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Velocity and orientation distributions of fibrous particles in the near-field of a turbulent jet

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ABSTRACT

Measurements of velocity, angular velocity and orientation of nylon fibrous particles of long aspect ratio in the super-dilute regime in the near field of a turbulent air jet with a Reynolds numbers of 70,000 are reported. These measurements were performed using Particle Tracking Velocimetry (PTV) based on the two end-points of each fibre, following a method reported previously. The particles were fed via a hopper into a pipe of 34 diameters in length. The fibres' vertical and horizontal velocity and orientation were calculated to analyse the aerodynamic behaviour of these fibrous particles. The key findings are as follows: 1) fibre orientations at the centre of the jet are distributed over a wide range spanning 30° to 90° and the most probable orientation of the fibres is at 54° to the axial, while few fibres are aligned with the direction of the flow, which contrasts with previous findings in a turbulent pipe flow using water as the working fluid; 2) the axial velocity of the fibres on the jet axis is found to change little with an increase in number density, which contrasts with previous findings in free-falling cases where the fibres' settling velocity increases significantly with the volume fraction; 3) the influence of number density on orientation of the fibres in this turbulent jet within the super dilute regime is much weaker than that for the free-falling case, where the orientations decrease with the volume fraction; 4) the absolute mean angular velocity of the fibres increases significantly with the radial distance from the axis to the location of the greatest mean shear; and 5) at the centre-line of the jet, the fibres' normalised radial velocity is an order of magnitude larger than that of spheres with a similar Stokes number.

1. Introduction

The transport of fibrous particles in suspension within a turbulent flow occurs in numerous industries, including pulp and paper making, the combustion of biomass in boiler and polymer suspensions. However, the motion of these particles is much less well understood than that of their spherical counterparts due to the added complexity caused by their more complex shape. In addition to translation, fibrous particles exhibit rotation and their drag coefficient also depends on their orientation. An improved understanding of their aerodynamic behaviour is a prerequisite to optimising their performance in applications such as biomass combustion. This, in turn, requires detailed measurements in relevant environments, such as in co-flowing jets, which are not yet available. The objective of the current work is to begin to address this gap.

The most relevant experiment to the transportation of biomass fibres in air is the measurements of Bernstein and Shapiro [1] in water. They measured the orientation distribution of glass fibres with a wide range of Reynolds numbers on the axis of a pipe flow using an optical technique. These measurements are directly comparable with the exit plane of a jet issuing from a long pipe because the conditions at the exit plane of a pipe are nominally identical to those within it. A comparison of their data with new measurements performed in a jet using air as the working fluid will provide insight into the effect of density ratio, which is three orders of magnitude different. Zhang et al. [2] simulated the suspension of fibres in a turbulent pipe flow at *Re* of 11,000 and proposed a model to predict the orientation distribution of the fibres. They validated their model against the data of Bernstein and Shapiro's [1] work and found quite good agreement. Marchioli et al. [3] simulated inertial fibres in turbulent channel flow and found the fibres' orientation at the centre of the channel (i.e., far from the wall) to be approximately 60° to the flow direction. The results of their simulation will also be compared with those of the present experimental data.

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Mandϕ and Rosendahl [4] studied orientation-dependent models of non-spherical particles at high Reynolds numbers and pointed out that the inertial effect is sufficient to force non-spherical particles to change their motion state. They gave the following equation to calculate the torque due to resistance acting on fibrous particles:

$$T = \rho d\left(\omega_f - \omega_p\right)^2 L_p^4 \left(\frac{1}{64} + \frac{1}{3.36\left(\frac{\rho d\left(\omega_f - \omega_p\right)L_p}{\mu}\right)^{\frac{2}{3}}}\right), \tag{1}$$

where L_p and d are the length and diameter of the fibrous particles, respectively, while ω_f and ω_p are the angular velocities of the fluid and particles. This equation can be used to estimate the torque acting on the fibre in the present study. Rosendahl [5] also proposed that the location of the centre of pressure is a function of the orientation and aspect ratio of the fibres according to the following relationship:

$$x_{cp} = \frac{L_p}{4}\left(1 - e^{1-\frac{L_p}{d}}\right)\left(1 - \sin^3\theta\right), \tag{2}$$

where θ is the incidence angle.

Stover et al. [6] investigated experimentally the fibres' orientation in simple shear flow by employing a cylindrical Couette device. They found that the fibres are approximately aligned with the flow direction under these conditions. Carlsson [7] measured the distributions of fibre orientations at different wall normal positions in a turbulent headbox. He found that the fibres were more aligned with the flow direction at the position nearest to the wall, where the shear rate is the highest. Lin et al. [8] simulated the fibres' orientation distribution in a round turbulent jet of fibre suspensions. They found that the fibres' orientation increases with radial distance. However, this simulation needs to be verified with experimental data.

Lin et al. [9] simulated suspensions of fibres in a round jet flow. They assessed the influence of the volume fractions of the fibres on the mean axial velocity profile and concluded that the volume fraction does not significantly influence the shape of the mean axial velocity profile of the gas phase. However, the authors did not report on the effect of volume fraction on the fibrous particle phase. Hence, a particular aim of the present work is to explore this effect using experimental data. Jayageeth et al. [10] studied the effect of a bounding wall on the dynamics of suspended fibres in a boundary layer using a Stokesian dynamics simulation and they found that the fibres' rotation increases significantly as a fibre approaches a region of maximum shear.

