Numerical Design of a Liquid Fueled Combustor*

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Abstract

The design of an experimental combustor being developed at Georgia Tech., is addressed in this paper. The primary objective here is to study the effect of liquid fuel droplets and its atomization on the emission characteristics (primarily CO) in the combustor under development. A steady state code developed at NASA LeRC, ALLSPD-3D is used for this purpose. Effects of varying the initial liquid droplets size distribution and injection angle on evaporation, combustion and CO emission are studied. It is determined that a smaller range of initial droplet sizes evaporate quite efficiently and hence, burn quite effectively, while a larger range of initial droplet sizes is not as effective and can result in incomplete combustion. This results in increased CO emission. Inclusion of swirl increases the combustion efficiency and reduces CO emission. The results of this study provide baseline performance characteristics for the combustor currently being built for active control studies.

1 Introduction

Efficient fuel consumption and low emission in aircraft gas turbine engines have now become desirable design issues due to the projected increase in fuel costs and the upcoming mandated international guidelines for emission into the atmosphere. For example, it is required that the Advanced Subsonic Transport combustor must reduce NOx emission by at least 70 percent compared to current ICAO standards. Maintaining combustion efficiency and flame stability while simultaneously reducing NOx (and CO and unburned HC especially during takeoff and landing) emissions is not feasible without innovative design changes in the fuel-air mixing process. Current attempts are focussed on modifying the fuel-air mixing by changing the fuel injection process. Designs such as multiple injection using micro-laminate screens and advanced swirler cups are currently under study at General Electric and NASA. These methods attempt to break up the initial dense spray so that a well characterized dilute spray is set up. Even in this case, it is not clear what should be the optimum initial droplet distribution that will result in enhanced combustion efficency and reduced emissions at the same time. Some recent studies have foccused on these aspects. Silverman et al. (1993) studied the effects of stoichiometry and initial droplet size distribution on premixed spray flames. Bossard and Peck (1996) suggested that the initial droplet size distribution can have a direct influence on the vaporization and on the burning characteristics of ploydisperse fuel sprays.

To control the atomization and the combustion processes it will be necessary to determine the proper relationship between fuel injection, atomization, vaporization and mixing processes (Faeth, 1996). A research program at Gerogia Tech is currently underway to investigate fuel injection control to optimize the combustion process and to extend the stable operating margins. In particular, control goals are to achieve low emissions, better fuel efficiency, stable combustion in the lean limit and yet maintain uniform temperature at the combustor exit. Active combustion control methodologies are being explored to achieve these (somewhat contradictory) objectives. The investigation involves both experimental and computational studies. Although, the eventual aim is to study mixing and combustion using a time-accurate approach based on large-eddy simulations (Menon and Pannala, 1997), an effort to ob-

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tain baseline performance characteristics of the experimental combustor using a steady state solver is reported in this paper. Steady-state Reynolds Averaged Navier-Stokes (RANS) approach is computationally more efficient (although unable to capture the unsteady effects) and, therefore, can be effectively used to investigate the general trends. To achieve this objective, a recently developed ALLSPD code of NASA-LeRC is employed.

2 Computational Methodology

ALLSPD-3D (Chen et al., 1996) is a finite difference, compressible flow code with a low Mach number preconditioning solver. It can be used in the 3D, 2D and axi- symmmetric modes. The various capabilities of this code have been noted in Chen et al. (1996) and, therefore, not repeated here. Briefly, this code uses a partially decoupled, implicit steady-state algorithm to improve efficeincy and accuracy. It allows incorporation of generalized finite rate chemistry and transport properties. Turbulence modeling is based on the standard k-ϵ model and the well known eddy breakup model is used for the chemical source term closure. The droplets injected into the stream is tracked using a Lagrangian approach based on the stochastic separated flow (SSF) spray model (Faeth, 1996). Although complex flow geometries can be studied, a limitation of this code appears to be that it employs relatively very simple inflow/outflow boundary conditions. These conditions can cause some numerical problems and, therefore, proper care needs to be taken to accurately model the boundary effects.

The test geometry used for these calculations is identical to the experimental combustor (which is still under construction). The computational geometry studied here consists of a air tube of outer diameter 0.9525 cm (0.85 cm ID) that contains a fuel injector of outer diameter 0.635 cm. The fuel is injected into the air stream through a nozzle (orifice diameter 0.051 cm) upstream of the air exit plane. The partially premixed liquid fuel-air mixture enters the combustor which has a dump plane used for flame stabilization. Figure 1 shows the schematic of this combustor along with other relevant scales. The air stream velocity was varied in this study, however, all studies are reported here are for a reference air velocity of 30 m/s. The flow speed in the fuel injector is around 5 m/s. The Reynolds number based on the air flow and air jet diameter is around 23,000.

