RESEARCH STATEMENT

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My research is primarily concerned with fluid mechanics, with a particular focus on multiphase flows. I am mostly interested in fundamental problems which typically find applications in geophysical and microfluidic contexts. I use and develop numerical methods to solve complex systems of equations and favor finding analytical solutions to simplified problems whenever possible. I entertain collaborations with researchers from engineering, physics and chemistry departments and I greatly benefit from these interactions, both as a source of interesting problems and as a way to keep in touch with realistic applications. The three main areas of my research are briefly described below.

Sedimentation in stratified ambients

Sedimentation is characterized by the settling of a large number of small particles in a fluid and is an important environmental issue in the contexts of fluvial plumes, volcanic ejecta, microorganisms in the oceans, waste disposal, etc. Using a continuum hypothesis, suspensions are typically treated as fluids with modified properties (density, viscosity) and the particles are assumed to move with the flow and settle under the influence of gravity. In many cases, such as in lakes, oceans and the atmosphere, the density and viscosity of the suspending fluid is not homogeneous.

I have studied the effects of the concomitant presence of settling particles and of a diffusing component such as a solute or heat. The particle settling speed dependence on the local particle concentration, ϕ, may combine with ambient stratification to generate unusual flows. Studies by Kynch have demonstrated that in a uniform ambient ϕ remains constant along characteristics and may form shocks or expansion fans, depending on initial conditions. My research has shown that in the presence of a stable density gradient, these behaviors are altered: as particles settle, their density difference with the ambient decreases and their settling speed is reduced, causing ϕ to increase along characteristics. Moreover, a new type of instability may develop: convective plumes may be generated if a region of high particle concentration forms over a particle–depleted region. Enhanced mixing may result, despite the fact that both the initial particle distribution and the initial fluid density profile were statically stable. Hindered settling in a stratified ambient is relevant to all cases where the settling speed varies significantly within a given system, as is the case for plankton in the oceans and crystals in magma chambers.

The work of Schmidt has shown that double–diffusive instabilities may arise when two diffusing components have opposing vertical concentration gradients (e.g. hot and salty fluid overlying cold and fresh fluid). However, the stability of the corresponding set-ups where one of the components also has a non-zero settling speed had not been studied. I performed a linear stability analysis of this scenario, focusing on the effect of the particle settling speed on the stability of the system. Double–diffusive instabilities were recovered in the limit of small particle settling speed, but particles larger than a critical size, approximately 10 μm in water, were seen to behave in a qualitatively different manner. A non-zero particle settling speed renders particle concentration gradients inefficient as stratifying agents. That is to say, stable gradients are less stable than they would be if particles were replaced by a solute, and unstable gradients are less unstable. This work is still ongoing and the influence of the dependence of particle diffusivity on ϕ in particular remains to be explored.

I have also researched particle clouds, relevant in waste disposal in the oceans and the stratified Boycott effect, with applications to magma chambers. The latter problem is motivating an ongoing study of the stability of a density gradient bounded by a vertically moving wall, an idealized set-up relevant to plumes, thermals and settling in inclined containers.

Depending on the system at hand, particles may be dynamically passive and be simply carried by the flow, or act as the driving force to generate large scale fluid motions, or go from one to the other as the system evolves. Moreover, the competing effects of particle settling, fluid motion and particle diffusion generate a variety of flows. The complexity of suspensions is such that lots of research remains to be done is this area, particularly in studying the combined effects of heat and chemical transport and those of particle settling. Understanding the evolution of particles suspended in an inhomogeneous fluid allows for better predictive capability of natural phenomena and optimization of certain industrial processes and may even uncovers new instabilities, as my research has shown.

Gravity Currents

Particle–laden gravity currents occur when a mass of particle–laden fluid spreads horizontally beneath a particle–free ambient. Such currents, have important geological and industrial applications in particular on the location of oil and gas fields. In that respect I have collaborated with engineers and geologists as well as oil companies to investigated the evolution and deposits left by gravity currents.

