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Scaling of the Two-Phase Flow Downstream of a Gas Turbine Combustor Swirl Cup: Mean Quantities

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ABSTRACT

A production gas turbine combustor swirl cup and a 3x-scale model, both featuring co-axial, counter-swirling air streams are characterized at atmospheric pressure and in the absence of reaction. Spatially-resolved measurements of continuous phase (gas in the presence of spray) and droplet size and velocity are acquired downstream of the production and 3x-scale swirl cups by using two-component phase Doppler interferometry. The effect of scale on the behavior of the continuous phase and droplets is investigated by comparing the continuous phase velocity and droplet size and velocity at geometrically analogous positions. The continuous phase flow field scales well at the exit of the swirl cup. Farther downstream, differences occur which are due to disparity in entrainment. The droplet velocities scale reasonably well, but the sizes show some differences. However, the difference in size is less significant than it is between the two atomizers in the absence of the swirl cup assemblies.

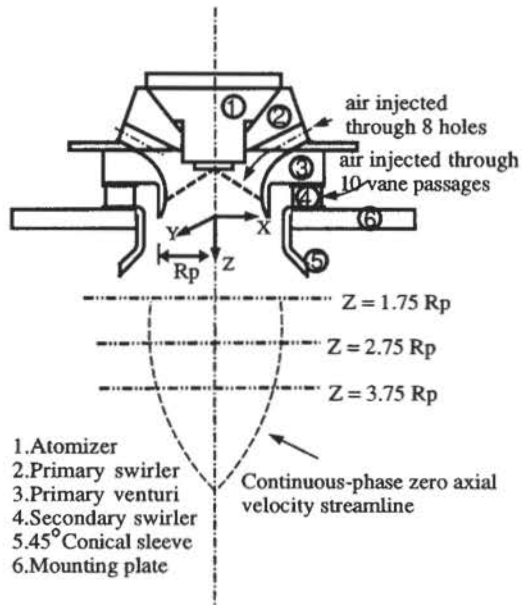

Figure 1. Swirl Cup Assembly.

INTRODUCTION

Co-axial, counter-swirling air streams have been studied for a variety of applications in combustion and other systems. Most of the studies have been conducted at non-reacting, single-phase (i.e., gas-phase in the absence of spray) conditions. Some of these studies (e.g., Habib and Whitelaw, 1980; Vu and Gouldin, 1982; Gouldin, Depsky and Lee, 1983) determined that only counter-swirl produced recirculation, while others (e.g., Samimy and Langenfeld, 1988; Mehta, Shin, and Wisler, 1989) found that both co-swirl and counter-swirl generate a recirculation zone. Wang, et al. (1991a) also found the production of a recirculation zone with counter-swirl.

One of the applications featuring two co-axial counter-swirling streams is the GE CFM56 engine combustor swirl cup, which is shown schematically in Figure 1. In this swirl cup assembly, fuel is injected by a simplex atomizer mounted in the center of the swirl cup. Part of the droplets injected convect directly downstream, and the remainder impinge onto the inner surface of primary venturi (which separates the primary swirling air from the secondary swirling air), form a thin liquid film, and are then re-atomized in the shear field produced between the two counter-swirling air streams. A goal of this swirl cup assembly is to produce uniformly distributed fine droplets.

Due to the complexity of the co-axial, counter-swirling air flows and the lack of adequate advanced diagnostics, few studies have been conducted on gas-liquid two-phase flow in the presence of such flows. However, such flows have been considered in a series of tests recently conducted at the UCI Combustion Laboratory (e.g., Wang et al., 1991a,b,c; 1992).

In the present study, the droplet size and velocity distributions are obtained downstream of a production GE CFM56 engine combustor swirl cup upon which the 3x-scale model is based. The effects of scale are studied by comparing the

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quantities acquired downstream of both the production (i.e., "1x") and 3x scale hardware. The liquid and air mass flow rates in the 1x test are about 1/9 of those in the 3x test, following the ratio of the air inlet area of the practical swirl cup to that of the 3x scale model swirl cup. The purpose of this choice aims at keeping the swirling air outlet velocity from the swirlers and liquid loading rate (or air-to-liquid ratio) the same in both 1x and 3x scale tests.

The objective of this study is to (1) study the effect of scale on droplet size and velocity distributions, and (2) provide insight into the physics associated with scaling. The data acquired in these studies can also be used for the validation and development of models and codes for the complicated two-phase flow simulation.