3 Results and Discussions

In the following, the results obtained using ALLSPD is reported. Before discussing the results obtained in the Georgia Tech combustor, some results obtained in another combustor is briefly discussed to demonstrate preliminary validation of the code. Note that, the ALLSPD code has been extensively employed at NASA LeRC for various applications and its basic capabilities are assumed to be established. The facility simulated here is still under construction at Georgia Tech and therefore, there is no data for comparison.

3.1 Gas Fueled Combustor

The ALLSPD code has been first employed to study the flow in a gas fueled combustor developed at Pratt and Whitney (PW-100) and extensively studied in the past (e.g., Roquemore et al., 1991, Sturgess et al., 1991, 1994). The purpose of this study was to establish the computational accuracy of the ALLSPD code. The PW-100 combustor consists of coaxial jets with a 27mm inside diameter central fuel jet surrounded by a 40mm diameter annular air jet. The fuel used is propane and the jets are located centrally in a 150mm diameter duct. A backward facing step (as in Fig.1) of height 55mm is used to stablize the flame. Thus, other than the dimensions and the fuel employed, this device is quite similar to the liquid fueled combustor of current interest. Only cold flow calculations were performed for this flow. The variation of axial velocity in both longitudinal and radial directions are shown in Figs. 2a and 2b, respectively. Results from the ALLSPD code compare well with experimental and computational (obtained using a completely different code) results presented earlier (Sloan et al., 1994).

3.2 Vaporization in Liquid Fueled Combustor

The combustor shown in Fig. 1 was first used to investigate the effect of initial droplet size distribution on the spreading of the spray. The fuel studied for both the vaporization and combustion case is methanol. Methanol has a critical temperature of 360 K and therefore, the vaporization studies assumed that the air stream was at 400 K. A computational grid 75x45 was used for all cases discussed below. The droplets are injected axially over a few grid points (6-

10) around the injector location inside the air stream. The initial droplet size distribution determines the number of droplet groups (used to resolve the droplets of different sizes within the specified range) that must be tracked. As a result, a large size distribution requires a larger number of groups. This can increase the computational time significantly. In the present study, the number of groups were chosen in such a way as to represent the selected size range reasonably well without significantly increasing the computational cost and without sacrificing the accuracy of the results. Calculations were carried out till steady state was achieved (approximately 4-5 orders of magnitude decrease in the residual). In all the results presented, the length scales have been nondimensionalized by the fuel injector diameter.

Two initial size distributions in the range 5-20 μm and 10-100 μm are discussed in detail (although other initial distributions were also stuidied). For the former size range, 200 droplet groups were required while for the latter case around 1000 droplet groups were needed to adequately resolve the droplet sizes in the range. Figures 3a and 3b show, respectively, the droplet scattering at steady state for these two initial size distributions. Since the droplets undergo vaporization as they spread into the air stream, the various sizes in these figures show the final stage of the flow field. In ALLSPD, all droplets below 5 μm are assumed to instantaneously vaporize and become gaseous. As noted recently (Menon and Pannala, 1997), this assumption is likely to be flawed since the final stages of mixing is very critical for fuel-air mixing. However, further reducing this cutoff in a steady state code is computationally very expensive.

It can be seen from Fig. 3a that due to vaporization the droplet size reduces from 20 μm at the point of injection to sizes between 5 and 10 μm further downstream axial locations. Further downstream no droplets are present suggesting that all the drops have completely vaporized (or have become smaller than the cut-off size). The droplets also do not radially spread significantly and remain close to the injection region. On the other hand, for the larger initial size distribution (Fig. 3b), the vaporization process continues further downstream in the combustor with siginificant presence of droplets near the outflow. The radial spreading of the droplets is also quite large (when compared to the 5-20 μm case) and is caused primarily by the smaller drops. The larger droplets in this case continue to travel downstream without any significant spreading. It can also be seen that substantial number of injected droplets leave the computational domain before completely vaporizing. This is primarily because the larger drops take longer to vaporize and as it vaporizes, the temperature in the gas surrounding the droplet decreases and this further inhibits the vaporization process.

These results appear to suggest that if the initial droplet distribution is limited to a small size range the fuel-air mixing is likely to be completed very close to the injector. Whether this implies stable combustion with reduced emission is of interest here and is discussed in the next section.

3.3 Combustion in Liquid Fueled Combustor

Combustion of methanol in the same combustor was then investigated using the same two intial droplet distributions. A simple two-step mechanism of methanol combustion including the formation of CO was adopted from conditions reported in Westbrook and Dryer (1981). All other conditions were the same except that the initial air and fuel temperature was 300 K and ignition was triggered just downstream of the injection plane as suggested for ALLSPD. During this study, it was determined that for the larger size distribution, stable combustion was only achieved above a critical fuel flow rate. This was also noted earlier (Silverman et al., 1993) and appears to be due to the fact that the larger drops take longer to vaporize (both spatially and in time). Here, it was determined that the mass flow rate of fuel for the 10-100μm distribution needs to be approximately twice the mass flow rate for the 5-20μm size range case for stable combustion. It is not clear at present if there are any other mitigating factors causing this behavior. Therefore, to directly compare the results of the two size distribution, the 5-20μm case was also rerun using the same mass flow rate as for the larger size distribution.

