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Fundamental Issues Related to Flow Boiling and Two-Phase Flow Patterns in Microchannels - Experimental Challenges and Opportunities

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In recent years, flow boiling in microchannels has received considerable attention due to its capability for thermal management of microelectronic equipment, high power devices and development of compact evaporators for a wide range of applications. The present paper focuses at understanding the mechanisms of boiling heat transfer in rectangular microchannels in an attempt to identify methods to improve the heat transfer performance and develop of physically based models of heat transfer.

To further explore the scale effects on flow boiling in microchannels and minichannels, a scaling analysis presented in this paper to identify the effect of various forces. Using data of dual-beam laser scanning and laser-induced fluorescence, the characteristics of few basic flow patterns are discussed for rectangular microchannel. It was found that the transition flow and annular flow should be characterized by statistical parameters. New approach for determination of the flow pattern, based on measuring the lifetime of liquid plugs and interfacial waves on liquid interface was proposed and discussed. Using this approach, the equivalent film thickness model was formulated and verified experimentally for prediction of transition to annular flow in microchannels.

Annular flow model is of fundamental importance to the prediction of convective boiling in two-phase microchannel heat sink. The proposed annular flow model is designed for microchannels with rectangular cross-section that is typical for microchannel heat sink and considers the peculiarities of heat transfer after breaking of the evaporating liquid film. It formulates the condition for curved film rupture near the channel corner and rivulet formation. In vicinity of contact line the surface tension and evaporation rate determine the interface shape and heat transfer enhancement.

The purpose of the present paper is to discuss the mechanism of flow boiling heat transfer, drawing on the earlier published work and the data for refrigerants R-134a, R-21, R-141b and water flow boiling in single rectangular microchannel and microchannel heat sink. Experiments were performed using a closed loop that re-circulates refrigerant or water. The copper plate of microchannel heat sink with rectangular microchannels was made by precise milling. It contains 21 microchannels with 335x930 μm cross-section at total plate thickness of 2.5 mm. The microchannel plate and heating block were mounting in the stainless steel container which has the partition wall for the local heat flux measurements. Distribution of local heat transfer coefficients along the length and width of the microchannel plate were measured in the range of external heat fluxes from 50 to 500 kW/m^2; the mass flux was varied within 70-700 kg/m^2 s, and static pressure was varied within 1.2-16 bar.

The primary objective of this study is to establish experimentally how the heat transfer coefficient and pressure drop correlate with heat flux, reduced pressure, mass flux, vapor quality and surface roughness. For refrigerant R-134a flow boiling at reduced pressure nearly 0.2, the obvious impact of heat flux on the magnitude of heat transfer coefficient was observed. It typically occurs, when nucleate boiling is the dominant mechanism of heat transfer. Another important mechanism of flow boiling heat transfer is suppression of nucleate boiling at high vapor quality. For refrigerant R-21 and R-141b at the range of reduced pressures from 0.06 to 0.11, the obvious impact of the evaporation of liquid film becomes essential at low heat flux. Nevertheless, the nucleate boiling is still dominant mechanism of heat transfer at high heat flux and high mass flux.

A proposed model of the flow boiling considers nucleate boiling suppression and liquid film evaporation in microchannels. This model predicts the reduction of heat transfer coefficients at high vapor quality, if nucleate boiling suppression is predominant. If the interface shear stress is sufficiently high to produce extremely thin liquid film, the model predicts enhancement of the heat transfer. The results of the calculation according to proposed model are compared with available experimental data and published models of flow boiling heat transfer.

Differ significantly from the above cases is the flow boiling of water at reduced pressure less 0.01, when noticeable impact of heat flux and vapor quality on the magnitude of heat transfer coefficient was not observed. Special model was designed and verified experimentally for this case, when the evaporation enhancement near the contact line becomes dominant mechanism of flow boiling heat transfer.

The data obtained define the conditions under which heat transfer enhancement is determined by increasing the heat transfer surface. However, this is associated with a severe pressure drop penalty which can be carefully weighed using Lockhart-Martinelly model and proposed annular flow model.

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