Abstract

Boiling is a highly efficient process of thermal energy transfer widely found across various engineering and industrial applications such as nuclear power reactors, water distillation, cryogenic fuel storage, steam power plant, refrigeration and air conditioning and thermal management of electronic devices. It uses latent heat of vaporization to transfer significantly large quantity of heat at a very low temperature difference. Consequently, it offers remarkably high heat transfer coefficients (HTC), making it a preferred mechanism for higher heat dissipation applications. However, the maximum heat flux in boiling is limited by the critical heat flux (CHF). After reaching the CHF, a vapor layer tends to develop over the heated surface, thereby HTC decreases significantly. Enhancement in boiling performance directly contributes energy efficiency, environmental sustainability and water resource utilization. Moreover, the ever-growing demand for compact, lightweight, and high-performance electronic devices calls for advanced thermal management solutions capable of handling higher heat dissipation rates to ensure reliable and efficient operation. Therefore, simple and inexpensive methods are required to further enhance both HTC and CHF to simultaneously increase the efficiency and operational range of systems. Various active and passive methods have been explored to improve boiling heat transfer. The current research work mainly focusses on the development of scalable, cost-effective and easy to implement enhancement technique for the pool boiling.

In this work, two new microchannel configurations, i.e., asymmetric dual V-groove microchannels (VM) and orthogonally intersecting asymmetric dual V-groove microchannels (OIVM) have been introduced to study enhancement in pool boiling. The heat transfer enhancement due to the modified surfaces is established by comparing the heat transfer rates from a reference plain surface. Moreover, to investigate the effect of reentrant channel geometry on heat transfer, two novel structured surfaces, namely trapezoidal reentrant microchannel (TRM) and segmented trapezoidal reentrant microchannel (STRM) are developed and boiling characteristics are experimentally investigated. A scalable porous copper coating is also developed to enhance heat transfer in pool boiling. The effect of surface characteristic parameters on the heat transfer performance is investigated. The submerged wall jet flow over a top-facing horizontal surface has also been investigated on the plain and the coated surfaces to improve the pool boiling heat transfer.

In these studies, experiments have been performed using deionized water under saturation temperature at one atmosphere pressure. The bubble dynamics and interface morphology at various heat flux levels have been captured using high-speed camera and discussed in detail. Finally, to explore the combined effect of surface structure and surface additive on the pool boiling performance, investigation has been carried out on the VM and OIVM surface using Triton X-100 surfactant solution.

It was observed that microchannels on the heated surface improve the heat transfer in pool boiling. The OIVM surface provides an increase of 5.3 times in the maximum HTC and 2.4 times in the CHF compared to the reference plain surface. Similarly, the VM surface provides an improvement of 2.2 times in HTC and 1.7 times in CHF compared to the plain surface. The increased heat transfer rate with the OIVM and VM surfaces can be ascribed to large area for heat exchange, increased bubble initiation sites, bubble motion promoted macroconvection and efficient rewetting mechanism. The TRM surfaces exhibit an enhancement factor of 2.08 to 2.91 times in the CHF and 2.33 to 3.96 times in the HTC compared to the plain surface. The top-performing STRM surface shows the CHF of 4555.2 kW/m^2 which is 290% higher than the plain surface CHF. This surface demonstrates a maximum HTC of 842.5 kW/m^2K. The better heat transfer performance with the STRM surface compared to the TRM surface demonstrates that separated vapour release and liquid supply pathways, and better rewetting are the main reason for delayed CHF and higher HTC.

The coated surfaces provide better heat transfer performance than that of uncoated surface. The best-performing coated surface exhibits a HTC of 290.3 kW/m^2K and a CHF of 2700.3 kW/m^2, representing enhancements of 5.1 times in HTC and 2.3 times in CHF than the uncoated surface. The coated surface initiate boiling earlier and maintains lower surface superheats across the entire range of heat flux compared to the uncoated surfaces. The larger number of active nucleation sites on coated surfaces contributes to improving the heat transfer rate. The coated surface also exhibits capillary wicking properties. The enhancement ratio of CHF on coated surfaces demonstrates a linear relationship with the nondimensional wicking number (Wi). In the wall jet flow boiling study, it is observed that the wall jet flow effectively enhances the boiling performance in the low heat flux nucleate boiling regimes for both coated and plain surfaces. At higher heat fluxes, the heat transfer results for different jet velocities coincide and they overlap the pool boiling results. Hence, nucleate boiling predominantly governs the heat transfer in this regime, with minimal effect of wall jet flow. However, the wall jet flow significantly delays the CHF limit, which shows a linear relationship with jet velocity.

The VM and OIVM structured surfaces exhibit better heat transfer performance compared to the plain surface with the use of the surfactant solution as the working fluid. The OIVM surface provides enhancement of 334.2% in HTC and 110.9% in CHF. The VM surface demonstrates a 101.8% increase in the HTC and a 41.8% improvement in the CHF. The plain, VM, and OIVM surfaces demonstrated improvement in HTC when tested with the surfactant solution, as compared to their performance with pure deionized water, across all levels of heat flux. However, despite this enhancement in HTC, the use of the surfactant solution results in a reduction in enhancement of CHF relative to the corresponding values observed with deionized water. This decline in CHF is primarily due to vapor bubble crowding near the heated surface at higher heat flux conditions, which obstructs effective liquid rewetting and leads to early surface dryout. The pool boiling enhancement methods proposed in the present research work are simple, cost-effective, mechanically robust and easily scalable. Therefore, they can be employed for efficient heat transfer in a wide range of industrial applications.