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Experimental and numerical investigations of local condensation heat transfer in a single square microchannel under variable heat flux☆

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ABSTRACT

This paper presents an experimental investigation on the local and average condensation heat transfer in a single noncircular microchannel. Furthermore, it develops one dimensional model for annular condensation flow in a microchannel under variable heat flux condition. The condensate film thickness is calculated for each location in a microchannel including the effects of capillary number, Boiling number, contact angle, heat flux, vapor pressure, and hydraulic diameter. A comparative study shows that the present model well predicts the experimental data concerning local condensation heat transfer coefficient. The mean deviation between the local predictions of the theoretical model with the measurements for local heat transfer coefficient is 20%. It is found that the correlation of Quan et al. (2008) [19] gives the good predictions of the measurements with maximum deviation of 13% at high Reynolds number.

1. Introduction

In recent reviews of the literature, various fundamental researches on two-phase heat transfer and pressure drop characteristics in microchannels have been conducted. Numerous studies have focused on evaporation or boiling inside microchannels since they are basic processes used in microcooling systems at high heat fluxes. However, efficiency of two-phase loop heat pipe used for cooling is mainly influenced by thermal performance of both condenser and evaporator. Analysis of condensation heat transfer in micro/minichannels is very important in development of next generation of ultra-compact and high performance two-phase flow cooling loops. Recent experimental and theoretical results indicate that the physical mechanisms of condensation in microchannels are quite different from those that occurred in conventional scale channels. Gravity and buoyancy are the typically forces governing condensate flow in macrochannels. Reduction of the channel size from macroscale to the microscale channel induces surface tension and shear stress as the dominating forces in microchannels as explained by El Mghari et al. [1].

Condensation in macrochannels involves many engineering applications and it has been widely studied and understood. Recently, systems miniaturization brings new challenges and opportunities particulary, in the flows with phase change applications. Additionally, small channels size can resist to high system pressure allowing the use of high pressure fluids as carbon dioxide in transcritical cycle equipment. However, correlations of condensation heat transfer and pressure drop in macrochannels cannot be directly applied in the microsystems field. Various studies on condensation in microchannels are focussed on two-phase flow patterns. Louahlia-Gualous and Mécheri [2] studied experimentally steam condensation flow patterns in a single capillary glass tube. By varying the inlet pressure and cooling rate, annular flow, stratified flow, bubble flow and elongated spherical bubbles were observed. El Mghari et al. [3] studied nanofluid condensation heat transfer inside a single horizontal smooth square microchannel. The numerical results are compared to previous experimental predictions, and show that the heat transfer coefficient can be improved 20% by increasing the volume fraction of Cu nanoparticles by 5% or increasing the mass flux from 80 to 110 kg/m^2 s. Wu et al. [4] investigated condensation flow in wide rectangular silicon microchannels with the hydraulic diameter of 90.6 μm and width/depth ratio of 9.668. Droplet-annular compound flow, injection flow, and vapor slug-bubbly flow are observed along the microchannel. Chen et al. [5] studied condensation flow patterns in the silicon triangular microchannels. They proposed correlations of bubbles injection location in the microchannel, bubbles frequency and condensation Nusselt number. Chen and Cheng [6] carried out flow visualization for steam condensation in trapezoidal microchannels with 75 μm hydraulic diameter, cooled by natural air convection at room temperature. Odaymet et al. [7] analyzed relationship between condensation heat transfer and various flow patterns in a single silicon microchannel. They measured local heat transfer through microinstrumentation of the microchannel. Louahlia-Gualous and Odaymet [8] showed that bubbles velocity is variable along the microchannel length and coalescence phenomenon increases flow velocity and reduces bubbles frequency.

Concerning condensation heat transfer, Garimella et al. [9] investigated effect of various multimicrochannels shapes and sizes on

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Nomenclature

A	area (m^2)
a	width of rectangular microchannels (m)
b	depth of rectangular microchannels (m)
C	coefficient
C_p	specific heat (J/kg °C)
D_h	hydraulic diameter (m), $\equiv 4A/\mathcal{P}$
f	friction factor
h	heat transfer coefficient ($W/m^2{}^\circ C$)
hfg	latent heat ($J\ kg^{-1}$)
L	annular condensation length (m)
l	length of the end part in condensation(m)
$\dot{m}$	mass flux ($kg\ s^{-1}$)
Nu	Nusselt number, $\equiv hD_h/\lambda$
P	pressure (Pa)
$\mathcal{P}$	perimeter (m)
Pr	Prandtl number, $\equiv \mu C_p/\lambda$
q	heat flux ($W\ m^{-2}$)
R	curvature radius (m)
Re	Reynolds number
T	temperature, (°C)
U	velocity ($m\ s^{-1}$)
X_{tt}	Martinelli parameter
z	axial coordinate (m)

