Abstract

Rotational microfluidics finds its importance in several emerging applications, including affordable diagnostics at the point of care. While there have been significant technological advances in this field over the past decades, several aspects of fundamental flow physics, including the mechanisms of hydrodynamic instability that are strongly connected with the device performance, remain unresolved.

In this Thesis, the aim is to delve into the hydrodynamic instabilities in the time-dependent convective flows through a microchannel, subjected to externally applied rotation about an axis perpendicular to the mean flow direction. Linear stability analysis is applied to investigate convective flows confided by two rigid walls, where Centrifugal force drives the radial flow through the microchannel and Coriolis force destabilizes the samevia small perturbations.The rotationally actuated channel flows are considered for three different configurations, to bring out the explicit effect of Coriolis force on this matter. The following configurations are taken into consideration: (i) flow of Newtonian fluid through uniform channel (single fluid flow), (ii) viscosity stratified two-fluid channel flow with same density but different viscosities and with a thin miscible layer between the fluid layers, and (iii) flow of a non-Newtonian fluid with viscosity varying throughout the channel followingtheCarreau model (which can be potentially used to model the blood flow through a microchannel) and (iv) spin dewetting of an ultra thin film under the influence of a complex interplay between van der Waal's force, centripetal force and Coriolis force.

The modal stability analysis of the primary base flow (steady and locally parallel flow)is performed within the framework of modified Orr-Sommerfeld and Squire equations. Using a normal mode analysis, the linear instability behaviours are determined with respect to the infinitesimal perturbations of the flow variables. The final system constitutes an eigenvalue problem and is numerically solved by using Chebyshev spectral collocation method. The growth rate of the amplitude of the perturbations and neutral stability maps are obtained in the parameter regimes governing the flow system. The influences of rotational forces, rotational

direction,viscosity stratification and other critical parameters on the stability properties of the flow systems are explored.

Organization of the Thesis is as follows.In Chapter 1, different forces on a fluid element in a rotational platform are discussed, having contextual relevance with the pertinent unit operations. In Chapter 2,the governing differential equations for different flow configurations, mentioned earlier, are discussed. In Chapter 3, the different Chebyshev spectral collocation methods applied to acquire the eigenvalues and eigenvectors for different flow configurations are discussed.

In Chapter 4,the existence of four different types of unstable modes $(Type-I$ to $Type-IV)$, for single-component rotational flow, is reported,. Results indicate that $Type-I$ and II modes exhibit competing characteristics, and thus can play an important role in transition to turbulence. The other two modes, $Type-III$ and $Type-IV$, have a relatively small growth rate but can be useful in realizing rapid mixing over micrometer scales. Computational results also indicate that those unstable modes set in as two- or three-dimensional modes, either stationary or non-stationary in natur,e depending on parameter regime. Moreover, the structures of roll-cells corresponding to the spanwise perturbations are traced out.An excellent qualitative agreement with previously reported experimental results on roll-cells is obtained.

In Chapter 5, the stability of stratified multi-phase Newtonian flow with a spanwise system of rotation is discussed. The impact of Coriolis force on a rotating two-fluid flow of miscible fluids having specified vaiations in viscosity over a stratified layer is elucidated. Orr-Sommerfeld-Squire analysis is used to estimate the critical flow parameters which are, in turn, responsible for regulating the instability mechanism for different viscosity contrasts and mixed layer thicknesses. Usually, viscosity stratified flow with respect to streamwise disturbance becomes more unstable for a thinner mixed layer. On the contrary, the present numerical computation confirms a completely discrepant scenario by considering Coriolis force driven instability of a miscible flow system on account of spanwise disturbances. Possible physical mechanisms for the same are discussed in terms of the base flow pattern and the energy fluctuation between the perturbed and base flow. Comparison of three-dimensional disturbances of the flow field, in both clockwise and anticlockwise directions (for two different viscosity ratios), is executed to provide an insight into the dynamics of the flow system. Distributions of the velocity perturbations display a critical bonding between the vortices near and away from the mixed layer. These vortices are, in turn, responsible for the variation in instability mechanism with respect to different viscosity ratios and rotational directions.

In Chapter 6,Coriolis force modulated rotational instability of shear-thinning fluids (such as blood) is discussed, using the Carreu model. Reported results on shear-thinning flow with streamwise disturbances indicate that the critical Reynolds number for the flow transitionwith viscosity perturbation is nearly half of that of the critical value for the same without viscosity perturbation. In sharp contrast, the present analysis considering spanwise disturbances reveals that the critical Reynolds numbers with and without viscosity perturbation remain virtually unaltered under rotational effects.However, the viscosity variation has no significant influence on the Coriolis force-based instability.Numerical results confirm that a momentous destabilization is possible by aid of the Coriolis force via generating secondary flow inside the channel. The roll cells corresponding to the instabilities at lower time constants exhibit the existence of two distinct vortices, and the centre of the stronger one is essentially settled towards the unstable “stratified” region. Moreover, for a higher value of the time constant, only one vortex occupies the entire channel. This, in turn, may turn out to be of fundamental importance in realizing new instability regimes facilitating efficient mixing in rotationally actuated fluidic devices deployed for biochemical analysis and medical diagnostics.

In Chapter 7, theoretical formulation for instability mechanisms leading to pattern formation in spin dewetting processes is presented, the later concerning in-situ dewetting of a dilute solution over a homogeneous flat substrate resulting in an isotropic array of nearly equal sized droplets. The theoretical model, premised on non-linear wave theory, predicts that the dominant wavelength of the instability or the gap spacing between the spin dewetted droplets depends on a complex interplay between van der Waal’s force, centripetal force and Coriolis force. It is shown that the dominant wavelength of the instability decreases with increase in the concentration of the casting solution vis – a – vis the effective thickness of the film, which is in complete contrast to the nature of scaling observed in case of dewetting of a thin film. The results are validated with the experimental results from a collaborating research group.

Summarily, the stabilizing or destabilizing effects of rotational forcesas elucidated in this work can be favourably exploited to suggest the strategy inmonitoring the instabilities that occur in this class of wall bounded Coriolis force drivenflows. This, in turn, may lead to the foundation of an optimal parametric regime in which rotationally-driven mirofluidic platforms need to operate, depending on the specific applications on hand. Further experimental verification and direct numerical simulation, however, may be deemed to substantiate some of the conjectures, which may form the basis of further scope of work in this area.