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The study of boiling heat transfer in vertically and horizontally oriented rectangular minichannels and the solution to the inverse heat transfer problem with the use of the Beck method and Trefftz functions

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ABSTRACT

The paper presents experimental studies of boiling heat transfer in a rectangular, asymmetrically heated minichannel which is 1.0 mm deep, 60 mm wide, and 360 mm long. It is oriented vertically with the bottom-up flow and horizontally at two different positions (180° difference). The investigations focus on the transition from single-phase forced convection to nucleate boiling, that is, from the zone of boiling incipience further to developed boiling. The experiment is carried out with FC-72 at a mass flow rate range of 165 kg/(m^2 s) and a pressure of 120–140 kPa at the inlet to the minichannel. Owing to the liquid crystal layer located on the heating surface contacting the glass, it is possible to measure the heating wall temperature distribution while increasing the heat flux transferred to the liquid flowing in the minichannel. The flow structure is observed simultaneously on the opposite side of the minichannel through another piece of glass. The first objective of the calculations is to evaluate a heat transfer model and numerical approach to solving the inverse boundary problem, and to calculate the heat transfer coefficient. The inverse problem is solved with the use of sensitivity coefficient method (Beck method) in combination with Trefftz functions. Calculations are supplemented with an error analysis focused on determining the errors including those of heating foil temperature measurements with liquid crystals thermography and of heat transfer coefficient for the transition from a single phase to boiling incipience. The second objective of the paper is to determine the void fraction for cross-sections of selected images for increasing heat fluxes supplied to the heating surface. These results are presented as void fraction dependence along the minichannel length for the selected cross-sections.

1. Introduction

Transferring large heat fluxes is one of the most significant issues of today's technology. An increasing number of high-tech heat exchange devices are based on heat transfer to fluid during flow boiling in minichannels of various geometry and spatial orientation. Owing to the change of state that accompanies boiling, it is possible at the same time to meet two contradictory demands: to obtain the largest possible heat flux at small temperature difference between the heating surface and the saturated liquid, and to keep small dimensions of heat transfer systems. Boiling incipience, a fundamental problem in boiling heat transfer, is also a practical problem in terms of ensuring that the used equipment remains safe and operational. It is known that under certain circumstances, the wall of the system can reach a temperature that exceeds the saturation temperature of liquid before boiling begins. Under certain conditions, the temperature level required to initiate boiling may be larger than the allowable maximum wall temperature of the system, which can result in the destruction of the object being cooled, as early as the single-phase regime. This "temperature overshoot" called "nucleation hysteresis", is conspicuous when highly wetting dielectric fluids are used. Thus the heat transfer coefficient, the accompanying incipience of nucleate boiling in minichannels, and its behaviour under certain conditions constitute some of the most important issues of heat transfer mechanism. The knowledge of boiling incipience guarantees safe operation of devices. The investigated heat transfer during flow boiling in minichannel can be applied to cooling, thermostabilization and thermoregulation of those devices which generate large heat fluxes, especially for heat exchangers and electronic devices equipped with microscale cooling systems.

Nucleation hysteresis for boiling on smooth surfaces was discovered by Corty [1] and van Camp [2]. Numerous results of experimental investigations and attempts of their theoretical explanation, both for pool boiling and flow boiling were presented in review paper by Bräuer and Mayinger [3] and Bar-Cohen [4]. Bräuer and Mayinger [3] presented two types of models for explaining the necessary surface superheating above saturation temperature for the onset of boiling:

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Nomenclature

A	cross section area, m^2
a, b, c	linear combination coefficient
G	mass flux, $kg/(m^2 s)$
H	error functional
I	current supplied to the heating foil, A
J	natural number
L	minichannel length, m
N	number of Trefftz functions used for approximation
P	number of measurement points
p_{inlet}	pressure at the inlet to the minichannel, N/m^2
q	heat flux density, W/m^2
q_V	volumetric heat flux, (capacity of internal heat source), W/m^3
T	temperature, K
u	velocity, m/s
V	volume, m^3
$v(x, y)$	Trefftz functions
W	width, m
x, y	spatial coordinates
Z_j	sensitivity coefficient

Greek

α	heat transfer coefficient, $W/(m^2 K)$
Δ	absolute error
ΔT_{sub}	inlet liquid subcooling $(T_{sat} - T_l)_{inlet}$, K
ΔU	the voltage drop across the foil, V
δ	depth, m
λ	thermal conductivity, W/(mK)
σ	relative error
φ	void fraction, %
ϕ	foil temperature for fixed heat flux, K
Θ	auxiliary temperature, K
Ω	flat domain

