STUDY OF TWO-PHASE FLOW DOWNSTREAM OF A GAS TURBINE COMBUSTOR DOME SWIRL CUP

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ABSTRACT

The two-phase axisymmetric flowfield downstream of the swirl cup of an advanced gas turbine combustor is studied numerically. The swirl cup analyzed is that of a single annular GE/SNECMA CFM56 turbofan engine that is comprised of a pair of coaxial counter-swirling air streams together with a fuel atomizer. The atomized fuel mixes with the swirling air stream resulting in the establishment of a complex two-phase flowfield within the swirl chamber. The analysis procedure involves the solution of the gas phase equations in a Eulerian frame of reference. The flow is assumed to be nonreacting and isothermal. The liquid phase is simulated by using a droplet spray model and by treating the motion of the fuel droplets in a Lagrangian frame of reference. Extensive Phase Doppler Particle Analyzer (PDPA) data for the CFM56 engine swirl cup has been obtained at atmospheric pressure by using water as the fuel (Wang et al., 1992a). This includes measurements of the gas phase velocity in the absence and presence of the spray together with the droplet size, droplet number count and droplet velocity distribution information at various axial stations downstream of the injector. Numerical calculations were performed under the exact inlet and boundary conditions as the experimental measurements. The computed gas phase velocity field showed good agreement with the test data. The agreement was found to be best at the stations close to the primary venturi of the swirler and to be reasonable at later stations. To compare the droplet data, a numerical PDPA scheme was formulated whereby several sampling volumes were selected within the computational domain. The trajectories of various droplets passing through these volumes were monitored and appropriately integrated. The calculated droplet count and mean droplet velocity distributions were compared with the measurements and showed very good agreement in the case of larger size droplets and fair agreement for smaller size droplets.

INTRODUCTION

Imparting of swirl to the incoming air stream is an essential feature of modern gas turbine combustors. By introducing swirl, mixing is enhanced and a recirculation zone is established that improves flame stabilization. This mixing can be further enhanced by having an air pair of co-swirling streams that are counter-rotating. The injected fuel, the oncoming air stream, and the hot reaction products would all get well mixed.

Much work has been done to understand the nature of both reacting and nonreacting single phase swirling flows (Mehta et al., 1989; Habib and Whitelaw, 1980; Ramos and Somer, 1985; Gouldin et al., 1983). All of these studies have been of experimental nature wherein the mean velocities, turbulence intensities, and Reynolds stresses within the swirl region have been measured using hot wires, five-hole probes, and Laser Doppler Anemometry (LDA). These measurements have revealed that under both co-swirl and counter-swirl conditions, a closed recirculation zone is created at the centerline. The recirculation zone was found to contain low velocity fluid with large turbulence intensities and high dissipation rates.

More recently, experiments have been conducted to characterize the droplet and continuous phase flow fields within a swirling air stream introduced co-annularly around a liquid atomizer (Wang et al., 1992a, 1992b, 1991; Bachalo et al., 1990). Droplet sizes and droplet velocities were measured at several axial stations using a Phase Doppler Particle Analyzer (PDPA), which provided information regarding the degree and efficiency of atomization. The droplets were found to recirculate together with the continuous phase. Also, significant slip velocities were observed that were greater for larger size droplets.