EXPERIMENT

Swirl Cup Assembly

Hago simplex atomizers, having flow numbers of 0.65 and 7.30 (based on ratio of flow rate, in lb/hr, to square root of injection pressure differential, in lb/in^2), were used in the 1x test and 3x tests, respectively, and are located as shown in Figure 1. A separate mounting plate and PVC pipe section (254.0 mm 1x; 336.5 mm for 3x) was fabricated and attached to each swirl cup. A 6.35 mm polycarbonate honeycomb (101.6 mm thick) was placed about 50 mm above the top of the swirl cup in both cases to provide a uniform velocity profiles at the entrance plane to the swirlers.

Characterization Chamber

Two different characterization chambers were utilized. Although not specifically designed for these tests, each chamber is similar in design, and that used for the 3x test is, fortuitously, a 2.7 times scale version of that used for the 1x tests. In both chambers, the test article is centrally located within a square duct (495mm x 495mm for 1x; 1330mm x 1330mm for 3x) and oriented downwards. The test article is attached to a vertical traverse which is connected to the chamber. The chamber itself is suspended from an optical table using a two dimensional traverse, thus giving the test article three degrees of freedom. In each case, the diagnostics are fixed, and the test article is moved. Additional details about each facility are available elsewhere (3x--Wang et al, 1991c, 1x--Wang et al, 1990; McDonell and Samuelsen, 1991).

Instruments

A two-component PDPA (Aerometrics Model 3100-S) was used to measure the droplet size and velocities. An Ar^+ laser provides the laser beams for PDPA measurement. The PDPA setup used for both tests is shown in Table I.

Test Condition and Sample Points

Test Condition. The inlet area of the swirlers for the production swirl cup is 1/9 of the 3x model. To make the air outlet velocities through the 1x swirlers the same as those of the 3x model, the 1x tests were conducted at an air flow rate of 0.017 kg/s (30.2 scfm), which is 1/9 of the air flow rate used in GE 3x scale test.

Water is used in both tests. To maintain the liquid-to-air ratio the same as a stoichiometric ratio of a kerosine fuel (about 14.78), the liquid flow rate of the production and 3x-scale swirl cups should be 1.1 g/s and 0.010 kg/s respectively. While the 3x tests were conducted at 10 g/s (Wang, et al., 1991a, b), the 1x hardware was operated at 0.86 g/s due to flow limitations in the test stand. This provided a liquid-to-air loading rate of 5.0% rather than 6.5% in the 3x model test. However, because this flow field is dominated by the aerodynamics (Wang, et al., 1991a,b), this difference is considered negligible with respect to affecting either the two-phase flow field or droplet dispersion.

TABLE I. Characteristics of PDPA 3100-S.

	1x	3x
Transmitter		
0.5145 micron line (U, D)*		
Fringe Spacing (μm)	9.03	9.88
Waist (μm)	223.32	187.17
0.4880 micron line (V or W)^2		
Fringe Spacing (μm)	9.31	9.84
Waist (μm)	211.82	177.53
Receiver		
Collection Lens (mm)	629 f/5.7	1000 f/9.3
Focusing Lens (mm)	238	238
Spatial Filter (μm)	100	100
Collection Angle	30° Off-Axis Forward	

*U, V, W and D are axial, radial, tangential velocity and droplet diameter respectively.

Sample Points. The measurements were conducted at three axial locations: Z = 1.75, 2.75, and 3.75 R_p (where R_p is the radius of the primary venturi exit plane and is 9.7 mm herein), and along the centerline of the swirl cup. The origin of the coordinates is at the center of the primary venturi exit plane.

RESULTS AND DISCUSSION

From the myriad of data collected, selected measurements are presented and specific characteristics are identified that are particularly germane to the behavior observed at both scales.

Atomizer Comparison in the Absence of the Swirl Cup

Since two different atomizers were utilized at slightly different injection pressures, the sprays in the absence of the swirl cup assemblies were characterized to provide a baseline against which to compared differences observed in the presence of the swirl cup. An example of the D_{32} comparison is shown in Figure 2 at an axial location of 15 mm. Large differences are observed which are associated with the order of magnitude difference in mass flow and the slight variation in injection pressures. This illustrates the difficultly in scaling the atomizer flow independent of the aerodynamic flow. However, as shown below, far less difference is observed in the presence of the swirl cup assemblies, revealing the domination of the spray by the aerodynamic flow field.

