Experimental validation studies for large-eddy simulation of a gas turbine main burner

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1. Motivation and objectives

Large-eddy simulation of a gas turbine combustor is a challenging goal. As part of that goal, various aspects of the simulation must be validated against realistic test flows in order to assess the validity of the final computation. The goal of this work is to provide a combustion platform on which a variety of LES validation flows can be realized.

The design of a combustor intended for LES-validation purposes is defined, in part, by the physics being investigated and by the geometric flexibility of the code under development. The experiments discussed here support two LES development efforts. The first code is intended to address chemistry/turbulence interaction. It is a block-cylindrical, low-Mach-number, single-phase, combustion code (Pierce & Moin 1998a). The second code is intended to address momentum transfer, evaporation, and particle dispersion in a spray flame. It is a compressible, curvilinear, two-phase LES combustion code (Oefelein 1997). In each case swirl is used for flame stabilization. Because of the different requirements of the two LES efforts, we have developed two separate combustion geometries, one for each code.

The gas-phase combustor provides laboratory data on air and fuel velocity statistics, mean temperature profiles, combustion products, and flame stand-off distance. Another requirement is that the inlet boundary conditions be well defined and 'clean.' Therefore, the combustor must have a minimum of any asymmetries, must avoid separation, and must also be independent of external laboratory conditions. Finally, the method in which the air and the fuel are swirled must be consistent with the manner in which the LES calculation produces swirling air and fuel (e.g. azimuthal body force). Given these constraints, the combustor must still produce a compact, low-sooting, stable, acoustically inactive, lifted flame with complete combustion.

The spray combustion code can accommodate a higher degree of geometric complexity than the gas-phase code. The spray combustor, therefore, can be more geometrically complex while providing the same sort of data as the gas-phase combustor. At the same time, this combustor must also provide information on the fuel spray and its statistics. This will allow for validation of momentum transfer, evaporation, and particle dispersion models in both non-reacting and combusting environments. Acoustic boundary conditions must also be well controlled in this experiment since combustion acoustics are to be measured in this facility as well.

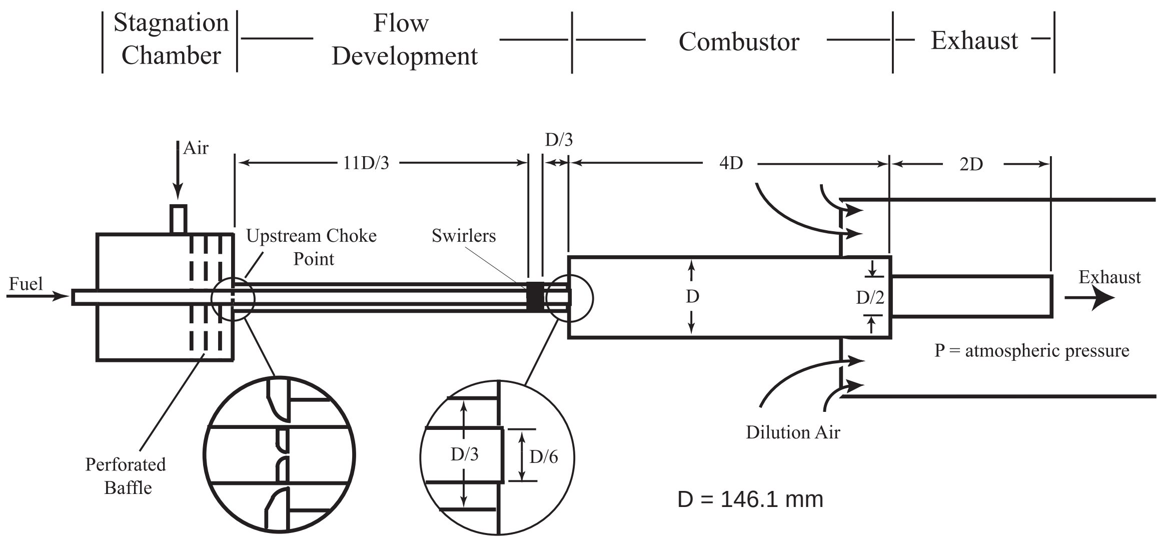

Figure 1. Schematic of the gas-phase combustor.

