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Brief Summary of Past and Ongoing Research

My research expertise (in experimental fluids) broadly encompasses **turbulence, interfacial dynamics, multi-phase flows (turbulent and laminar), drag reduction in turbulent flows, environmental flows and fluid-structure interactions**. • I am currently a Postdoctoral Research Fellow in the Department of Aeronautics and Astronautics at the University of Southampton (UK). My post-doctoral work involves laboratory experiments to model "pollution dispersion in indoor and outdoor environments" under atmospheric boundary layer conditions. My research involves collaboration across different universities in the UK with expertise in numerical simulation and experiments. • Prior to my current position, I obtained my PhD from the Department of Mechanical Engineering at the Indian Institute of Science (IISc), Bangalore, India. My thesis, titled "Interaction of Bubble(s) and Buoyant Rigid Particles with Vortical Structures: Towards Understanding Bubbly Turbulent Flows," encompasses a variety of research problems. These ranged from examining the complex coupled interactions between single vortical structure and air bubbles (and rigid particles), to applications of bubbly flow, such as drag reduction via bubble injection in (water) turbulent boundary layers. • Prior to this, I obtained my master's at IISc, with my thesis work focusing on "thrust generation using rigid and flexible flapping foils".

I have gained experience working in various experimental facilities, including large-scale wind tunnels, water tunnels, and water channels, to moderately simple set-ups, e.g., water tank experiments. I earned expertise in a number of flow visualization and measurement techniques, including Particle Image Velocimetry (time-resolved, phase averaged, 2-phase), Laser-Induced Fluorescence (LIF), Laser Doppler Anemometry (LDA), Fast Flame Ionisation Detection (FFID), dye visualization, particle tracking, shadowgraphy, drag measurement, high-speed Imaging, Image Processing, force and moment measurements, etc.

Post-doctoral work

At Department of Aeronautics and Astronautics, University of Southampton, UK

Area of research: "Pollutant dispersion in environmental flows": Over the past few decades, rapid urbanization has significantly degraded the air quality in both indoor and outdoor environments. Most work focuses on pollutant dispersion and transport mechanisms in indoor or outdoor spaces, in configurations such as flows around the scaled-down solid building(s) and flow through the hollow building(s) under atmospheric boundary layer conditions (see Fig. 1(a)). This work involves a diverse parametric space, including the effects of pollutant source location (indoor vs outdoor), flow Re, boundary layer to building height ratio (δ/H), and flow angle of incidence.

Project I: "Experimentally simulating flow through an isolated hollow building in an urban environment: towards understanding indoor-outdoor exchange of pollutants": Cross ventilation plays a crucial role in dispersing indoor pollutants through the exchange of indoor and outdoor air. To understand the pollutant transport mechanisms in such scenarios, I experimentally investigate the flow through a hollow cube with an indoor pollutant source (Rhodamine dye, as a passive scalar) immersed in an atmospheric boundary layer inside a water tunnel (see Fig. 1(a)). ***Novelty:*** I characterize the scalar transport mechanisms by measuring the advective and turbulent scalar fluxes from simultaneous scalar [using Planar laser-induced fluorescence (PLIF)] and velocity [Particle-Image Velocimetry (PIV)] measurements, which has not been reported earlier in such flow configurations. Further, I report substantial effects of window opening positioning (see Fig. 1(b,c,d)) on the indoor flow and the scalar concentration, distribution and time-scales. The results from the experiments are further used to construct an analytical model to help predict indoor pollutant concentration in such cross-ventilating flow configurations. [*Flow, Cambridge University Press. 2024 (click for PDF)*]