Olson and Kerekes [11] analysed the motion of a single fibre suspended in turbulent fluid and obtained equations of mean and fluctuating velocities in rotation and translation. They derived the following rotational and translational dispersion coefficients of a fibre:

$$D_r = 24\overline{u'^2}\frac{\tau}{L^2}\frac{\Lambda}{L}\left(\mathrm{erf}\left(\frac{\pi^{0.5}L}{2\Lambda}\right) + \frac{16}{\pi^2}\left(\frac{\Lambda}{L}\right)^3\left(1 - e^{-\frac{\pi L^2}{4\Lambda^2}}\right) + \frac{2}{\pi}\frac{\Lambda}{L}\left(e^{-\frac{\pi L^2}{4\Lambda^2}} - 3\right)\right). \tag{3}$$

$$D_t = 2\overline{u'^2}\tau\frac{\Lambda}{L}\left(\mathrm{erf}\left(\frac{\pi^{0.5}L}{2\Lambda}\right) + \frac{2}{\pi}\frac{\Lambda}{L}\left(e^{-\frac{\pi L^2}{4\Lambda^2}} - 1\right)\right). \tag{4}$$

This model implies that for long fibres, rotational and translational dispersion coefficients, D_r and D_t are functions of the fluid Eulerian integral time scale, τ, the Eulerian integral length scale, Λ, and the streamwise component of the fluctuating velocity, u'. Based on convection–dispersion function that governs the evolution of the fibre orientation distribution, $\Gamma(r, p, t)$, in turbulent flows, they further derived a form of the Fokker–Planck equation to describe the orientation distribution of the fibre in turbulent flows, as follows:

$$\frac{\partial \Gamma}{\partial t} = D_r \nabla_r^2 \Gamma - \nabla_r \cdot (\omega \Gamma) + D_t \nabla^2 \Gamma - \nabla \cdot \left(\overline{V}\Gamma\right), \tag{5}$$

where $\nabla_r = \boldsymbol{p} \times \partial / \partial \boldsymbol{p}$ is the rotational operator, $\boldsymbol{p}$ is the unit orientation vector, $\overline{V}$ is the fibres' mean velocity and ω is the fibres' angular velocity. Eq. (5) relies on many assumptions, some of which do not apply in the present experiments. Firstly it assumes that the fibres are neutrally buoyant, which is far from true in the present experiments. It also assumes that the inertial forces on the fibre are negligible, i.e., that the Stokes number is $\ll 1$ and that the relative velocity between the fibre and the fluid is zero. None of these assumptions are true for the present case, therefore this equation does not apply in particle-laden flows with

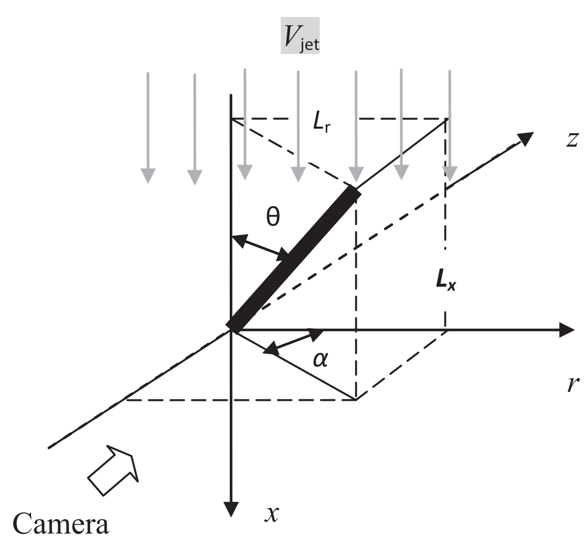

Fig. 1. The notation used to define orientation of a fibre in jet flows, relative to the axis of the jet and to the camera image plane.

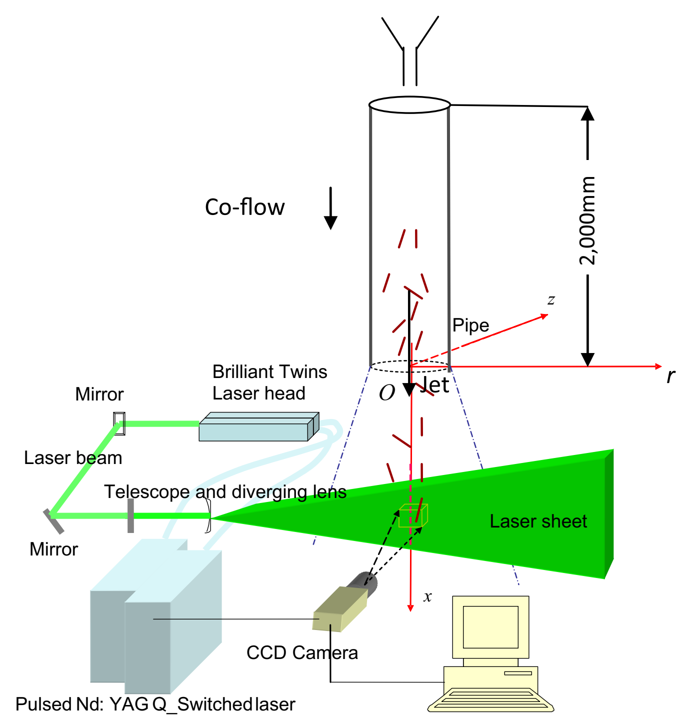

Fig. 2. Experimental arrangement (not to scale). The walls of the surrounding wind tunnel (650 mm × 620 mm cross section) and the cyclone are not shown for clarity. The bulk-mean velocity of the jet was 18 m/s, while the co-flow velocity was 8 m/s.