2. Accomplishments

2.1 Gas-phase combustor

A swirl-stabilized, gas-phase combustor consistent with the previously stated requirements has been designed, prototyped, and manufactured. Measurements are currently under way to characterize the combustor for use as a validation tool.

Figure 1 is a schematic of the gas-phase combustor. The combustor itself is composed of three principle sections: the flow preparation section, the test section, and the exhaust section. Each section is cylindrical in cross-section with sharp-cornered transitions between sections.

The flow preparation section consists of a fuel tube centered inside an air tube. Regulated, high-pressure air and fuel (methane) are supplied to plenums with appropriate baffling. At the entrance to the tubing, there is a sonic choke in each passage to accurately meter the gases and to provide a well defined acoustic boundary condition. Both passages have inline, helical swirlers (see below for details) and exit into the combustor. The fuel and air streams are co-swirled to provide liftoff of the flame from the fuel delivery tube. One challenging requirement of the chemistry/turbulence model will be to accurately predict the stand-off distance of the flame. This will test both the finite-rate kinetics and the combustion/turbulence models incorporated into the code.

Swirling flows are particularly sensitive to inlet asymmetries. A small deviation of the supply tubes from concentric will produce a large inhomogeneity in the distribution of the air. For this reason, we have designed the combustor to have independent positioning of the air stream choke and the exit of the gas tube within the air annulus. This ensures that both the air delivery into the flow preparation section and the flow entering the combustor section are uniform in the azimuthal direction.

Mass flowrate of air	31.0 g/s
Mass flowrate of methane	0.9 g/s
Firing rate	45 kW
Equivalence ratio	0.5
Mean velocity in air tube	23 m/s
Re(gap height) in air tube	14000
Mean velocity in fuel tube	2.9 m/s
Re(diameter) in fuel tube	4350
Momentum Ratio (air/fuel)	270
Re(diameter) in combustor	5340
Gap height at air sonic choke	0.7 mm
Throat diameter at fuel sonic choke	2.14 mm
Combustor diameter (cylindrical section)	146 mm (D)
Diameter of air tube	48.6 mm (D/3)
Inner diameter of fuel tube	24.3 mm (D/6)
Total length of combustor	584 mm (4D)
Length of octagonal section of combustor	305 mm
Length of cylindrical section of combustor	279 mm
First swirler location from the combustor inlet	48.7 mm (D/3)
Second swirler location from the combustor inlet	487 mm (10D/3)
Average stand-off height of the lifted flame	10 mm

Table 1. Operating conditions of the gas-phase combustor.

There is a competition between the design requirements of a good, swirl-stabilized flame in the laboratory and those for modeling that impacts the location of the swirler. In practice, swirlers are placed very near the flame stabilization point to prevent the swirl imparted to the flow from decaying. One manner of modeling a swirling flow using LES is to apply a body force to a fully-developed turbulent flow and to allow that flow to relax to a nominally universal flow profile along some flow development length (Pierce & Moin 1998b). The gas-phase combustor is designed to permit the placement of the swirler in two locations to investigate the possibility of allowing the swirling flow to relax as it enters the test section. Initial tests have shown that flames of sufficient stability and mixedness can be achieved with the swirlers in either position.

