International Journal of Heat and Fluid Flow 71 (2018) 275–287

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Development and validation of an MRI-based method for 3D particle concentration measurement

Daniel D. Borup*, Christopher J. Elkins, John K. Eaton

Department of Mechanical Engineering, Stanford University, 488 Escondido Mall, Building 500, Stanford, CA 94305, USA

ARTICLE INFO

Keywords:
Multiphase flow
Magnetic resonance imaging
Particle-laden flow
Experimental techniques

ABSTRACT

A novel method, denoted MRP (short for Magnetic Resonance Particle concentration), was developed to obtain 3D volume fraction measurements for a dispersed particulate phase in turbulent water flows using Magnetic Resonance Imaging (MRI). MRI images taken near a single stainless steel particle suspended in agarose gel showed good agreement with the analytical solution for the disturbance to a uniform magnetic field induced by an immersed sphere. For a random distribution of particles, a linear relationship between the MRI signal decay rate (R_2^*) and particle volume fraction (ϕ_v) has previously been predicted in the MRI literature. This relationship was investigated for various types of particles suspended in agarose gel vials. Good agreement with theory was observed for particles with a high magnetic susceptibility difference from water. R_2^* was also measured in a square channel flow containing a uniform distribution of titanium particles at two fully turbulent Reynolds numbers. Experimental results again agreed well with theory in the majority of the channel for both Reynolds numbers studied. Data from this flow were used to examine the expected SNR and dynamic range for MRP in future experiments. Some discrepancy was observed near the entry region of the channel, with possible explanations including inflowing fluid and large-scale flow structure effects behind the channel's mixing pin array. Finally, the new method was used to measure the 3D concentration distribution for a streak of titanium particles injected into a turbulent square channel flow with angled ribs. The transport of the streak was analyzed quantitatively, and a minor asymmetry in the channel geometry was shown to have important implications for the mean transport of the particle streak.

1. Introduction

1.1. Background

Turbulent, dispersed multiphase flows occur across a wealth of applications, from complex engineered systems to biological and environmental flows. Canonical examples from the engineering arena include the behavior of particulate matter ingested into gas turbine engines (Dunn et al., 1987), particle suspension and dispersion in fluidized bed reactors (Berruti et al., 1995), or process flows that may contain liquid, solid, and/or gas phases (Sinnott et al., 2011). In the medical arena, particulate transport (either medicinal or noxious) is of critical importance in the human airway system (Kleinstreuer and Zhang, 2010) and the intestinal tract (Sinnott et al., 2017). Environmental particle-laden flows are found in volcanic eruptions (Mastin et al., 2009), coastal sedimentary environments (Papanicolaou et al., 2008), and dust storms (Griffin et al., 2001).

Dispersed multiphase flow prediction requires several interdependent models, with the foundation being a method to predict turbulent flow of the carrier phase in realistic geometries. Computer codes used in engineering design cycles typically solve the Reynolds-Averaged Navier Stokes (RANS) equations for the carrier phase mean velocity field, with a separate model for the particle motion and, in some cases, a third model to compute back effects of the particles on the carrier phase. The addition of particles introduces a myriad of new physical processes that must be either resolved, modeled, or neglected. At an absolute minimum, the drag force of the fluid on the particulate phase is required to determine the particles' motion and resulting concentration distribution. In systems with high mass loading, additional coupling terms are required to accommodate the particle-to-fluid forces and particle-particle collisions. But these momentum transfer terms are still only the tip of the iceberg; particle agglomeration, deposition and erosion along walls, gravitational settling, electromagnetic forces, chemical exchange, and heat transfer may play significant roles in determining particle motion. In the case of volcanic plumes, for example, nearly all of these processes play a key role.

There is a severe lack of experimental data sets for quantitative comparison and validation of multiphase flow simulations in complex

* Corresponding author.
E-mail address: borup@stanford.edu (D.D. Borup).

https://doi.org/10.1016/j.ijheatfluidflow.2018.04.006
Received 31 October 2017; Received in revised form 6 March 2018; Accepted 10 April 2018

geometries. As an example, consider the study of Singh et al. (2014), who used Large-Eddy Simulation (LES) to simulate particle-laden flow through a two-passage ribbed square channel of relevance to the gas turbine industry. Wall impact statistics from the LES were used to identify impact-prone regions and to suggest design improvements, which could easily be implemented by engine designers. Complementary experimental measurements were carried out in the same flow by using adhesive tape to visualize regions of high particle deposition. This facilitated a qualitative comparison to the LES, but little insight was available as to how predictions could be improved. As the authors note in their final conclusion, improved experimental capabilities are needed.

At minimum, a viable validation data set should combine well-understood inflow conditions with robust and quantitative particle phase data. 3D data sets are more useful than pointwise or planar data for understanding complex multiphase phenomena. Pointwise particle measurements can be obtained for some geometries using probes. Akilli et al. (2001), for example, used a fiber optic probe to measure particle concentration and velocity in a turbulent round pipe flow downstream of a 90-degree bend. The experimental data consisted of one-dimensional traces at ten streamwise locations for a total of around 200 data points, a fairly typical number for probe data. So, while the geometry may be somewhat complex, the amount of data is limited when probes are used.