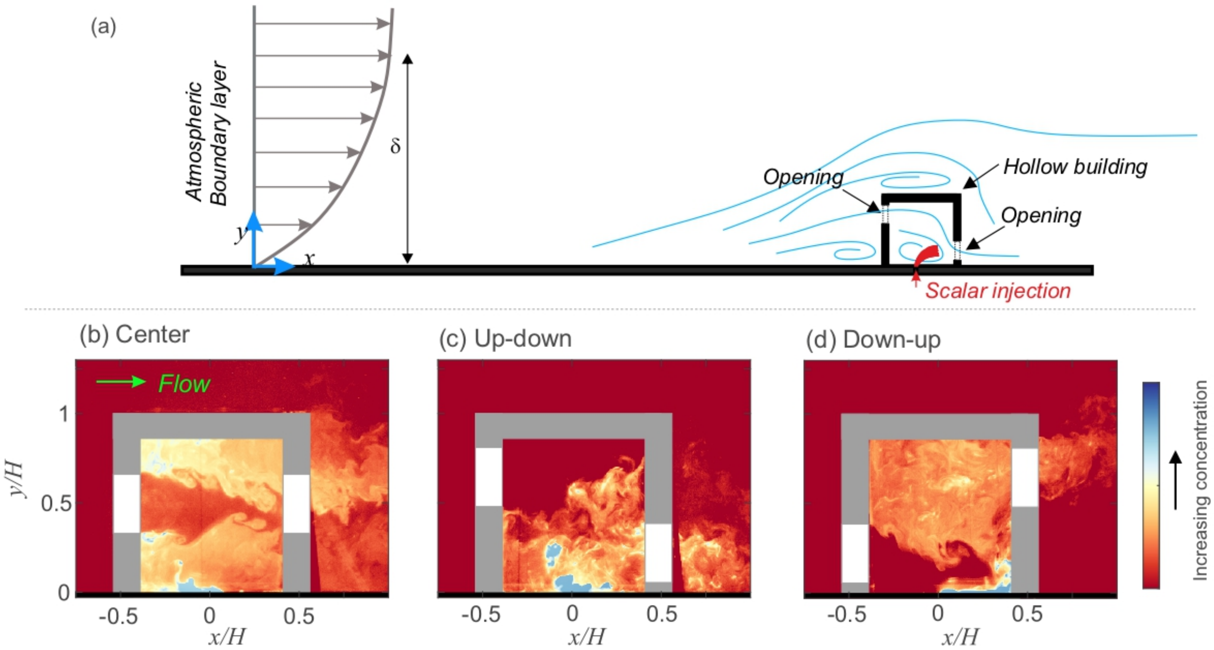

Figure 1: (a) Schematic of the side-view of a hollow cube with openings upstream and downstream and a scalar source on the building floor, immersed in an atmospheric boundary layer. (b-d) Instantaneous scalar concentration fields are shown for three window opening configurations.

Project II: "Scalar transport in a flow through and around a hollow cube with an upstream source: Wind and water tunnel measurements": In cross-ventilating flows (Fig. 1(a)), the pollutant source location (indoor vs outdoor) would be critical since bad outdoor air would deteriorate the indoor air quality (see Fig. 2) and very different indoor dispersion characteristics. ***Novelty 1:*** With the configuration as in Fig. 1(a), I perform a series of experiments with an outdoor pollutant source (placed upstream) and characterise the pollutant transport around and within the cube. Subsequently, the findings are compared with sets of analogous experiments performed in a wind tunnel with a gaseous (Propane) scalar source; here, the velocity fields are measured using Laser Doppler Anemometry (LDA), and scalar dispersion is characterised using a Flame Ionisation Detector (FFID). ***Novelty 2:*** Most experimental studies on flow and pollutant dispersion predominantly utilize wind tunnel facilities, while the use of water tunnels for similar studies remains relatively limited. Our comparative approach is the first one to report flow and scalar dispersion measurements from two facilities simultaneously, highlighting the similarities and differences. This would help to establish consistency and reliability of dispersion measurements across different experimental arrangements. [*manuscript to be submitted in- Journal of Fluid Mechanics*]

(Collaborator: Prof. Matteo Carpentieri, Centre for Aerodynamics and Environmental Flow, University of Surrey, UK)