Some laser measurement techniques do not work well through curved glass windows (e.g., LDV, phase-Doppler interferometry). At the same time, other optical techniques benefit from having unimpeded optical access afforded by the use of a cylindrical test section. To accommodate both requirements, the test section is made of two parts. The first half of the test section is an octagon comprised of flat-faced, fused-silica windows. This allows laser beams to enter without the focusing and redirection that would occur with a curved window. The octagonal shape was chosen to maintain a high degree of circular symmetry while still allowing sufficient optical access. The second half of the test section is a cylindrical quartz tube. The

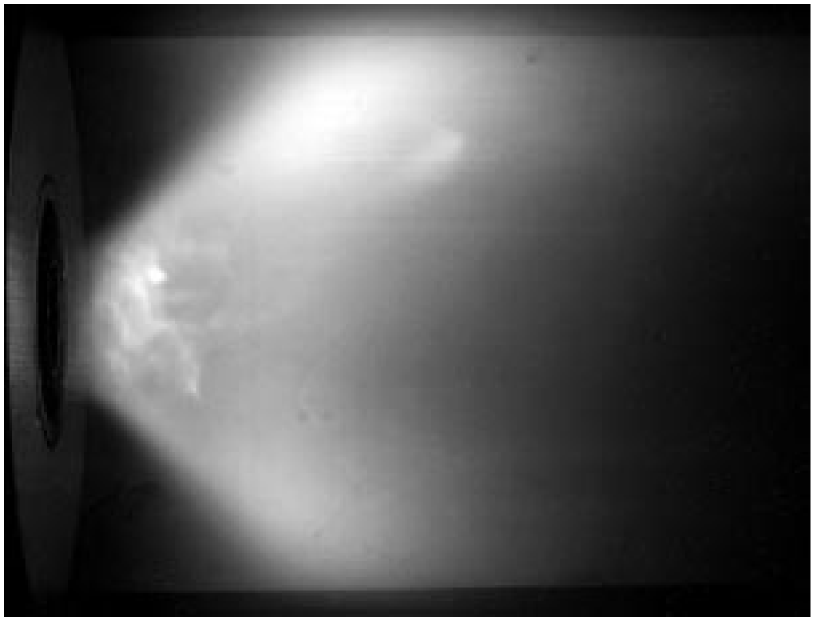

FIGURE 2. Photograph of the gas-phase (methane) combustor in operation. The flame is highly turbulent and lifted from the fuel entrance plane. Although well mixed and compact, the heat release is sufficiently distributed to reduce potential combustion acoustics effects to a negligible level.

cross-sectional area of the octagon was chosen to match that of the cylindrical section. The two sections can be interchanged to allow any type of measurement to be taken throughout the entire combustor.

The combustor is terminated by an exhaust section of a smaller diameter than the test section. The exhaust contraction serves two purposes. First, it produces a positive pressure gradient to combat the tendency of swirling flows to have very long vortex cores that can ingest air from outside the combustor. Second, it helps to complete the mixing of the combustion products to provide a more homogeneous mixture for exhaust gas analysis.

Early prototyping of methane flames demonstrated the difficulties inherent in producing a well mixed, compact, lifted, stable, low-soot flame utilizing the simple geometry desired. At a given equivalence ratio the flame structure was very dependent upon air/fuel momentum ratios, swirl numbers of both the air and the fuel, and the firing rate of the combustor (which for a given combustor geometry and momentum ratio can be thought of as an influence of the Reynolds number). However, suitable conditions were identified and are listed in Table 1. Figure 2 is a photograph of the flame operating at these conditions.

The fuel and air streams in the gas combustor can be independently seeded with TiO_2 or Al_2O_3 particles for imaging and LDV measurements respectively. One window of the octagonal test section can be replaced with a panel to allow for the insertion of thermocouple probes, water-cooled gas sampling probes, or suction pyrometers. The upstream face of the test section is fitted with a pressure transducer

