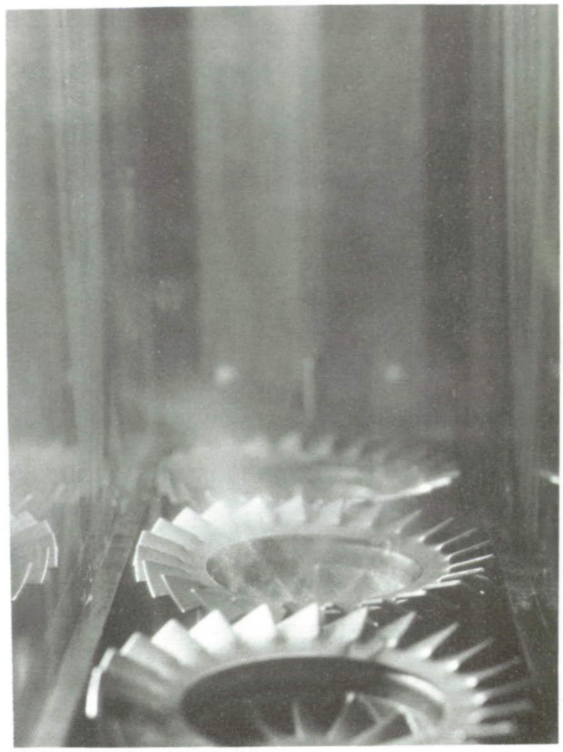
(c-2) At z/D = 3.03.

(c-3) At z/D = 4.54.

(c) Profiles of τ_2 for three positions downstream of array.

Figure 8. - Air velocity profiles and turbulence intensity profiles across swirl-can module array for swirl-can design 5 at operating condition simulating combustor inlet air pressure of 62 newtons per square centimeter (90 psia), inlet air temperature of 589 K (600° F), and reference velocity of 25.4 meters per second (83.5 ft/sec). Characteristic dimension of swirl-can module D = 3.35 centimeters (1.32 in.); average velocity V_{ave} = 58 meters per second (190 ft/sec).

(a-1) Swirl-can design 1; fuel-air ratio, 0.015.



(a-2) Swirl-can design 2; fuel-air ratio, 0.015.

(a-3) Swirl-can design 5; fuel-air ratio, 0.026.

(a-4) Swirl-can design 6; fuel-air ratio, 0.026.

(a) Test condition 1. High power condition of combustor inlet air pressure of 62 newtons per square centimeter (90 psia), inlet air temperature of 589 K (600° F), and reference velocity of 25.4 meters per second (83.5 ft/sec).

Figure 9. - Photographs of fuel distribution from center swirl-can module for swirl-can designs 1, 2, 5, and 6 operating at two simulated conditions.

(b-1) Swirl-can design 1; fuel-air ratio, 0.02.

(b-2) Swirl-can design 2; fuel-air ratio, 0.02.

(b-3) Swirl-can design 5; fuel-air ratio, 0.026.

(b-4) Swirl-can design 6; fuel-air ratio, 0.026.

(b) Test condition 2. Altitude relight condition of a combustor inlet air pressure of 5.5 newtons per square centimeter (8.0 psia), inlet air temperature of 311 K (100° F), and reference velocity of 14.8 meters per second (49 ft/sec).

Figure 9. - Concluded.

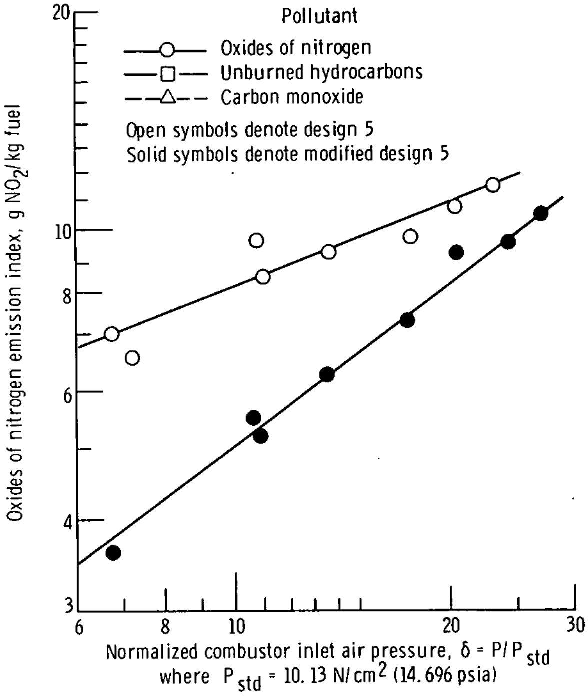


Figure 10. - Pollutant emissions measurements of swirl-can design 5 and modified design 5 operating in single module combustor rig (from ref. 11, reported as models 8 and 9). Combustor inlet temperature, 733 K (860° F); reference velocity, 23.2 meters per second (76 ft/sec); fuel-air ratio, 0.02.