Figures 4a-c show, respectively, the temperature, the water and CO mass fraction contours for the 5-20 μm initial droplet distribution. Figures 5a-c shows the corresponding plots for the 10-100 μm initial droplet distribution. The flame temperature in both cases reaches values close to the adiabatic condition. The flame is thin since injection occurs over only a small region. The flame (in the case of 5-20 μm case) extends (from x=0.376 m to x=0.5226 m) around 50 times the droplet injection width. For the larger size distribution, all the droplets are not fully vaporized even though combustion is taking place. The droplet scatter data showed that a large number of droplets of sizes between 5 and 10 μm still exist even far downstream of the injection domain. This results in a longer flame length as can be seen by comparing figs. 4a and 5a.

From a design perspective, this suggests that to achieve complete combustion in a compact combustor, it is necessary to ensure that the droplet size distribution is limited to a small size range. This is also suggested by Bossard and Peck (1996). This constraint may be considered a control objective for the development of an actively controlled liquid fuel injector and may impose constraints on the injector design. As noted earlier, it was also observed that the flame for the larger size distribution case could not be sustained in the lean limit. This was also observed by Marchese and Dryer (1996) and appears to be due to the fact that condensation of the water produced by the burning of smaller droplets on the large droplets delays or inhibits further evaporation and extinguishes the flame. This suggests another design constraint for the injector if it is to operate in the lean limit.

It can also be seen from Figs. 4c and 5c that there is substantial differences in the CO contours (both distribution and magnitude) for the different size distributions. This is more clearly seen in Fig. 6 which compares the CO profile at the exit plane for the two cases. For the smaller size case, the peak CO concentration is at the centerline while for the larger distribution it peaks approximately 0.02 m above the centerline. Regardless, the peak value is substantially lower (by a factor of atleast 10) for the smaller size distribution case. For the larger size distribution case, the CO mass fraction at the centerline is still much larger than for the smaller size case. This is because more particles are left unvaporized in the larger size case and complete combustion does not take place before many of the droplets leave the computational domain.

The above study employed axial injection of the fuel at the injector. To determine how the injection angle effects the emission, a calculation was carried out with the 5-20 μm distribution but with the fuel injected over a 10 degree angle relative to the horizontal. Figure 7 compares the CO emissions at the exit plane for the two cases. These cases were computed using a mass flow rate 50 percent smaller than the case shown in Figs. 4 and 6. However, as mentioned earlier, the 5-20 μm distribution case achieved stable combustion at a lower mass flow rate. Clearly, using an angled injection substantially reduces the CO emission suggesting that both the initial size distribution and the initial spray orientation are important for improving combustion efficiency. Comparing with Fig. 6 shows that increasing the mass flow rate does increase the CO emission. However, the droplet vaporization for the 5-20 μm case is still efficient and therefore, the increase in CO emission with increase in fuel flow rate is not very significant (at least when compared to the 10-100 μm range case).

3.4 Effect of Swirl

The above study was repeated by incorporating swirl into the inflow to the combustor. Swirl is a well known method used in practical gas turbine combustors to increase the breakdown of the droplets and to enhance fuel-air mixing. Thus, it is expected that substantial improvement in combustion will occur when swirl is included. The present results confirm this. For the smaller size distribution, inclusion of swirl almost completely eliminated the CO emission from the combustor (not shown) while for the large size distribution a 50% reduction was observed. Figure 8 compares the CO mass fractions at the exit plane with and without swirl for this case. The peak CO location also shifts closer to the centerline. This follows the trend towards peak emission at the centerline seen in the smaller distribution case and suggests that with swirl most of the partially vaporized larger droplets are confined closer to the centerline while more of the other droplets (away from the centerline) are getting completely burnt.

4 Conclusions

The present study focussed on the vaporization and the combustion processes in a liquid fueled combustor that is currently being built at Georgia Tech to develop actively controlled fuel injectors. The goal of this study is to enhance the combustion process in a compact combustor while at the same time reducing the fuel consumption and emissions. Here, steady state calculations using a well established code were carried out to obtain some baseline results for this combustor. Methanol vaporization for a range of initial droplet size distribution was first studied followed by combustion studies using a two-step global mechanism. It has been determined that the initial size distribution has a significant impact on the vaporization process. Smaller size range leads to faster evaporation and mixing and, hence, burning occurs closer to the injection plane itself. This results in a shorter flame length and reduced CO emission from the combustor. Increasing the fuel flow rate for the small size range case does increase the CO emission but this increase is not very significant since most of the fuel gets vaporized and burnt. Increasing the injection angle and introducing swirl can further enhance the vaporization and combustion process resulting in a reduced CO emission. The larger size distribution case also required a significant increase in the fuel flow rate to stabilize the flame. This coupled with the fact that all the droplets do not get fully vaporized and burnt resulted in a significant increase in the CO emission. These results suggest that fuel injectors that result in a large variation in the initial droplet sizes are likely to be less fuel efficient, unstable in the lean limit and have poor emission characteristics. How the droplet range effects NO emission is another issue that is under investigation.