While all the work described so far is experimental, the goal of this present study is to perform a numerical analysis of the swirling flow in a real combustor swirl cup and to compare the calculated results against corresponding experimental PDPA data. The combustor chosen for this purpose is the GE/SNECMA single annular CFM56 engine combustor and is shown schematically in Fig. 1. The encircled portion is the swirl cup region that is shown separately further below in the figure. The swirler is a dual-stage counter-rotating swirler assembly shown in greater detail in Fig. 2. The swirler assembly is comprised of four principal components. Air flow from the primary
swirler is injected through eight equally spaced holes drilled into the part at a compound angle, 24 degrees relative to vertical and 20 degrees tangential. The primary swirler component also contains the retainer for the fuel injector. The flow coming out of the primary swirler is strictly three-dimensional, but is approximated to be two-dimensional axisymmetric to simplify the analysis. This approximation is done by matching the mass flow and by forcing the axial, radial, and swirl velocity components to scale in proportion to the flow angles of the swirler hardware. The inlet velocity distribution is thus determined based on continuity. The secondary swirler is of the radial inflow type. It contains ten equally spaced vanes at an angle of 70 degrees relative to the radial. The flow coming out of the secondary swirler is definitely two-dimensional. A venturi section is used to separate the two counter-rotating air streams initially. Fuel from the injector nozzle is initially sprayed onto the surface of the venturi where it forms a thin film. As the fuel film travels to the end of the venturi, it encounters the shear generated between the two counter-rotating air streams. The high intensity turbulence in this shear layer serves to re-atomize the fuel film at the trailing edge of the venturi into fine droplets that then exit the swirler assembly through a 90 degree conical exit flare. The flare controls the radial dispersion of the mixture as it leaves the swirler and enters the combustion chamber. PDPA data for this swirl cup has been obtained by Wang et al. (1992a). The air was at atmospheric pressure and water was used in lieu of liquid fuel. The flow conditions and other details of the experiments have been described in Wang et al. (1992a) and will not be repeated here. Droplet size and velocity information have been obtained at three axial stations downstream of the injector.

The flowfield was calculated under the same experimental conditions by assuming that it is two-dimensional and axisymmetric. A Eulerian-Lagrangian approach was used. The gas phase equations are solved in a Eulerian frame of reference by using a fully elliptic two-dimensional body-fitted computational fluid dynamics (CFD) code based on pressure correction techniques (Patankar, 1980). The liquid phase is modeled by treating the motion of the fuel droplets in a Lagrangian frame of reference. The gas phase calculation provides the updated velocity and turbulence field required by the trajectory analysis. To make a one-on-one comparison with the measurements, a numerical PDPA scheme was set up wherein several sampling volumes were selected, and the trajectories of the different droplets passing through them were monitored and appropriately integrated.

**METHODOLOGY**

**Mathematical Description of the Gas and Liquid Phases**

The governing equations for the gas phase are those representing the conservation of mass and momentum in the two coordinate directions. All three velocity components, including the swirl velocity, are considered, but they are each functions of only two coordinates. Turbulence is modeled using the standard k-ε model along with the wall function treatment for near-wall regions. Using a coordinate transformation, these equations are transformed from an arbitrary physical domain to a rectangular parallelepiped. After making finite difference approximations to the equations, they are solved using the SIMPLE algorithm (Patankar, 1980). The numerical algorithm details are available in Tolpadi and Braaten (1992) and in Tolpadi (1992).
The treatment of the liquid phase has been described in detail in Tolpadi (1992) and only the important details will be given here. A droplet spray model is used. The trajectories of the fuel droplets that are assumed to be spherical are obtained within the calculation region based on the gas phase velocity and turbulence field obtained from the CFD code. Ordinary differential equations are written for the droplet motion that is integrated to give the drop velocity and position during its travel. The integration is performed using a Runge-Kutta method. It is assumed that there is no evaporation thus implying that the drop diameter does not change with position. The drag coefficient on the droplet is obtained from experimental correlations taken from Wallis (1969).

**Numerical PDPA Scheme**

The Phase Doppler Particle Analyzer makes pointwise measurements that are essentially Eulerian, that is, the PDPA focuses on a point in the flowfield and makes measurements of the droplets as they pass through the point. Various droplet characteristics are measured. The PDPA makes measurements over several size ranges. For each size range, the following are measured (among others): (1) the droplet number count, i.e., the number of droplets detected per unit time, (2) the mean droplet velocity, and the (3) rms velocity. The PDPA system used in Wang et al. (1992a) measured two perpendicular velocity components simultaneously. The third velocity component was obtained by rotating the PDPA by 90 degrees. This procedure was used to obtain the droplet information at various selected locations in the flow.