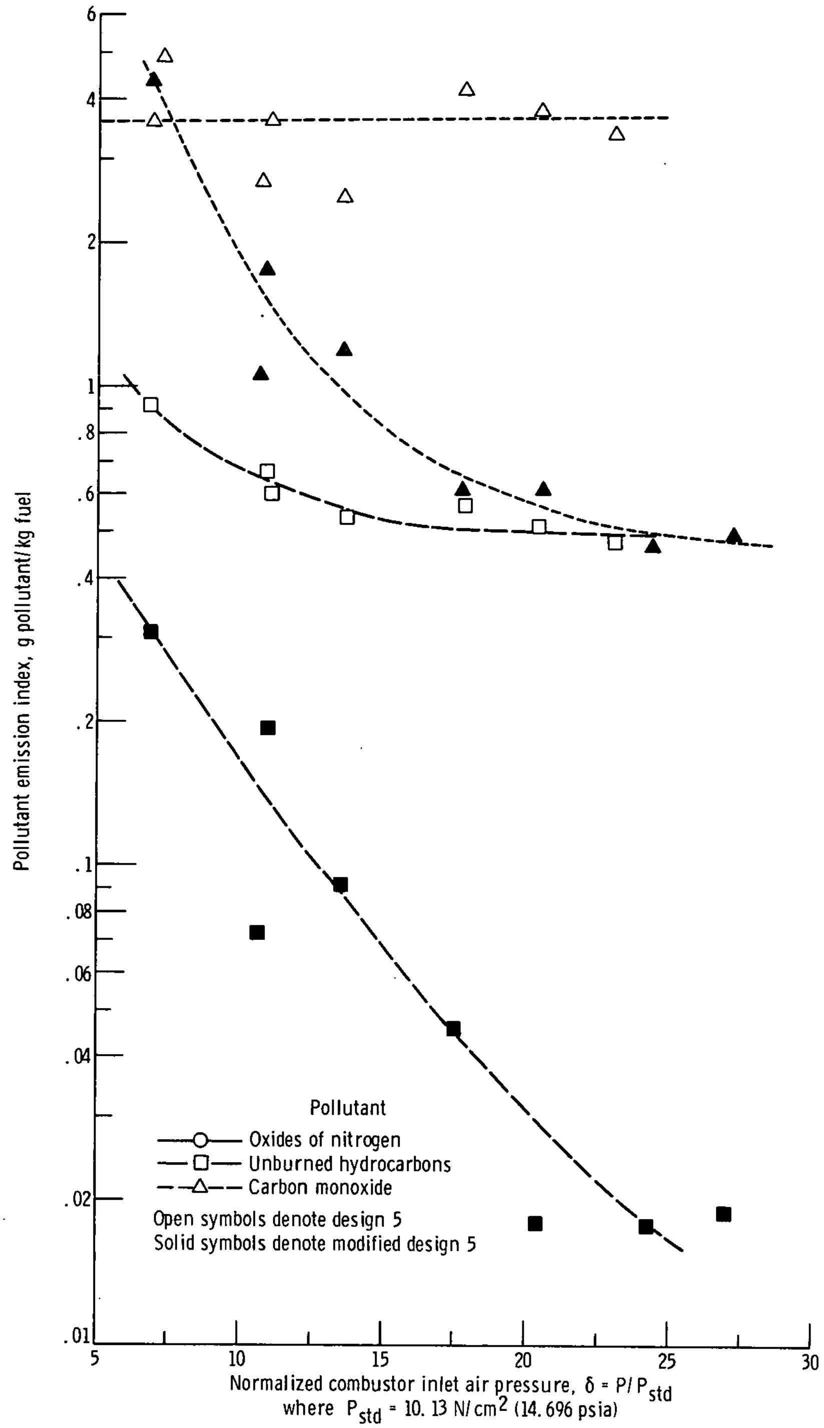


Figure 10. - Concluded.

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