Flow Boiling Heat Transfer in Mini or micro channels

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11-june-2021

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1 : Introduction

Now a day there is continuous and rapid advancement in technologies like use of supercomputers, heavy electronics in hybrid cars IGBTs modules, refrigeration system and heavy power devices increase the need to transfer the high heat flux within small or confined space and without much change in the surface temperatures to maintain the efficient working of system. Such a high heat transfer coefficient with confined space we can obtain using single phase or two phase flow boiling in mini or micro channel. Microchannels obtain high heat transfer coefficient because of high surface area to volume ratio. Eg . Kang at al tested a counter flow micro channel heat exchanger with demonized water having surface area to volume ratio of 15294 m^2/m^3.

Typically the advanced hybrid car uses high power batteries with IGBTs (insulated gate bipolar transistor). IGBTs are the small chips of metal. Heat flux in IGBTs depends on rated voltage and current flowing. Particularly the heat flux in future insulated gate bipolar transistor could be 5 MW/m^2 and need to maintain the surface temperature well below the 125 C.Conventional flow boiling techniques are not able to achieve such high heat flux. To obtain such a high heat flux we have to move towards the Flow boiling in micro channels.

Even with all these above advantages of micro channels we have some basic fundamental issue due to limited research in this area.

1. Definition of micro channels

2. Flow patterns

3. Heat Transfer mechanisms

4. Flow instability

5. High Degree of superheat For ONB (onset of nucleate boiling)

6. High pressure drop

2 : General Flow boiling curve

From point A to C single phase convection heat transfer coefficient the heat flux increases linearly with wall temperature.At point C Wall temperature reaches to the threshold value for onset of nucleate boiling. From C to D Single phase convection decreases (suppression) and nucleate boiling increases(enhance).The point D indicate fullely devloped flow. As fluid continuously absorb the heat saturated boiling is evaluated at point E.After point E vapour quality increases till dryout.

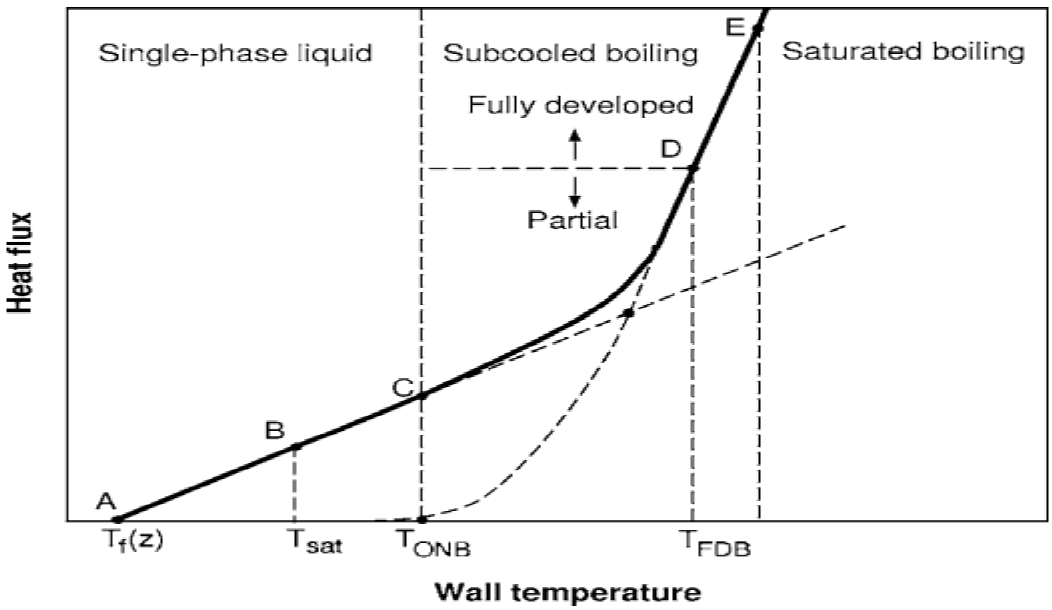


Fig 1: Flow Boiling curve : variation of heat flux with wall temperature

3 : Definition of Micro channel

The definition of microchannel is a controversial issue hence Researchers divided it into two groups.