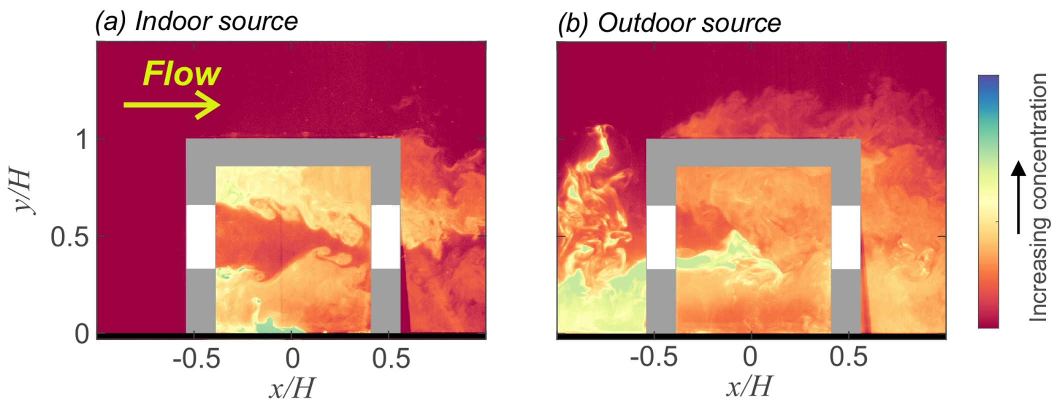

Figure 2: Instantaneous scalar concentration fields are shown for (a) indoor scalar source, and (b) outdoor (upstream) scalar source.

Project III: "Characterization of flow over an isolated tall building through laboratory experiments and large-eddy simulations": In order to understand the complex outdoor flows in urban environments, most studies focuses on shorter buildings involving configurations such as flow over low aspect ratio (AR) surface-mounted bodies (e.g., cube). However, high aspect ratio buildings (as in Fig. 3), often exhibit flow behaviours considerably different from low AR structures. ***Novelty:*** I examine the flow over an isolated tall structure (Fig. 3) characterising several aspects, such as the turbulent kinetic energy, re-circulation lengths, spatial correlation maps and recovery downstream, using experiments (in a water tunnel). The results are further compared with 3D Large-Eddy simulations (in collaboration). The results show the flow characteristics to be considerably different from low AR bodies (cubes). For example, the wake recovery behaviour shows that the tall building exhibits a substantial velocity deficit, considerably higher than that for a surface-mounted cube. [*Under review in- Journal of Wind Engineering and Industrial Aerodynamics*]

(Collaborator: Prof. Zheng-Tong Xie, Aerodynamics and Flight Mechanics Group, University of Southampton, UK)

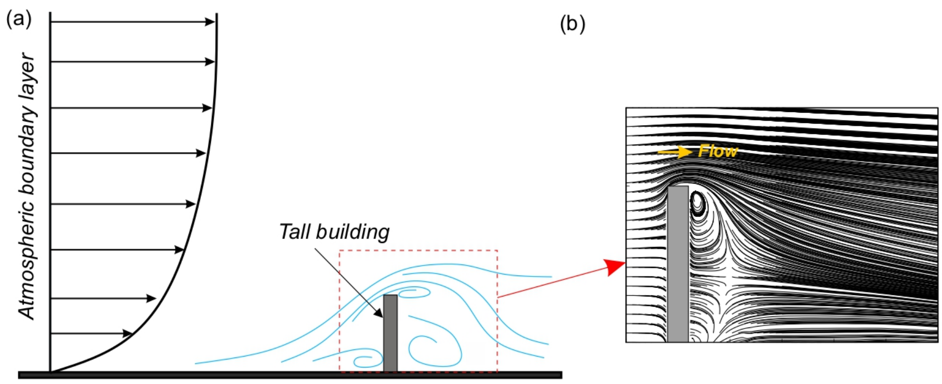

Figure 3: (a) Schematic showing a tall building immersed in an atmospheric boundary layer condition. (b) Streamlines shown in the streamwise center plane.