The present results, which agree with earlier experimental observations, provide a baseline performance characteristics of the experimental combustor currently under construction. The planned active control studies of liquid fuel injection in this combustor needs to achieve controlled, stable combustion in the lean limit without increasing CO emission. The present study suggests that to achieve these design goals, an injector that can generate very close to the injector plane, a droplet distribution that is limited to small sizes and in range is needed. Achieving this goal in a practical device may require judicious combination of the injector shape, injection pattern, initial droplet size distribution and swirl. Further studies are planned to systematically investigate the effect of these parameters to perhaps identify appropriate design constraints that will have to be met to achieve the overall goals of this research study.

Acknowledgements

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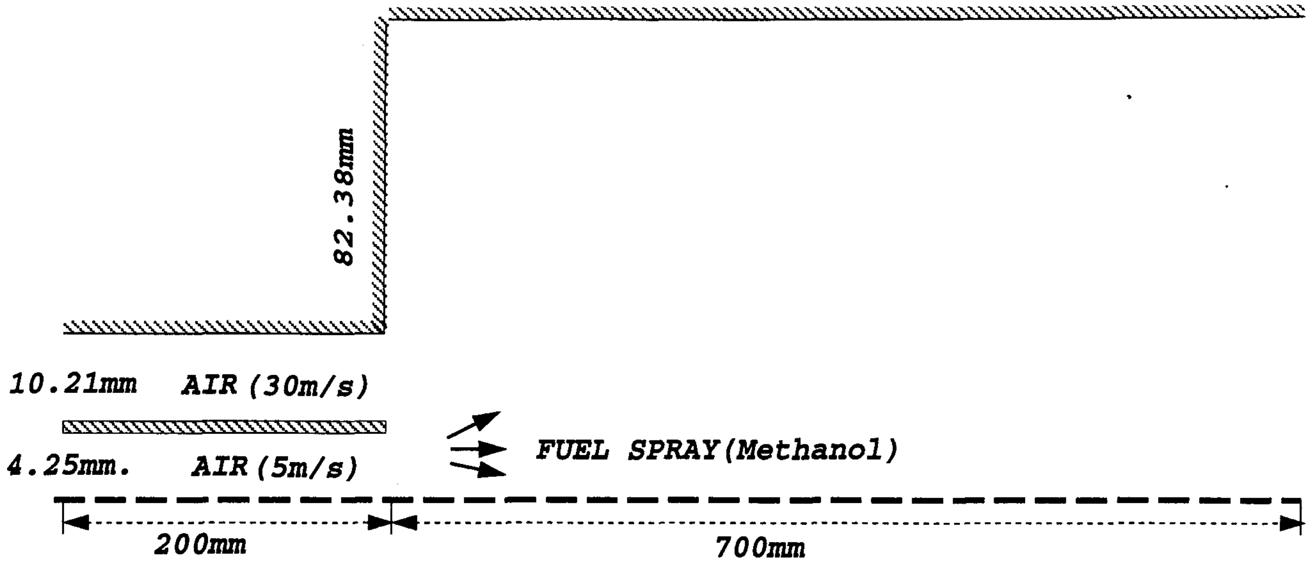