Greek symbols

β	half of right angle (°)
δ	film thickness (m)
μ	viscosity ($kg\ m^{-1}s^{-1}$)
λ	thermal conductivity (W/m°C)
φ	angle (°)
θ	contact angle (°)
ρ	density ($kg\ m^{-3}$)
σ	surface tension coefficient ($N\ m^{-1}$)
τ	shear stress ($N\ m^{-2}$)

Subscripts

c	critical
g	gravity
in	inlet
l	liquid
lw	liquid–wall interface
lv	liquid–vapor interface
red	reduced
v	vapor
t	total

condensation heat transfer and pressure drop. They developed a pressure drop model predicting 90% of the measured data within 28%. Recently, Quan et al. [10] measured steam condensation heat transfer in two trapezoidal silicon microchannels under three sides cooling conditions. A semi-analytical method for annular condensation is developed basing on turbulent flow boundary layer theory of liquid film. Wang and Rose [11] developed a new model of film condensation in noncircular microchannels including effects of microchannel inclination and shape (square, triangle, inverted triangle, and circular). Louahlia-Gualous and Asbik [12] developed a numerical model for annular film condensation heat transfer of a binary mixture refrigerants inside a circular miniature tube. The two-dimensional governing equations are solved in the liquid and vapor phases including the interfacial conditions of heat and mass transfer. Chen et al. [13] investigated annular condensation in triangular microchannels. They analyzed the film curvature radius distribution along the microchannel and the total condensation length under various sizes of the microchannel.

From the above literature review, it is clear that there is no reliable model for predicting condensation heat transfer coefficients in a noncircular microchannel including variation of the local coolant heat flux. Also, a major part of the experimental studies on condensation in the microscale channel are conducted through multimicrochannels. In this paper, an experimental setup on condensation heat transfer inside a single silicon microchannel is investigated. An innovative technique to measure local condensation heat transfer coefficient in a silicon microchannel is proposed. This paper reports also the first numerical results of condensation in a noncircular microchannel under variable local heat flux.

2. Experimental setup

Experiments on steam condensation heat transfer in a single silicon microchannel are carried out in the test loop shown in Fig. 1a and described in references [7,8]. The working fluid pressure is controlled in a steam generator (1). The saturated vapor was directed to the preheater (3) in order to prevent condensation in tubes (5). A 2 μm filter (2) was used to eliminate any dust in the working fluid. The vapor mass flow rate at the microchannel entrance is adjusted through a regulating valve (4). Flow temperatures at the microchannel inlet and outlet are measured using 75 μm microthermocouples. Pressure is measured by strain gage type pressure transducer. The test section (Fig. 1b) is cooled by water with a controlled inlet temperature. The cooling system consists of the tank containing a thermostatic water (9), a pump (10) for driving the water to the test section inlet and a flow meter (12) with an uncertainty of 4%. Water leaving the test section, is cooled in the heat exchanger (13). The vapor flowing the test section was led into a condenser (6) where it was completely condensed. The collected liquid was weighed during a known period of time with an electronic balance of high precision. The inlet and the outlet temperatures of the cooled water were measured through the microthermocouples (K-type, 75 μm).

2.1. Description of the test section and experimental procedure

A 50 mm microchannel is etched in a silicon wafer having a thickness of 1000 μm (Fig. 1b). It is covered using a thin transparent Pyrex glass (500 μm thickness), anodically bonded to the silicon plate top surface. Pyrex glass allows condensate flow visualization in the microchannel. Seven chromel-alumel microthermocouples (50 μm diameter) are placed inside the rectangular microgrooves to measure wall temperature as shown in (Fig. 1b). They are located at 20 μm from the microchannel inner surface. Condensation process is studied using rectangular microchannel with hydraulic diameter of 305 μm (depth of 310 μm and width of 300 μm). Microthermocouples are placed at 1 mm from the channel inlet and being equally spaced with 8 mm up to the channel outlet.

Before starting the tests, the vapor generator is degassed and steam pressure is adjusted at the microchannel inlet. Vapor temperature and pressure at the microchannel entrance are measured and controlled in order to make tests at the saturated state. During all tests, the microchannel is illuminated by a cold light source using two optical fiber arms that does not affect the microchannel heat transfer. A high speed camera detecting up to 16,000 frames/second is used to record different flow structures in the microchannel.

2.2. Experimental data and uncertainties

Condensation local heat transfer coefficient is estimated at steady state by

$$h_z = \frac{q_{channel,z}}{T_{s,z} - T_{sat,z}} \tag{1}$$