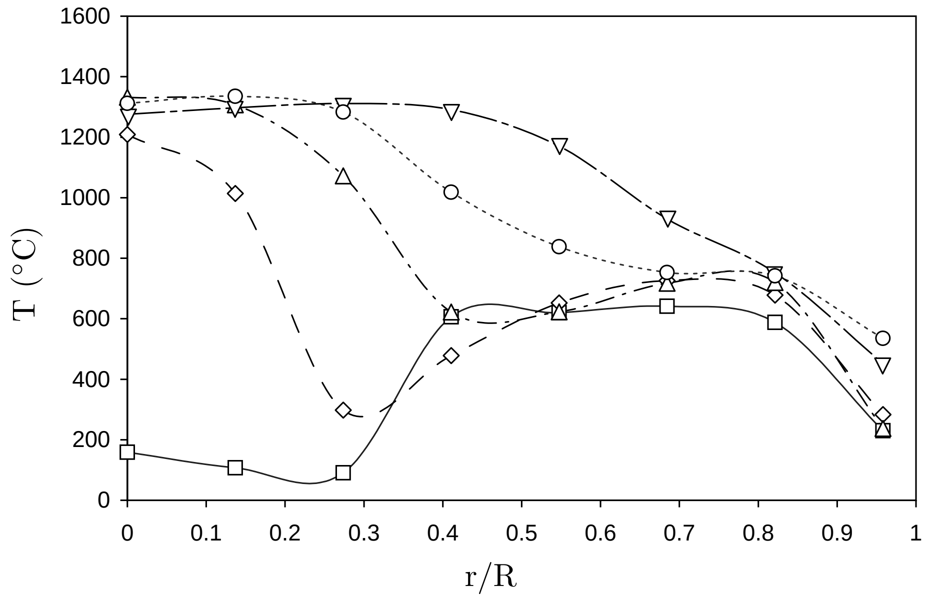

FIGURE 3. Radial mean temperature profiles near the combustor inlet at 5 different axial locations. □ z/R = 0.10, ◇ z/R = 0.35, △ z/R = 0.60, ○ z/R = 0.84, ▽ z/R = 1.09.

for acoustic measurements. Finally, the exhaust section is fitted with a sampling probe for global exhaust gas analysis.

Figure 3 shows the mean temperature profiles measured by thermocouple. Since the flame is lifted there is a region of cold fluid along the centerline of the combustor at the plane closest to the entrance. The flame front is stabilized by the central recirculation. The recirculation zone at the top plane of the combustor carries hot products along the outside wall of the combustor, resulting in the uniformity of mean temperatures observed near the combustor wall.

2.2 Spray combustor

Conceptual design and prototyping of the spray combustor has also been completed. Knowledge gained while designing, manufacturing, and operating the gas-phase combustor has been applied to the design of the spray combustor. Figure 4 shows the prototype flame adopted for study.

Many (if not most) spray combustors utilize a secondary air stream introduced beyond the stabilization zone to terminate the recirculation region and to complete the combustion process. However, due to the complexities in experimentally characterizing and modeling such a setup (many discrete jets in a swirling crossflow), the spray combustor we have designed supplies all of the combustion air at the face of the combustor. As such, our model combustor is like a lean, direct-injection (LDI) combustor (with two co-annular, counter-swirled air streams) rather than a conventional gas turbine burner.

Figure 5 is a schematic of the spray combustor. The test section of the combustor is identical to that of the gas-phase combustor with only one difference. The exit tailpipe of the gas-phase combustor is replaced with a contoured nozzle in keeping