Figure 1. Configuration of the experimental combustor

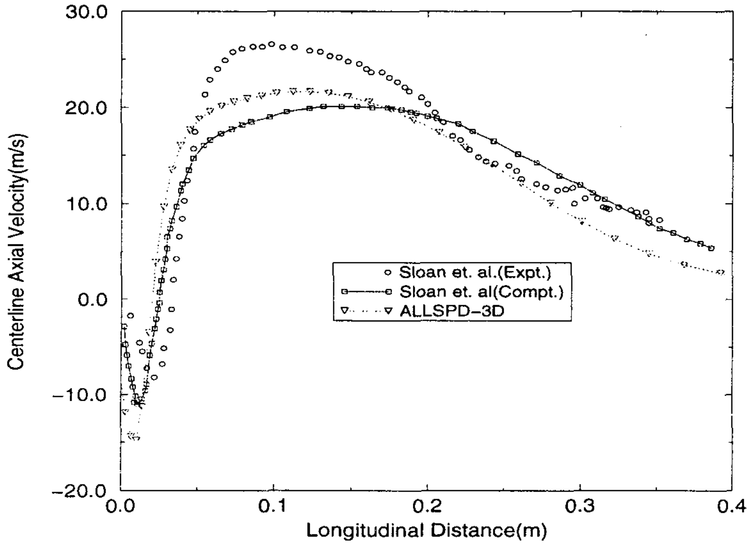

Figure 2a. Comparison of Centerline Axial velocity profiles

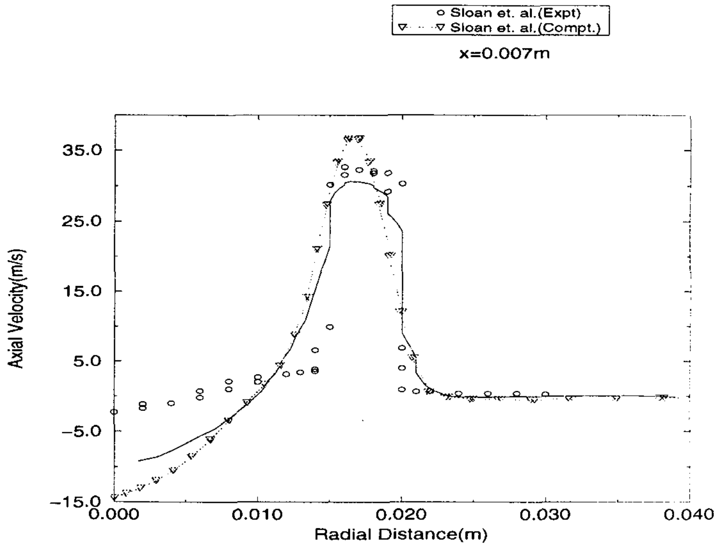

Figure 2b. Comparison of Mean axial velocities

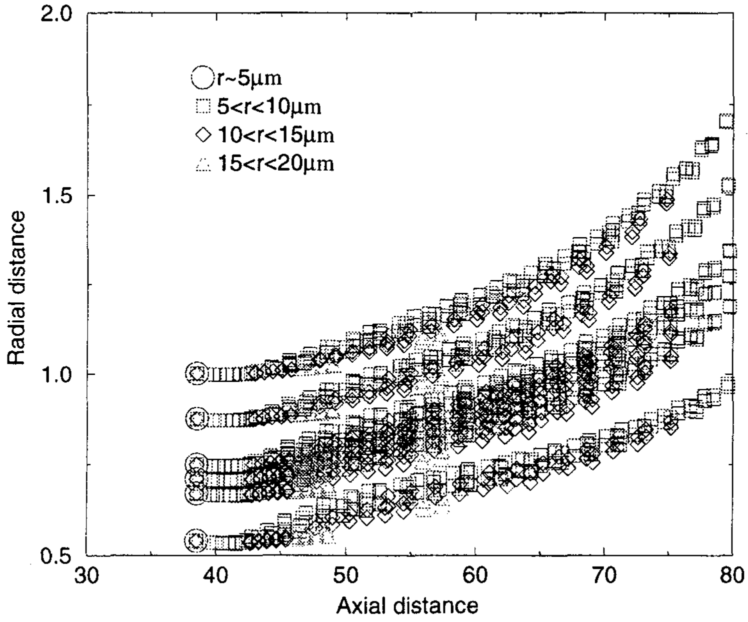

Figure 3a. Spatial distribution of droplets for 5–20 μm case

