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Normalising particle-distribution biases using jet injection

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Abstract

The distribution of particles in a jet with an initial bias is assessed using planar nephelometry, which is a planar imaging technique using Mie-scattering. In this study, a two-phase jet flow with a controlled initial bias is generated and various strategies are explored to correct this bias. The investigation compares the usefulness of injecting air at high momentum ratio under swirl or radial configurations.

Radial injection of momentum is found to be superior to injection of swirl, consistent with swirl being a magnifier of eccentricities of a flow. Radial injection upstream from the nozzle can achieve a renormalised flow to develop prior to the exit, but may also lead to downstream biases in particle distribution for some conditions. Swirl injection inside the nozzle can modify the initial particle distribution, but will also have an enduring effect on the emerging near- and far-field flow.

Introduction

This study is motivated by the challenge to understand and control particle distributions in jet flows. Distributions of particles in a pulverised fuel flame have a controlling influence on the combustion behaviour, including pollutant formation [1,2]. Asymmetric particle distributions can be exacerbated by gravitational settling of large or dense particles (typical for alternative fuels) or introduced as flow irregularities by complex piping systems (in pulverised coal systems).

It is now well established that changes in inflow conditions propagate throughout a jet [3,10]. Despite the significance of this issue, to the best knowledge of the authors, no systematic study of this issue has been reported, either of the influence of an initial bias on the downstream distributions, nor on the effectiveness of possible strategies to mitigate such a bias. This study seeks to systematically assess the effectiveness of strategies designed to mitigate a controlled initial bias in particle distributions within a two-phase jet.

The response of a particle to a turbulent flow is characterised by the Stokes Number,

$$\mathrm{Sk}_p = \rho_p U d_p^2 / 18\mu L \qquad (1),$$

which describes the ratio of particle response time to a characteristic eddy time. Here ρ_p and d_p are the particle density and diameter, respectively, U and L are the characteristic velocity and length scales of the large-scale turbulent eddies.

The larger the particles, (higher Sk_p), the less responsive will be an initial bias to corrections by turbulent motions of the jet, and the greater the need for redistribution prior to the combustion chamber. This highlights the need for information on this issue for alternative fuels in particular, since it is not feasible to pulverise alternative fuels down to the same size as pulverised coal [4].

The strategy employed in the present paper to redistribute an initial bias in particle distribution is termed *lofting*. This entails introducing a secondary stream of high velocity jets to mix and redistribute the dispersed phase prior to emerging from the nozzle. This secondary stream is typically introduced some distance upstream from the jet exit through a ring of small, high velocity jets, which allows its mass flow rate to be kept small relative to that of the conveying stream. An advantage of limiting the net mass flow of the conveying stream is that lowering the total conveying air mass flow can reduce NO_x emissions, e.g. in cement kilns [8]. A disadvantage is that high velocity jets require high pressure to drive them. Hence there is a need to optimise the configuration to minimise both the mass and momentum required for effective redistribution.

The two obvious configurations in which to arrange a ring of lofting jets are radially aligned and swirling configurations, both of which have been employed for different reasons in burner designs for many years. However, while the influence of these kinds of flows on the downstream flow [9], particle distributions [16] and combustion [12,13] have been studied for many years, their potential to modify initial particle distributions in a pipe is not reported.

Methodology

Experiments were conducted in the vertical wind-tunnel at the Centre for Energy Technology Multiphase Flow Facility at the University of Adelaide. The wind-tunnel arrangement and diagnostic setup is show schematically in Figure 1. The working section is constructed of Perspex and is 1500 mm in length, vertically orientated to avoid bias due to gravity. The cross-section of the working section is 650 mm × 650 mm. The co-flow conditioned with a honeycomb section and turbulence generating grids, and the velocity was measured to be approximately 6.8 ± 0.3 m/s. The upstream location of the radial inlets is $x_i/D = -5$.