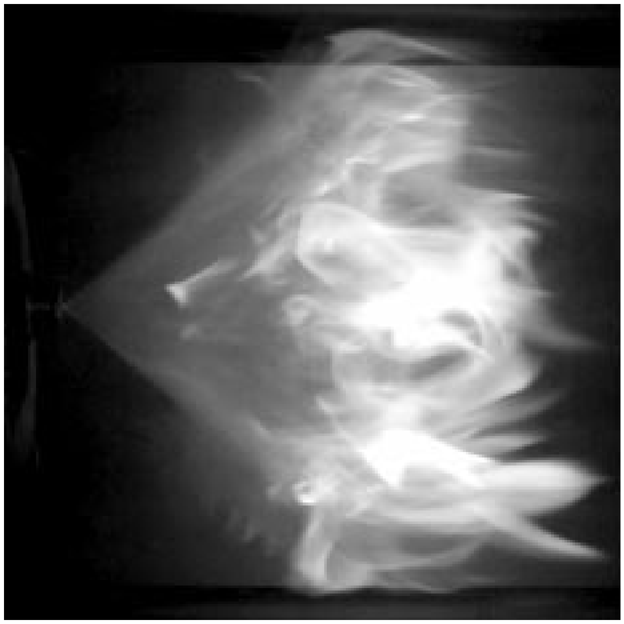

Figure 4. Photograph of the prototype spray flame (hexane). The flame is stabilized on the internal recirculation zone inside the spray. Both vaporization and combustion are complete within one combustor diameter.

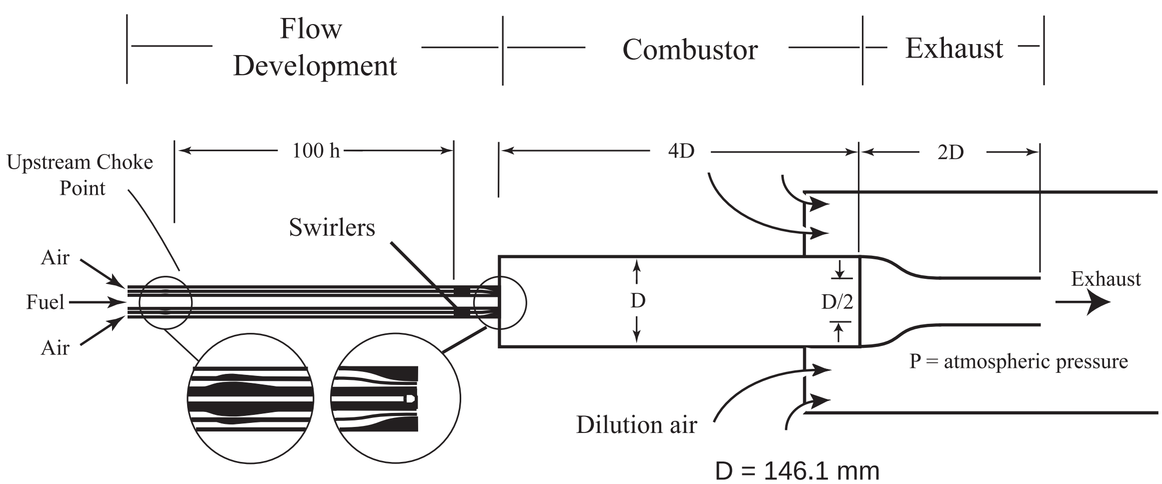

Figure 5. Schematic of the spray combustor.

with the capabilities of the curvilinear LES code. In this combustor, the two co-annular air streams are choked and then diffused back to the original passage size. The flow is then allowed to develop for a length greater than 100 gap heights to produce a fully developed turbulent flow before reaching the swirlers. Each passage has its own swirler and a nozzle at the entrance to the test section to accelerate the flows.

Since this combustor is expected to be used for thermo-acoustic combustion instability studies, the acoustic boundary conditions are of prime importance. The

