SYNOPSIS

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The dynamics of bubble formation during boiling is highly significant considering its influence on the heat transfer rate associated with various applications. Depending on the heat flux, the mode of boiling transforms from the nucleate boiling regime to the film boiling regime. The present thesis is focused on the study of the varying characteristics of boiling regimes through direct numerical simulations. The liquid-vapor interface-capturing is performed using the CLSVOF (Coupled Level-Set and Volume of Fluid) approach. In the film boiling regime, the phenomenon of bubble formation is governed by the instabilities at the liquid-vapor interface instigated by the combined influence of surface tension, buoyancy, heat flux, vapor thrust or any other applied external field (electric field in the present study). The dynamical disturbances destabilize the interface which results in bubble formation with the passage of time. The bubble release during film boiling is found to be more of a deterministic phenomenon with the separation distance between any two adjacent bubbles being manifested as a function of the most dominant wavelength of disturbance at the interface. Further, the diameter of bubble after departure from the interface is a function of the critical wavelength, which depends on the surface tension and density-ratio between the liquid and the vapor phases. The distance of separation between any two adjacent bubbles is governed by the instability mode at the liquid-vapor interface. The interface growth is found to be governed by the Rayleigh-Taylor mode of instability at low superheat values and when the superheat is higher it is found to be governed by the Taylor-Helmholtz instability-mode. The bubble morphology is also observed to be highly dependent on the degree of superheat — discrete bubbles are seen at the lower range of superheat values while continuous vapor columns are evinced in case of high superheat values. This in turn affects the heat transfer rate significantly. Bubble growth and departure from the interface follows a regular periodic pattern (both in space and time). As the superheat increases, the time period of bubble-release decreases.

Electric field force results in destabilizing the interface and enhancing the bubble growth rate. Through the applied numerical model of electric force, it was found that the application of electric field normal to the heating surface results in increase of both spatial and temporal frequencies of bubble-formation along the heated surface. The dominant wavelength of disturbance decreases, which in its turn decreases the separation-distance between adjacent bubbles. At a high intensity of electric field, the periodicity of bubble-release diminishes leading to a vigorous and random generation of bubbles. The increased rate of vapor release is accompanied by an increase in vapor-generation and enhanced heat-transfer-rate. The bubble morphology and heat transfer rate is significantly affected only above a minimum threshold-intensity of the applied electric field.

As buoyancy is one of the dominant factors influencing the growth-dynamics of bubbles during boiling, change in the gravity-level results in an apprehensive variation in boiling characteristics. Analyses have been performed at different levels of gravity to determine the changes in bubble morphology and heat-transfer rate. The bubble release-rate decreases as a result of decrease in gravity-level, which goes on to reduce the heat-transfer rate. The application of electric field compensates for this reduction in the heat-transfer rate and recovers the same rate of heat-transfer as in normal gravity. The dominance of electric field force also increases in case of reduced gravity conditions. Both the length and time scales increase appreciably as a result of reduction in the level of gravity. Variation in geometrical parameters like maximum height and radius of bubble has been analyzed with change in the gravity-level. Bulging of the interface leading to bubble formation and departure is a singularity- phenomenon. During the initial stage of bubble growth, the interfaces exhibit self-similar profiles i.e. the bubble-interface at different instants of time can be converged on a single profile defined by a fitting-function, in which, the variables are normalized using proper scaling-parameters.

Unlike in the film boiling regime, the bubble generation and growth in nucleate boiling is rather intricate. In nucleate boiling, the bubble generation is not instability-dependent but a random process which depends on the heat flux from the surface and the surface-properties. The nucleation starts at cavities as a result of existence of pre-occupied gaseous or vapor phase or due to extreme heat-flux. The rate of bubble growth occurs due to vapor generation at the interface as a result of heat transfer from the superheated-liquid and also due to the microlayer-evaporation. The liquid-microlayer beneath the bubble evaporates completely during the growth of bubble and the region gets dried-out. The dry-out region again gets rewetted when the contact line retracts leading to departure of the bubble from the solid-surface. In the present study, numerical simulations have been performed by incorporating a microlayer-model to account for the contribution of microlayer-evaporation in the growth of a single bubble. The growth rate is found to be affected by the surface-superheat, the wettability of the surface and the degree of subcooling of the ambient liquid. The liquid-subcooling results in condensation of the vapor at the top of the bubble, resulting in the reduction in the growth-rate of the bubble. For a higher degree of subcooling, the bubble does not even depart from the surface. The balance between the evaporation rate and the condensation rate prohibits the buoyancy to dominate and make the bubble depart from the surface; thus, the bubble keeps oscillating at its position. Behavior of the bubble after departure from the surface has also been analyzed at different levels of liquid-subcooling. Extreme reduction in bubble diameter is observed when subcooling of the liquid is increased. The reduction in bubble-size leads to a continuous variation in bubble-rise-velocity in subcooled liquid.

The mode of bubble generation - whether it is from nucleate boiling or film boiling - depends on the intensity of heat flux from the surface. Film boiling occurs at a much higher value of surface-superheat than the nucleate boiling. In between these two above-mentioned regimes, there is a transition regime which exhibits the characteristics of film boiling as well as nucleate boiling. This regime is marked by the existence of both — vapor layer and liquid-solid contact at certain regions of the heated surface. At a superheat higher than the minimum film boiling temperature, the boiling mode transforms to film boiling. The transition regime is highly affected by the wettability of the heated substrate. Simulations have been performed at various values of wettability of the surface to analyze the phenomenon of transition from the film to the nucleate regime of boiling. At high wettability, i.e. at lower contact angle, there is a higher affinity of the surface for the liquid. It has been observed that for surfaces with high wettability, the transition to nucleate boiling from film boiling occurs due to the frequent liquid to solid contacts. For the same value of superheat, such transition is not observed for surfaces with low-wettability. However, when an electric force is applied across the vapor film, liquid-solid contact occurs in low-wettability surfaces too, leading to transition.