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Direct estimation of local convective boiling heat transfer coefficient in mini-channel by using conjugated gradient method with adjoint equation☆

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ABSTRACT

The purpose of this paper was to present an inverse heat conduction method used for determining the local convective boiling heat transfer coefficient in mini-channel for pure water, copper nanofluid by using three different concentrations of nanoparticles: 5 mg/L, 10 mg/L and 50 mg/L. Conjugated gradient method with adjoint equation is used to solve the IHCP and estimate directly the space-variable convective heat transfer coefficient. Direct estimation local convective boiling heat transfer coefficient is a nonlinear inverse heat problem. The uncertainties in the estimated in heat transfer coefficient are calculated using bias and variance errors. This method is able to estimate local convective boiling heat transfer coefficient very well.

1. Introduction

Boiling is defined as the process of phase changing the state of a substance from liquid to gas by heating it past its boiling point. Different types of boiling can be defined according to the geometric situation and to the mechanism occurring. Regarding the geometry, it is possible to distinguish between pool boiling, where the heat is transferred to a stagnant fluid, and flow boiling, where the fluid has a velocity relative to the heating surface. The three different boiling heat transfer mechanisms are nucleate boiling, where heat is transferred by means of vapor bubbles nucleating, growing and finally detaching from the surface; convective boiling, where heat is conducted through the liquid and evaporates at the liquid–vapor interface without bubble formation; and film boiling, where the heat is transferred by conduction and radiation through a film of vapor that covers the heated surface and the liquid vaporizes at the vapor–liquid interface. Nucleate boiling and film boiling may occur in both pool boiling and flow boiling, while forced convective boiling occurs only in flow boiling. In addition, if the temperature of the liquid is below the saturation temperature, the process is called subcooled boiling, whereas if the liquid is maintained at the saturation temperature, the process is known as saturated boiling.

To achieve higher heat dissipation rates for micro-electronics and optical technologies, the fundamentals of two-phase heat transfer in micro-channels are being studied ever more extensively. Micro-channel heat sinks are devices that provide liquid or two-phase flow through parallel channels of diameter less than, say, 1 mm. Kandlikar [1] presented the flow boiling correlations to transition, laminar and deep laminar flows in micro-channels. Thome et al. [2] proposed a new heat transfer model for evaporation in the elongated bubble regime in micro-channels. The model describes the transient variation in local heat transfer coefficient during the sequential and cyclic passage of a liquid slug, an evaporating elongated bubble and a vapor slug. Zhang et al. [3] proposed a correlation for flow boiling heat transfer in mini-channels.

Nanofluids are the innovative idea for thermal engineering, although many questions remain unanswered and need researching. According to the previous studies [4–6], the thermal conductivity of nanofluid could be hundreds of times greater than those of base fluids. Extensive research has been conducted to understand the heat transfer coefficient and nanofluids properties for single and boiling flow. Convection heat transfer was studied for various nanofluids with various suspended nanoparticles: Al_2O_3 water [7], CuO water [8], Ag water [9], etc. Research has shown that degradation of pool boiling heat transfer was obtained with nanofluids compared to base fluids. Nanofluids show a great enhancement in critical heat flux particularly at very low nanoparticle volume fraction [10]. Major researches on boiling heat transfer characteristics of nanofluid are conducted on pool boiling heat transfer [11,12]. It is clear that reducing hydraulic diameter of channels in cooling systems offers appreciable advantages such as high heat transfer coefficient, high compactness and small working fluid quantity. Additionally, using nanofluids as a working fluid contributes also to enhance heat transfer obtained by reducing hydraulic diameter. Thus, several

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Nomenclature

d	conjugate direction used in Eq. (9)
D	bias error
h	heat transfer coefficient (W/m^{2}K)
K	thermal conductivity (W/m K)
E	plate length
L	plate thickness
M	time index
N	number of discrete measurements
Np	number of unknown parameters
Ns	number of sensors
q	heat flux vector (W/m^2)
q_w	heat flux subjected on top surface (W/m^2)
RMS	root mean square error
S	sum of squares (K^2)
T	vector of calculated temperatures
V	variance error
X	sensitivity coefficient matrix (K/W)
x, y	space coordinates
Y	measured temperature