Using a combination of spectral decompositions and finite differences, I have performed direct numerical simulations of two and three-dimensional gravity currents spreading over a complex bottom boundary. The effect of the bottom topography, crucial in such flows, was simulated using a locally varying gravity vector, an efficient, easy to implement and flexible method. This powerful tool allows for precise estimates of the current's structure, bed stress and resulting deposits. I also incorporated the effects of particle resuspension from the bottom surface, an important feature of these currents which allows them to increase their mass as they travel downslope. My work has helped characterize the conditions under which turbidity currents are self-sustaining, as well as the influence of resuspension on particle deposits. Such simulations are currently constrained to smoothly varying bottom surfaces, but I plan to extend their applicability by using an immersed boundary method which would allow to model flow in the presence of sharper boundaries such as canyons and man-made obstacles (pipelines, oil platforms, cables etc).

The long term objective of this research is to simulate the accumulation of sediments on the ocean floor from numerous gravity currents, thus reproducing actual observations of natural deposits. More complex features of these flows such as the simultaneous presence of several types of particles, and the cumulative effects from repeated currents are currently under investigation. A better understanding of the resuspension process also remains to be attained and I plan to investigate particle reentrainment by combining fluid dynamical simulations with techniques borrowed from studies of granular material to determine what is the flux of particles into suspension for given flow parameters.

Interfacial Flows

On small scales, multiphase flows involving two or more fluids may be dominated by the presence of surface tension. Microscale multiphase flows are relevant to the dynamics of emulsions, bubbles and raindrops as well as microfluidic devices. Interfacial flows are particularly complicated as they involve coupled boundary conditions at the interface, where the inner and outer stresses must be related, as well as a free boundary whose position is determined by the flow. Applications of microfluidic devices in biological and medical sciences are becoming ever more abundant and the demand for a better understanding of the influence of surface tension in such contexts is ever more pressing.

Using two and three dimensional numerical simulations of the full Navier-Stokes equations and tracking the position of the interface to include the effects of surface tension, I have obtained new insight into the evolution of drops in micro-capillaries. Experimentally, each drop is used as a mini-laboratory and effective mixing may therefore be of primary importance. My simulations have for the first time enabled me to accurately determine the shape of the drop and visualize the streamlines of the flow in various parameter regimes. I have found that the flow within drops in capillaries is composed of six recirculating rings rather than two as was previously thought. Therefore, the use of a sinusoidal capillary typically results in good vertical mixing but poor horizontal mixing, as most fluid is confined to a pair of circulating rings.

I have also explored the surprising phenomena of multiple coalescence, by which a drop coming in contact with a horizontal interface only partially merges with the bulk fluid and leaves behind a smaller (daughter) drop. More than 50 years after the phenomena was first observed, I was able to provide a mechanism for this phenomena by making use of detailed simulations. I have found that capillary waves generated in the early stages of coalescence play a determinant role in their capacity to stretch the drop vertically as they converge on the drop's summit. When the vertical collapse is thus sufficiently delayed, surface tension induces a horizontal collapse that leads to the formation of a daughter drop. I have also characterized the conditions required to observed pinch off and identified other possible behaviors such as the formation of satellite drops. Similar pinch off can occur when two drops of different radii coalescence, and is therefore relevant to raindrops and emulsion dynamics. Comparisons with experimental observations provided by my collaborators have further validated my results.

These studies open the door to further research in multiphase flow where surface tension play an important role. In particular, the evolution of suspensions of droplets may now be investigated as a natural expansion of my previous work. I plan to study how settling droplets may be used to enhance heat transport without generating any chemical transport. I am currently developing novel numerical techniques to study systems where surface tension varies locally as a result of surfactants, temperature or chemical gradients, particularly in the context of microfluidic devices. I am also studying boundary integral methods which are applicable to viscously dominated flows relevant to micron size drops and bubbles.

By combining numerical simulations and analytical methods, my research attempts to paint as complete a picture as possible of flows arising in the context of multiphase fluids. In the coming years, I wish to continue to describe fundamental aspects flows such prevalent in suspensions and gravity currents as well as interfacial flows . At the same time, I plan to keep interacting with researchers in neighboring fields to ensure that my work remains ultimately driven by actual applications.