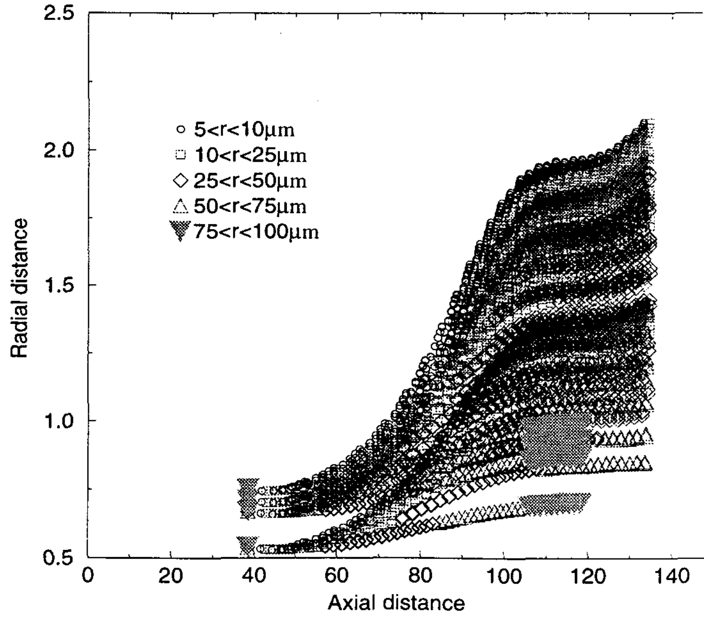

Figure 3b. Spatial distribution of droplets for 10–100 μm case

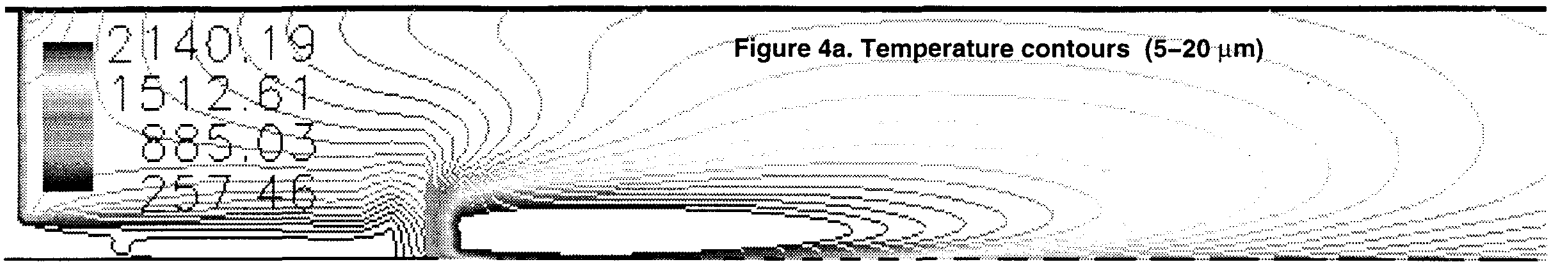
Figure 4a. Temperature contours (5–20 μm)

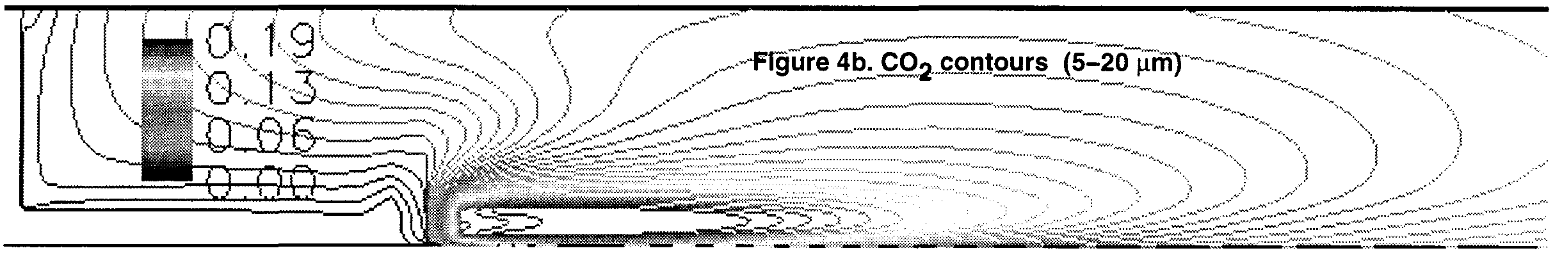
Figure 4b. CO_2 contours (5–20 μm)

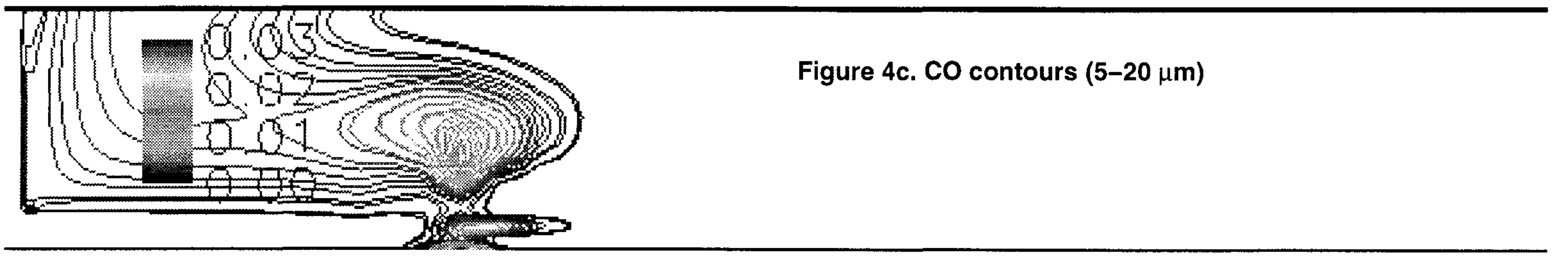
Figure 4c. CO contours (5–20 μm)