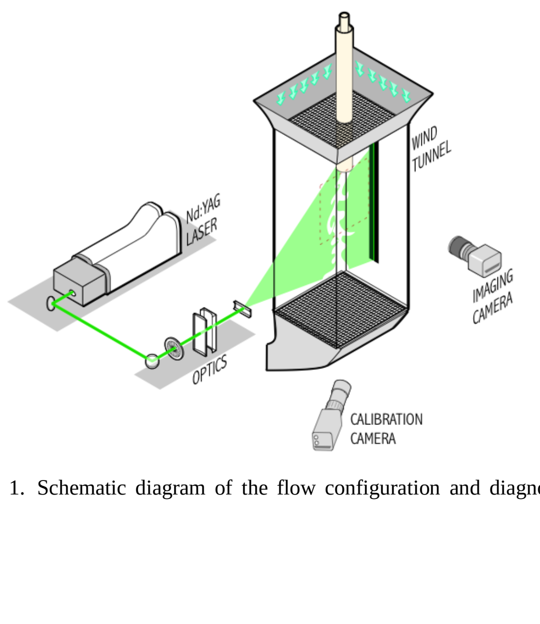

Figure 1. Schematic diagram of the flow configuration and diagnostic setup.

The nozzle consists of a 36 mm diameter central tube, through which flows air at 1.53 × 10^{-2} m^3/s, which gives a bulk exit velocity of 15 m/s. The central pipe is fitted with a series of radially distributed holes, at several positions upstream of the exit plane to facilitate a lofting mechanism, as shown schematically in Figure 2. For both geometries, an array of 24 × 1-mm diameter holes were used, inclined 20 degrees to the flow axis.

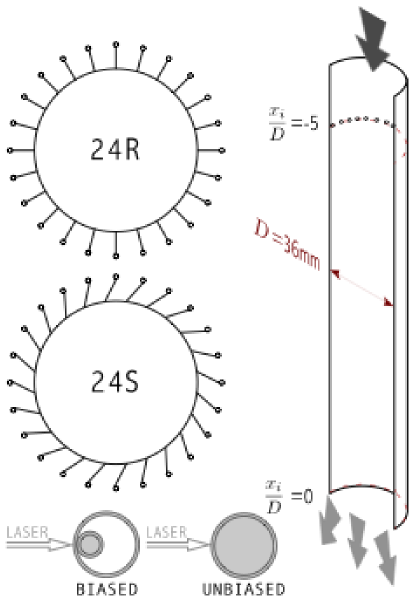

Figure 2: Schematic diagram of the nozzle and lofting injectors.

The momentum flux of a jet is defined as

$$G = \dot{m}^2 / A\rho \qquad (2),$$

where $\dot{m}$ is the mass flow rate, ρ is the fluid density, and A is the cross sectional area. The momentum flux is measured in Newtons (N). The addition of particles to the central jet will increase the momentum of that stream, as described in Equation (3),

$$G = G_f + G_p = \frac{\dot{m}_f}{A\rho_f} + \frac{\dot{m}_p}{A\rho_p} \qquad (3),$$

where subscripts *f* and *p* designate fluid and particles, respectively.

The degree of lofting is characterised by the ratio of momentum flux of the lofting streams, G_i, to the axial momentum flux of the man jet, G_{ax}. The results for strong lofting (G_i/G_{ax}=5.87) are reported here, corresponding to an injection velocity of 200 m/s.

The central air was heavily seeded with the Q-cel hollow glass particles. These particles have a density of approximately 700 kg/m^3. The mean particle diameter, based on surface area, of the particles used in the current investigation was determined to be approximately 21 µm.

The mass flow rate of particles is fixed at 1 g/s. The mass ratio of the solid-phase to gas-phase, β, is 1:18 and is lower than particle loadings expected in practical solid fuel jets. However, the density of the hollow glass particles is lower than that of pulverised coal, and therefore the volume ratio is directly comparable to that of many practical solid fuel jets.

