ME – PhD Thesis Defense

Particle-laden Rayleigh-Bénard convection

Mr. Thota Srinivas, PhD student, Department of Mechanical Engineering, IISc Bengaluru

July 9th, 2025, at 09:00 AM

Venue: Conference room, ME@IISc

ABSTRACT

Particle-laden flows are ubiquitous in nature and industries. For example, water droplets in clouds, fine dust particles in strong winds leading to dusty storms, dunes, ejection of solid particles and ash during volcanic eruptions, spray coating, etc. In all these scenarios, particles are much smaller than the length scales in the underlying fluid flow, and the number of particles per unit volume is enormous (for instance, a few hundred per cubic centimetre in clouds). Hence, fully resolved direct numerical simulations are computationally very expensive. Computationally efficient formulations are being proposed in the literature to tackle these problems. That is, when the three length scales, particle size d_p, inter-particle separation λ, and the smallest length scale in the underlying flow η (size of the smallest eddy) are well separated ($d_p \ll \lambda \ll \eta$), it is preferred to consider the particles as a continuous medium with a concentration field. This formulation is called the Euler-Euler formulation. On the other hand, if $d_p \ll \lambda \sim \eta$, each particle is treated as a Lagrangian point particle and tracked by solving their equation of motion. Hence, the resulting formulation is called as the Euler-Lagrange formulation.

In this thesis, we analyse the settling of inertial particles in Rayleigh-Bénard convection. We performed linear and weakly nonlinear stability analysis using the Euler-Euler formulation. The linear stability shows that the particles tend to stabilise the flow, especially when the particles are thermally interacting with the fluid. More specifically, the stability of the flow is increased with an increase in particle volume fraction. However, the initial temperature of the particles shows a non-monotonic effect on the stability of the flow. Near the onset of convection, we derive the evolution equation for the disturbance amplitude called the Landau cubic equation using the weakly nonlinear stability analysis. We established the supercritical bifurcation to the particle-laden Rayleigh-Bénard convection. We show the existence of the steady finite amplitude equilibrium solution, which depicts the flow pattern as stable straight rolls. We perform direct numerical simulations of incompressible Navier-Stokes equations coupled with Lagrangian point particles to study the systems far from the critical point in one-way and two-way coupled regimes. In the one-way coupling case, we propose the scaling laws to estimate the position of particle clouds, the horizontal separation between the two adjacent clouds and the final particle volume fraction when the quasi-steady state is reached. The predictions from the scaling laws are in good agreement with the numerical results. In the case of two-way coupling, we study the effect of particle volume fraction on the particle settling dynamics. We show that the rate and the fraction of particles settled are more when the initial particle volume fraction is of the order of $(\rho_f/\rho_p)Fr^2$ here, ρ_f and ρ_p are the densities of fluid and particles, respectively, and Fr is the Froude number.

Finally, in the Euler-Lagrangian formulation, when the particle size is comparable to the underlying Eulerian grid size, the undisturbed flow field needed to compute the various hydrodynamic forces is not readily available. Hence, a two-way coupled, 3D extended Euler-Lagrange formulation is proposed to compute the undisturbed velocity field that considers the disturbance in the flow caused by the dispersed particles to obtain the undisturbed fluid flow field essential for the accurate computation of force closure models. A generalised correction scheme is proposed to obtain the undisturbed flow field in non-Stokesian conditions.

ABOUT THE SPEAKER

Thota Srinivas joined the Department of Mechanical Engineering as a direct PhD student in January 2018 and is working under the guidance of Prof. Gaurav Tomar. Srinivas's research interests include the numerical simulations of multi-phase flows, linear stability analysis, and weakly nonlinear analysis of convection problems.