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MODELLING LONG TERM PRESSURE AND TEMPERATURE OSCILLATIONS IN THE FLOW BOILING IN MICROCHANNELS

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ABSTRACT

Heat exchangers equipped with microchannels have many industrial applications. This is due to their capability for transfer of high heat fluxes. In flow boiling in microchannels three different flow regimes: steady bubbly/slug flow regime, bubbly/annular alternating flow and annular/mist alternating flow have been observed.

In the present paper the model of heat and mass transfer in microchannels system has been proposed. Oscillations between quasi steady state of boiling in microchannels have been considered. Changes of two-phase flow in microchannels have been described by the relations between: heating surface temperature, vapour quality, liquid mass flux, pressure drop in microchannels and heat flux absorbed by boiling liquid. Simulation results indicate that shape of curve pressure-drop-versus-flow-rate is responsible for appearance or disappearance of heating surface temperature and pressure oscillations.

INTRODUCTION

Long term oscillations generally called "pressure-drop type oscillations" were first discussed and classified by Stenning in his works [1-3]. Kakac et al. extensively investigated oscillations of flow rate and system pressure in different types of microchannels. It is commonly recognized that four types of oscillations exist in a microchannel: pressure-drop oscillations, density-wave oscillations, acoustic oscillations and thermal oscillations. The mechanism of pressure drop oscillations was discussed in paper [4]. An analysis of temperature and pressure changes shows that for flow boiling in microchannels, the relation between the mass flux and heat flux determines the behaviours of the two-phase flow inside the channels [3,10]. The appearance of vapour inside microchannels blocks the liquid flowing into the microchannel. Therefore, the inlet liquid pressure increases and mass flux increases as well. When the heat flux is not large enough, the boiling inside the microchannels with high mass flux leads to decreasing in the heating surface temperature, and consequently to the decrease of boiling intensity or boiling disappearance. The bubbles stop blocking the microchannel and inlet pressure decreases. Wu and Cheng carried out a simultaneous visualization and measurement investigation of flow boiling of water in parallel silicon microchannels of trapezoidal cross-section with hydraulic diameter of 158.8 and 82.8 μm respectively [7].

NOMENCLATURE

Bo	-	Boiling number
d_h	[m]	hydraulic diameter
G	[kgm^{-2}s^{-1}]	mass flux
i	[Jkg^{-1}]	enthalpy
k_f	[Wm^{-1}K^{-1}]	thermal conductivity
Nu	-	Nusselt Numer
p	[Pa]	pressure
q	[Wm^{-2}]	heat flux
t	[s]	time
T	[K]	temperature
x	-	vapour quality
Special characters		
Δ	-	difference
α	[Wm^{-2}K^{-1}]	heat transfer coefficient
β	-	channel aspect ratio
δ	[m]	linear dimension of heating element
Subscripts		
b		effective
in		inlet
l		liquid
lv		phase change (vaporization)
max		maximum value
min		minimum value
n		iteration
out		outlet
sp		single-phase
tp		two-phase
v		vapour
w		Wall

Large-amplitude/long-period fluctuations with time in wall temperatures, fluid temperatures, fluid pressures and fluid mass flux were recorded for the first time during flow boiling in the microchannels [5, 7]. Bargles et al. noted that pressure drop oscillations occur when compressible volume upstream of the boiling channel exists and the channel pressure drop decreases with increasing mass flow rate in the negative-slop flow region [8]. Steinke and Kandlikar investigated flow boiling using water in six horizontal, parallel microchannels with hydraulic diameter of 206 μm. They found that reverse flow conditions were caused by the rapid growth of bubbles. Dry-out conditions were noted in the experiment [9]. The significant progress in this field was made by other investigators [10, 11, 12].

Gurgenci et al. [13] used homogeneous flow model with constant properties and drift-flux model with variable properties to predict oscillations in a single channel boiling system. Comparison with experimental results indicated the better agreement of drift-flux model. Padki et al. [14] classified pressure-drop oscillations and the Ledinegg instability using bifurcation theory. Many investigators conducted theoretical and experimental investigations of pressure-drop oscillations, thermal oscillations, density-wave instabilities in forced convection boiling system [15,16]. Guodong et al. [17] compared flow boiling instabilities of water in parallel and single microchannels. He observed 3 different flow boiling modes which occur at certain conditions. The stable boiling flow regime with no periodic oscillations, unstable boiling flow regime with long term oscillations and unstable boiling flow with short-period oscillations were observed. Each of mentioned modes appeared in parallel microchannels at higher heat and mass flux ratio in comparison with behaviours observed in single microchannel.

