Influence of Surface Tension on Hydrodynamic Instabilities

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The Rayleigh-Taylor (RT) instability in 2D and 3D cases are considered. There are two situations corresponding to miscible (gases, salt solutions) and immiscible (fluids separated by surface tension) mediums. A capillary scale Bo= 1 which appears in the immiscible situation limits a size of the finest droplets in the processes of turbulent fragmenting, where Bo is Bond number Bo= $1/\Sigma = (\rho_h - \rho_l) g L^2/\sigma$, $\rho_h, \rho_l, L, \sigma$ are densities of heavy and light mediums, typical scale, and a coefficient of surface tension. Therefore mixtures of immiscible fluids may be separated back into pure initial mediums when a gravity acceleration g changes its sign from unstable to stable. In the miscible situation such back separation of mixtures mixed at molecular level may takes astronomicaly long times. The miscible and immiscible situations become more close with increase of Bond number - a separation of emulsions is slow. But even rather small Σ may defines dynamics at main scale. There are examples from hydraulics (e.g., sparging) of fast motion of two-phase system in a slug regime with constant velocity opposite to a slow turbulent diffusion regime of mixing in case $\Sigma = 0$ with velocity decaying in time.

Including of the surface tension σ into numerical simulation of RT turbulence (RTT) is a very difficult task (RTT+σ). Till now there are no examples of such simulations. Here we present results obtained by Density Functional Methods (DFM). In principle the DFM may be applied to the difficult problem RTT+σ. We consider development of single-modes (SM) and many modes (MM) in ideal fluids (small viscosity) when the Laplace pressure jump across the contact surface is significant (SM+σ). Initial perturbation of velocity for each modes has a velocity potential $\phi \propto \mp \exp(-k|z|) \cos kx$, while at $t = 0$ the contact is plane $z = \eta(x, t = 0) = 0$, where in ϕ the $-$ sign is for $z > 0$. Half of period is considered and symmetry conditions are imposed on lateral sides $0 < x < \pi/k$ of a rectangular simulation domain. Density ratio is $\mu = \rho_l/\rho_h \sim 1$. Even small surface tension significantly influences surface topology preventing surface from rolling into mushrooms. Bubble rise velocity v_b has been found numerically by DFM as a function of Σ in 2D plane geometry at the bubble tip displacements $(0.2 - 0.6)\lambda$, $\lambda = 2\pi/k$. Velocity $v_b(\Sigma)$ decreases as Σ grows. Bubbles can not penetrate into dense fluid at large value of Σ.

We also have generalized high order expansion analytical approach (MAC, Inogamov 1992, Inogamov and Chekhlov 1993, $\mu = 0$) to include σ and control DFM computations. In the order N the surface η and potential ϕ are expanded as $\eta_0 + \eta_1 x^2 + .. + \eta_N x^{2N}$ and $a_1 e_1 c_1 + .. + a_N e_N c_N$, where $c_N = \cos Nkx$ and η_n, a_n are constants as the problem stationary in the frame comoving with the bubble is considered. The computations show that MAC follows decrease of function $v_b(\Sigma)$ up to $\Sigma \approx 0.2\Sigma_{crit}$, where Σ_{crit} corresponds to $\gamma = 0$ of the RT+σ increment $\gamma^2 = \mathrm{At}gk - \sigma k^3/(\rho_h + \rho_l)$. This means that even small surface tension significantly ties together parts of the surface η. Therefore the expansion MAC valid near the bubble tip and based on transition to free fall outside the tip ceases to approximate flow.