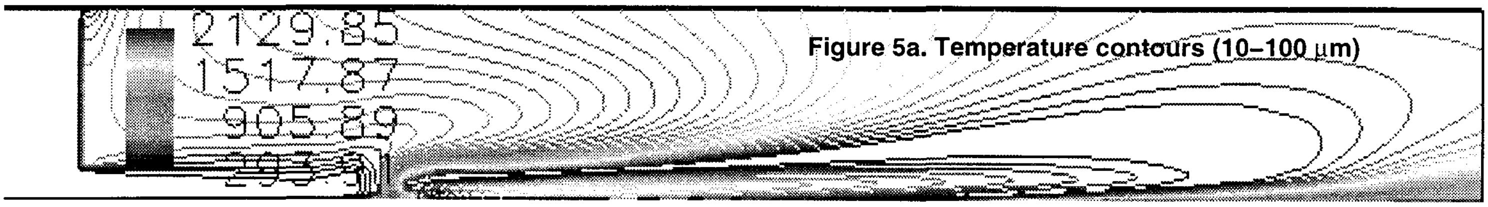
Figure 5a. Temperature contours (10–100 μm)

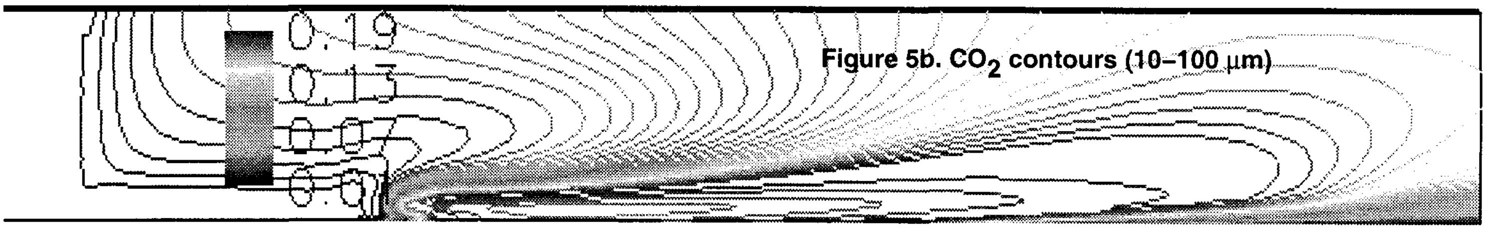
Figure 5b. CO_2 contours (10–100 μm)

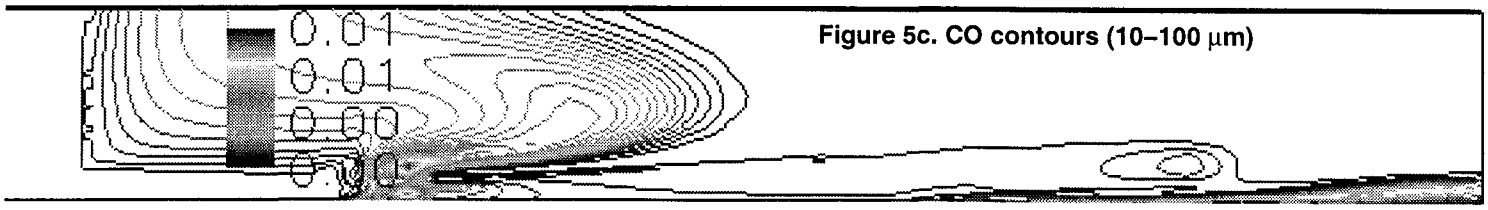
Figure 5c. CO contours (10–100 μm)