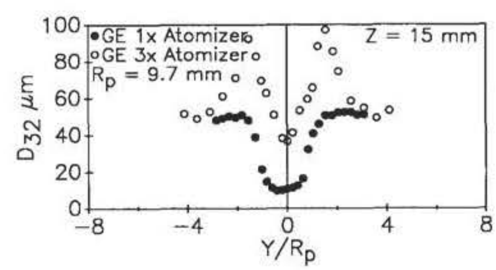

Figure 2. Comparison of D_{32} Between Atomizers in the Absence of the Swirl Cup Assemblies.

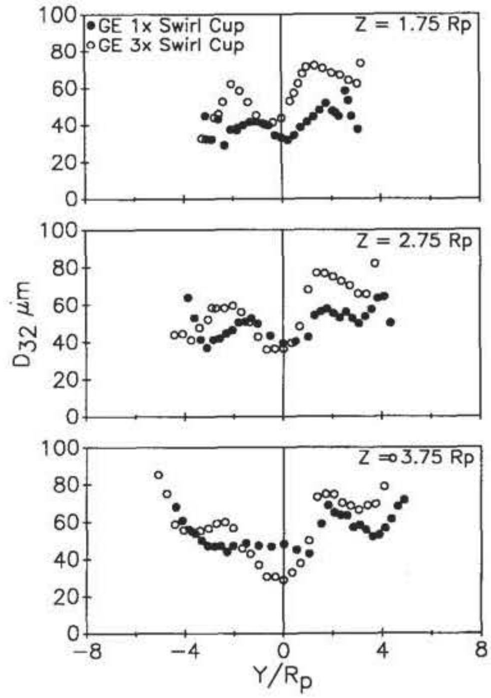

Figure 3. Comparison of Droplet Distribution D_{32}.

Comparison of 1x and 3x Swirl Cup Results

In the following, comparisons are presented for radial profiles at three axial planes (Z = 1.75 Rp, 2.75 Rp, and 3.75 Rp). In addition, for the velocity results, a centerline profile is included and appears in the top portion of the figure. Data are provided for the following representative droplet size groups:

- "Small" 11-20 microns
- "Medium-Sized" 30-40 microns
- "Large" 74-88 microns

Droplet Size and Data Rate. As shown in Figure 3, the distribution D_{32} in the 3x test is greater than that in the 1x test except in the recirculation zone at $Z = 3.75\ R_p$. Part of the reason for the large drops is attributed to the differences in the initial droplet size distribution. Additional insight is offered by the data rate results shown in Figure 4.

The data rate for the small droplets is about an order of magnitude greater in the 1x test than the 3x test at all locations. The medium sized droplets show a similar data rate in both tests except in the recirculation zone at $Z = 3.75\ R_p$. The large droplets in the 3x case have a higher data rate than those in the 1x case, except at the centerline at Z = 3.75 Rp.

For the large droplets, the data rates are quite low, usually below 100 H_z. The twin-peak droplet data rate distributions suggest that the shear layer is a highly populated with droplets and thus high in liquid volume flux.

Mean Axial Velocities. Figure 5 presents results for the mean axial velocity. Note that a centerline profile appears in the top part of the figure and the three radial profiles appear in the lower part. A slightly wider recirculation zone exists downstream in the 3x test compared to that in the 1x test as shown in Figure 5a which is attributed to differences in entrainment rates between the two cases. At the exit of the swirl cup, the axial velocity profiles are identical for both cases.