Models of heat and mass transfer in microchannels can be divided into two groups. There are: models defining the mean values of parameters characterizing the heat and mass transfer, (such as pressure drop and heat transfer coefficient) and models describing the changes in time of the system state. The models describing the dynamics of heat and mass transfer are based on differential equations which describe the non-stationary processes. Performing the simulations using such models requires the application of complex numerical methods and fast computers. The model proposed in the paper is based on difference equations that describe the evolution of the system between subsequent quasi-stationary states. The model enables the simulation of chaotic changes of heat flux and pressure drop in long time period. Such model can be useful for simulation of interactions between parallel microchannels.

HEAT AND MASS TRANSFER IN MICROCHANNELS – BASIC CORRELATIONS

In Figure 1 there has been presented the qualitative changes of function $\Delta p(G)$ [4]. The two characteristic points have been shown in Figure 1. The point OFI identifies the onset of flow instabilities and point ONB identifies the onset of nucleate boiling. For the mass flow rate greater than ONB only the liquid flow appears in the channel. For the flow rate less than ONB the two-phase flow appears in the channel. Further decrease of mass flux causes an increase in pressure drop until the curve reaches its peak, in which the vapour single-phase flow appears.

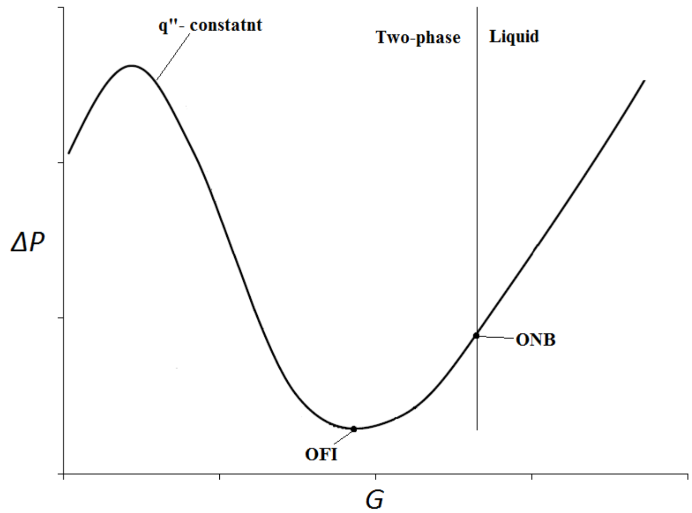

Figure 1 Pressure drop vs mass flux for constant heat flux. The chart has been prepared based on data presented in [4].

Pressure drop vs heat flux is presented in Figure 2. After passing the ONB point, the abrupt increase in pressure drop is observed [18].

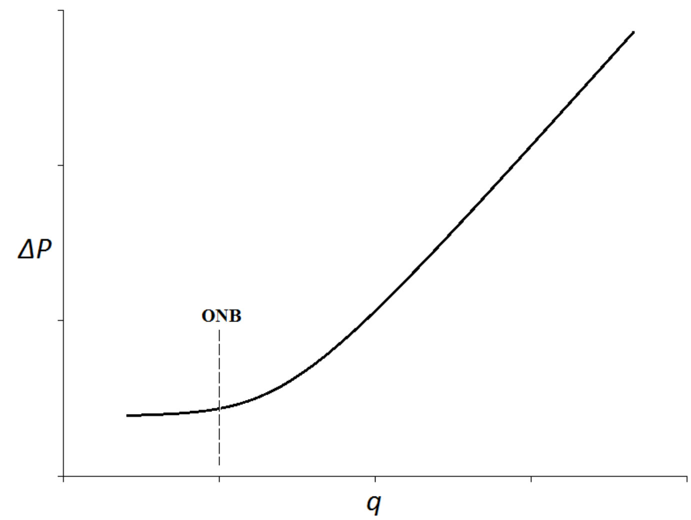

Figure 2 Pressure drop vs heat flux. The chart has been prepared based on data presented in [18].