Planar data increases spatial coverage at the cost of limitations on the geometric complexity of the flow that can be studied; most planar techniques make use of a planar laser sheet with a camera oriented at 90° to the sheet, and thus require undistorted optical access from two perpendicular planes. For many application-relevant geometries this requirement can be prohibitive, but for simpler building block flows, particle concentration and 2D velocity can be obtained using well-established techniques such as Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV). More recent experimental advances include the use of stereoscopic or tomographic imaging configurations (Scarano, 2012), defocused images (Willert and Gharib, 1992), and digital holography (Pan and Meng, 2003); Stereo-PIV can provide three-component, two-dimensional (3C-2D) data, while the other techniques provide three-component velocity in three dimensions (3C-3D).

Multi-camera PIV was recently applied by Liu and Kiger (2016) to make improved, simultaneous concentration and 3-component velocity measurements for a dispersed phase at volume fractions approaching 1%. Their method makes use of a thin light sheet and three cameras; particle locations are identified based on the correlations between images from the three cameras, which provides improved resistance to light blocked between the imaging plane and camera at higher volume loadings. However, this setup maintains most of the traditional limitations of optical techniques. Undistorted optical access is required from *four* planes (the three cameras plus light source). In addition, measurements in flow were only made in one thin 2D plane, although the authors suggest that 3D capability could be feasible by scanning across a volume at high speed.

Planar Laser Nephelometry has also been used to study denser suspensions where resolving individual particles is prohibited. This technique also employs a laser-camera pair, but individual particles are not resolved. Instead, the intensity of the Mie-scattered light is measured by the camera and used to infer the volume fraction over larger regions of the flow. The technique was first presented by Kalt and Birzer (2005), with later corrections to account for attenuation and scattering of the light source introduced in Kalt et al. (2007) and Kalt and Nathan (2007). These validation papers studied concentrations up to 0.01% by volume, while more recent work has provided quantitative data for local volume fractions just below 0.1% (Lau and Nathan, 2016). Once again, the use of a laser and camera requires undistorted optical access, a significant restriction for application-relevant geometries.

1.2. Magnetic resonance imaging

Magnetic Resonance Imaging (MRI) is a widespread technology that is finding increasing application to fluid mechanics problems. MRI-based techniques have a significant advantage over both probe-based and planar laser measurements: 3D data can be obtained without the need for any optical access. A typical data set comprises millions of data points on a regular Cartesian grid with 0.6-mm resolution. The achievable resolution varies depending on geometry, flow, and other parameters and may be better or worse than 0.6 mm. Current capabilities include mean 3-component velocity (Elkins and Alley, 2007), passive scalar concentration (Benson et al., 2010), and temperature (Spirnak et al., 2016) measurements in turbulent flows. The majority of MRI-based techniques provide time-averaged data, although phase-averaged measurements in periodic flows and 2D time-resolved measurements are also possible. MRI has been used to provide 3D measurements inside a wide range of geometrically complex flows including a coral colony (Chang et al., 2009), a double-inlet swirl generator (Grundmann et al., 2012), porous fins (Coletti et al., 2014b), a vacuum cleaner nozzle and cut-pile carpet (Lee et al., 2015), a patient-specific human airway model (Banko et al., 2015), and a rotating vertical-axis wind turbine (Ryan et al., 2016).

1.3. Objectives

The motivation for the present work is to extend the suite of available MRI diagnostics to include measurement of the mean particle concentration distribution in turbulent flows. This protocol will be known as Magnetic Resonance Particle concentration—MRP, for short. A pilot study was undertaken by Coletti et al. (2014a) in which a high-concentration streak of glass microspheres was injected into a round turbulent pipe flow with a 180-degree bend. It was observed that the MRI signal dropped by up to 90% in the core of the streak, which contained 20% particles by volume. The proof of concept study was limited to a qualitative visualization of the particle streak, while the end goal is a fully quantitative, well-validated technique suitable for application-relevant studies. The goals of this work were to identify the physical processes governing the MRP method, perform validation experiments both with and without flow, and demonstrate the ability to measure the 3D particle concentration distribution quantitatively in a turbulent flow relevant to gas turbine cooling systems.

2. Theoretical framework

Magnetic Resonance Imaging makes use of the tendency for charged atomic nuclei (e.g., the proton nucleus of a hydrogen atom) to precess around an applied magnetic field. The rate of precession is known as the Larmor frequency and is governed by the magnetic field strength, B_0, and a parameter known as the gyromagnetic ratio, γ, according to the relationship:

$$\omega_0 = \gamma B_0 \tag{1}$$

Typical full body medical MRI scanners use 1.5 or 3 T primary magnets.

Imaging is carried out by sequentially acquiring data points in spatial wavenumber space, i.e., discrete samples of the 3D Fourier Transform (3DFT) of the physical signal. This process occurs as follows. First, a radio frequency (RF) excitation pulse is used to rotate the protons, initially aligned with the B_0 field, into the transverse plane. The protons immediately begin to precess at the Larmor frequency, but can be considered stationary and in-phase in a reference frame rotating at ω_0. Next, linear magnetic field gradients are applied in the three Cartesian directions to vary the local resonance frequency across the sample. By controlling the gradient amplitude and duration, different degrees of phase accumulation can be achieved in each direction. This is the physical analogue of multiplication by a complex exponential basis function in the Fourier transform, where the wavenumber is