PhD PROJECT PROPOSAL

## **PhD Project Title**

Analysing the topological features of particle-induced turbulence through direct numerical simulations

## **PhD Supervisory Team**

Principal Supervisors: Dr Bruño Fraga, [b.fraga@bham.ac.uk](mailto:b.fraga@bham.ac.uk), CFD Special Interest Group, School of Engineering

## Associated Academics: Dr Immanuvel Paul, [immanuvel.paul@ncl.ac.uk](mailto:immanuvel.paul@ncl.ac.uk), Engineering, Newcastle University

## **Project Abstract**

*This project seeks motivated candidates interested in modelling and topology applied to fluid dynamics. The chosen candidate will be conducting ground-breaking research on turbulence of particle-laden flows. We know that turbulence in multiphase flows has very different features from the ones we find in single phase fluids. This is particularly relevant with particle-laden flows, where there is a dispersed phased (particles) embedded in a fluid matrix (water, air, etc). The practical relevance and applications of such flows is extremely relevant, ranging from reactors in industrial processes, sediments in rivers, aerosols in the air or microplastics in our rivers and oceans.*

*The successful candidate of this PhD will conduct high-resolution numerical simulations to elucidate the relationship between the flow topology and the distinct signature of turbulent kinetic energy transfer in particle-laden flows.*

## **Detailed Project Description**

Multiphase turbulence: relevance and questions

Examples of turbulent flows involving a dispersed phase are abundant in the natural and man-made environment. From microplastics in aquatic systems to bubbles in nuclear reactors, fuel sprays in engines or saliva droplets exhaled while speaking, we can find dispersed multiphase flows in innumerable processes of key importance to our health, environment or industry. Intensive experimental and numerical studies done in the past two decades have improved our understanding on (1) the modulation of continuous phase turbulence (Balachandar & Eaton 2010), (2) the transition between different flow regimes (Capecelatro et al. 2018), (3) the enhancement of turbulent mixing brought by the dispersed phase and (4) the collective effects of particle wakes (Riboux et al. 2013). Yet, much remains unclear regarding the behaviour of dispersed multiphase flows and, in particular, their relationship with turbulence.

The signature of multiphase turbulence differs quantitatively from that of single-phase flows. The turbulence cascade is a cornerstone of turbulence theory, albeit its role in multiphase flows has received little attention – it was assumed to be the same as in single phase scenarios. The cascade refers to how the kinetic energy (TKE) is transferred among turbulent eddies of different sizes. In classic Richardson-Kolmogorov phenomenology, kinetic energy is passed down from the energy-containing (large) eddies to the viscous dissipative (small) eddies through the inertial subrange. The most counter-intuitive feature of the cascade is that eddies of intermediate size within the inertial subrange only passively transfer the received energy to smaller ones. This postulate is true for flows at large Reynolds number and illustrated by the famous -5/3 spectral slope scaling in the spatial/temporal spectra of velocity fluctuations.

However, the picture of the energy cascade in general two-phase flows is less clear. The dispersed phase is another source of TKE in addition to fluid mean shear. The scales over which this extra production source occurs are limited by the characteristic size of the dispersed phase e.g. diameters of particles. The -5/3 signature of the inertial sub-range is not universally present in dispersed multiphase flows. Instead, a -3 (or-8/3) spectral slope has been proven a common feature of these flows. This was first observed by Lance & Bataille (1991) and corroborated by many experimental and numerical works over the last decade.

The implications of such observation go beyond the quantitative difference. Some pertinent questions are: 1) are the assumptions of single-phase turbulence applicable to multiphase flows? 2) is there an inertial sub-range in the presence of particles? 3) does the energy cascade model that sustains classis turbulence theory apply or explain multiphase turbulence? We are on the verge of a paradigm switch regarding our fundamental understanding of fluids and turbulence.

The role of topology

The large-scale terms of turbulence are represented by velocity fluctuations while the turbulent small-scale terms are written in terms of velocity gradients. The literature on particle-induced turbulence that most of the studies have focused only on the large-scale features. On the other hand, the small scales of turbulence are unaffected by the problem parameters, hence a universal turbulence theory can be developed only based on it. There are two ways to analyse the small scales of turbulence. In the first method, the small scales are studied for the statistical behaviour in terms of their joint probability functions.

Despite of the mathematical tools we choose to study turbulence, as the physical phenomenon it is, its quantitative manifestations are necessarily rooted in dynamics that develop in time and space. The presence of a dispersed phase disrupts the mechanisms of turbulence generation and dissipation substantially; this is the key behind the distinct signature. Investigating the topology of such flows is key to understand these mechanisms, their prevalence and their evolution in time and space. In particular, the way in which vortex stretching is disrupted by tube-like dissipative structures (Paul et al., 2022) at the particles’ wakes has not been yet fully quantified nor investigated, and it constitutes a crucial departure from single phase turbulence.

Numerical Simulations

Direct Numerical Simulations (DNS) solve the Navier-Stokes equations at high spatio-temporal resolutions without any pre-assumption on the dissipative turbulent structures. This technique is the main tool to obtain data that enables a detailed analysis of fine-scale turbulence (hence, topology) given the difficulty to obtain high-resolution experimental data.

Aims and Objectives

The aim of this project is to further understand the role of wake flow topology on particle-induced turbulence and inter-scale energy transfer through numerical simulations. This aim will be achieved through the completion of the following objectives.

O1: to conduct a thorough review of the state-of-the art regarding particle-induced tuburlence.

O2: to create a DNS model of a gravity-driven particle-laden flow and validate it against experimental data.

O3: to explore the topology of the fine-scale turbulence in the DNS datasets through conditional statistics.

O4: to connect the topological description of the flow structures and mechanisms observed in the DNS data to the distribution of turbulent kinetic energy.

O5: to explore the sensitivity of the observations in O4 and O5 throughout the parameter range (particle Reynolds number, deformability and volume fraction).

O6: to formulate new scaling laws for particle-induced turbulence.

The supervisory team

Dr Bruño Fraga has ample experience in the simulation of multiphase flows, with over 20 publication on the field, and in particular in DNS of particle-laden flows, a topic that granted him a scholarship by the prestigious Centre for Turbulence Research of Stanford University.

Dr Immanuvel Paul has developed his research profile on the detailed analysis of grid-generated and bubble-induced turbulence. He completed his PhD on the former in Imperial College and was a postdoctoral researcher in Stanford University before obtaining his lectureship at Newcastle University.

References

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