The vapour quality is one of important parameters characterising the heat and mass transfer in channels. According to Warrier's [19] for the narrow rectangular channel the heat transfer coefficient can be expressed by the following correlation:

$$\alpha_{tp} = \frac{Nu_3}{Nu_4}(E\alpha_{sp}) \qquad (1)$$

where

$$\alpha_{sp} = Nu_4 \frac{k_f}{d_h}$$

$$E = 1.0 + 6Bo^{\frac{1}{16}} - 5.3(1 - 855Bo)x^{0.65}$$
$$Nu_3 = 8.235(1 - 1.883\beta + 3.767\beta^2 - 5.814\beta^3 + 5.361\beta^4 - 2.0\beta^5),$$
$$Nu_4 = 8.235(1 - 2.042\beta + 3.085\beta^2 - 2.477\beta^3 + 1.058\beta^4 - 0.186\beta^5),$$

Considering that:

$$\alpha_{tp}(x) = \frac{q}{(T_w - T_{sat})} \tag{2}$$

the equation (1) allows us to calculate the function $x(T_w)$. In Figure 3 the function $x(T_w)$ obtained for constant q is presented.

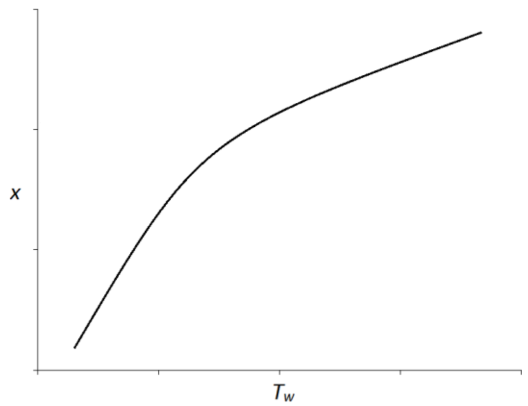

Figure 3 Vapour quality vs heating surface temperature.

According to [19] the following equation describes the relation between vapour quality and average mass flux:

$$x_e = \frac{i_{in} - i_{l,sat}}{i_{lv}} + \frac{A_w Bo}{A_c} \tag{3}$$

where $Bo = q/Gi_{lv}$

i_{in} inlet enthalpy

$i_{l,sat}$ enthalpy of saturated liquid

i_{lv} latent heat of evaporation

In Figure 4 there has been shown the function $x(G)$.

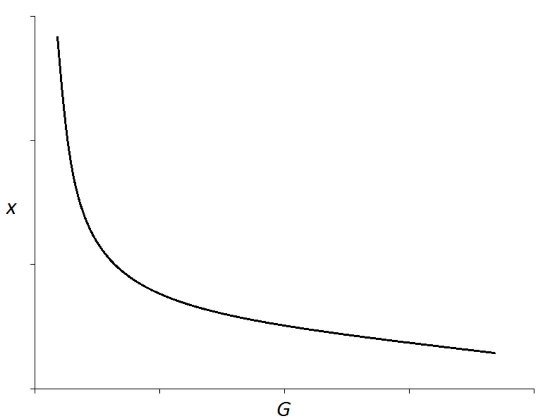

Figure 4 Function $x(G)$ according to the Eq.3.

MODELLING

In the present paper, the simple model of heat and mass transfer in microchannels has been proposed. Oscillations between quasi steady state of boiling in microchannels have been considered. The schematic drawing of heat and mass transfer model in microchannel has been presented in Figure 5.

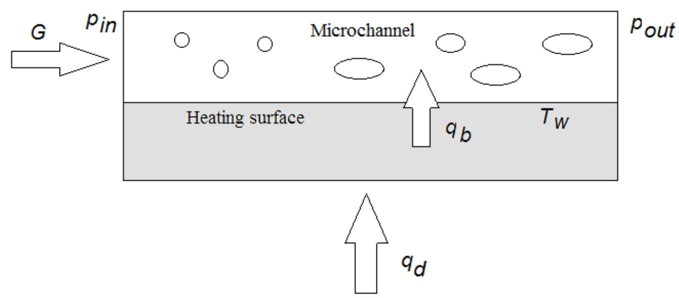

Figure 5 Schematic drawing of heat and mass transfer model in microchannel. Where q_b is a heat flux absorbed by boiling liquid, then q_d is a heat flux delivered to the system.