Project IV: "Effects of wind direction on flow and pollutant dispersion": Wind direction is very critical in governing the inflow conditions to buildings. This influences the indoor-outdoor air exchange rate and, hence, spatiotemporal characteristics of the indoor scalar dispersion. I perform at different wind directions, measurements on flow and dispersion (in wind tunnel) in a flow through and around a hollow cube. ***Novelty:*** Involving indoor and outdoor (upstream) pollutant sources, I aim to identify the critical wind angle at which a substantial change in the ventilation effectiveness and indoor pollutant concentration occurs, for different window opening configurations (as in Figs. 1(b,c,d)). [*manuscript under preparation*]

Doctoral work

At Department of Mechanical Engineering, Indian Institute of Science, Bengaluru, India

Thesis title: Interaction of bubble(s) and buoyant rigid particles with vortical structures: Towards understanding bubbly turbulent flows

Bubble/particle-laden turbulent flows involve the complex interaction of many bubbles/particles with vortical structures (Fig. 4) having a range of length scales. ***My work*** experimentally investigated an idealization of these flows, namely, the interaction of a vortex ring (in water) with air bubble(s) and rigid particles (Fig. 5). Following these, I further studied an application of bubbly flows, namely, drag reductions using air bubble injection into a (water) turbulent boundary layer in a channel flow.

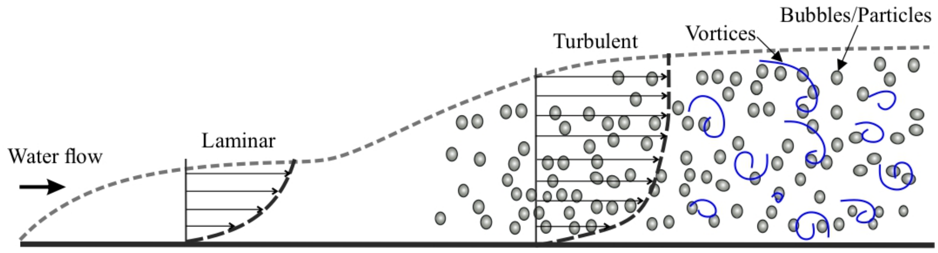

Figure 4: A schematic showing bubbles/particles interacting with vortical structures in a turbulent boundary layer.

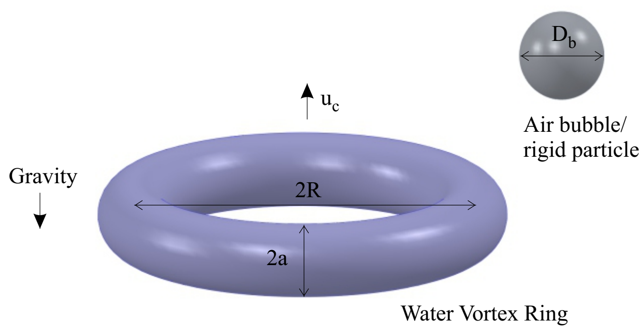

Figure 5: A schematic of an air bubble/particle of diameter D_b and a vortex ring of diameter $2R$ and core diameter of $2a$ travelling with a speed u_c.

The thesis broadly comprised four main parts. In part I, the interaction between a single vortex ring with a single deforming bubble is studied (see Fig. 6(a)), with the focus being on the relative size of the bubble to the vortex ring. An important aspect of these interactions is the deformability of the bubble. To better understand this aspect, I studied in the part II, the interaction between a rigid buoyant particle and a vortex ring (Fig. 6(b)), where there is no deformability, but the interactions are again quite strong as the buoyant particle is also captured by the ring as in the bubble case. In part III, I went one step closer to bubbly-turbulent flows by investigating the interaction of a vortex ring with a large number of bubbles (Fig. 7), namely, a bubble swarm. This was followed by part IV involving a study of an application of bubbly-turbulent flows, namely, drag reduction in a water boundary layer by injection of a large number of air bubbles into a fully developed turbulent channel flow (Fig. 9 & 10). The motions and deformation of the bubble(s) in all four cases were directly imaged using high-speed visualizations, while the flow field information was obtained using time-resolved Particle-Image Velocimetry (PIV) in the first three cases and from stream-wise pressure drop measurements within the channel in the latter case.

