ABSTRACT

Keywords: Thermal management, Flow boiling, Slug flow, Pressure drop, Heat transfer coefficient, Microchannel heat sink, Nucleation frequency, Compressible buffer volume, 3D IC, Micro pin-fin heat sink, Embedded chip cooling.

The emerging trend of large-scale integrations and compact form factors for electronic systems has led to a quantum shift in heat dissipation rate. This increased thermal load has put a severe restriction on the cooling capacity of conventional techniques like natural convection, forced air-cooling and even forced single-phase liquid cooling and compelled scientists and engineers worldwide to focus on developing futuristic cooling strategies with enhanced heat transfer rates. In this context, flow boiling in microscale heat sinks has a promising potential to dissipate high heat fluxes from devices like electronic chips, IGBTs, batteries and fuel cells, radar systems, high-power LEDs, laser systems, high performance photovoltaics, advanced RF systems and spacecrafts. The present dissertation focuses on the investigations of flow boiling phenomenon in microchannels and micro pin-fin based heat sinks using mechanistic modeling, experiment and computational simulation.

At first, a transient 1D flow-boiling model based on slug flow regime has been developed to describe the pressure drop and heat transfer mechanism in a microchannel of rectangular cross-section. The model was capable of simulating all transport processes for a single bubble from its inception till it leaves the microchannel. The effects of variation in channel dimension, flow velocity, heat flux and properties of working fluid on pressure drop and heat transfer coefficient have been studied using this model. Later, the model was further extended to assess the pressure drop and heat transfer characteristics in a rectangular microchannel, emphasizing the impacts of nucleation frequency and compressible buffer volume. In addition, the combined influence of nucleation frequency with channel height, inlet velocity and heat flux was also assessed. The flow reversal in the channel in presence of buffer volume has been mapped and a sensitivity analysis was performed to check how the operating parameters affect the flow reversal.

Apart from mechanistic modeling, an experimental investigation has been performed to study the heat transfer characteristics of acetone and methanol flow boiling in a heat

sink with multiple parallel microchannels. A parametric analysis was carried out to analyze the behavior of pressure drop and heat transfer coefficient over a range of mass and heat fluxes. Based on observed trends for heat transfer coefficient and corresponding flow patterns, distinct boiling zones and heat transfer mechanisms were suggested. The experimental heat transfer coefficient results from this study have been compared with sixteen existing empirical correlations and the accuracy was measured using mean absolute error and standard deviation. After a thorough evaluation of the prediction capabilities of existing correlations, a new correlation for the heat transfer coefficient was proposed based on present experimental data.

Finally, several computational simulations have been carried out using ANSYS Fluent to investigate the impact of the design of a micro pin-fin (MPF) array on thermo-hydraulics of a MPF embedded silicon heat sink in the presence of a hotspot. Initially, the model was employed for single-phase liquid cooling and thermohydraulic performance comparison was made for heat sinks based on homogeneous and heterogeneous MPF arrays. In addition, after achieving superior performance for heterogeneous MPF array, pin-fins with different cross-sections, i.e. circular, elliptical, and hexagonal, were considered for heat sink performance comparison. The key parameters controlling the thermal and hydraulic performance of the MPF embedded silicon heat sinks have been discussed in detail. Later, the model was reconfigured for two-phase liquid cooling. Circular, hexagonal and elliptical pin-fins were considered to compare the two-phase bubble dynamics, which inherently control the thermo-hydraulic performance of MPF heat sink designs.