3.1 by using fixed range of diameters or surface area to volume ratio

A : shah uses surface area density (Beta) as criteria to differentiate between conventional and micro channels'

Beta<700m^2/m^3 as a conventional and Beta>700m^2/m^3 as a mini or micro.

B : kandlikar uses hydraulic diameter D as Differentiating criteria

Conventional channel : D>3 ; mini channel : 3>D>0.2 ; micro channel D<0.2

But these researchers do not include the physical mechanisms like use of different fluids and orientation of flow channel.

3.2 : By considering the surface tension force

a. ong and thome consider confinement number Co as a base parameter Co=0.3 to 0.4 macro to mesho and Co =1 for mesho to micro

4 : Flow patterns in conventional and micro channels

4.1 : Flow pattern in conventional channel

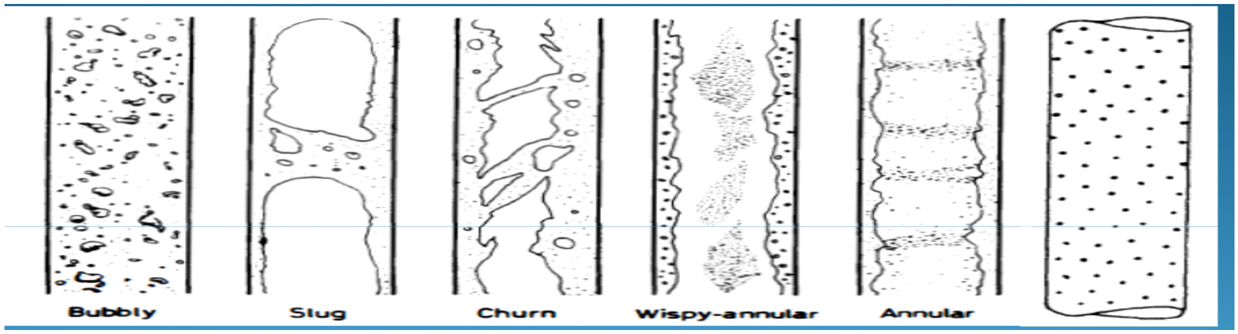


Fig 2: flow pattern in conventional channels

4.2 : Flow Patterns in Micro Channels

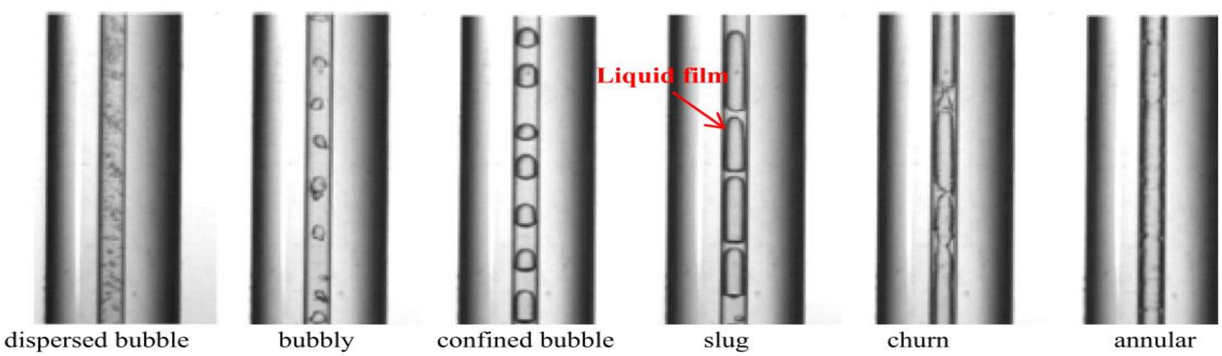


Fig 3 : Flow pattern in micro channels

From fig 2 and fig 3 we can say that the flow patterns observed in conventional flow boiling and micro channel flow boiling is nearly same. Because of small size ,The mechanism of bubble dynamics is different in micro channel flow boiling .The initial formation of bubble is similar to conventional nucleate boiling. Initially bubble form through an active nucleation site and then it grows in two stages

1. Partially confined growth where bubble grows only in its minor dimension and 2.fully developed growth where bubbles growth takes place in both the directions widthwise and lengthwise.

5 : Heat transfer Mechanism in conventional and micro channel

5.1 Heat Transfer mechanism in Conventional channel

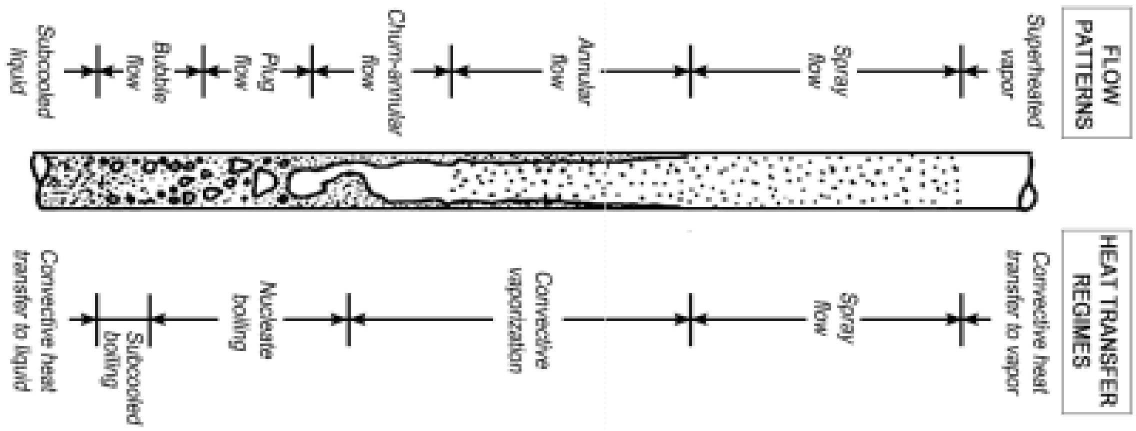


Fig 4 : Mechanism in Conventional Channel

5.2 : Heat transfer Mechanism in Micro Channel

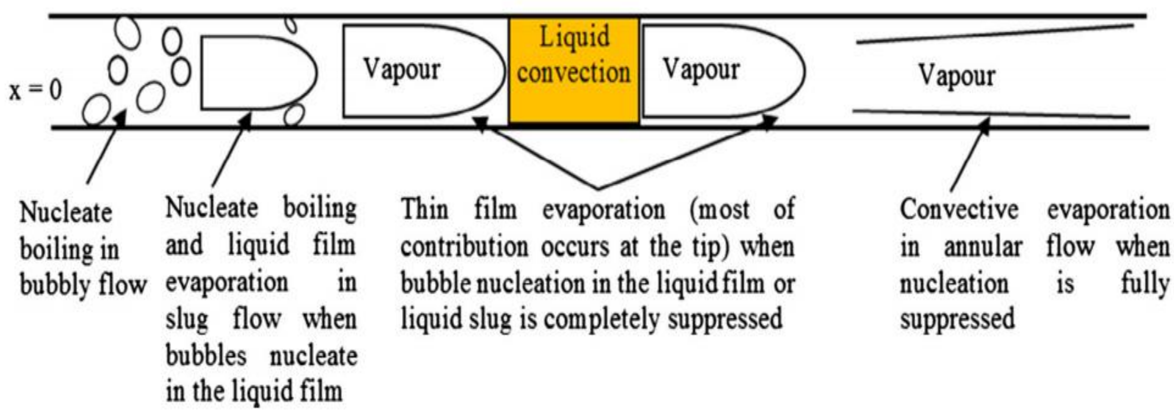


Fig 5 : Heat Transfer Mechanism in Micro Channels

There is controversial between the researches for the Dominating mechanism of flow boiling in Micro channel. Some of the researchers observed in their experiment that some nucleus are seen in liquid slug as well as in annular flow and based on this they concluded that nucleate boiling is the dominating mechanism for micro channel heat transfer. Others has been observed that the effect of nucleation get suppressed as the quality increases in the direction of flow and concluded the thin film evaporation or convective vaporization as a dominating mechanism for micro channels .Ali at al perform experiment on flow boiling of refrigerant R134a in a heated quartz tube of diameter 0.781mm.they did not observed any nucleating bubbles on the side of elongated bubbles in slug region. And concluded that as quality increases the nucleation get suppressed and thin film evaporation becomes dominating mechanism. Nucleation dominates only up to sub cooled region.

This controversial may due to

1. Difference in surface finish

2. Difference in cross section

3. single or multichannel flow

4.Difference in working medium

6 : Models to predict flow boiling heat transfer coefficient in micro channels :

6.1 : A Three zone model [Thome at al]

This heat transfer model describe the transient variation of heat transfer coefficient in micro channel due to cyclic process of 1] Liquid slug 2] Evaporating elongated Bubble and 3] Vapour slug

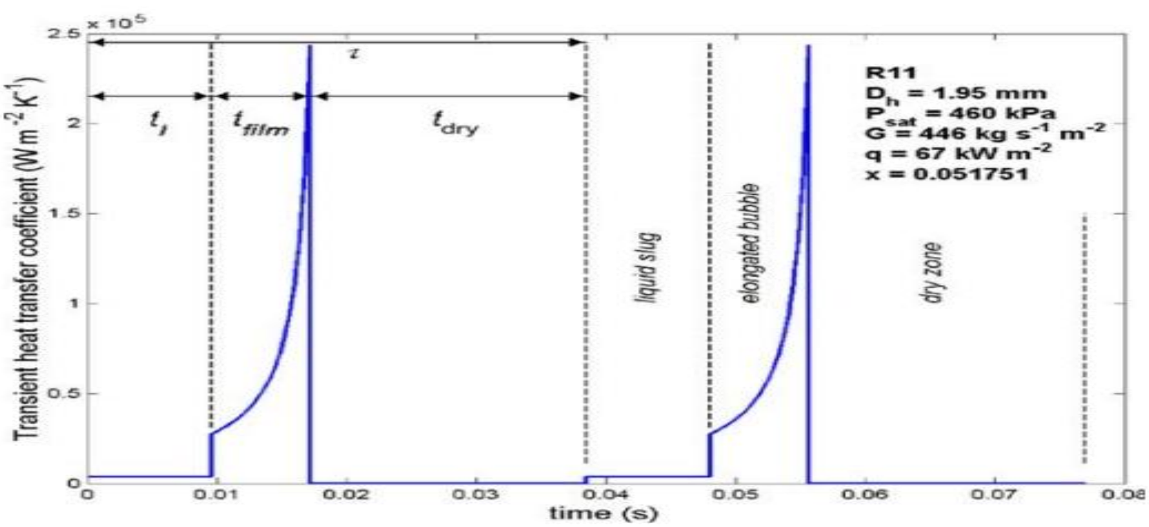


Fig : 6 Cyclic variation of heat transfer coefficient with time

Figure 6. Clearly shows that heat transfer coefficient in elongated bubble regime is much higher than liquid slug and vapour slug regime,This is because in elongated bubble regime heat transfer take place by thin film evaporation and nucleate boiling. This is a cyclic process and repeate after certain time constant.

6.2 : A four zone model for rectangular cross-section [wang et al]

Three zone model does not include the partially-dry out zone and not predicting the accurate results.[wang] included the partially-dry out zone to consider the effect of liquid at corner of elongated vaopur on local heat transfer coefficient.

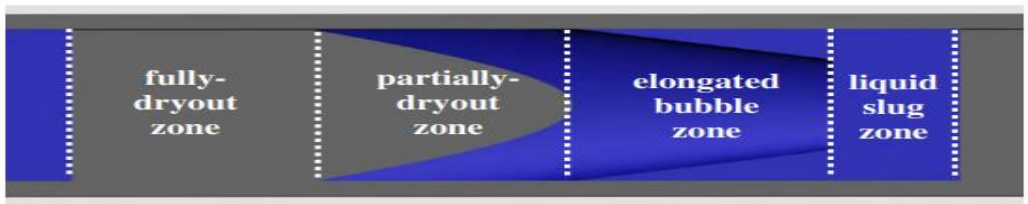


Fig : 7 four zones of heat transfer

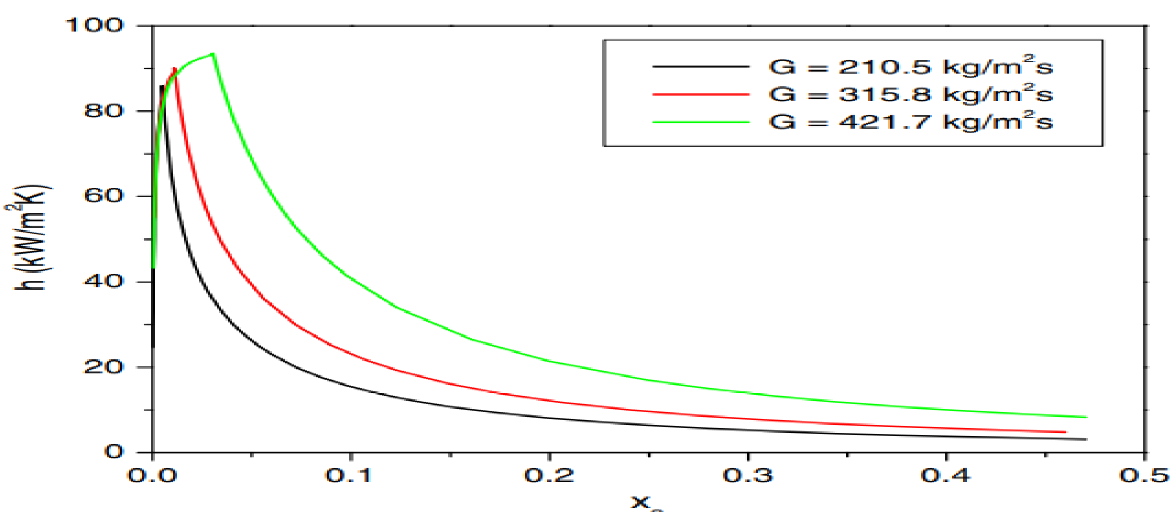


Fig : 8 heat transfer coefficient using four zone model at different mass flux

From Fig 8 its clearly observed that the spike in heat transfer coefficient at lower vapour quality and keep on decreasing with increase in quality. This is because at lower vapour quality fully developed nucleate boiling observed and heat transfer take place by nucleat boiling and convective vaporiation. Also with increase in the mass flux we can see that there is increase in heat transfer coefficient, This is because with icrease in mass flux the inertia of liquid flowing through channel increases this will detach the bubble quickly from surface. As soon as bubble depart from surface fresh liquid come in contact with surface This process increase the heat transfer and reduces the dryout condition.

This model agrees with experimental data with 13.9% of MAE.

6.3 : Five zone model with effect of shear stress on thin film depletion [Sateesh G et al]

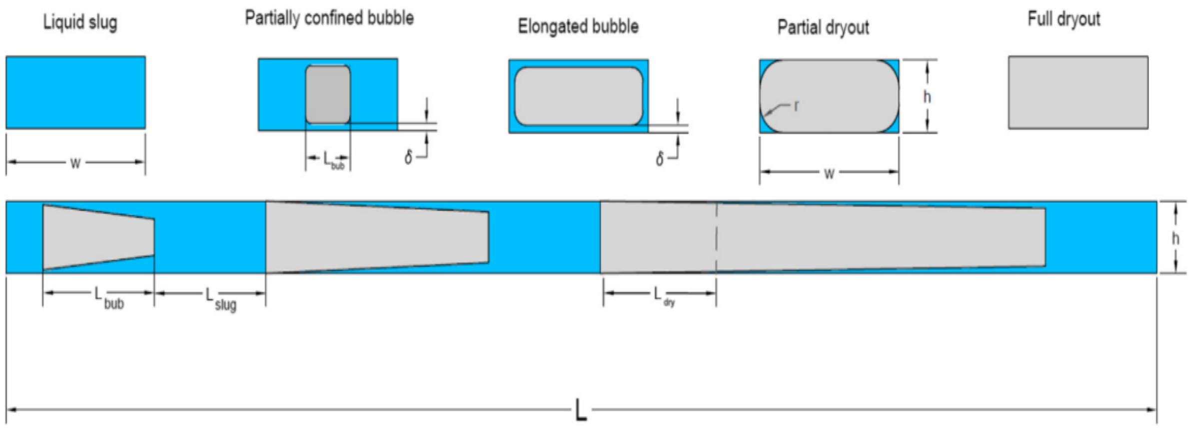
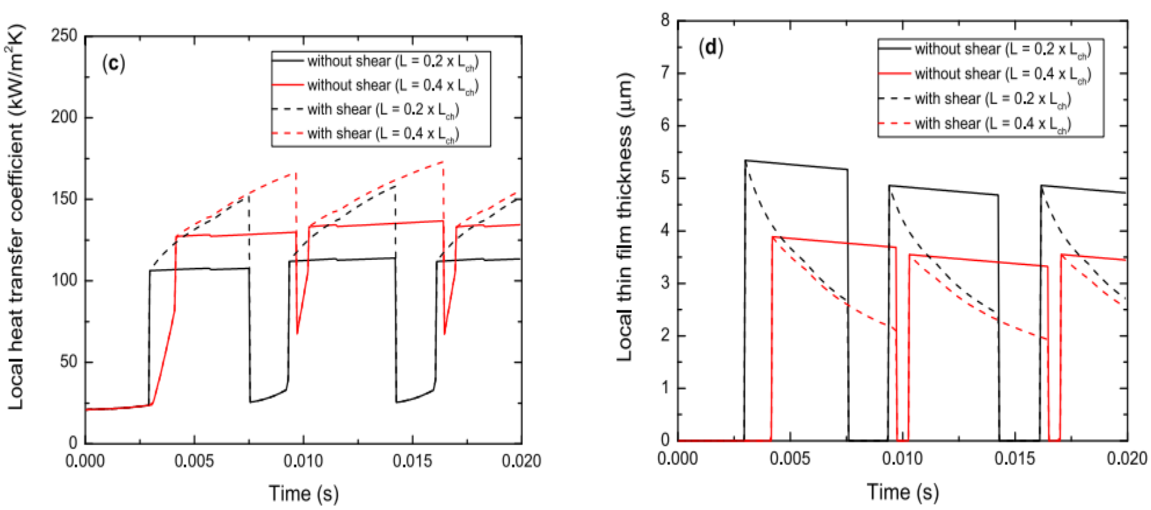


Fig 9 : Five zones of heat transfer

A fifth zone of partially confined bubble is consider along with four zones consider by [wang et al].This study consider the effect of shear stress on thinning of liquid film.



(c) Local heat transfer coefficient variation with time. (d) Local thin film thickness variation with time.

Fig 10 : Effect of shear stress on local heat transfer coefficient and local thin film thickness

Fig 10[d] shows that effect of shear stress on local film thickness. It is clearly shown that with shear stress the local film thickness smaller than without shear, also the rate of thinning of liquid film is higher. This higher rate of thinning of liquid film increases the heat transfer by thin film vaporization which can be seen in fig 9 [c].

Rate of thinning of thin film is directly proportional to the initial film thickness. Hence the depletion rate is higher at the entry of liquid. As liquid flows , in the direction of flow due to vaporization the velocity get increases ,results in decrease in film thickness and hence decrease in the rate of depletion.

Correlation used to calculate heat Transfer coefficient in different zones [five zone model]

a: Liquid slug and fully dryout

For turbulent flow $Nu = 0.00222Re^{1.09}Pr^{0.4}$

b. Partially confined bubble

$$\frac{\mathbf{1}}{\boldsymbol{h_{film}}} = \frac{\boldsymbol{\delta}}{\boldsymbol{k_l}} + \frac{\mathbf{1}}{\boldsymbol{h_{int}}}$$

h_{int}= liquid vapor interfacial heat transfer coefficient ... [10^7... W/m^2]

$$h_{film} = \frac{k_l}{\delta_{eq}}$$

c. Elongated bubble

$$\frac{\mathbf{1}}{\boldsymbol{h_{elong}}} = \frac{\boldsymbol{\delta_{eq}}}{\boldsymbol{k_l}} + \frac{\mathbf{1}}{\boldsymbol{h_{int}}}$$

d. Partial dryout region

$$\frac{\mathbf{1}}{\boldsymbol{h_{liquid}}} = \frac{\boldsymbol{\delta_{eq}}}{\boldsymbol{k_l}} + \frac{\mathbf{1}}{\boldsymbol{h_{int}}}$$

7 : Pressure drop in micro channel

Jain and Gedupudi perform the experiment and observed that the pressure drop effect such as frictional loss due to vapour bubble relative motion, the loss due to momentum change across the bubble,the pressure drop caused by the interface curvature are negligible than frictional or viscus and acceleration pressure drop.

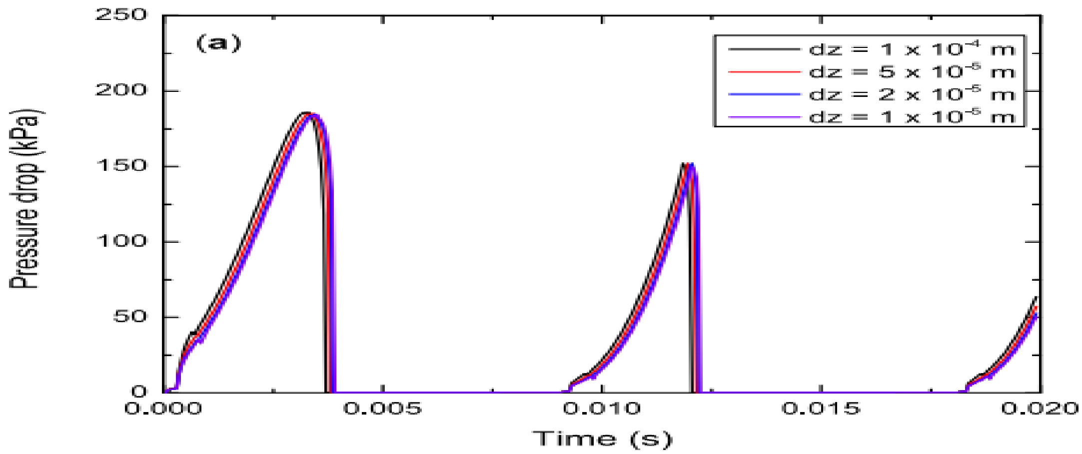


Fig : 11 Transient pressure drop variation

Fig 11 shows the transient pressure drop variation .Its shown that pressure drop variation is a cyclic in nature.As The effect of frictional and acceleration pressure drop are dominating.once the bubble is form it will start to move at higher local velocity which will increase the frictional and acceleration pressure drop.Once the bubble depart from surface fresh liquid comes in contact with surface and wait till bubble grow during this period the pressure drop losses are reduces.

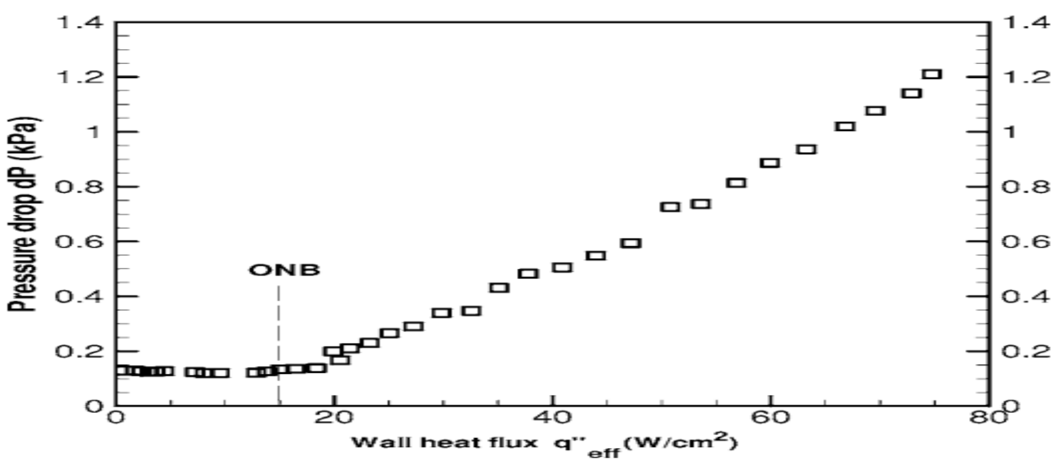


Fig 12 Variation of pressure drop with wall heat flux

Fig 12 shows effect of wall heat flux on pressure drop.These pressure values are measured at upstream and downstream section of test section. Its shown that there is slight decrease in pressure drop in subcooled liquid region this is due to with increase in temperature the liquid viscosity decreases and hence frictional pressure drop reduces.After the onset of nucleat boiling the vapour quality increases and hence the frictional and acceleration pressure drop increases.

8 : Flow instability

Flow instability is an important issue which should take into consideration during design of micro channels. Instability in flow boiling cause high fluctuation in mass flow rate , temperature and pressure. These fluctuation may reduce the system performance and responsible for thermal damage of system.

Following are the reasons for flow instability in micro channels

8.1 : Rapid bubble growth

Bubble are grow rapidly in flow channel and het elongated in forward and backward direction. Underneath of bubble thin film get evaporates and a white patch is observed for small period. This white patch sudden increases the wall temperature and pressure in flow channel.

8.2 : Size of outlet section

As the size of outlet channel increases up to a certain size the flow instability get reduced , further increase in size cause the more and more bubble get accumulated and complete flow channel come in contact with vapor bubble. This will cause sudden increase in quality, pressure drop , wall temperature and reduction in mass flux.

8.3 : Inlet compressibility of fluid

Lie at al Conducted a experiment and concluded that with known compressibility at inlet there is reduction in pressure pulsation and increase in heat transfer coefficient by 30% .

8.4 : Onset of nucleation in channel

Nucleation in micro channel affect on flow reversal and Flow reversal affect on pressure and temperature pulsation. Nucleation near exit of channel cause no flow reversal and hence stable boiling or less instability. Nucleation near inlet increases flow reversal and hence unstable boiling or more instability.

9 : Methods to overcome the flow instability in micro channels

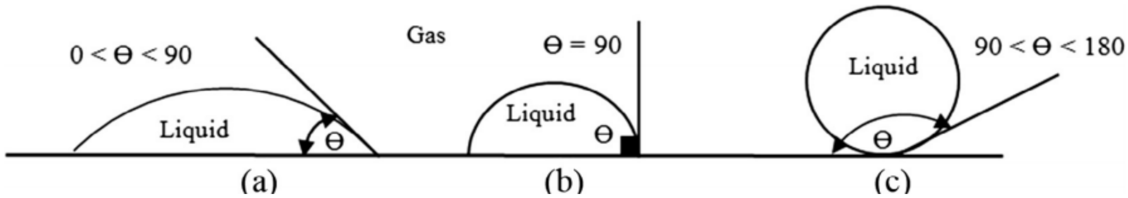
9.1 : Modifying the design

As suggested by Xingchi Jiang : We can minimize the flow instability to a grater extent by modifying the micro channel design to a counter current type heat exchanger. This design alter the flow pattern in micro channel and avoided the white patch which will decrease the flow instability.

9.2 : Surface characteristics

Flow instability can be reduced by modifying the surface characteristics in such way that there will be large number of nucleation site available for nucleation. This will reduce the wall superheat required for nucleation and hence reduce the temperature fluctuation.

9.3 : Surface wettability



a. wetting surface (hydrophilic) b. Non wetting c. Highly non wetting (hydrophobic)

Fig 13: Wettability of Different Surfaces

As surface wettability increases the surface tension forces increases which increases the bubble departure diameter. Large bubble departure diameter needs more time to grow and depart from surface. In that mean period they get elongated in upstream and downstream direction and produces the white patch on surface which will increases the wall temperature and pressure pulsation in micro channel.

10 : Conclusion

High heat transfer coefficient is a need of current and future emerging technology which can be full fill by single or two phase heat transfer in micro channel.These are having high surface area to volume ratio which can obtain high heat transfer coefficient within less space.At lower vapour quality we can obtain higher heat transfer coefficient because the nucleate boiling and thin film vaporization are dominating heat transfer mechanism.Frictional and acceleration pressure drop losses are dominating and these are increases drastically as vapour quality increases.With improved surface characteristics we can obtain higher heat transfer coefficient in micro channel.

Dry patch and Dryout are mejor problem in micro channel.Dry patch result in pressure pulsation and sudden increase in wall temperature.These can be avoided with improved surface characteristics and high mass flux condition.

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