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Computational Analysis of Effect of Inlet subcooling on Flow Boiling in Micro/Mini Channels

Shoeb J. Inamdar

Research Scholar, Department of Mechanical Engineering, Government College of Engineering Amravati, (M.S) India

Dr. S. M. Lawankar

Assistant Professor, Department of Mechanical Engineering Government College of Engineering Yavatmal, (M.S) India

Abstract – Flow boiling in microchannels is an emerging field of interest. Researchers are working on this since two decades but as the inception of instabilities is evoked in the work area, the depth of work is significantly increased. The instabilities in the flow boiling is inherent and can not be avoided specifically in micro passages. In this paper the computational study is performed by assuming fundamental operating conditions and the effect of degree of inlet subcooling is studied on the stability and other parameters of flow boiling, A micro channel set of dimensions length(L)= 20 cm, width(w)= 1 mm, depth(d)= 0.5 mm, Base Area(A_b)= 6×10^{-3} m^2 and Hydraulic Diameter(D)= 6.66×10^{-4} m, is assumed and is subjected to the computational simulation with the operating Heat flux (q) = 30 kW/m^2 . Rate of Heat Transfer (Q) = 180 W, Mass Flux (G) = 150 kg/m^{2}s mass flow rate (m) = 1.5×10-3 kg/s. The calculations are performed for three different sections of flow i.e for four different vapor qualities x_1= 0.1, x_2= 0.2, x_3= 0.3 and x_4= 0.4. The results are then plotted and discussed with relevance to the stabilization of the flow instabilities**.**

Index Terms – Micro channels, Flow Boiling, Instabilities, Pressure drop, Inlet subcooling,

INTRODUCTION

In modern electronic equipment and supercomputing etc. has given rise to the problem of high heat flux generation. MEMEs, RADAR, satellites etc. operates on the principle of high frequency radiation. The radiation heat generated in the system needs to be dissipated in the immediate surrounding in order to maintain the thermal equilibrium [1, 2].

In upcoming future the chip heat flux densities are estimated to be as high as 4.7 MW/m^2 [3] and for military and defense applications it has exceeded the limits of 10 MW/m^2 [4]. Tuckerman and pease [5] introduced the micro channel cooling in early 1980s. Although other methods like air cooling, jet spray cooling are sufficiently effective still has their range limited as they involve only the sensible heat dissipation portion [6-8]. Flow boiling in micro channels involve the sensible as well as the latent portion of the heat and hence emerged as one of the dominant area in micro channels [9]. Two phase flow instabilities is the most vulnerable area of work in the section of flow boiling and researchers are doing significant research on it. Kandlikar [10], Mudawar[11], Cheng and Xia [12] are some of the prominent researchers who have done work in this domain. they all conclusively cited the comman finding that flow boiling instabilities depends upon the number of operating variables such as mass flow rate, flow regimes, bubble dynamics, inlet subcooling, inlet compressibility and coolant properties.

Inspite of the fact that the inlet conditions of flow can affect the flow stability very few work has been done on it [13-15]. The classical model made bu Hsu[16] satates that the size and range of the effective cavities is a function of degree of inlet subcooling.Similarly kandlikar [17] has predicted that the nucleation criteria as well as flow boiling instability is highly dependent on inlet subcooling.

Hence the work in this paper involves the computational study on the effect of inlet subcooling on the flow boiling in micro and mini cahnnels.

TABLE I

NOMENCLATURE

Nomenclature		***Greek symbols***	
T	temperature, K	ρ	density, kg/m^3
A	area, m^2	Δ	gradient
x	Vapor quality		
D	hydraulic diameter, mm	***Subscript***	
L	length, m	*w*	Wall condition
G	mass flux, kg/m^2 s	*g*	vapour
h	heat transfer coefficient, W/m^{2}K	*fg*	liquid-vapour
i	latent heat, (j/kg)	*in*	inlet
H	Enthalpy, (kJ/kgK)	*out*	outlet

P	pressure, Pa	*b*	base
q	heat flux, W/m^2	*c*	cross cection
Q	total heat amount, Watt	*tp*	Two phase condition
F_k	Fluid constant	*le*	Liquid alone condition
Fr	Froud Number	*sat*	Saturation point
Bo	Bond Number		

ASSUMPTION OF OPERATING CONDITIONS

To perform the computational simulation study the standard operating conditions are assumed as follows.