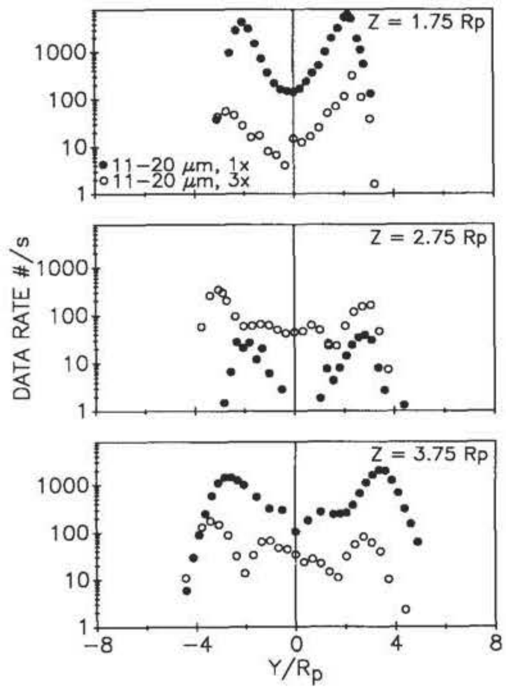

Figure 4. Comparison of Droplet Data Rate.
(a) Small Droplets

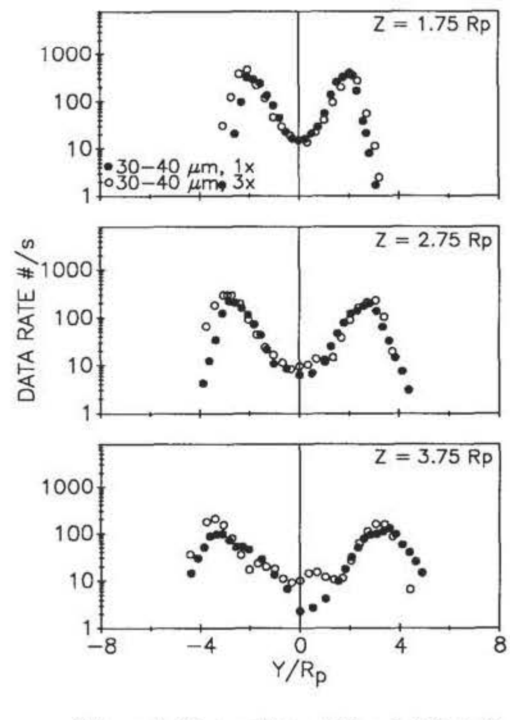

Figure 4. Comparison of Droplet Data Rate.
(b) Medium Sized Droplets

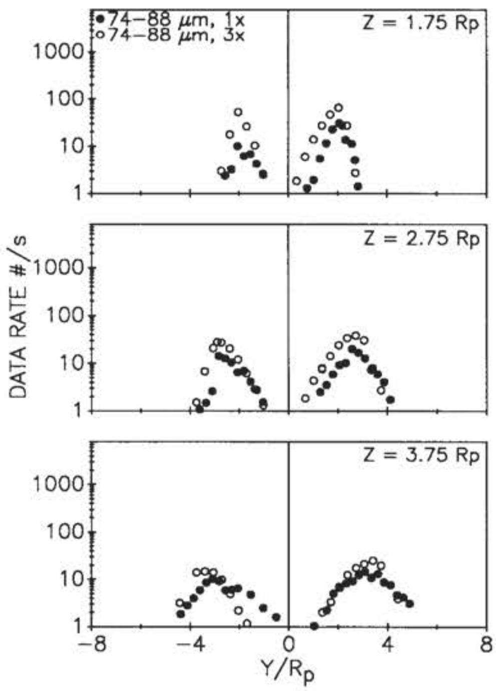

Figure 4. Comparison of Droplet Data Rate.
(c) Large Droplets

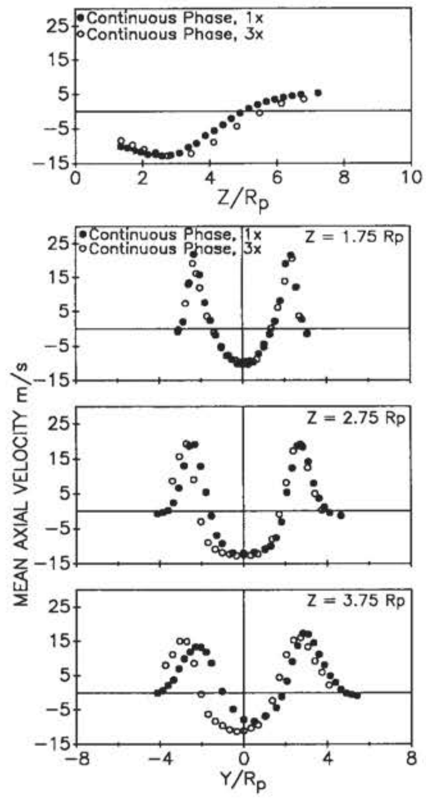

Figure 5. Comparison of Mean Axial Velocity.
(a) Continuous Phase

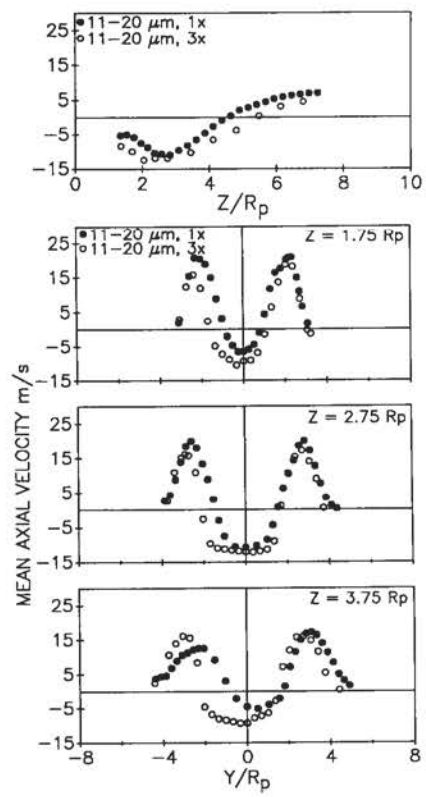

Figure 5. Comparison of Mean Axial Velocity.
(b) Small Droplets

The behavior of the droplets is shown in Figures 5b-d. While it is expected that the small droplets for both the 1x and 3x tests would mirror the continuous phase (Fig. 5b), it is interesting that the medium sized droplets only in the 3x test reflect this (Fig. 5c). Also, the large droplets in the 3x case are recirculated at Z = 3.75 Rp, whereas those in the 1x case are not (Fig. 5d). The differences are attributed to the relatively long distance traveled from the atomizer to the same geometrically analogous points in the 3x test compared to the 1x test. Given that the droplet velocities are similar in each case (as shown below), the medium sized droplets have more time to approach the velocity of the continuous phase in the 3x test than in the 1x test.

Mean Radial Velocities. Figure 6a compares the mean radial velocities of the continuous phase. Positive values on the +Y side and negative values on the -Y side indicate velocities away from the centerline. Near the swirl cup, the velocities scale well. However, downstream, the 1x case exhibits asymmetry which makes comparison difficult. The non-zero radial velocities along the centerline are due to a modest mismatch of the aerodynamic and geometric centerlines and the large gradients in the tangential velocity (Fig. 7).

The radial velocities of the droplets are well scaled at the upstream location Z = 1.75 R_p, as shown in Figure 6b-d. Downstream, the mean radial velocities for the small (Fig. 6b) and medium sized (Fig. 6c) sized droplets reflect an asymmetry in the 1x test observed in the continuous phase. Because of the insensitivity of the large droplets to the influence of the gas-phase flow field, the mean radial velocity of the large droplets is more symmetric, in the 1x test, than that of the small and medium sized droplets (Fig. 6d).

Noteworthy at Z = 3.75 Rp is the inward flow of small and medium sized droplets to the centerline at the contraction of the recirculation zone. This again mirrors the continuous phase. The large droplets are unaffected.