The heat and mass transfer in microchannel have been described by the following five functions:

$$\begin{aligned} T_w &= f_1(q_b), \\ x &= f_2(T_w), \\ G &= f_3(x), \\ \Delta p &= f_4(G), \\ q_b &= f_5(\Delta p) \end{aligned} \tag{4}$$

where T_w – heating surface temperature, x – vapour quality, G – liquid mass flux, Δp – pressure drop in microchannels, q_b – heat flux absorbed by boiling liquid.

It has been considered normalized functions where both function value and function argument are in range (0, 1). All functions, with exception of $\Delta p = f_4(G)$, are linear. Normalized functions under consideration can be treated as parts of charts presented in Figures 1, 2, 3 and 4, after its rescaling. The functions (4) have been shown in Figure 6.

Energy balance in time Δt, in a small element of heating surface with linear dimension δ, leads to the following equation:

$$q_d - q_b = \frac{\delta \cdot \rho \cdot c \cdot (T_w^{t+\Delta t} - T_w^t)}{\Delta t} \tag{5}$$

Increase of q_b with constant q_d leads to decrease of T_w. Therefore, the function $T_w = f_1(q_b)$ has been described by the linear function shown in Figure 6a. Next functions have been constructed as linear functions according to trends of functions presented in Figures 2, 3 and 4. Such functions can be treated as the regression lines defined according to experimental data. The function $\Delta p = f_4(G)$ presented in Figure 1 has a minimum and maximum. Therefore, in the model it has been considered two kinds of functions $\Delta p = f_4(G)$ describing pressure changes around the minimum and maximum of function presented in Figure 1. During the simulation the minimum value of function $\Delta p = f_4(G)$ has been changed. It has been shown schematically in Figure 6e.

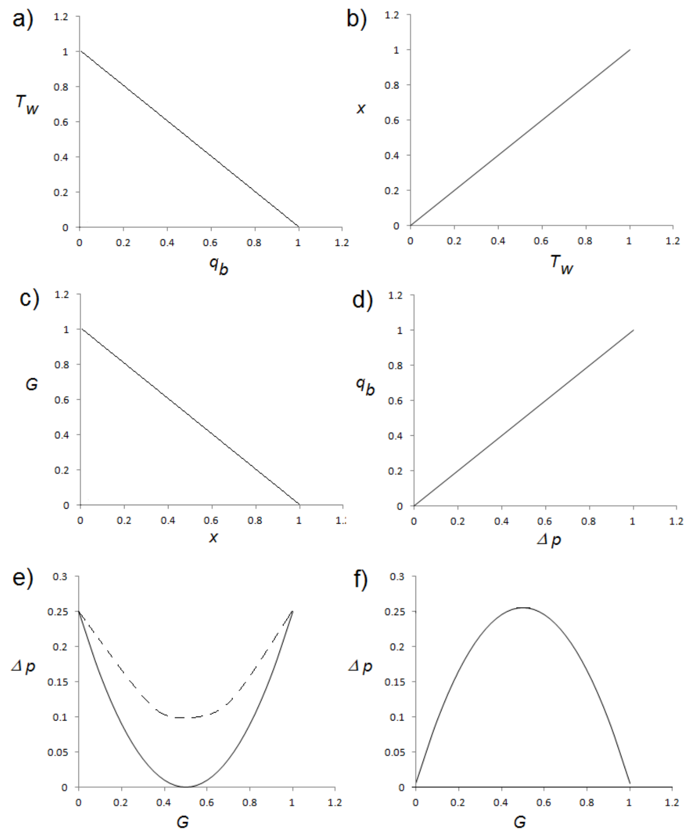

Figure 6 The functions (4). a) $T_w = f_1(q_b)$, b) $x = f_2(T_w)$, c) $G = f_3(x)$, d) $q_b = f_5(\Delta p)$ e) $\Delta p = f_4(G)$ representing changes of Δp around the minimum of function shown in Figure 1. f) $\Delta p = f_4(G)$ representing changes of Δp around the maximum of function shown in Figure 1.