A controlled and well-defined particle bias was introduced by conveying the solid particles in a separate tube (12 mm I.D., 16 mm O.D.) that is mounted eccentrically within the central tube. The biased particle-laden flow is located to the side of the main jet to simulate a horizontally oriented two-phase flow where particles settle out of the gaseous carrier under the influence of gravity. The bias tube is a further 16 mm upstream from the injector plane. The biased stream has a velocity of 50 m/s. The overall bulk velocity of the exit is constant at 15 m/s for both the biased and unbiased cases.

The velocity of the injector represent the worst case for biased flow where the solid phase is driven by momentum of the settling solid phase. The velocity of the solid phase flow is 5 times higher than the unseeded portion, though the relative velocities are such that the bulk exit velocity is uniform across all examined cases.

The nephelometry system, including instantaneous correction for laser sheet attenuation, is previously reported [5-7]. Mie scattering images are collected and corrected using a ray-tracing method to correct particle distribution images for laser sheet attenuation found in optically dense flows.

Results and Discussion

Figure 3 presents a triplet of images for the unbiased flow condition, without lofting. This represents the ideal case where the flow emerges without bias and without the need for particle lofting. Shown here are an instantaneous image, in which particle clusters are evident, the average image of the particle flow and the square root of the variance from the mean (root mean square, or rms) of particle concentrations, respectively. Colour scale indicates the average number of particles per cubic millimetre. It can be seen from the image triplets, that the instantaneous image is highly structured. Particularly evident are rib-like features of high-concentration whose width is thin compared with the diameter of the nozzle. The instantaneous details are smoothed out in the ensemble average distribution, which is symmetrical. The variance of particle concentration is quite small and the rms image does not show any localised regions of high variance. It can also be noted that the emerging jet is axisymmetric in both the mean and rms, which verifies both the effectiveness of the particle feeder system and the optical corrections.

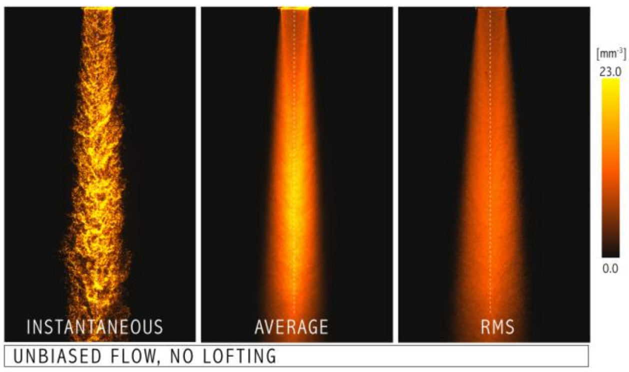

Figure 3: Particle concentration image-triplet of an unbiased flow without lofting: a) instantaneous; b) average; c) rms.

Figure 4 presents a triplet of images for the controlled bias case, where particles emerge eccentrically from the nozzle exit. The laser sheet slices through the images from left to right, and the particles are preferentially located on the up-beam (left) side of the nozzle exit. This case depicts the biased flow without any lofting strategies, or the worst-case scenario in terms of controlled particle bias used in this study.

It can be seen that the extent of clustering (i.e. the instantaneous structure) is comparable with the unbiased case (Figure 3). Accordingly, the instantaneous flow spatially corresponds to the ensemble mean flow and the rms image shows no regions of large variance. However, both the instantaneous and mean distributions are strongly asymmetrical, emerging to the left side of the nozzle axis. Furthermore, this bias does not diminish significantly with axial distance, but persists throughout the measurement domain.