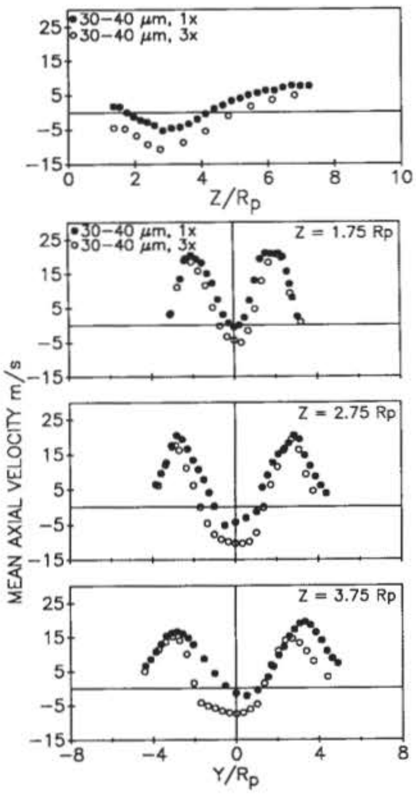

Figure 5. Comparison of Mean Axial Velocity.
(c) Medium Sized Droplets

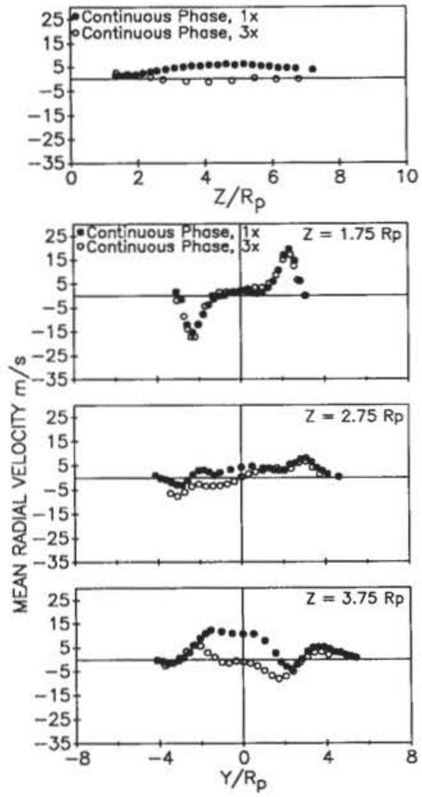

Figure 6. Comparison of Mean Radial Velocity.
(a) Continuous Phase

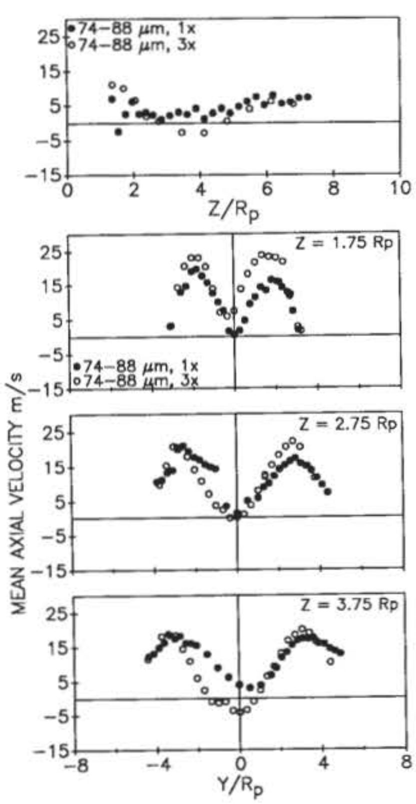

Figure 5. Comparison of Mean Axial Velocity.
(d) Large Droplets

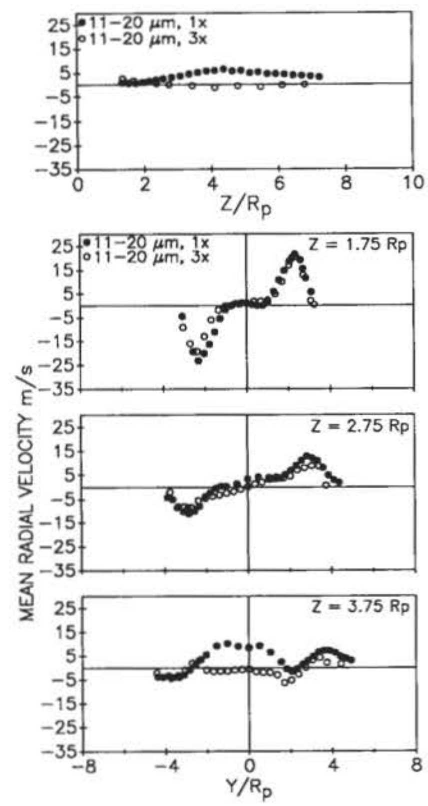

Figure 6. Comparison of Mean Radial Velocity.
(b) Small Droplets

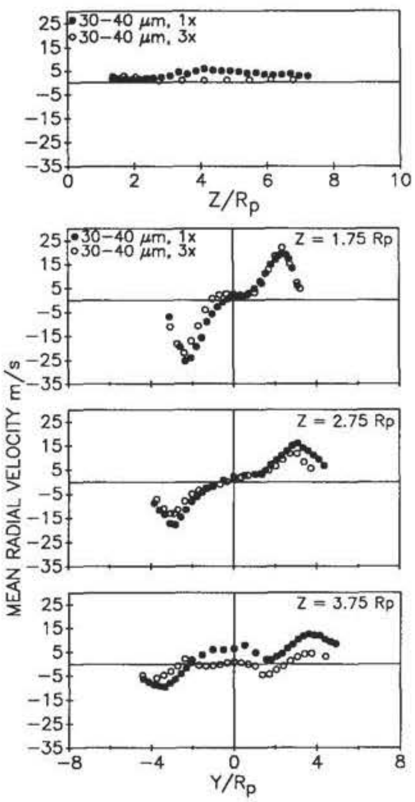

Figure 6. Comparison of Mean Radial Velocity.
(c) Medium Sized Droplets

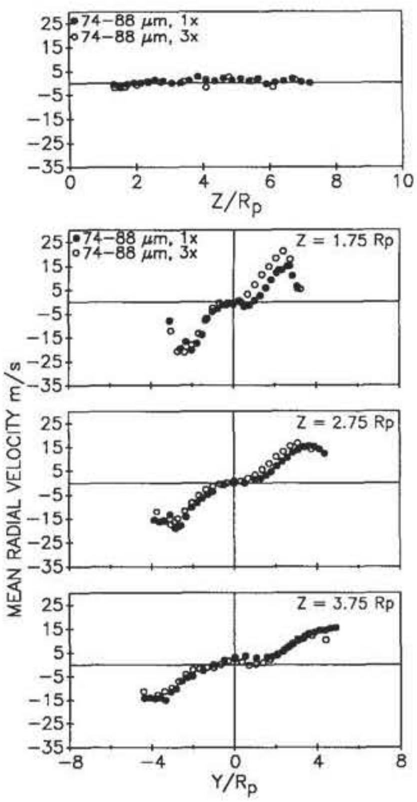

Figure 6. Comparison of Mean Radial Velocity.
(d) Large Droplets

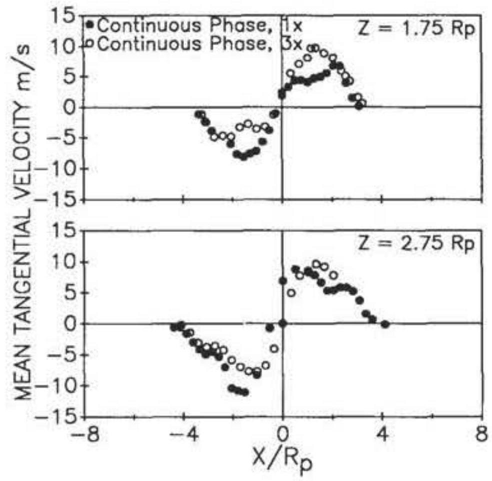

Figure 7. Comparison of Mean Tangential Velocity.
(a) Continuous Phase

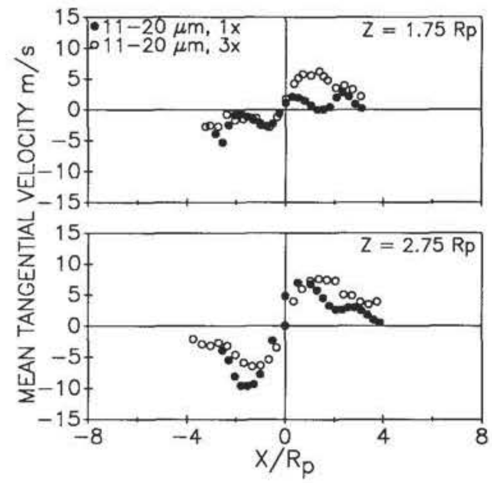

Figure 7. Comparison of Mean Tangential Velocity.
(b) Small Droplets

Mean Tangential Velocities. The continuous phase mean tangential velocities are presented in Figure 7a. Looking downstream from the swirl cup, positive values on the +X side and negative values on the -X side reflect counterclockwise rotation. At Z = 1.75 Rp, the results are not consistent on both sides of the centerline, which makes comparison difficult. At Z = 2.75 Rp, the results are better behaved, and similar behavior is observed. Specifically, the radial location where the peak tangential velocities occurs is the same and the decay of the profiles are similar.

The droplet mean tangential velocities, presented in Figures 7b-d, provide especially interesting insights with respect to the effect of scale. In particular, the droplet mean tangential velocity distributions display differences in magnitude and trend not observed in either the axial or radial velocity.

The mean tangential velocity distribution of the small droplets is presented in Figure 7b. The data for the small and medium sized droplets in the 1x test reveal a twin-peak distribution on either side of the centerline, with one inside the recirculation zone and the other outside of it. This occurs because three sources of small and medium sized droplets contribute to measurements: (1) droplets recirculating while swirling counterclockwise, (2) droplets produced from the edge of