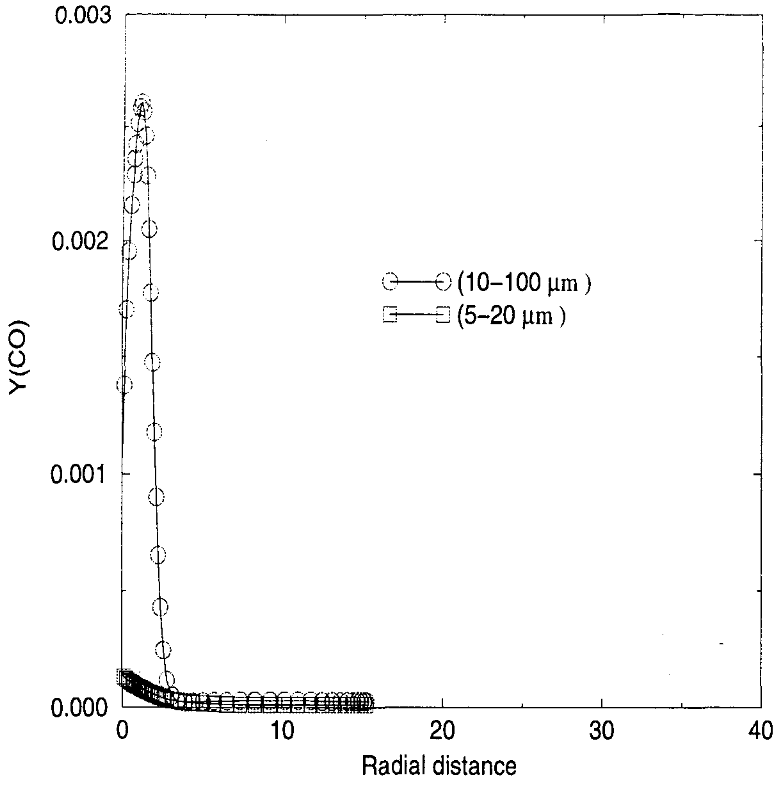

Figure 6. CO emission at the exit plane

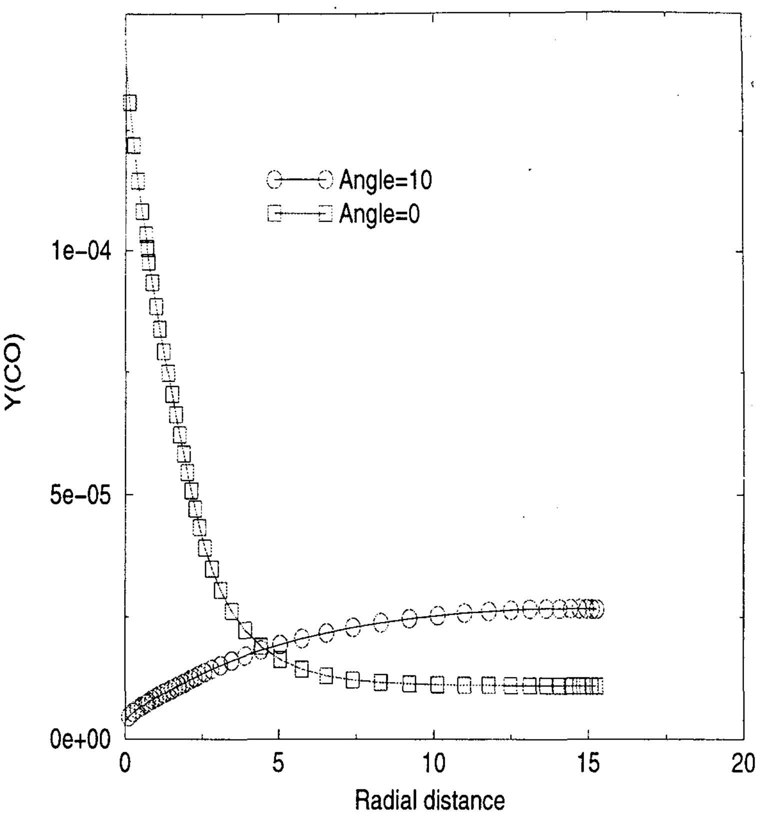

Figure 7. CO emission at the exit plane for the initial size range of 5–20 μm with and without angular injection

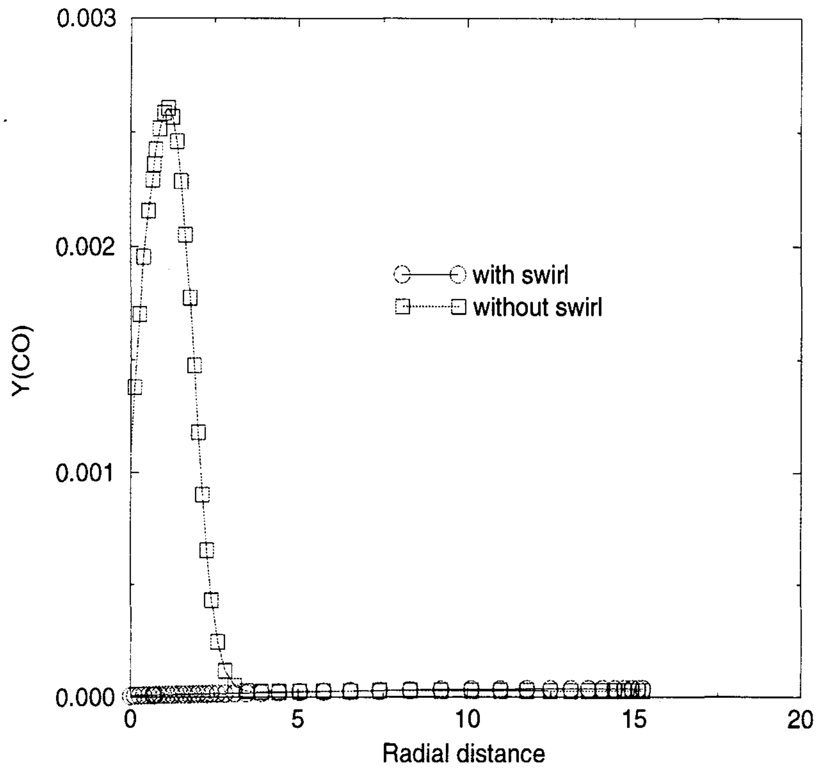

Figure 8. CO emission at the exit plane for the initial size range of 10–100 μm with and without swirl