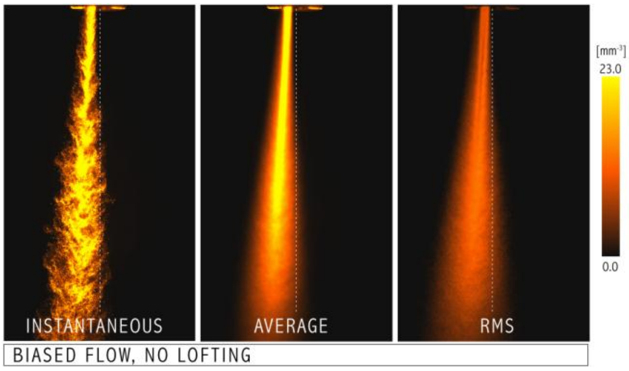

Figure 4: Particle concentration image-triplet of a biased flow without lofting: a) instantaneous; b) average; c) rms.

In Figure 5 d) the triplet for radial injection at $x_i/D = -5$ is presented. For upstream radial injection, at this location, the exit distribution of particles at the nozzle exit has overcome the initial bias. Also, the local velocity gradients around the injection streams appear to have dissipated by the exit-plane so that the flow emerges with mean and instantaneous particle distributions visually indistinguishable from the unbiased data. For radial injection at $x_i/D = -5$, the flow-field and particle distribution appear qualitatively identical to the unbiased flow.

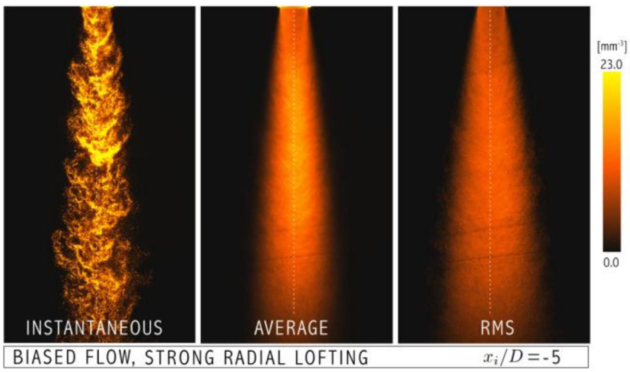

Figure 5: Particle concentration image-triplets for strong radial lofting ($G_i/G_{ax} = 5.87$) at upstream locations, $x_i/D = -5$.

Figure 6 presents the image triplets for the swirling cases. These reveal the sensitivity of the emerging particle distributions to the axial position of injection. Significant helical structures can exist out of the imaged plane in swirling flows, and their location and orientation is determined by the upstream location of the lofters. Injection far upstream, at $x_i/D = -5$, reduces the observed negative bias significantly, but not entirely. Moving the injectors towards the burner exit will make the persistent helical structures more obvious for swirling injection strategies.

Figures 7 and 8 show the particle concentration for the two lofting cases, along the centreline of the nozzle compared with the unbiased case. It can be seen that the upstream injection location causes an increase in the centreline decay rate (Fig 7), which implies an increase in the rate of mixing between the jet and the coflow.

Figure 8 shows that concentration half-widths shows good similarity between the unbiased and fully lofted cases. In can be seen however that there is a slight widening of the jet when radial lofting is used, as measured by the concentration half- widths of the particle-laden jet. This also shows that the upstream injection has a secondary effect of increasing the rate of mixing, consistent with Figure 7.

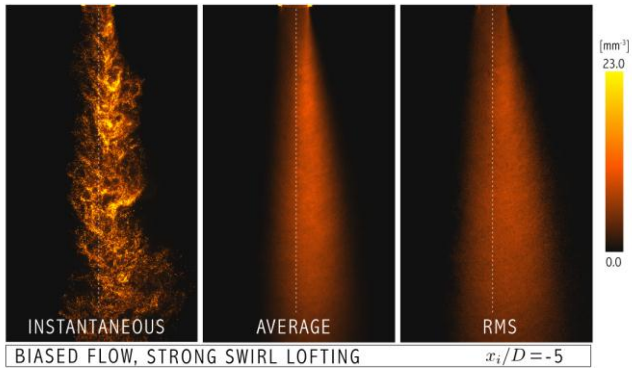

Figure 6: Particle concentration image-triplets for strong radial lofting ($G_i/G_{ax} = 5.87$) at upstream locations, xi/D = −5.