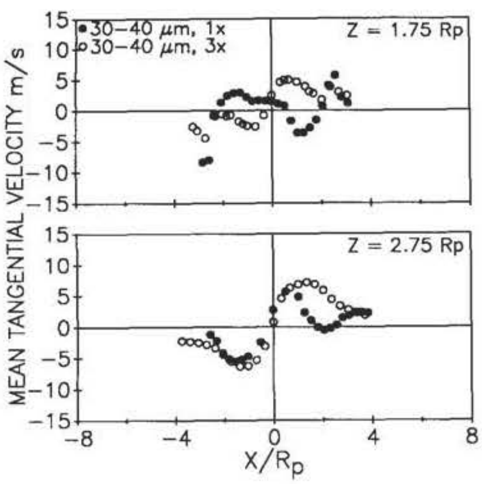

Figure 7. Comparison of Mean Tangential Velocity.
(c) Medium Sized Droplets

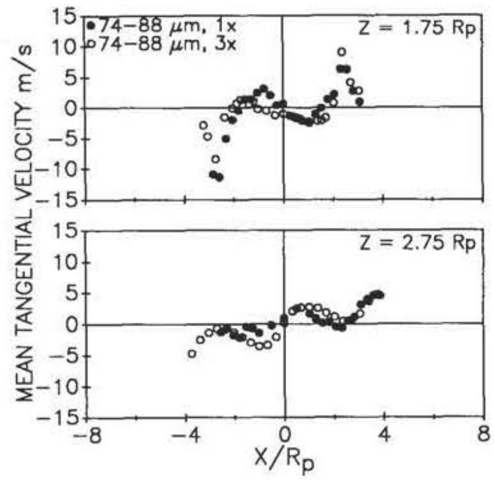

Figure 7. Comparison of Mean Tangential Velocity.
(d) Large Droplets

the venturi which are dominated by the counterclockwise-swirling secondary air, and (3) droplets injected directly from the atomizer, which are initially dominated by the clockwise rotating primary air. The relative contribution of these three sources results in strong bi-modal velocity distributions (Wang, et al., 1991b).

The relative contribution of small and medium sized droplets from the three different sources which create the peak within the recirculation zone are as follows: (1) many droplets are recirculated near the exit plane of the swirl cup (at approximately $Z = 1.75\ R_p$), (2) relatively few are directly injected from the atomizer which can overcome the negative pressure gradient of the recirculation zone and penetrate to this point and (3) even fewer arrive from the primary venturi since the centrifugal force causes droplets from this source to move radial outwards.

At the shear layer, a local minimum in the tangential velocity exists because of a balance in the relative contribution from the three sources (Fig. 7b and c).

The relative contribution of droplets resulting in the peak outside the recirculation zone are as follows: (1) very few are recirculated to this point, (2) many arrive directly from the atomizer, and (3) many from the edge of the primary venturi.

Note that the small droplets tend to reflect this twin-peak distribution at Z = 1.75 Rp in the 1x case. In the 3x case, the medium sized droplets reflects this behavior, but at Z = 2.75 Rp. This important difference is attributed to the relative time scales in the two cases associated with (1) droplet relaxation and (2) the droplet residence within the recirculation zone.

Large droplets penetrate farther in the axial direction, as shown in Fig. 7d. In this case, only two of the above source contribute because very few large droplets are recirculated. As a result, the measurements consist of clockwise rotating droplets which arrive directly from the atomizer and counterclockwise droplets arriving from the venturi. The behavior of the large droplets is similar for both cases because, compared to the small and medium sized droplets, the relaxation time is large.

In both cases, with increasing axial distance downstream, the twin-peak distribution transitions into a single-peak distribution because the flow is dominated by the counter-clockwise swirling secondary air flow.

CONCLUSIONS

The behavior of the continuous phase and droplets in the flow field downstream of a production and a 3x scale model engine combustor swirl cup has been studied. The goal was to assess the effect of scale on the processes that affect droplet and continuous phase behavior in such complex, realistic systems. Conclusions drawn from the study are as follows:

- The continuous phase scales well at the exit of the swirl cup in the present case because the low liquid loading ratio has little affect on the flow. Farther downstream, scaling is difficult to evaluate because of differences in entrainment and the presence of asymmetries, especially with the production hardware.
- The two atomizers used have different spray characteristics, despite being well scaled in flow rate and flow number. This illustrates the challenges associated with selecting parameters for scaling atomizers.
- In spite of the differences in the atomizer characteristics, the behavior of the droplet size and velocity is similar in both the production (1x) and 3x scale swirl cups indicating that, for this particular hardware and operating condition, the continuous phase dominates the flow field.
- The droplets in the production hardware join the recirculation zone in a narrower and shorter region than those in the 3x test based upon geometrical analogy.
- Due to the larger absolute size of the recirculation zone and similar maximum velocities, droplets have a longer residence time in the 3x scale. Hence, a greater proportion of medium sized droplets, for example, can be recirculated than in the production system.

- The droplet D_{32} in the 3x scale is generally greater than that in the 1x scale. This is due, in part, to differences in the initial droplet size distribution produced by the two atomizers. The extent to which the aerodynamic flow and droplet formation from the primary venturi contribute to differences observed cannot be determined at this point.
- The shear layer has a high droplet population and thus a high liquid volume flux for both 1x and 3x scale tests.

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