The numerical calculation of the droplets, as stated already, was performed in a Lagrangian frame of reference. The numerical PDPA scheme involved the transformation of this droplet trajectory information to the format of the experimental PDPA. In Wang et al. (1992a), experimental data has been obtained at three axial locations which were at distances of 17 mm, 26 mm and 36 mm from the end of the venturi (Fig. 2). At each of these axial positions, PDPA measurements were made at several radii. The experimental data at the first station was used as the initial condition for the trajectory analysis. Measurements were made over six droplet size ranges: 1 to 10.56 μm, 10.57 to 20.26 μm, 20.27 to 29.95 μm, 29.97 to 39.65 μm, 49.37 to 59.04 μm, and 73.61 to 88.14 μm. Each size range was considered separately, and a mean droplet size was assigned for the trajectory analysis. The droplet number count information at the first station was normalized, which provided the initial droplet distribution along the radius. A statistically large number of trajectories were initialized at the first station in the same proportion as the normalized distribution. Their initial velocities also corresponded to the measurements.

Now, at the second station (26 mm), the radial location where each of these trajectories passed through was obtained. Thus, a similar number count distribution was obtained at the second station—also normalized and directly compared to the measured number count distribution at this station. In addition, the velocity components of the droplets as obtained from the trajectory calculation at the second station were averaged and compared to the measurements. This same procedure was repeated at the third station (36 mm) as well.

The effect of turbulence on the droplet motion was accounted for by using a stochastic approach, which essentially requires the knowledge of the instantaneous gas phase velocity at every position along the droplet trajectory. This is obtained from the computed mean velocity and the turbulence kinetic energy. The turbulence is assumed to be isotropic and to possess a Gaussian probability distribution in the fluctuating velocity, whose standard deviation is $(2k/3)^{1/2}$ (Gosman and Ioannides, 1983). The distribution is randomly sampled during the flight of a droplet to get the instantaneous gas phase velocity.

**RESULTS**

**Comparison of the Gas Phase Results**

As mentioned earlier, calculations were performed under the same conditions as the measurements. Figure 3 shows the grid for the swirl cup corresponding to the hardware shown in Fig. 2. This grid has 144 points in the axial and 93 points in the radial direction. This very dense grid was found to be sufficiently fine for the purpose of these types of swirl cup calculations. The grid was generated by using an elliptic grid generation procedure by treating the swirl cup as an internal obstacle and by suitably meshing around it. The finite differencing scheme used was QUICK (Leonard, 1979). The air flow rate through the primary swirler is 0.0070 kg/s and through the secondary swirler, it is 0.0100 kg/s. The inlet turbulence intensity was assumed to be 8%. The experiments in Wang et al. (1992a) were performed by placing this swirl cup in a large chamber in which the outer flow was axial and uniform. This outer flow was modeled by specifying a velocity of 0.495 m/s at the boundary as shown. The air was at atmospheric pressure and isothermal (temperature = 289 deg K). Figure 4 shows the calculated streamlines and indicates the presence of a strong recirculation zone just beyond the swirler close to the centerline. This recirculation zone is produced as a consequence of the counter swirling air stream coming out of the primary and secondary swirler. There is another relatively weak recirculation zone on the outside. Zero normal gradient conditions were used at the exit boundary, which was far removed to ensure that its position did not influence the solution close to the swirler where the measurements were made.
PDPA measurements of the gas phase flowfield were made by switching off the fuel injector and by seeding the flow with an agent of size one micron. Figure 3 indicates the locations of the three stations where the axial, radial, and swirl velocity components were measured. The radial profiles of these three velocity components at \( x = 17 \) mm have been compared against the corresponding calculated profiles in Fig. 5. The calculated axial and radial velocity profiles show excellent agreement with the measurements. Both the calculations as well as the measurements show negative values of the axial velocity near the centerline indicating the presence of a recirculation zone there. The profiles of the swirl velocity, although similar in shape, show some disagreement; an explanation of this observation will be given later.