1. Channel Dimensions:

A rectangular cross section micro channel set is taken of the following dimensions.

L =20 cm, w= 1 mm, d= 0.5 mm,

Base Area (A_b) = 6×10-3 m^2

C/S Area (A_c) = 10^{-5} m^2

Hydraulic Diameter (D) = 6.66×10^{-4} m

2. The operating heat flux is taken as Heat Flux (q) = 30 kW/m^2.

3. Rate of Heat Transfer (Q) = 180 W

4. The operating mass flux is assumed to be Mass Flux (G) = 150 kg/m^{2}s

5. The mass flow rate is found to be mass flow rate (m) = 1.5×10^{-3} kg/s

The Calculations are performed for four different sections of flow i.e for three different vapor qualities

x_1= 0.1, x_2= 0.2, x_3= 0.3 and x_4= 0.4.

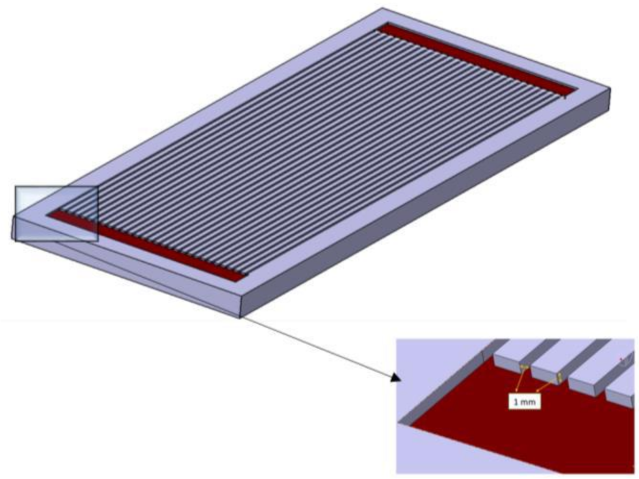

Fig. 1. Design of Microchannel heat sink

STEP BY STEP CALCULATIONS

Like most of the heat transfer analysis very first step involved is the calculation of heat transfer coefficient. In this case it involves two phase heat transfer hence, it is required to calculate the two phase flow heat transfer coefficient.

Set 1: For $(\Delta T_{sub})_1$ =10 K.

- **Heat Transfer Coefficient**

The generalize equation for two phase flow heat transfer coefficient is given by [18].

$$h_{tp} = 0.6683 \left(\frac{\rho_l}{\rho_v}\right)^{0.1} x^{0.16}(1-x)^{0.64} f(fr_l) h_{le} + 1058\, Bo^{0.7} F_k\, (1-x)^{0.8} + h_{le} \qquad (1)$$

Where,

h_{le} - Single phase heat transfer coefficient assuming only liquid flow

x – Vapor quality

$f\,(fr_l)$ – Function of Froude number

F_k – Fluid constant (for water F_k =1).

Kandlikar and balasubramanyam[18] simplified above equation for micro channels,

They recommended, for micro channels

$f\,(fr_l)$ = 1

Now the equation (1) reduces to

$$h_{tp} = 0.6683 \left(\frac{\rho_l}{\rho_v}\right)^{0.1} x^{0.16}(1-x)^{0.64} h_{le} + 1058\, Bo^{0.7}(1-x)^{0.8} + h_{le} \qquad (2)$$

Where h_{le} is calculated as

$$\frac{h_{le}D}{k_l} = C_l \qquad (3)$$

The suggested value of C_l = *4.36*

After substituting all the required values,we get,

h_{le} = 3862.46 W/m^{2}k.

The effect of Bond no. is very negligible in micro channels. Still calculated as

$$Bo = \frac{g(\rho_l-\rho_v)D^2}{\sigma} \qquad (4)$$

After substituting all the required values,we get,

***Bo* = 0.547**

And finally from Equation (2), we get

h_{tp} = 7985.58 W/m^{2}k

Now the entire above calculation is repeated for different vapor qualities, i.e for x_1 ,x_2 ,x_3 ,x_4.

We get,

for $x_2 = 0.2$, h_{tp} **= 6643.71 W/m²k**

for $x_3 = 0.3$, h_{tp} **= 5231.49 W/m²k**

for $x_4 = 0.4$, h_{tp} **= 4171.21 W/m²k**

Resuming further calculations for $x_1 = 0.1$

- **Wall Temperature**

Now the next step is to calculate wall temperature, it can be calculated from Eq. (5)

$$Q = h_{tp} A_b (T_w - T_{sat}) \qquad (5)$$

T_w **= 122.54 ºC**

- **Outlet Temperature**

Now the next step is to calculate outlet temperature, it can be calculated from Eq. (6)

$$Q = mC(T_{out} - T_{in}) \qquad (6)$$

For inlet subcooling $(\Delta T_{sub})_1$ = 10 ºC , the inlet temperature becomes $T_{in} = 90$ ºC,

Hence we get,

T_{out}**= 118 ºC.**

- **Length of Subcooled section**

The length of subcooled section in the channel is given by the Eq. (7)

$$L_{sc} = \frac{GAC\,(T_{sat} - T_{in})}{\pi D} \qquad (7)$$

After substituting all of the above values, we get

L_{sc}**= 0.06 m**

- **Determinations of stable operating region**

Phase change No. is given by

$$N_{pch} = \frac{Q\rho_{fg}}{m\rho_g}$$

N_{pch}**= 86.21**

And subcooling No. is given by

$$N_{sub} = \frac{(H_f - H_{in})\rho_{fg}}{i\rho_g}$$

N_{sub}**= 325.52**

RESULTS AND DISCUSSION

1. Subcooling Vs Length of subcooled boiling section:

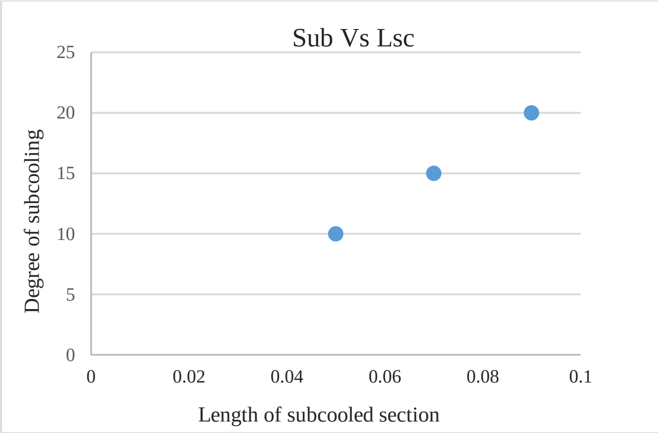

Fig. 2. Subcooling Vs Length of subcooled section

As the plot in Fig.2 illustrates that as the degree of subcooling is increased we can see an obvious increase in the subcool section length. As the length of subcool section increases the nucleation is stabilized and the pressure oscillations are damped and we see the more stable operation of flow regime. This finding ties up with the similar findings of Zhang et al. [20], Lee and Mudawar [21]. This enhancement can be attributed to the delayed Onset of boiling that causes lesser hindrances from the ideal operation.

2. Subcooling Vs Heat Transfer coefficient:

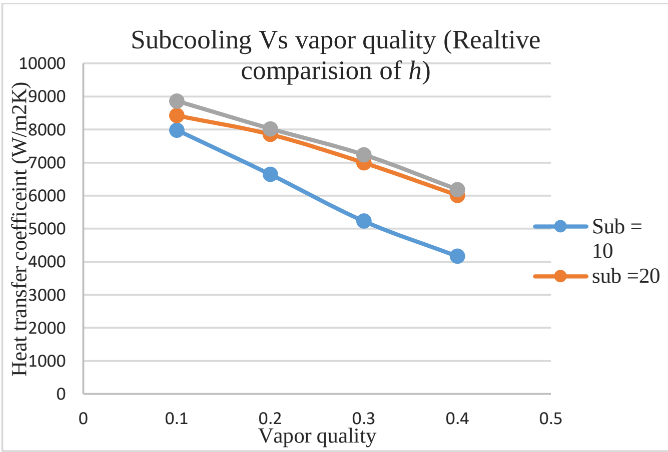

Fig. 3. Subcooling Vs Heat transfer Coefficient

Fig.3 depicts the fact that as we go on increasing the degree of sucooling then we can see a surge in heat transfer coefficient. for the improved vapor quality the heat transfer coefficient decreases this can be attributed to the increase in void fraction with increase in vapor quality. The rise in *h* with subcoolig is explained by the fact that with improved subcooling we get lesser flow instability, the critical heat flux and ONB is delayed with subcooling and the subcooled flow provided the condensing media for the bubbles formed and eases the early bubble departure and prevents the void creation [22-26].

3. Subcooling Vs Wall Temperature

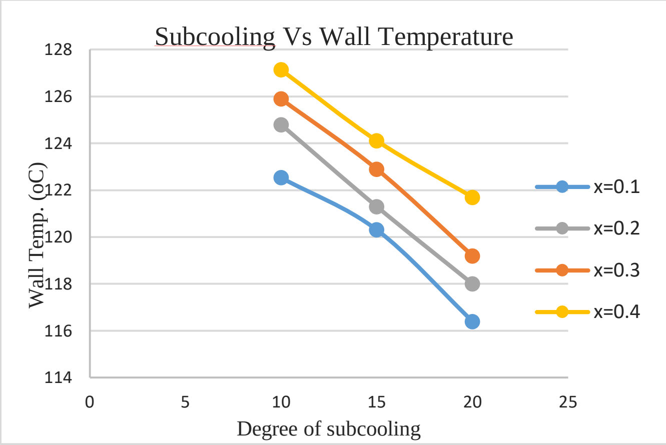

Fig. 4. Subcooling Vs Wall Temperature

Fig. 4 shows the variation of wall temperature with inlet subcooling. As briefed in the Fig. it can be seen that for the same vapor quality the higher subcooling degree have lower wall temperature. As the vapor quality increases the film boiling initiate in that region and the wall temperature increases significantly. for higher degree of subcooling the nucleation process in enhanced and we get stable bubble growth with proper departure from the wall without clogging the channel, due to this the flow transition is very much stable and film boiling is delayed and we get lower wall temperature which leads to less damage to the specimen and solder joints [26-30].

3. Determination of Stable operating region

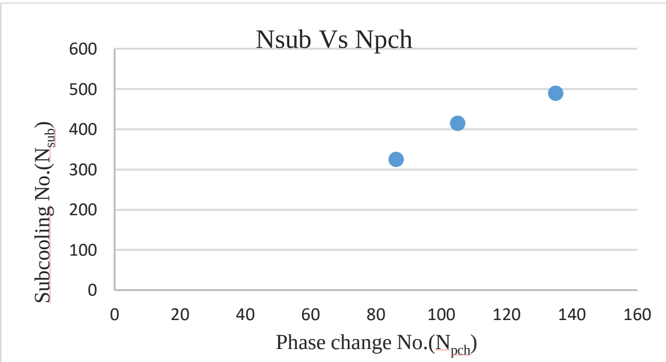

Fig. 5. N_{sub} Vs N_{pch}

Fig. 5 shows a graph between subcooling number (N_{sub}) and phase change number (N_{pch}). The area under this plot shows the regions of stable and unstable operation. The area right to the plotted points shows the unstable boiling region and the area left to the points shows the stable operating region. as both the numbers are increasing simultaneously it is clear that the slope of the line will be towards right and positive and hence we can conclude that with increase in subcooling the stable operating region increases[30-35].

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