International Journal of Heat and Fluid Flow 29 (2008) 665–674

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Study of scalar macro- and microstructures in a confined jet

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ARTICLE INFO

Article history:
Received 2 November 2007
Received in revised form 5 March 2008
Accepted 8 March 2008

Keywords:
Mixing
Passive scalar
Dissipation rate
Intermittency
Anisotropy
Multifractals

ABSTRACT

The scalar structures in a confined jet are studied at high Reynolds and Schmidt numbers. Both flow modes without the recirculation zone (jet mode) and with the massive separation and creation of the recirculation zone (r-mode) are considered. Despite of the big difference in the flow modes, the fine scale scalar structures gained from highly resolved PLIF measurements possess similar statistical properties such as the normalized cumulative distributions and probability densities of the dissipation rate. The fine scalar structures are distributed nearly uniformly in space with the scalar gradient vector having a slight preference to align with the most compressive mean strain axis. The scalar field exhibits small-scale intermittency which is strongly dependent on the flow mode. The intermittency is most pronounced in the front of the recirculation zone and becomes weaker on the centerline and downstream. The most contribution to the scalar variance is made by large scale motions whereas the contribution of fine scales smaller than typical inertial range scales is negligible. Examination of the multiplier distributions has not supported the concept of the multifractal nature of the scalar dissipation field.

1. Introduction

Mixing in coaxial confined jets has been investigated for a long time because of many practical engineering applications in, e.g. combustion chambers, injection systems, chemical mixing devices and many others. In this paper the coaxial axisymmetric jet mixer consisting of a nozzle of diameter d positioned along the center line of a pipe of diameter D has been considered (see Fig. 1). The fast inner jet (water) with the bulk velocity U_d is confined by a slower outer coflow (water) with velocity $U_D \ll U_d$. The most important parameters determining the mixing process are the flow rate ratio $\dot{V}_D/\dot{V}_d$, the diameter ratio D/d and the Reynolds number $Re_d = dU_d/\nu$.

Most publications on confined jets are devoted to the study of large scale effects in configurations in which the inner jet is much slower than the coflow $U_d/U_D \ll 1$ (see, for instance, Rehab et al., 1997; Mortensen et al., 2003; Lima and Palma, 2002). These investigations are motivated by two important applications: stabilization of flame fronts by swirl burners and the saturation of air coflow with molecules of substances transferred by the internal jet. Rehab et al. (1997) revealed and investigated sustaining low-frequency pulsations caused by the recirculating flow cavity arising on the axis in the inner jet region. The structure of this reverse flow zone is similar to the well known wake-type structure behind bluff bodies. Similar phenomena are discussed in this paper for the case of confined coaxial jets with $U_d/U_D \gg 1$ in which the reverse flow region is not on-axis but near the wall. Surprisingly, the case $U_d/U_D \gg 1$ has attracted less attention although this flow mode is very important for homogenization devices and free jet reactors. Two different flow modes can be observed in jet mixers, depending on the flow rate ratio $\dot{V}_D/\dot{V}_d$ (see Barchilon and Curtet, 1964). If $D/d < \beta(1 + \dot{V}_D/\dot{V}_d)$, where $\beta \approx 1$ is an empirical constant found from a simple entrainment model, the flow is similar to a free jet (henceforth referred to as jet-mode or j-mode for short). If $D/d > \beta(1 + \dot{V}_D/\dot{V}_d)$ a strong flow separation at the pipe walls results in a recirculation zone (see Fig.7 in Zhdanov et al., 2006) behind the nozzle (henceforth referred to as recirculation-mode or r-mode for short). A qualitative description of the r-mode is given by Barchilon and Curtet (1964). The large scale flow phenomena in a jet mixer has been the subject of our previous experimental and numerical works (see Kornev et al., 2005; Zhdanov et al., 2006; Hassel et al., 2006; Tkatchenko et al., 2007). Our study showed that the flow in the r-mode is highly unsteady and time averaged results do not describe properly the true nature of flow phenomena typical for this mode. The presence of long period temporal oscillations with a sort of opposition-of-phase of the flow is revealed and quantified. In the Section 3.1 we explain the physical mechanism causing such oscillations. The LES (large eddy simulation) model used in the present study is described in details in Tkatchenko et al. (2007).

Formation and dynamics of fine scalar structures in liquids at high Schmidt $Sc \sim 10^3$ and Reynolds numbers belongs to the most complicated fields of fluid mechanics. The resolution required for such a study is of the order of the Batchelor scale, defined as $\eta_B = \eta/\sqrt{Sc}$, where η is the Kolmogorov scale. For the full developed turbulent liquid flows, the Batchelor scale becomes so tiny that it is

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doi:10.1016/j.ijheatfluidflow.2008.03.011

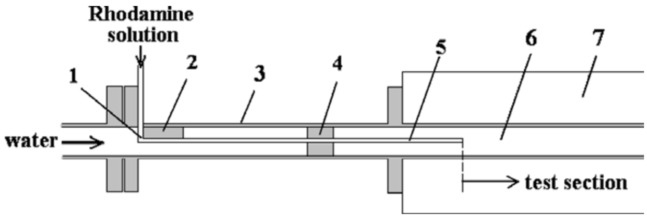

Fig. 1. Sketch of the flow: 1, knee bend of nozzle; 2, plate for damping of vortices shed from knee bend 1; 3, outer tube; 4, support plates; 5, nozzle; 6, test section; 7, water box.

hard to perform the DNS (direct numerical simulation) at reasonable computer costs. Some success has been achieved by DNS only for moderate *Re* and *Sc* numbers (see, for example, Schumacher and Sreenivasan, 2005; Kushnir et al., 2006). Experimentally, using modern PIV (particle image velocimetry) and PLIF methods researchers are capable of penetrating into the range of fine scales comparable with Batchelor ones. Most of the experimental progress in the field of scalar turbulence at high Schmidt numbers has been achieved by the group of Dahm (see, for example, Buch and Dahm, 1996). The three-dimensional measurement technique for scalar fields has been developed by Su and Clemens (2003) and Southerland and Dahm (1994). The state of the art in this field can be found in Su and Clemens (2003). The scalar dissipation rate determination is one of the most important aims of measurements. This procedure is complicated since it requires calculation of gradients. In this case the effects of the data processing, such as the smoothing filter and numerical stencil, are significant and must be considered. A detailed consideration of the accuracy assessment of scalar dissipation measurements is given by Wang et al. (2007).