Figure 6 compares the profiles of the three velocity components at \( x = 26 \) mm. Clearly, the agreement is still good but perhaps not as good as the agreement at \( x = 17 \) mm. To understand this fact, it is important to first understand that the computations were performed by assuming that the swirler geometry is axisymmetric, as evidenced from Figs. 5 and 6 in which the calculated radial and swirl velocity components decrease to zero at the centerline. However, the data indicates a nonzero value of the radial and swirl velocity showing that the measurements are nonaxisymmetric. This means that the geometric and aerodynamic centerlines are not coincident. This lack of axisymmetry in the measurements could be due to several reasons. Imperfections in the hardware could be a definite reason. Also, the flow from the swirler enters an open space creating secondary flows that could certainly displace the aerodynamic center from the geometric center. Since the flow is at atmospheric pressure, gravity could be a factor causing this displacement. This displacement of the two centerlines has also been observed in the LDA measurements of Mehta et al. (1989) and the PDPA measurements of Wang et al. (1991, 1992b). Ideally, at the centerline of an axisymmetric flow, a PDPA system should measure a nonzero axial velocity component and zero radial velocity (the swirl velocity, of course, has no meaning). In reality, because of the displacement of the two centerlines, the PDPA would be able to make a meaningful axial velocity measurement close to the centerline, but the perpendicular velocity component measured would be some combination of the radial and swirl velocity components. Away from the centerline, all three velocity components are clearly distinguishable and therefore the PDPA measurement of the radial and swirl velocities would be more reliable. The measured radial and swirl velocity at the centerline may be seen to increase with distance from the venturi indicating that there is greater deviation between the geometric and aerodynamic centerlines as one moves further away from the swirler. At \( x = 26 \) mm, the calculated radial and swirl velocities show better agreement with corresponding data at larger radii consistent with the explanations just given. Although not shown here, similar observations were made when the data were compared at \( x = 36 \) mm.
Comparison of the Liquid Phase Results

As explained earlier, the liquid phase results were compared by establishing a numerical PDPA scheme. The experimental PDPA data at x = 17 mm was used to obtain the initial conditions for the trajectory calculations. Six mean droplet sizes were chosen corresponding to each of the six droplet size ranges. These droplet sizes were 5.78 µm, 15.42 µm, 25.11 µm, 34.81 µm, 54.20 µm, and 80.88 µm, respectively. For each drop size, 1000 trajectories were initialized. The distribution of the initial positions along the radius corresponded to the normalized number count (dn/n) data obtained in Wang et al. (1992a). Figure 7 shows, for example, the percentage distribution of the initial trajectory locations (dn/n) for the 80.88 µm and 5.78 µm size droplets. In what follows, the normalized number count and mean droplet velocities calculated at the next two stations, x = 26 mm and x = 36 mm, will be compared with the PDPA measurements. A calculation was also performed by initializing 10,000 droplets, but the results obtained were essentially identical to those obtained with 1000 droplets. Thus, a total of 1000 droplets in each size range was considered to be statistically sufficient.

Figure 8 compares the calculated number count, mean axial velocity, mean radial velocity, and mean swirl velocity with the measurements at x = 26 mm and for the droplets of mean size 80.88 µm. To avoid any confusion between the plots, it may be noted that the ordinate of each plot is different and is appropriately indicated. The agreement between the number counts and the axial and radial velocity profiles may be seen to be excellent. The normalized number count shows two peaks in the measurements that can be seen in the computations as well. Generally speaking, the larger size droplets are less affected by the fluid flowfield and tend to follow a more independent path, whereas smaller size droplets tend to follow the fluid flowfield. It may be seen from Fig. 7 that the initial normalized distribution of the droplet count for the 80.88 µm droplet at x = 17 mm has two peaks which is still present at x = 26 mm showing that the fluid flowfield has a lesser influence on the trajectory of this particular size droplet. The mean axial and radial velocity distribution almost precisely follows the PDPA measurements. The mean swirl velocity distributions do not agree as well which may again be attributed to the deviation between the aerodynamic and geometric centerlines of the flow. In Fig. 8, the swirl velocity shows better agreement away from the centerline. The data again shows nonzero velocities near the centerline indicating once again the shift between the geometric and aerodynamic centerlines. Figure 9 shows the same comparisons at x = 26 mm for the intermediate size droplet of 34.81 µm. Again, other than the swirl velocity distribution which shows poor agreement, the other three droplet attributes show excellent agreement.

