ABSTRACT

Boiling has been an extensive and sustained area of research owing to its wide range of applications. Since most of the applications result from the high heat transfer rates achieved, a substantial volume of work has been dedicated to the study of nucleate boiling and determination of the critical heat flux, both from an engineering and fundamental perspective. Nevertheless, a significant number of studies also focus on post-dryout phenomena including film boiling. The study of film boiling is essential as a limiting case for heat transfer rates observed during boiling as also due to applications such as superconducting devices, cryogenics, metal quenching, and nuclear reactor accident analysis. Although the empirical studies continuing from several decades have matured our understanding of the phenomena significantly, the challenges associated with measurements at small spatiotemporal scales involved are notable. Additionally, a number of analytical studies have been carried out, which involve simplifying assumptions pertaining to various hydrodynamic and heat transfer aspects depending on the boiling configuration, conditions, and heater geometry, but have helped us to identify important dimensionless parameters and determine numerous useful semi-empirical correlations. Direct numerical simulations of two-phase flows with phase change alleviate such issues while providing additional insights that may be otherwise difficult to obtain.

Coupled level set and volume of fluid (CLSVOF) method has evolved as an important approach for modelling interfacial flows, combining the advantages of implicit mass conservation and accurate curvature estimation. However, most of the previous studies involving direct numerical simulations of boiling flows have focused on structured grids, thereby limiting their scope to flat heater geometries. At the same time, a fundamental understanding of film boiling over different heater surfaces is necessary owing to various applications where it is invariably observed. Consequently as one of the primary aims of the present study, a CLSVOF method is developed for two-dimensional unstructured grids to

perform direct numerical simulations of two-phase flows including phase change. This has not been the subject of any prior study and would allow to get insights into several important film boiling problems of practical interest. The volume fraction is advected using a multi-directional advection algorithm, where the flux polygons are constructed using vertex velocities and a scaling factor based on cell face velocities is used to correct the advected volume fraction. The level set field is advected using a total variational diminishing (TVD) scheme and geometrically reinitialized at the end of each time step. The developed computational framework has been validated qualitatively as well as quantitatively in detail with regard to accuracy of interface advection and reconstruction, surface tension, and phase change calculations, for both structured and unstructured grids.

Subsequently, the numerical solver is employed to investigate several important film boiling problems that are relevant from a fundamental as well as an application perspective, and involve different heater geometries and operating conditions. First, liquid-vapour interface evolution, heat transfer, vapour wake dynamics, and its interaction with the liquid wake are studied for saturated film boiling over a horizontal cylinder in an upward flow of saturated liquid. The problem is predominantly studied in the mixed regime that is characterized by a combined influence of buoyancy and flow inertia at low magnitudes of the Froude number (Fr). The onset of the mixed regime is observed at quite a low magnitude of Fr while the quasi-steady nature of ebullition cycle is gradually lost as Fr increases. The effect of several other hydrodynamic, geometrical, thermal and system parameters is discussed, and the observations pertaining to interface dynamics and heat transfer reveal an interplay of these parameters. The mutual interaction of the liquid and vapour wakes is then presented. Eventually, a comprehensive correlation for the Nusselt number in the mixed regime of flow film boiling is obtained. The effect of cross-flow orientation is shown to be non-trivial in the mixed regime by further considering orthogonal gravity and flow fields. An anomalous impairment of heat transfer with an increase in cross-flow velocity is identified with horizontal cross-flow under certain conditions, and is discussed in detail. A reduction factor (ξ) is conceived and determined as a function of Fr, which is used in conjunction with the correlation for upward cross-flow to quantify the heat transfer with horizontal liquid cross-flow. Saturated film boiling over an elliptical cylinder is then studied in the mixed regime under aiding and orthogonal liquid flow configurations. The role of the geometrical features such as aspect ratio and angle of incidence is ascertained in detail, and the results show some interesting aspects pertaining to the external flow film boiling behaviour. The heater aspect ratio affects the rate of vapour infusion into the wake. A peculiar heat transfer behaviour is observed with regard to cross-flow velocity as well as direction, and its cause is traced to a competing influence of buoyancy and inertia as an artifact of heater and cross-flow configurations. A shape factor (ψ) is proposed to comprehensively predict the heat transfer in conjunction with correlations for a circular heater.

Horizontal film boiling in the context of saturated natural convection film boiling over a wavy heater wall is investigated to determine the liquid-vapour interface evolution together with instability characteristics and heat transfer. The individual peaks of the wavy surface are shown to affect interface evolution only for heater wavelengths larger than the critical Rayleigh–Taylor wavelength, thereby revealing a link between geometrical and hydrodynamic aspects. Additionally, the wavy heater topology is observed to avert a hydrodynamic transition under certain cases that is characteristically observed at elevated wall superheats. Finally, steady film boiling from downward facing surfaces is studied in this work. The effect of heated surface geometry on heat transfer is analyzed, and the results indicate an enhancement of the overall heat transfer coefficient with surface curvature.