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Trefftz function-based thermal solution of inverse problem in unsteady-state flow boiling heat transfer in a minichannel

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ABSTRACT

The paper shows the results for flow boiling heat transfer in a 1.7 mm deep minichannel vertically oriented with FC-72 Fluorinert as a working fluid. The heated wall of the minichannel was formed with a thin foil. Thermocouples mounted at 18 points monitored the outer foil surface temperature. All experimental parameters were controlled using data acquisition stations. The measurements were performed at 0.01 s intervals. The observations of the flow structures were carried out concurrently on the internal surface of the foil contacting the fluid. The aim of the numerical calculations was to determine the heat transfer coefficient on the contact surface between the heated foil and FC-72. The heat transfer coefficient was calculated with the use of the Robin boundary condition. To do that, the foil and fluid temperatures and foil temperature gradient had to be known. The foil temperature was found by solving an unsteady-state two-dimensional inverse boundary problem with the use of the Trefftz method in time-space subdomains. A linear combination of Trefftz functions was used to approximate the foil temperature. The unknown coefficients of the Trefftz function linear combination were determined by minimizing the functional. Error propagation in time and mean relative differences determined between the measured and computed heated foil temperatures were presented.

1. Introduction

Minimizing the size of heat exchangers while maximizing their thermal efficiency, lifespan, run time and cost is a challenge for the designers of modern devices. One of the efficient cooling methods is the use of phase change heat transfer processes, such as flow boiling which has gained growing interest in thermal science for providing very high heat transfer coefficients compared to those from single phase convection. However, flow boiling heat transfer is characterized by unstable flow phenomena and various heat transfer regimes, which being dependent on heat flux, mass flow rate, pressure, channel wall roughness and properties of the working fluid, add to the complexity of the process.

Numerous research studies have been devoted to calculating flow boiling heat transfer in mini spaces but the results of these calculations need to be compared to experimental data. Experiment is critical especially in complicated heat transfer systems, with bubbles larger than the channel size, where predictions concerning heat transfer are limited. A brief review of similar issues reported by other researchers is presented below. Experiments concerning time-dependent flow parameters were conducted by [1–7]. The enhancement of heat transfer due to the Taylor bubble train flow presented in comparison with thermally developing single-phase flows was studied by [1]. The experiments presented in [2] were carried out to evaluate the transient heat transfer characteristics of a minichannel heat sink under high heat flux density. A method for the measurement of transient fluid temperature in high-pressure systems was developed by the authors of [3]. In [4], the dynamics of pressure and temperature fluctuations occurring in flow boiling in a minichannel was investigated. In [5], the author presented a mathematical model of a transient heat transfer process for non-contacting face seals described by the fractional heat conduction equation. In [6], unsteady-state flow boiling in a rectangular minichannel was described, with a flow stability criterion depending on two controlled parameters: heat flux and mass-flow rate. The authors of [7] reported periodic flow boiling investigations, including oscillations of channel wall temperature, local heat transfer coefficients and inlet and outlet pressure. A full analysis of the temperature measurements and pressure data obtained during the growth of a vapour bubble in the microchannel was provided.

Identification of a heat transfer coefficient is one of inverse heat conduction problems [8–10]. The method proposed in 1926 by Trefftz [11] has been found to be especially suitable for solving

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Nomenclature

A	surface area, m^2
a_{mijk}	coefficient of the linear combination
c_p	specific heat of the heated foil, J/(kg K)
H_k	functional
I	current supplied to the heated foil, A
I	number of subdomains in the x-axis direction
J	number of subdomains in the y-axis direction
K	number of time intervals in numerical calculations
K_{All}	number of recorded time intervals during the experiment
L	length, m
M	number of Trefftz functions
P	number of measurements
p	pressure, N/m^2
Q_m	mass flow rate, kg/s
q_{loss}	loss of heat to the surroundings, W/m^2
q_V	volumetric heat flux, W/m^3
T	temperature, K
t	time, s
$u(x, y, t)$	particular solution of the differential equation
$v_m(x, y, t)$	Trefftz functions
x, y	spatial coordinates, m