Subscripts

ch	minichannel
F	foil
G	glass
i, j, k	natural numbers
l	liquid
p	measurement point
sat	saturation
v	vapour

Superscripts

j	natural number
P	referenced to heat transfer measurement
Θ	referenced to auxiliary temperature
Z_j	referenced to sensitivity coefficient
$\sim$	referenced to function approximates

thermal (thermodynamic) and mechanic. Bilicki [5,6], Bohdal and Czapp [7], and Bohdal [8] conducted experimental investigations of zero boiling crisis (nucleation hysteresis) in refrigerant flow boiling. A thermodynamic analysis demonstrated that nucleation hysteresis is caused by latent heat transported by vapour bubbles forming in the liquid adjacent to the walls which act as heat sinks. Celata et al. [9] proposed describing hysteresis with a hysteresis coefficient dependent on the heating surface temperature drop and maximum superheat for the boiling incipience. Nucleation hysteresis which accompanied boiling incipience in the minichannels was observed in papers [10–20]. It occurred together with a considerable heating surface temperature drop, up to 70 K [18–20].

Following the classification by Kandlikar et al. it has been assumed that channels with hydraulic diameters between 200 μm and 3 mm are referred to as minichannels [21,22]. Much has been written on heat transfer experimental studies and analyses of flow boiling heat transfer in minichannels of various dimensions. For the purpose of this brief review of literature, the selected publications dealt with heat transfer and flow patterns in rectangular minichannels.

The results of investigations of heat transfer flow boiling conducted on test sections with rectangular, vertical, uniformly heated minichannels, which were single or arranged in systems, (the smallest characteristic dimension: 0.1–0.8 mm), at the flow of distilled water and/or methanol were presented in the studies of Peng and co-workers [23–26]. The authors studied the flow patterns and the effects of different parameters (channel geometry, liquid subcooling, flow velocity) on flow boiling in minichannels.

Orozco and Hanson, [27], investigated boiling in asymmetrically heated minichannels of various depths (1.59–25.4 mm), inclined at different angles. The researchers focused on the impact of selected parameters (different geometry of minichannels, spatial orientation, liquid temperature at the inlet, flow velocity) on R 113 flow boiling.

Hollingsworth et al. [11–13], dealt with heat transfer in R 11 flow through 1 mm deep vertical minichannel. Liquid crystal thermography was used to acquire the wall temperature data for forced convection in an asymmetrically heated channel. Discussed in [28] experiments were carried out in upward flow in rectangular channels with 2.0, 1.0, and 0.5 mm spacing and aspect ratios of 1:10, 1:20, and 1:40. The focus of the experiments was on the determination of the local heat transfer coefficient and the investigation of the effect of thermal and flow parameters on its values. In [13] it was proposed a parameter to denote the boiling incipience as dependent on the course of nucleation hysteresis. The parameter was described as “turning angle” and was defined as a scalar measure of the transition path to a fully developed boiling.

Ammerman and You [29] studied FC-87 flowing through an asymmetrically heated horizontal minichannel of different square cross-sections with sides of 2, 1 and 0.5 mm. They concentrated on heat transfer in boiling and forced convection.

Wambsganss et al. identified the flow patterns occurring in flow boiling in minichannels, both circular and rectangular [30–32]. In [32] boiling heat transfer experiments were performed in a small circular channel with diameter of 2.46 mm and a small rectangular channel with hydraulic diameter of 2.40 mm, with Refrigerant 12. The effects of channel geometry and fluid properties on heat transfer were studied, together with heat transfer mechanisms in small channels.

In [33], the authors investigated flow boiling heat transfer characteristics of water and hydrocarbons in mini- and microchannels. A circular channel with a hydraulic diameter of 1500 μm, and rectangular channels with height values of 300–700 μm and a width of 10 mm were used in the investigations. Infrared (IR) thermography was employed for determining wall temperatures. These allow the identification of different boiling regions, boiling mechanisms, and the determination of the local heat transfer coefficients.

The analysis of flow boiling heat transfer in a rectangular minichannel of 0.5–4 mm^2 cross-sections was discussed in [34]. The article described the two-phase flow pressure drop analysis conducted by ranging several mass flow rates for a chosen heat flux