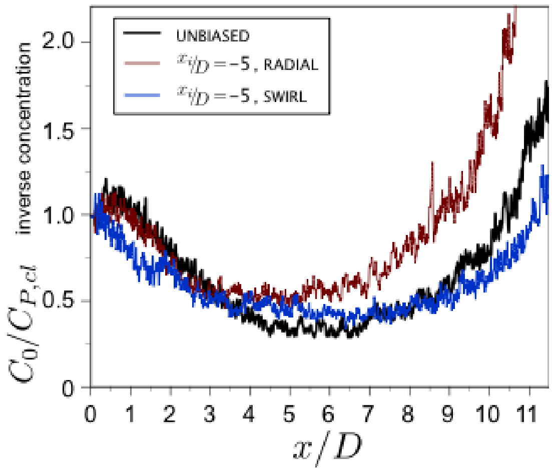

Figure 7: Particle concentration image-triplets for strong radial lofting ($G_i/G_{ax} = 5.87$) at upstream locations, xi/D = −5.

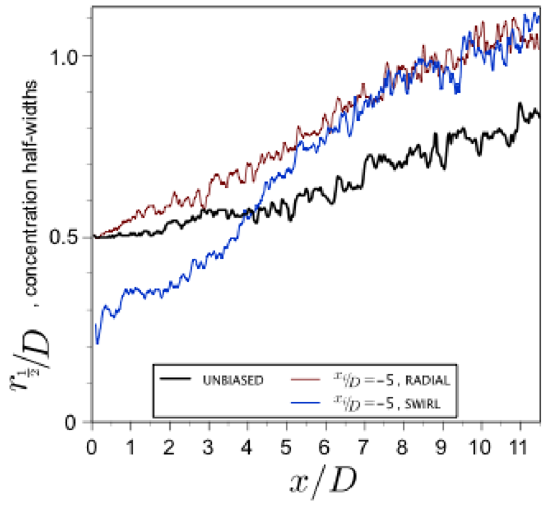

Figure 8: Particle concentration image-triplets for strong radial lofting ($G_i/G_{ax} = 5.87$) at upstream locations, xi/D = −5.

Conclusions

In conclusion, it has been found that the use of high velocity jets within a pipe can be effective in redistributing an initially biased distribution of particles to correct for bias. However, the redistribution method has a secondary effect of also increasing the spread and decay rate of the jet. Furthermore, relatively high velocities and momentum ratios of the lofting streams are required to fully overcome the bias.

Radial injection of momentum is found to be superior to injection of swirl if the intention is the simple re-normalisation of particle distributions at the nozzle exit. Swirling injection of the secondary air is also very successful at modifying the particle distribution at the nozzle exit. Swirl injection will persist into the near field and may substantially modify the velocity fields of the emerging flow. Furthermore, swirl is known to be a magnifier of initial eccentricities in a flow and will have an influence on the flow-field beyond simply re-normalising particle distributions. Therefore, imperfections in the inflow conditions may be magnified, and strongly swirling flows can introduce asymmetries that would not otherwise be present.

The upstream location of secondary air injection has a weaker, but still significant, influence on the emerging flow-field. Radial injection upstream of the nozzle exit will renormalise particle distributions in the nozzle, but the momentum of the injection jets will quickly dissipate after interaction with the internal walls of the nozzle. However swirl injection will cause tangential velocities that are primarily dampened by wall friction and can persist for many diameters.

Injecting secondary air upstream of the nozzle exit allows the re-homogenised flow to develop prior to the exit. Original biases in particle distribution may reform determined by what caused the original biases, and the timescale taken for the eccentricities to develop. If the intention is to renormalise particle distributions with minimal effect the emerging flow near-field, then radial high-momentum injection, sufficiently far upstream to allow the modified flow to redevelop is the superior lofting strategy.

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