Greek symbols

α	heat transfer coefficient, W/(m^2 K)
ΔU	drop in voltage along the foil, V
δ	thickness of the heated foil, m
κ	thermal diffusivity coefficient, m^2/s
λ	thermal conductivity of the heated foil, W/(m K)
ρ	density of the heated foil, kg/m^3
Ω	time-space domain

Subscripts

f	fluid
in	minichannel inlet
l	liquid
out	minichannel outlet
p	measurement point
sat	saturation

inverse problems. It employs a linear combination of functions that satisfy differential equations identically, Trefftz functions, for approximating the unknown solution of the differential equations. All you have to do is to adjust the approximate value to the boundary conditions and, in nonstationary problems, also to the initial conditions. Details about the Trefftz method can be found in [12–15]. The Trefftz functions-based method can be used to solve both stationary [16,17] and nonstationary problems [18–22] and for constructing base functions in FEM [23–29]. Spatial-temporal base functions are presented in [23,26].

Experimental data were the basis for the analysis of steady-state flow boiling heat transfer in minichannels performed by the authors of this paper in their previous works [28,30–34]. Currently, their research interest is focused on unsteady-state flow boiling heat transfer in rectangular minichannels.

2. The experimental database

2.1. Experimental stand

The essential part of the experimental stand - the testing module with a minichannel, flow loop and data and image acquisition system, are presented in Fig. 1. The test module is composed of two 16 mm wide and 180 mm long minichannels (1). The PTFE spacer (3) is used to achieve a specific dimension of the minichannel depth (1.7 mm). A thin foil (4) provides the heated wall for FC-72 Fluorinert flowing in the minichannels. The foil, made of Haynes-230 alloy, has a guaranteed precision thickness of approximately 0.1 mm. In the main minichannel, the foil temperature is measured with K-type thermocouples (T_1–T_{18}). Two additional thermocouples (T_{19}, T_{20}) were installed at the inlet and outlet of the minichannels. This contact temperature measurement method is used to obtain the basic data of the heated minichannel wall for calculations in one minichannel while in the other minichannel foil temperature is monitored by an infrared camera (8). Infrared thermography as a contactless temperature measurement method is used for the comparison of temperature measurements from thermocouples, at selected time intervals. The other side of the heated foil is observed through a glass pane (2) to visualize the two-phase flow patterns in minichannels using high-speed camera (9) and the lighting system. The data acquisition system is made up of two data acquisition stations (11, 12), a computer (13) and appropriate software. A mass flow meter (18) is used to control the fluid flow in the flow loop. Fluid inlet and outlet pressure are also measured due to pressure converters. The supply and control system contains an inverter welder, a shunt, an ammeter and a voltmeter.

2.2. Experimental methodology and uncertainties

Each experimental series with the laminar flow of FC-72 in minichannels lasted approximately two minutes. The temperature of the foil surface was monitored continuously at 18 points by K-type thermocouples placed at the outer surface along the central, axially symmetric axis of the main minichannel. The signals from the thermocouples controlling foil temperature at the selected points (marked as $T_1 \ldots T_{18}$ in Fig. 1a) and the two thermocouples installed at the inlet and outlet of the minichannels (marked as T_{19} and T_{20}) were recorded using a DaqLab 2005 data acquisition station (11). Simultaneously, two-phase flow structures in the minichannel were observed using a JAI Coaxpress high-speed camera (9) and foil temperature was monitored by a FLIR E60 infrared camera (8). The pressure of the fluid at the minichannel inlet (p_{in}) and outlet (p_{out}), the current supplied to the foil (I), the voltage drop across the foil (ΔU) and mass flow were also recorded using an MCC SC-1608G data acquisition device with analog signal conditioning (12). The measurements were carried out with a frequency of 0.01 s. All parameters recorded during the experiment and the apparatus used for measurements (with accuracy) are listed in Table 1.

3. Determining heat transfer coefficient

Two-dimensional nonstationary heat flow was assumed. The temperature variation along the minichannel width was not taken into account. Two dimensions were accounted for: dimension x along the flow direction and dimension y perpendicular to the flow direction, related to the thickness of the heated foil.

The Robin boundary condition was used to calculate the local values of the heat transfer coefficient: