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A method for identifying and characterising particle clusters in a two-phase turbulent jet

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ABSTRACT

A novel technique for identifying and characterising clusters of particles from measurements within a densely seeded two-phase flow is reported. This technique involves the smoothing of normalised instantaneous planar images of particle concentration followed by the application of a robust and unambiguous dynamic threshold to identify particle clusters. Also reported is a method to extract quantitative cluster data including cluster length, width and number of branches. The method employs an algorithm to morphologically skeletonize images of clusters, and subsequently, prune skeleton branches to select those which most strongly represent the shape of the cluster. Together, these techniques have been shown to identify and characterise two-dimensional slices of three-dimensional particle clusters of complex shapes, including those that are bent, wrinkled and branched, with an uncertainty of ≈4% relative to the manually determined values. This method was applied to planar measurements of particles in a heavily seeded turbulent jet with an exit Stokes number of $Sk_D = 1.4$ and Reynolds number of $Re_D = 10,000$, based on the pipe diameter, D. The results show that particle clusters are already present at the exit plane and have a characteristic width that is narrowly distributed around an average value of ≈0.17D. This implies that particle clusters are generated inside the pipe at this preferred length scale. The results also show that the average cluster length at the pipe exit is ≈1.0D, which, together with the observation that the clusters are oriented at oblique angles to the axis of the jet, suggests that the length of these clusters within the pipe is limited by the pipe diameter. The aspect ratio of the cluster slices was found to be typically $AR \approx 6-7$, consistent with the observations that the clusters form long, thin, filament-like structures.

1. Introduction

Particle-laden turbulent jets are utilised in many scientific and industrial applications, most notably in the applications for the combustion of pulverised fuels, the processing of minerals, and more recently, in concentrating solar thermal reactors. In these flows, it has been observed that the instantaneous spatial distribution of particles differs significantly from a random distribution, with particles within the flow being preferentially distributed into instantaneous regions of localised, high particle concentration called "clusters" (Birzer et al., 2011a, 2011b; Longmire and Eaton, 1992; Zimmer and Ikeda, 2003). This naturally occurring phenomenon has been shown to have a significant impact on reacting flows, affecting heat transfer, ignition distance, ignition temperature, stoichiometry and emissions, because they imply a non-uniform distribution of fuel within the flame (Abbas et al., 1993; Annamalai and Ryan, 1992; Cassel and Liebman, 1959; Smith et al., 2002). However, while their significance is well understood, a quantitative analysis of the significance of particle clustering in two-phase flows is currently limited. In particular, a systematic and statistical assessment of particle clustering in turbulent flows in the two-way coupling regime, whereby the particle number density is sufficiently high that the particles affect the gas-phase, is almost entirely absent. Therefore, the overall aim of the present paper is to begin to meet this need for quantitative measurements of clusters in flows with high particle number density.

Previous studies on preferential concentration of particles have highlighted the importance of the Stokes number in determining the extent of particle clustering (Aliseda et al., 2002; Bec et al., 2007; Calzavarini et al., 2008; Eaton and Fessler, 1994; Fessler et al., 1994; Gualtieri et al., 2009; Hogan and Cuzzi, 2001; Monchaux et al., 2010; Rouson and Eaton, 2001; Wang and Maxey, 1993; Yoshimoto and Goto, 2007), where the Stokes number is defined as the ratio of time-scales of particle response to characteristic fluid eddy. In particular, clustering has been shown to be most

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significant where the Stokes number is of order unity (Bec et al., 2007; Calzavarini et al., 2008; Fessler et al., 1994; Gualtieri et al., 2009; Rouson and Eaton, 2001; Wang and Maxey, 1993; Yoshimoto and Goto, 2007). Because turbulence comprises a spectrum of scales, from the smallest dissipative length scales to the largest inertial length scales, it is likely that more than one length scale can influence particle clustering (Aliseda et al., 2002; Bec et al., 2007; Eaton and Fessler, 1994; Goto and Vassilicos, 2006; Gualtieri et al., 2009; Monchaux et al., 2010; Yoshimoto and Goto, 2007). Evidence for this can be found in the range of length scales associated with clusters, such as their length, width and spacing. Hence there is a need for detailed measurements of cluster dimensions and shapes.

