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Flow instability and transient flow patterns inside intercrossed silicon microchannel array in a micro-timescale

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Abstract

The objective of this study is to visualize the transient flow patterns and heat transfer behaviors at low mass fluxes and high heat fluxes. The silicon chip consists of the intercrossed microchannel array with 10 triangular microchannels with the hydraulic diameter of 155.4 μm, and five transverse trapezoid microchannels, separating the triangular microchannels into six independent zones. The chip is horizontally positioned. Liquid acetone is used as the working fluid. Tests were performed in the range of mass flux 40–80 kg/m^2 s and heat flux 107–216 kW/m^2.

It is found that all the microchannels repeat the flow patterns in the timescale of milliseconds, with three substages: liquid refilling stage, transient stratified flow stage and partial/fully dry-out stage.

Stratified flow is the dominant flow due to the low liquid Froude numbers. The axial liquid film thickness for each separated microchannel zone is increased along the flow direction, caused by the large momentum force due to evaporation on the interface of the vapor and the settled liquid film, and the high vapor shear stress applied on the vapor/liquid interface. The non-uniform axial liquid film distributions cause the earlier dry-out of the triangular microchannel upstream. However, dry-out always takes place earlier in the downstream zone than that in the upstream zone. The vapor slug near the triangular microchannel exit may be entrained in the long liquid plug during the liquid refilling stage. Besides, the steep jumped liquid film thickness may take place near the channel exit for the stratified flow. Both indicate the strong geometry effects.

Due to the compact size and high thermal conductivity of the silicon chip, the chip surface temperature variations versus time are identified by the infrared radiator image system, especially in the ending area of the thin film heater.

Keywords: Microchannel; Flow patterns; Flow instability; Micro-timescale; Stratified flow; Liquid film

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1. Introduction

An important topic in the two-phase flow and heat transfer field is the flow instabilities, which have been studied widely in the past several decades in macroscale. They can take place in nuclear reactors, boilers, heat exchangers, etc, leading to the mechanical vibration, the disturbance of the electronic control device, the local overheating of the heat transfer surface and the high thermal stress of the solid walls (Ding et al., 1995).

The two-phase flow instabilities consist of the static and dynamic flow ones. The static flow instabilities can be caused by the flow rate excursion, the transition from one flow pattern to another one, and the transition of the heat transfer mechanisms. The commonly encountered dynamic flow instabilities are the pressure drop type oscillations, the density wave oscillations, and the thermal oscillations. The thermal oscillations are not independent ones, but sometimes occur accompanying with other type of flow instabilities. Almost all of the dynamic flow instabilities take place with large oscillation amplitudes and long cycle periods. The cycle periods are in the order of seconds and even minutes. These flow instabilities are well studied in macroscale, due to their wide applications in industries.

There are increasing numbers of articles dealing with the single/two-phase flow and heat transfer in microchannels. This is due to the high demand for the understanding and application of the micro devices or systems for high heat flux electronic cooling, bio-MEMS chip, micro thrusters, etc. However, little studies were performed for the two-phase flow instabilities in microchannels. Wu and Cheng (2003a) reported the experimental studies with water as the working fluid flowing in horizontal silicon microchannels. Various modes of boiling instabilities occur after the boiling incipience. An unsteady liquid/two-phase/vapor alternative flow (LTVAF) takes place in the microchannels. Wu and Cheng (2003b) used two sets of parallel microchannels with the hydraulic diameters of 155.8 μm and 82.8 μm. It is found that the fluid pressures, wall temperatures and flow rates are oscillating with large amplitudes and long periods. With the aid of a microscope and a high speed camera, the flow patterns were observed such as bubbly flow, slug flow, churn flow and other peculiar flow patterns. They stated that such kind of flow instabilities occurring in microchannels can be self-sustained if the pressure drops and the mass flow rates have phase differences. Wu and Cheng (2004) reported the further studies on the two-phase flow instabilities with the hydraulic diameter of 186 μm and the length of 30.0 mm. Three types of flow instabilities appear: the liquid/two-phase alternative flow at low heat fluxes and high mass fluxes, the continuous two-phase flow at medium heat fluxes and mass fluxes, the liquid/two-phase/vapor alternative flow at high heat fluxes and low mass fluxes. Again some flow patterns were observed.

Peles et al. (2001) concerns the forced convective liquid flow in heated microchannels, dividing the whole flow length into the liquid part and the vapor part. A number of dimensionless parameters, such as the Peclet number (*Pe*), Jacob number (*Ja*) and dimensionless heat fluxes, are defined. Both of the numerical and experimental findings show that boiling two-phase flow in capillary channels is unstable for the outlet mean vapor mass qualities less than unity. In a recent study by Hetsroni et al. (2005), it is found that long vapor bubbles occurring in microchannels at low liquid Reynolds number, which is not similar to the classical annular flow. This phenomenon is considered as the explosive boiling with periodic wetting and dry-out. The pressure drops are found to be oscillating which is enhanced with increasing the vapor mass qualities.

Xu et al. (2004) conducted an experiment in a single capillary stainless tube with the inside diameter of 500 μm. Two types of flow instabilities were identified. The first type is the long period/large amplitude liquid/two-phase alternative flow, occurring at the inlet liquid temperature of nearly saturated condition. It regards the feedback control of the mass flow rate in the capillary tube and the entrance liquid temperature of the microtube, incorporating the system geometry, dimensions and the microchannel itself. The second type of unsteady flow occurs when the liquid temperature in the water tank varying from room to 80 °C, and it is named as the long period/small amplitude periodic subcooled boiling. Xu et al. (2005a) conducted the static and dynamic flow instability of a parallel copper microchannel heat sink at high heat fluxes using water as the working fluid. The onset of flow instability (OFI) occurs at the channel outlet temperature of 93–96 °C, which is several degrees lower than the saturated temperature of 100 °C corresponding to the exit pressure. If the mass flow rate is less than that of OFI, three types of flow instabilities appear: the large amplitude/long period oscillation, the small amplitude/short period oscillation. The thermal oscillations are observed to be accompanying the above two oscillations.