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Correlations for flow boiling heat transfer in minichannels with various orientations

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ABSTRACT

The paper presents the results of using known correlations for boiling heat transfer in a minichannel 1 mm deep, 40 mm wide and 360 mm long, with three spatial orientations: vertical, position 90° and two horizontal orientations: positions 0° and 180°. The heating element for cooling liquid flowing laminarly in the minichannel is a single-sided microstructured foil. Liquid crystal thermography was used for measuring the temperature distribution on the plain side of the heating surface. The observations of the flow structures were carried out on the microstructured side of the foil contacting fluid in the minichannel. 12 selected correlations for boiling heat transfer have been used in calculations. It was found that the majority of correlations enabled the predicting of heat transfer coefficient within an acceptable error limit (±30%) only in a specific orientation of the channel. For the horizontal channel, position 0°, the highest compliance occurred when Mikielewicz et al. correlation was applied, for the vertical channel – when Liu and Winterton correlation was used and for horizontal channel, position 180° – by the application of Cooper correlation. The own correlation, with taken account for the microstructured heating wall, was proposed in two forms: for saturated boiling and for boiling incipience and subcooled boiling. Most experimental data show congruence with theoretical correlations with the tolerance ±35%.

1. Introduction

Heat transfer in small channels has been dealt with significant attention over the last few years, especially for application to electronics cooling. Mini heat exchangers are used to provide higher cooling capability for new technologies. It means a reduction of their sizes and costs, while the power is identical. The use of microstructured surfaces allows additional intensification of the process. There have been many reports on experiments covering heat transfer and analyses of flow boiling heat transfer in minichannels varied in terms of their dimensions. [1,5] contains the summary of relevant literature focused on heat transfer in minichannels. Although the literature review leads to the conclusion that boiling heat transfer in small channels has been widely discussed, the references do not lead to any generalized, universal correlation described heat transfer for minichannels of different geometries and orientations. The equations for small channel systems heated by smooth surfaces are often verified experimentally but using enhanced surfaces in such systems are poorly identified. It can be emphasized that studies concentrating on enhanced structure systems attract attention due to their use in their theoretical enhancement potential for heat transfer.

The series of studies pursued at the Kielce University of Technology includes research on flow boiling heat transfer in a cooling fluid flow along the minichannel with microstructured heating wall and various orientations. The results were described in numerous publications, e.g. [1-5]. This paper compares results of the experimentally determined Nusselt number with theoretically calculated values from correlations proposed by other researchers. The own correlation, with taken account for the microstructured heating wall, was proposed in two forms: for boiling incipience and subcooled boiling and for saturated boiling.

2. The experimental database

2.1. Experimental stand

The essential part of the experimental stand is the test section with a rectangular minichannel (Fig. 1(a)), 1 mm deep, 40 mm wide and 360 mm long. The heating element for FC-72 flowing in the minichannel (1) was the thin alloy foil (2) designated as Haynes-230. A plain side of the heating foil (between the foil and

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Nomenclature

A	cross-section, m^2
c	specific heat, J/(kg K)
$a, b, c, d, E, F, F_{Fl}, f, f_z, N, P, R_{M-S}, S$	coefficient
d_h	hydraulic diameter, m
G	mass flux (density), kg/(m^2 s)
H	sum of recesses' heights, μm
h_{lv}	latent heat of vaporization, J/kg
I	current supplied to the heating foil, A
i, N	natural number
L	length, m
M	molecular mass of the fluid, kg/kmol
n	number of recesses
p	pressure, N/m^2
q_w	heat flux density, W/m^2
R^2	determination coefficient
Ra	surface roughness parameter, μm
S_{dev}	developed (microstructured) surface, μm^2
T	temperature, K
u	flow velocity, m/s
V_{rec}	share of the recesses
X	vapour quality
x	distance from minichannel inlet, m