Greek Symbols

α	thermal diffusivity (m^2/s)
σ	standard deviation of noise
ε	noise value
β	search step size used in Eq. (11)
δ	Dirac function
γ	conjugate coefficient used in Eq. (10)

classifications for transition from microscale to macroscale heat transfer have been proposed. For phase change heat transfer, Cheng et al. [13] have proposed a classification of micro-channels based on Bond number: (i) micro-channel (Bo < 0.05), (ii) mini-channel (0.05 < Bo < 3) and (iii) macro-channel (Bo > 3). Bond number takes into account the effects of temperature, pressure, and physical properties of working fluid. Boudouh et al. [14] shown that that the local heat flux, local vapor quality and local heat transfer coefficient increase with copper nanoparticle concentration. The surface temperature is high for deionized water, and it decreases with copper nanoparticle concentration. We used the inverse heat conduction method to obtain the steady and transient convective heat transfer coefficient. It is advantageous because it can be carried out with simple, low-cost instrumentation and subsequent numerical procedures. In this technique, temperatures measured at some proper interior locations are used to estimate a thermal boundary condition. The word "estimation" is used here, as temperature measurements always contain noise. The inverse heat conduction problem (IHCP) is mathematically "ill-posed" in the sense of Hadamard [15], and this causes the IHCP to be particularly sensitive to measurement errors. The IHCP can be classified according to factors such as (1) linearity, (2) time domain used (sequential vs. whole domain) and (3) dimensionality. Many investigators have developed various inverse schemes over the past 40 years. Tikhonov's [16] regularization technique and Beck's [17] function estimation method are among the most well-known approaches in inverse heat transfer. Another method that has been widely used is the conjugate gradient method (see, e.g., [18]), which belongs to the class of iterative regularization techniques. Masson et al. [19] applied the iterative regularization and function specification methods (FSMs) with a spatial regularization to estimate the two-dimensional heat transfer coefficient. Taler [20] compared two techniques—singular value decomposition (SVD) and Levenberg–Marquardt—used in determining the space variable heat transfer coefficient on a tube circumference. Good agreement was found between the results in a simulated experiment. The estimation of the surface heat flux or heat transfer coefficient of the quenchant from the measured temperature data during quenching is based on the inverse heat conduction (IHC) method. Babu and Prasanna Kumar [21] estimated the surface heat flux and temperature using the IHC method for different initial soaking temperatures during quenching and modeled the surface heat flux as a function of dimensionless parameters. The purpose of this study is to use the solution of a transient, sequential IHC scheme (conjugated gradient method) to estimate the distribution of the steady-state and transient convective boiling heat transfer of nanofluid in rectangular channel. The input data (simulated temperatures) for IHCP are generated using finite element method. The temperatures at discrete regular times are modified by adding Gaussian random errors.

2. Problem description

As the channel size becomes small, the Reynolds number also becomes low for mass flux 512 kg/m^{2}s.

Visual observation [14] revealed that three zones are identified. The first one at low x (40 mm < x < 85 mm), the two-phase flow was constituted by the isolated bubbles (Fig. 1a). The nucleate boiling dominates in this zone (63 mm < x < 107 mm), and the void fraction is low. After this zone, the wall temperature increases because the bubbles coalescence occurs and mass vapor occupies the maximum part of the channel section (Fig. 1a). The third zone (110 mm < x < 155 mm) is identified at the upstream flow where the void fraction is high and a partial dry out occurs nearly to the channel outlet (Fig. 1a). Therefore, the wall temperature attains its maximum value and saturation sate.

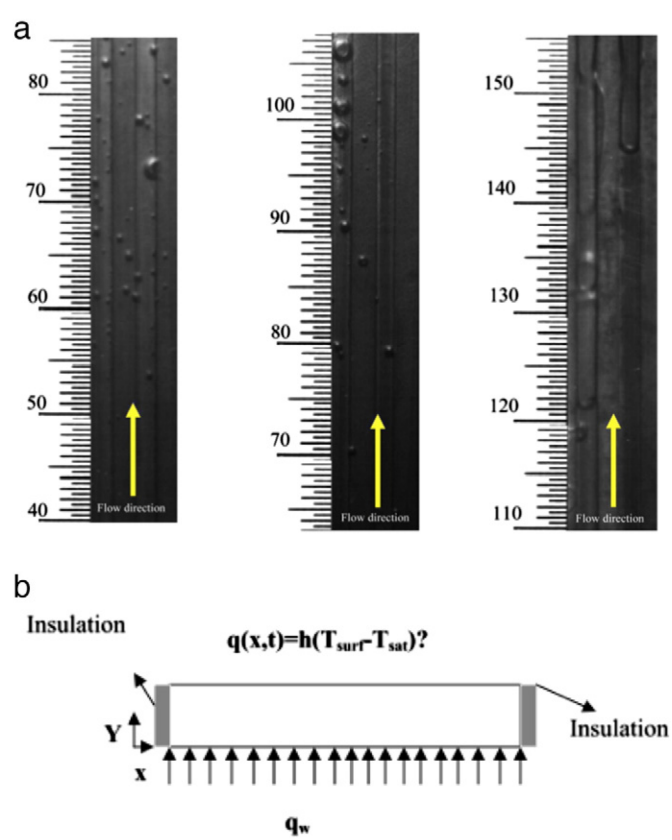

Fig. 1. (a) Boiling flow patterns along the channel length [14]. (b) Schematic of the experiment setup.