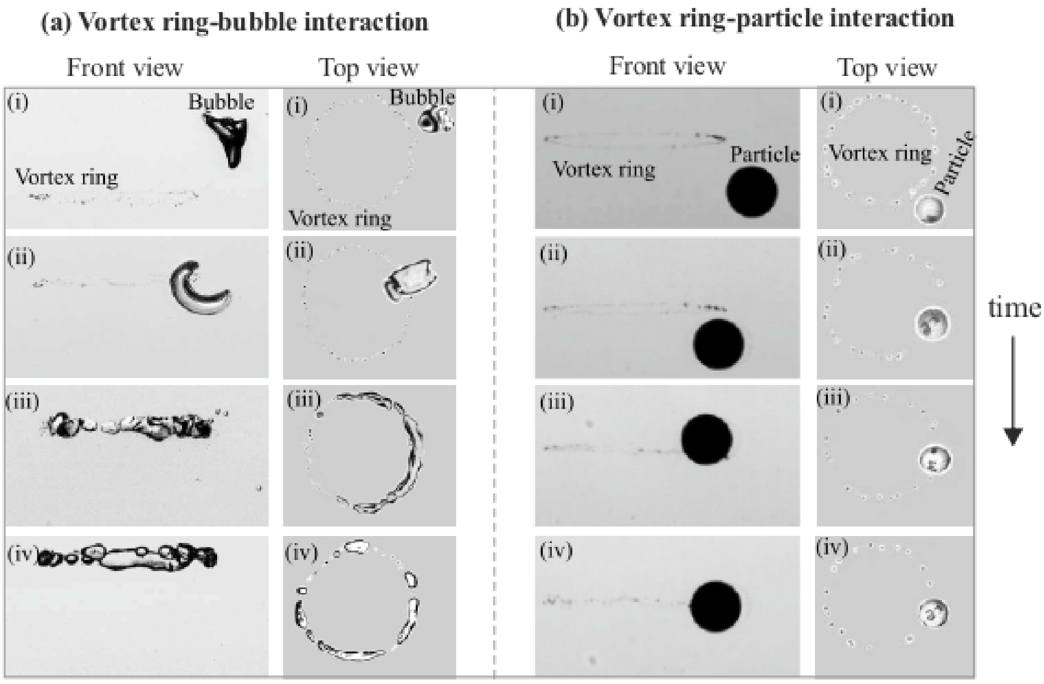

Figure 6: Time sequence of the front and top view visualization images of (a) a deforming bubble and (b) a rigid buoyant particle, interacting with a single vortex ring.

Part I: "Vortex ring and bubble interaction: Effects of bubble size on vorticity dynamics and bubble dynamics": In most studies on bubble deformation/breakup in turbulence, the influence of the bubble size is not considered individually since it would be accounted for in Weber number (We). However, alongside We, the bubble size is also a critical parameter since it could influence the bubble's dynamical characteristics and hence, its interaction with the vortices. To understand these two-way interactions, • I studied the interaction of a single vortex ring with a deforming air bubble, at different bubble-to-vortex ring size ratios (Φ) over a wide range of Weber numbers (We=Vortex strength/surface tension). In ring-bubble interaction, the bubble is first captured by the low pressure within the core of the ring, then stretched azimuthally within the core, and gradually broken up into a number of smaller bubbles. During the bubble elongation and breakup, simultaneously, the vorticity within the core of the ring is also modified due to the presence of the bubble(s) within its core. ***Novel findings:*** On the bubble dynamics side, varying Φ brings striking changes in both the bubble deformation and breakup dynamics, even at a fixed We, in the initial stage of interaction. I characterised these with a range of scalings in the We-Φ plane. However, at a later stage, the statistics are nearly independent of Φ and governed by We only. On the other hand, the vortex ring dynamics depend on both Φ and We. For example, the reductions in the ring's propagation speed and enstrophy caused by the bubble (at later stages) are found to follow a scaling of $\Phi^2/\sqrt{We}$. In addition, the effects of the bubble are more dramatic above a critical Φ of 1.2, with a large ring deformation and fragmentation of the vortex core (Fig. 8). [*Physics of Fluids, vol. 35, no. 8 (click for PDF)*]