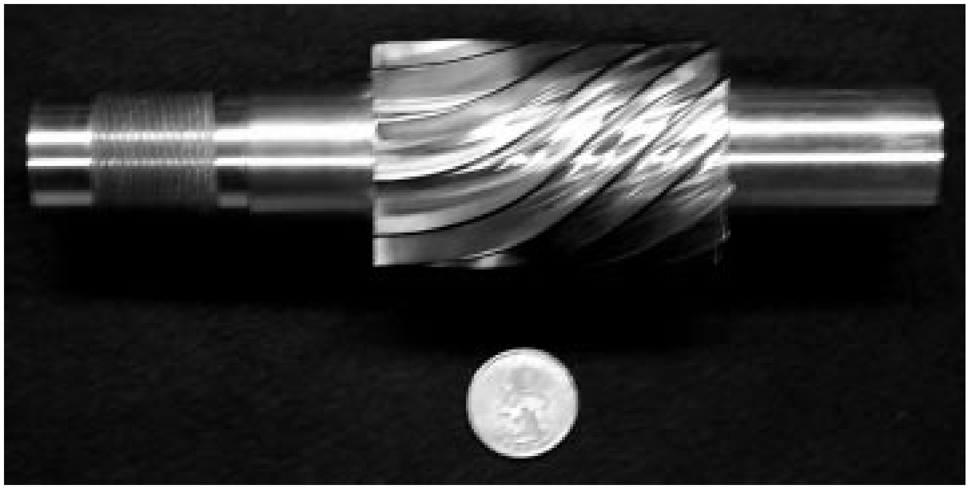

FIGURE 6. Air swirler for the gas-phase combustor. This particular swirler has a blade angle of 45°. The quarter is included to demonstrate scale.

choked nozzles at the tube inlets provide a well defined acoustic boundary condition. Accelerating the flow as it exits the combustor also helps to provide a better acoustic boundary condition at the exit of the combustor.

The design of this combustor allows for validation of a variety of calculations. Independent seeding of the air streams provides for measurement and visualization of the shear layer created at the interface between the two air flows. The experiment can be run in a non-reacting mode with either non-evaporating or evaporating sprays. The most complex case is the fully reacting case.

2.3 Swirlers

Because of the requirement to minimize bluff-body effects and separation of the inlet air (and the fuel in the case of the gas-phase combustor) traditional flat-blade swirlers or tangentially-injected air jets were considered unacceptable. A low-blockage swirler design based on curved channel flow was designed to create a 'clean' swirling flow free of bluff effects or separation. The idea is that the fins of the swirler break the annular flow of the air into separate regions that can each be approximated as a 2-D curving air channel. Each channel is then gradually transitioned from a purely axial flow into a helical flow at the desired angle. The rate of transition is based on experience with turning vanes in wind tunnels so as to avoid separation on the back side of the blades. Maximizing the number of vanes reduces the risk of separation and more closely approximates a quasi-2D curved channel flow. Minimizing the number of vanes reduces the overall blockage of the swirler. Therefore, the number of vanes was chosen to keep the gap height of the annular passage approximately equal to the spacing of the vanes, thereby producing a channel with an aspect ratio of unity. A similar swirler was designed for the fuel tube that minimizes the size of the central hub required to connect the vanes of the swirler. Figure 6 is a photograph of the air swirler used in the gas-phase combustor.

In the case of the curvilinear LES code, it is possible to calculate the flow as it passes through the swirler instead of using the applied body force method, if desired. Although the swirlers may appear geometrically complex, the layout of the blades is governed by only a few simple design rules. Therefore, the spatial description of the blades could be supplied to an LES code with high fidelity.

3. Future plans

Each combustor has been designed to produce a high-quality, stable flame in the vicinity of the nominal operating condition. Specific measurements are to be taken at key locations in the combustor to provide experimental data against which to validate LES results. The following measurements will be performed on the gas-phase combustor:

- Mean temperature field
- Velocity statistics (means, turbulence intensities, Reynolds stresses, etc.)
- Mean stable species concentrations

Once the experimental objectives of the gas-phase combustor have been met, the spray combustor will go online. All of the above data will be collected. In addition, phase-Doppler interferometry will be employed to measure drop size and velocity statistics where appropriate. The LES spray code is to be validated from the simplest to the most complicated case as follows:

- Two counterswirled air flows, no spray
- Air flows with non-evaporating spray
- Air flows with evaporating spray, non-reacting
- Full combustion conditions

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