The main focus of the present paper is the study of fine structures of passive scalars in the liquid phase using highly resolved PLIF (planar laser-induced fluorescence) measurements. The following questions are considered in the paper:

- What kind of flow structures are responsible for the appearance of sustaining low-frequency oscillations in the r-mode? Why are the oscillations nearly antisymmetric?
- What kind of scalar microstructures are created in a confined jet?
- What are the statistical properties of the microstructures in different flow modes?
- How does the intermittency of the scalar field behave along the jet for different flow modes?
- What is the preferential orientation of the scalar microstructures?
- Which scales do make the main contribution to the scalar variance?
- Does the scalar dissipation field exhibit the multifractal properties ?

The paper is organized as follows. Section 2 briefly describes the experimental facility. Section 3.1 reports the peculiarities of the macroflow and explains the physical mechanisms behind the longitudinal oscillations in the jet mixer under consideration. The rest of the paper (Sections 3.2–3.8) focuses on the study of the fine scalar structures. A special attention is paid to the problems which solution can be useful for further development of theoretical models capable of mixing modelling at high *Sc* numbers (Sections 3.6–3.8). Conclusions are presented in the final section.

2. Experimental facility

The flow field investigated here is the turbulent axisymmetric jet developing in a coflow confined by a pipe of diameter $D = 50$ mm and length 5000 mm. A schematic of this flow system is given in Fig. 1. Medium in both flows was water ($Sc \sim 10^3$). The inner tube 5 had diameter $d = 10$ mm and the length 600 mm chosen from the condition that perturbations caused by the knee bend are suppressed near the nozzle exit. The test section of the mixer was installed in a Perspex rectangular box filled with water to reduce refraction effects. More detailed information about the hydrodynamic channel can be found in Zhdanov et al. (2006). Since the Reynolds number based on the jet exit velocity U_d is $Re_d = dU_d/\nu = 10^4$ the jet can be considered as a fully- developed turbulent jet. Two sets of measurements with the recirculation zone and without it have been performed. Table 1 lists the experimental conditions for each set. A scalar field was measured by the planar LIF method. The turbulent jet contains a fluorescing substance (Rhodamine 6G) with a concentration of 0.5 mg/l. In experimental measurements, to prevent changes in the flow background intensity due to contamination of water by the Rhodamine solution, the charged coflow vessels and the vessels collected mixture behind the test section were separated. The *x*-axis of the coordinate system is aligned along the pipe centerline downstream. The coordinates *y* or *r* are measured from the *x*-axis. The point $r/D = 0$ or $y/D = 0$ means that the centre of the measurement window is on the mixer axis. Measurements were performed at positions ranging from $x/D = 0.1$ to $x/D = 9$ downstream of the nozzle exit. A measuring system comprised a Nd:YAG laser operating at a wavelength of 532 nm and with a pulse duration of 7 ns, a sensicam qe camera (1376×1040 pixel, 19.8 fps, exposure times 500 ns) with a K2 long-distance microscope system, and an optical unit to make a laser sheet. The binning 4×4 was applied to improve the quality of measurements. The use of the K2 system equipped with the objective CF-2 enables to record the scalar field in the window of 2.74×2.075 mm with a spatial resolution up to $\sim$31 μm. The resolution has been fixed using USAF target at the measurement conditions. The laser sheet was formed vertically along the mixer axis by two convex lenses of 200 mm and 100 mm focus lengths, a concave lens of (−50) mm focus length and a cylindrical lens of (−250) mm focus length. The laser sheet thickness has been estimated using the beam generated by the diode continuum laser DD532-25-3 (Picotronic GmbH) at the same length 532 nm as the Nd:YAG laser. The thickness measurements performed with the Beam Scan (model 11801, Photon Inc.) indicate that the laser thickness doesn't exceed 40 + 8 μm within the measurement window. Since the laser beam quality of the diode laser is worse than that of the impulse laser Nd:YAG (Continuum, PREC II 8000) it is assumed that the laser thickness used in further experiments with Nd:YAG lies within the same range.

Time resolution was limited by the 10 Hz frequency of laser used as an external trigger of the camera. Mixture fraction distributions *f* were calculated from the emitted Rhodamine intensity distributions *I* referred to the maximum intensity I_0 determined on the centerline in the first cross-section at $x/D = 0.1$. The measurements at each cross-section x/D produced a data volume composed of 3000 successive highly resolved two-dimensional spatial data planes arranged sequentially in time. Each data plane is, in turn, composed of an array of 344×260 individual point measurements of the local conserved scalar field value *f*.

Following the suggestion from Buch and Dahm (1996), the derivatives of the function *f* were calculated using the Sobel

Table 1
Parameters of experiments

Flow mode	$U_d (ms^{-1})$	$U_D (ms^{-1})$	$\dot{V}_D/\dot{V}_d$
r-mode	1.0	0.06	1.3
j-mode	1.0	0.1	5.0