Despite their importance, there is a lack of data of the magnitude of cluster length scales, in part because of the limitations of current methods to determine them. While methods of analyzing particle clustering, such as statistical box counting (Aliseda et al., 2002; Bec et al., 2007; Fessler et al., 1994; Hogan and Cuzzi, 2001; Rouson and Eaton, 2001; Wang and Maxey, 1993), the radial distribution function (Gualtieri et al., 2009; Salazar et al., 2008), the pair correlation function (Goto and Vassilicos, 2006; Saw et al., 2008; Yoshimoto and Goto, 2007), Minkowski functionals (Calzavarini et al., 2008) and Voronoï analysis (Monchaux et al., 2010; Obligado et al., 2014) are capable of providing useful information such as the characteristic cluster length scale and the degree of global clustering, they crucially require that individual particles be spatially resolved. This, in turn, requires probe sizes that are significantly smaller than the inter-particle spacing. As the limiting probe dimension in typical laser diagnostic measurements is the light sheet thickness, the resolution of individual particles is only possible at low volumetric loadings. This limits the detection of clusters with existing methods to the dilute regime, i.e., to flow conditions whereby the particle volume loading, β, and/or the particle number density, $\tilde{N}_p$, is small (see Table 1). As there is significant practical and scientific interest in two-phase flows in the two-way and four-way coupling regimes, where volumetric loadings are large (Elghobashi, 2006), there is a clear need for a method to detect clusters from images in which individual particles are not resolved. Furthermore, the requirement to capture the largest length scales of a cluster, which can be of the order of the local jet diameter (Birzer et al., 2011a, 2011b), together with the practical constraints of detector arrays also limit the capacity to resolve both the particle size and the maximum dimensions of a cluster. This provides a further need for methods to detect clusters under conditions in which individual particles are not resolved.

The identification and characterisation of particle clusters in a densely-seeded turbulent flow from planar images is non-trivial, because particle clusters within the same flow may have different sizes, concentrations, orientations and shapes. In previous studies this process typically involves the use of an arbitrary global threshold in conjunction with spatially averaging or binning of the particle concentration field across a specified length scale (Birzer et al., 2011a, 2011b; Monchaux et al., 2012; Zimmer and Ikeda, 2003). While no absolute measure of a cluster is possible, it is desirable to replace the use of these arbitrary parameters with statistically robust parameters that are unambiguous and justifiable.

Once clusters are identified, a further step is required to measure and classify the characteristic dimensions of these clusters. One such scheme, albeit for a different class of flow, was introduced by Qamar et al. (2011), who fitted equivalent ellipses to soot sheets to determine their characteristic lengths and widths. This method was further improved by Chan et al. (2014), who modified the equivalent-ellipse method for use with curved or bent soot sheets. However, as is demonstrated within the analysis in the current paper, neither of these methods are suitable for use on clusters with highly irregular, wrinkled, or branched shapes.

Table 1
Summary of conditions utilised in previous experimental measurements of particle clustering. Also included are the conditions for the current experiment. Here d_p is the particle diameter, ρ_p is the particle material density, β is the volume loading, $\tilde{N}_p$ is the number of particles per pixel (bulk), *LST* is the light sheet thickness, Θ_b is the bulk particle number density, Δ_p is the average inter-particle spacing and $\tilde{P}_{>1}$ is the relative probability that 2 or more particles are located within the same measurement volume. Values denoted by the asterisk are values that have been inferred from published data.

First author	d_p (µm)	ρ_p(kg/m^3)	β	$\tilde{N}_p$	*LST* (µm)	Θ_b (mm^{-3})	Δ_p (µm)	$\tilde{P}_{>1}$ (%)
Aliseda (2002)	≈25	1000	1.5×10^{-5} to 7.5×10^{-5}	O(10^{-3}) to O(10^{-2})	≈1000	≈2 to 10*	≈478 to 817*	≈0.1 to 1.1*
Fessler (1994)	25 to 90	700 to 8800	O(10^{-5}) to O(10^{-4})*	N/A	≈1000	≈3	≈607 to 1257*	N/A
Monchaux (2010)	≈50 to 100	1000	O(10^{-6}) to O(10^{-5})	O(10^{-4}) to O(10^{-3})*	≈2000	≈0.03 to 0.5*	≈1300 to 3200*	O(10^{-2})to O(10^{-1})*
Obligado (2014)	≈50	1000	O(10^{-5}) to O(10^{-4})	O(10^{-3}) to O(10^{-2})	≈1000	≈0.8 to 3*	≈690 to 1094*	≈0.3 to 1.4*
Salazar (2008)	≈6.1	1375	O(10^{-7})	N/A	N/A	≈2	≈1000*	N/A
Current	20	1200	4×10^{-4}	≈0.1	≈350	≈100	≈220	≈4.1 to 8.3