Greek

α	heat transfer coefficient, W/(m^2 K)
Γ	surface development parameter
ΔT_{sub}	inlet liquid subcooling $(T_{sat} - T_l)_{in}$, K
ΔU	the voltage drop across the foil, V
δ	width, m
δ	standard error
ε	diameter or the longest size of the recess, μm
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, kg/(m s)
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

cb	convective boiling
D-B	Dittus–Boelter
exp	experimental
F	foil
in	at the inlet
l	liquid
nb	nucleate boiling
$pred$	predicted
r	reduced
ref	referenced
sat	saturation
SP	single phase
th	theoretical
TP	two phase
v	vapour

Dimensionless numbers

Bo	$q_w/(G \cdot h_{lv})$
Co, N_{Co}	defined in the text
Fr	$G^2/(\rho^2 \cdot g \cdot d_h)$
Nu	$(\alpha \cdot d_h)/\lambda_l$
Pe	$Re \cdot Pr$
Pr	$(\mu \cdot c)/\lambda$
Re	$(G \cdot d_h)/\mu$
We	$(u^2 \cdot d_h \cdot \rho)/\sigma$

the glass) is covered with thermosensitive liquid crystal layer (3). The foil is microstructured on the side which comes into contact with fluid in the channel (8). Two types of microstructured heating surfaces: one with micro-recesses distributed evenly, and another with mini-recesses distributed unevenly, were used. The micro-recesses were performed by laser drilling. The diameter of the single micro-recess is usually 10 μm, its depth is 3 μm. 5–7 μm high layers of melted metal deposit annularly around the recesses, forming structures that can be named as "craters". Micro-recesses are evenly distributed every 100 μm in both axes. The mini-recesses were obtained by spark erosion. The melted metal foil and an electrode material, a few μm high, reaching locally 5 μm, accumulates around the recesses. The depth of the cavity craters is usually below 1 μm. 3D photos of the microstructured foil with micro-recesses and mini-recesses are presented in Fig. 1(b) and (c). It is possible to observe both surfaces of the minichannel through glass panes. One pane (4a) allows observing changes in the temperature distribution on the plain side of the foil thanks to the liquid crystal thermography. The latter one (4b) allows to observe the two-phase flow patterns on the microstructured foil side. K-type thermocouples and pressure converters are installed in the inlet and outlet of the minichannel. The test section was oriented vertically with the bottom-up flow and horizontally at two different positions set in various angles to the plate, i.e. 0, 90 and 180 degrees. The crucial element of the research stand is data and the image acquisition system with digital cameras, data acquisition station, a computer with special software and lighting systems, presented in detail in [1–5]. Information about the accuracy of the heating foil temperature measurements with liquid crystal thermography and other experimental data errors are described in [2,4,5].

2.2. Experimental heat transfer coefficient determination

Various methods of the determination of the local heat transfer coefficient in the two-dimensional approaches, obtained from solving the inverse problem were proposed. The finite element method in combination with Trefftz functions [2] was one of these solutions, while others employ include the sensitivity coefficient method or apply the nodeless method. The above mentioned methods employ Trefftz functions. Here, the simple one-dimensional approach was used [1]. The resulting heat transfer coefficient for the subcooled boiling was determined by the Eq. (1), while that for saturated boiling – by Eq. (2), as follows:

$$\alpha_{exp}(x) = \frac{I \cdot \Delta U / A_F}{T_F(x) - T_l(x) - \frac{I \cdot \Delta U}{A_F} \cdot \frac{\delta_F}{\lambda_F}} \quad (1)$$

$$\alpha_{exp}(x) = \frac{I \cdot \Delta U / A_F}{T_F(x) - T_{sat}(x) - \frac{I \cdot \Delta U}{A_F} \cdot \frac{\delta_F}{\lambda_F}} \quad (2)$$

3. Review of boiling heat transfer correlations

The following boiling heat transfer correlations chosen for the analysis are presented below:

– for pool boiling (Cooper),
– for saturated flow boiling, subsequently for:
- conventional channels (Shah, Liu and Winterton),
- minichannels or channels of small hydraulic diameter (Lazarek and Black, Tran et al., Kew and Cornwell, Kandlikar and Steinke, Warrier et al., Mikielewicz et al., Sun and Mishima, Bertsch et al., Dutkowski).