Part II: "Interaction of a rigid buoyant sphere and a deforming bubble with a vortex ring: The role of deformability": In bubbly flows, the deformability of bubbles is critical in governing the dynamics of both the carrier and dispersed phase. To better understand this aspect, I have studied the interaction between a rigid buoyant particle (a non-deforming bubble) and a vortex ring (Fig. 6(b)) at a fixed Φ, and compared with the results on bubble-ring interactions. Distinct differences can be seen right from the capture phase (see Fig. 6). For example, unlike the bubble which had a quicker capture time due to its large elongation and lower drag, the non-deforming particle took longer to get captured due to a higher drag. Post-capture, the particle does not deform and stays more localised within the ring, unlike the bubble that spreads azimuthally inside the ring. These differences lead to distinct differences in the ring's dynamics. ***Novel findings:*** In particular, the measurements indicate that the localized large perturbation to the vorticity in the rigid particle

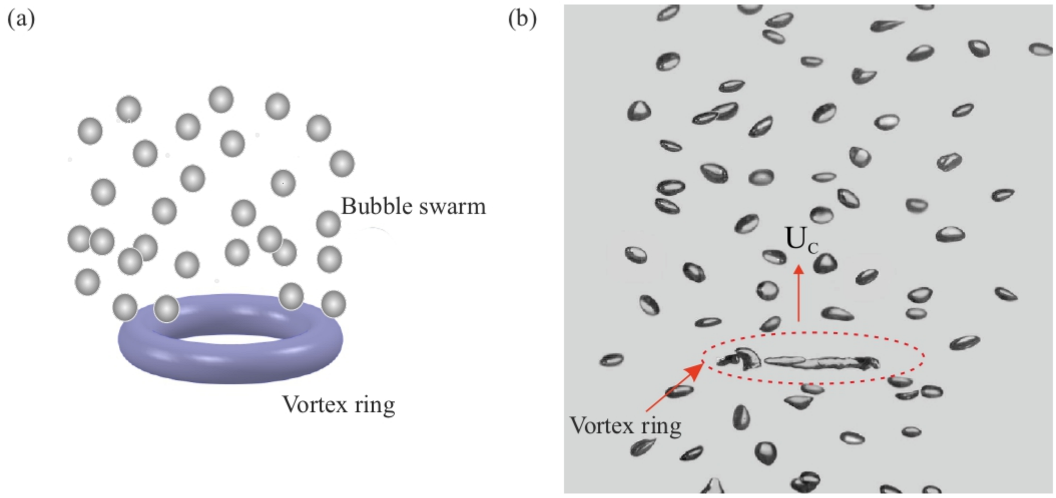

Figure 7: (a) Schematic representing a vortex ring and a bubble swarm, and (b) showing the front view visualization image of a vortex ring travelling in a bubble swarm. The vortex ring convects vertically upwards through the bubbles, while the ring continually captures bubbles into its low-pressure vortex core.

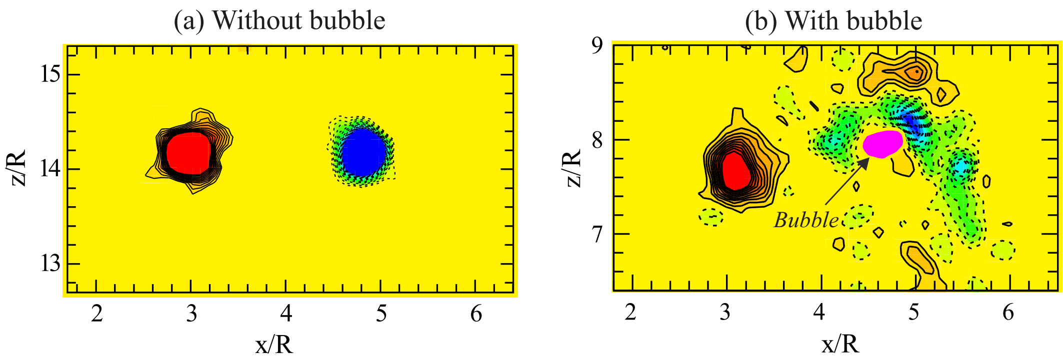

Figure 8: Azimuthal vorticity field of both the cores for (a) without bubble, and (b) with bubble. In the interaction case, we can see that bubble can fragment the vortex core. On the other hand, in the without bubble case, the cores are intact.

case (an equivalent of a rigid bubble, We=0) leads to a larger disruption of the vortex ring as seen in terms of higher reduction in the ring convection speed and azimuthal enstrophy than for the deforming bubble (non-zero We) case [*Physical Review Fluids, vol. 7, no. 9, pp. 094302 (click for PDF)*]. • I further varied the particle size and found a number of regimes characterising the motion of the particle within the vortex ring. In addition, the scalings related to the modified ring's characteristics are found to be substantially different than in the case of a bubble, and the critical particle size is smaller than the bubble. [*Accepted in- Journal of Fluid Mechanics*]

Part III: "Effect of single and multiple bubbles on a thin vortex ring": I studied the interaction of multiple air bubbles, namely a swarm of bubbles, with a single vortex ring formed in the water medium (Fig. 7). This is essentially the first problem of the thesis, with the added complexity of the presence of many bubbles. In particular, the focus of the work is to both contrast and find similarities in the interaction of a vortex ring with a single bubble and a swarm of bubbles. ***Novel findings:*** As the ring travels through this swarm of bubbles, the ring continuously captures the bubbles, resulting in a time-varying ratio of "total volumes of bubbles within the ring-to-ring volume", thus making their interactions more dramatic and killing the ring much faster, than in the single bubble case. [*Journal of Flow Visualization and Image Processing, vol. 27, no. 1 (click for PDF)*]

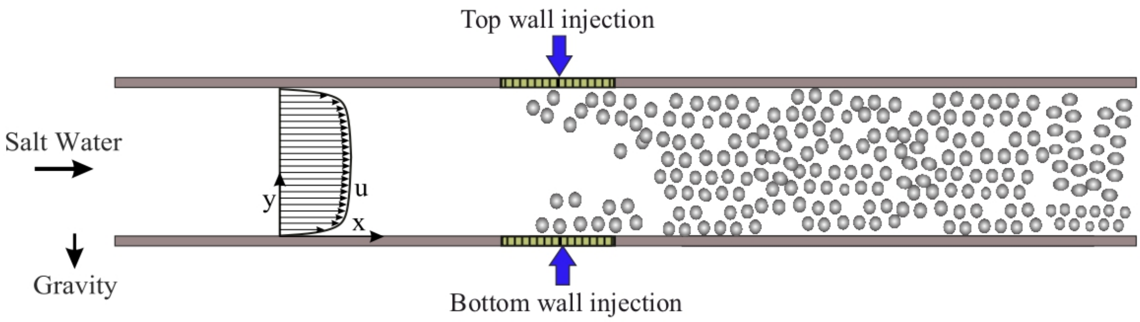

Figure 9: Schematic showing the side view of the injection of multiple bubbles into a fully developed turbulent channel flow.

Part IV: "Effects of salt concentration on wall bubble injection in a turbulent channel flow: bubble dynamics and wall drag reduction": Most applications related to bubble drag reduction (BDR) occur in contaminated environments (e.g., sea water) where the presence of different surface active agents modify bubble coalescence and, hence, affect flow drag. However, most studies are performed in freshwater (without salt/surfactant) and hence would not be a true indicator of BDR in a contaminated environment. ***Novelty:*** I experimentally investigated the effects of salt concentration (M) on the air-bubble dynamics and drag modification in a fully developed horizontal turbulent channel (water) flow (Fig. 9 & 10). The spatial and temporal aspects of the bubble dynamics were captured by high-speed visualizations, while the streamwise pressure drop through the channel was measured at different wall-normal locations. ***Novel findings:*** Increasing M led to a reduction in bubble coalescence and, consequently, in bubble size that modified bubble deformability, migration, and distribution (Fig. 10), with the changes being dependent on the Re and injected bubble volume fraction (α). At low Re, the addition of salt leads to a dramatic reduction in bubble sizes (∼100 microns) from the very large coalesced bubbles (∼cm) seen in the no-salt cases. The reduction in bubble sizes with M led to an increase in drag, which saturated beyond a critical concentration ($M_{Critical}$). With increasing Re, the bubble dynamics was found to be less susceptible to modifications by M, and hence, resulted in a smaller increase in drag and a lower $M_{Critical}$. [*Experiments in Fluids, vol. 65, no. 3, pp. 34 (click for PDF)*]

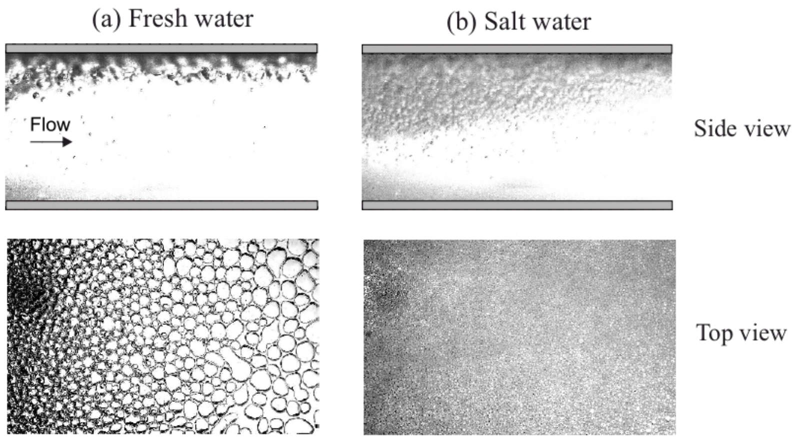

Figure 10: Side view and top view visualization images of bubbles injected into the flow from the bottom channel wall.

Master's work

At Department of Mechanical Engineering, Indian Institute of Science, Bengaluru, India

"Experimental investigation of thrust generation using 2-D and 3-D rigid and flexible foils": Fishes employ flapping motions to generate thrust where the basic source of locomotion is their oscillating tail. Investigating these would help understand and mimic fish's efficient thrust-generating mechanism. I experimentally studied thrust generation from the sinusoidal pitching motion of rigid, flexible, and hybrid foils (Fig. 11) for varying shapes immersed in a uniform flow at varying pitching amplitudes, flow Re, and flexibility (EI). The transient shapes of the flexible foils were characterised through image processing and then associated with the increased/reduced thrust obtained from the measured unsteady forces and moment using a Load cell.

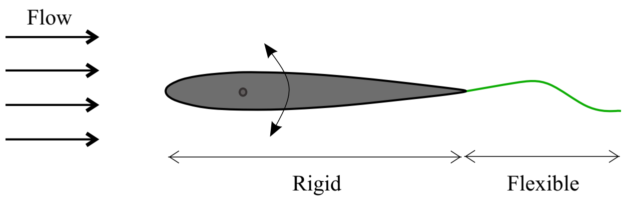

Figure 11: Schematic showing a pitching foil in a uniform flow.