Figure 10 makes the corresponding comparisons for the case of the smallest droplet of size 5.78 µm at the axial station of x = 26 mm. What is immediately noticeable is that the droplets in the calculations are detected only over the radius interval of approximately 25 to 35 mm, whereas the measurements have detected droplets over the entire range of 0 to 45 mm. Several possible reasons could be hypothesized to explain this discrepancy. An important assumption being made in the spray computations is that the droplets do not evaporate. Strictly speaking, vaporization does occur. Vaporization is caused by gradients in concentration, but it has not been accounted for in the computations at the present time. Since the vaporization rate is much greater
Fig. 8. Calculated and measured radial profiles of the normalized droplet number count and mean droplet velocity components for droplets of mean size 80.88 µm at x = 26 mm.

Fig. 9. Calculated and measured radial profiles of the normalized droplet number count and mean droplet velocity components for droplets of mean size 34.81 µm at x = 26 mm.
droplets of smaller size, this assumption of no evaporation would be less applicable for small droplets and hence the discrepancy in Fig. 10. Another important assumption is also being made in this analysis. For all droplet sizes, the trajectories are assumed to start at the station \( x = 17 \text{ mm} \) at precisely those radial locations corresponding to the PDPA measurements. These radial locations can actually be seen in Fig. 7. In reality, the droplets originate at all other intermediate locations as well, but information about these locations is unknown since measurements were made only at a finite number of points. This assumption could be a probable reason for the detection over a much shorter range in Fig. 10. Basically, a plausible scenario is that droplets of size slightly greater than 5.78 \( \mu \text{m} \) originate from several intermediate locations at \( x = 17 \text{ mm} \), partially vaporize (due to concentration gradients) along their path and become smaller droplets, get trapped in the recirculation zone, and get detected at \( x = 26 \text{ mm} \). It was seen from Fig. 8 that the calculated normalized number count distribution for the 80.88 \( \mu \text{m} \) droplet more closely followed the corresponding initial condition of Fig. 7. The fact that for the 5.78 \( \mu \text{m} \) droplet the distribution is clustered more around a finite radius interval shows that these droplets follow their way around the outside of the recirculation zone.

The number of comparison plots that can be presented are endless; however, one more figure will be shown that is representative of the comparisons obtained at \( x = 36 \text{ mm} \). Figure 11 shows the droplet attributes for the 80.88 \( \mu \text{m} \) droplet. The comparison between the calculations and the data may be seen to be quite good but not as good as the matching obtained for this droplet size at \( x = 26 \text{ mm} \). This is again because of greater and greater deviation between the aerodynamic and geometric centerlines further and further downstream from the venturi. The comparisons obtained were found to be relatively poorer for smaller size droplets at \( x = 36 \text{ mm} \), as expected.

**CONCLUSIONS**

The following conclusions can be drawn:

1. The gas phase flow field and the spray characteristics have been calculated for a CFM56 engine swirl cup that have been compared against experimental data. The CFM56 swirl cup represents a real piece of combustion hardware.
2. The calculated gas phase flowfield shows the presence of a large recirculation zone near the centerline which was confirmed by the PDPA measurements.
3. The gas phase velocity profiles obtained from the computations compared quite well with the PDPA data.
4. As for the comparison of the liquid phase, the computations of droplet number count and mean droplet velocities showed very good agreement with the PDPA data for large and intermediate size droplets. However, the comparison was poor for small droplets; the corresponding reasons were given earlier.
5. All comparisons of both the gas and liquid phases were found to be best at the initial stations close to the venturi but got worse further downstream because of the deviation observed between the geometric and aerodynamic centerlines in the measurements.
6. Smaller droplets were found to have a tendency to recirculate and follow the gas phase flowfield. Larger droplets were observed to be less affected by the flowfield.
Fig. 11. Calculated and measured radial profiles of the normalized droplet number count and mean droplet velocity components for droplets of mean size 80.88 μm at x = 36 mm.

ACKNOWLEDGMENTS

The authors wish to acknowledge several useful discussions they had at various stages of this work with Dr. Vince G. McDonell and Dr. G. Scott Samuelsen of the University of California, Irvine. The help offered by Dr. McDonell in interpreting their PDPA data is appreciated.

REFERENCES