Finally, the heat flux absorbed by boiling liquid in microchannels in subsequent time periods is described by the following equation:

$$q_{n+1} = f_5(f_4(f_3(f_2(f_1(q_n))))) \qquad (6)$$

In Figure 7 there has been shown the heating surface temperature fluctuations for different minimum value of functions $\Delta p = f_4(G)$.

When min (Δp) = 0.2, the fluctuations of temperature and other parameters are periodic (Figure 7a), but when min (Δp) = 0.1, then the fluctuations of temperature and other parameters are chaotic (Figure 7b). When min (Δp) = 0.4, the fluctuations of temperature and other parameters disappear (Figure 2c).

Minimum of function $\Delta p = f_4(G)$ appears close to ONB point. Oscillations of mass flux obtained in the simulation appear around the minimum of function $\Delta p = f_4(G)$. On the right side of minimum of function $\Delta p = f_4(G)$ the bubble flow appears, and on the left side - the annular flow. Therefore, the obtained oscillations simulate the long term oscillations between bubble flow and annular flow which were observed in the experiment [19]. On the right side of Figure 7, there has been shown the schematic drawing of the flow patterns in microchannels during the oscillations. The solution of the equation (6) are the time series of subsequent values of q_b, T_w, x, Δp, G.

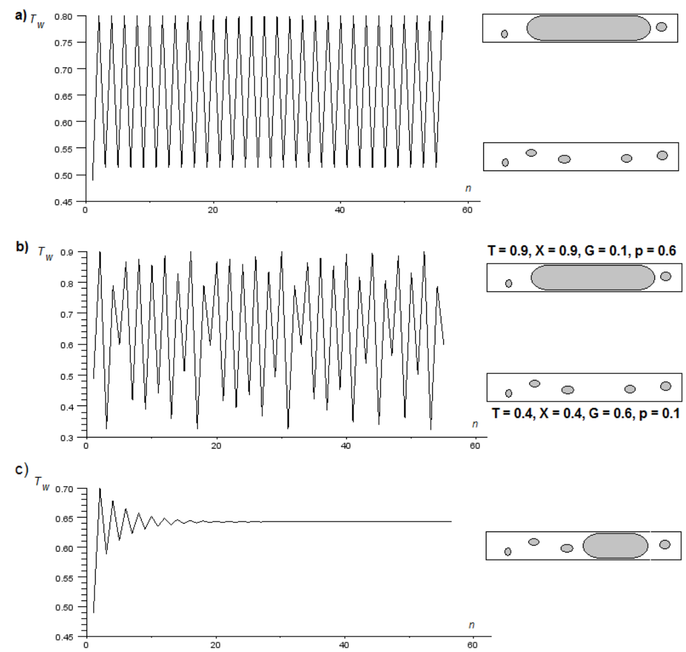

Figure 7 Heating surface temperature fluctuations for different functions $\Delta p = f_4(G)$. a) min (Δp) = 0.2, b) min (Δp) = 0.1, b) min (Δp) = 0.4. On the right side of charts it has been shown the type of two phase flow in microchannel.

When the shape of function $\Delta p = f_4(G)$ is as presented in Figure 6f, then from mathematical point of view the same kind of oscillations like in Figure 7 appear. But from the physical point of view there are oscillations between annular flow and mist flow.

CONCLUSION

In flow boiling in microchannels the three different flow regimes: steady bubbly/slug flow regime, bubbly/annular alternating flow and annular/mist alternating flow have been observed [19]. The model presented in the paper allows us to simulate the unstable regimes of boiling in microchannels. Obtained results of simulations show that stability of boiling in microchannels is determined by extremes of function of $\Delta p = f_4(G)$. These results correspond with conclusions formulated in the paper [19], in which it is shown that the stability threshold is determined by the minimum in the pressure-drop-versus-flow-rate curve.

The model presented in the paper has the qualitative character. Its validation will be possible when functions f_i in equation (6) will be replaced by functions constructed based on experimental data.

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