Evaluation of Heat Transfer Shear of Different Mechanisms in Subcooled Nucleate Boiling

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Abstract

Since the mean characteristic of nucleate boiling is bubble formation and collapse near the heating surface, in this study attempts have been made to investigate heat transfer effects due to the bubbles ebullition and collapse cycle. All possible heat transfer mechanisms are studied qualitatively and quantitatively. For quantitative calculation of the heat transfer portion by each of the introduced mechanisms, a series of bubble parameters was selected from the experimental data provided by the high-speed photography of a heated rod containing nucleate boiling regime on its surface. According to the present results, the portion of the mechanisms such as latent heat transfer, super heated layer mixing and single-phase heat transfer are between 6~15%, 12~17%, and 3~5%, respectively. The results also show that the two mechanisms of the turbulence induced by the bubble formation and collapse and quenching have the main performance in transferring heat from the heating surface to the bulk flow. The shared percentage of these two mechanisms is estimated between 23~58.5% and 20.5~40% respectively.

Keywords: *Bubble, Heat Transfer, Nucleate Boiling, Quenching & Turbulence*

1. INTRODUCTION

The ability of subcooled boiling flow for transferring high heat loading in compact area without a significant void fraction and heating surface temperature increase has caused it to be widely used in industry. Because of the special characteristics of subcooled boiling flow, this technique is used for making compact heat exchangers, or transferring high heat loadings in nuclear plants. Using the subcooled boiling technique, transferring heat fluxes of up to 10^8 W/m^2 are reported to be attainable through high velocities, large subcooling, small diameter channels and short heated lengths [1].

Vandervort et al. (in 1992) have identified all possible mechanisms for subcooled boiling [2]. Their explanation is divided into two different parts of; 1) the bubble growing on the heated surface and 2) the bubble detachment from the heated surface.

In recent studies Nematollahi et al. [3] ,according to their experimental study, addressed the nine mechanisms as the following:

(1) Single-phase forced convection
(2) Local dispersion of the super heated layer around the active cavity due to implosive bubble formation that is referred to as super heated layer
(3) Latent heat transport due to bubble collapse
(4) Vapor/liquid interchange due to the bubble departure that is addressed as quenching
(5) induced micro-convection due to evaporation of the entrapped water from the cavity
(6) induced micro-convection due to the boundary layer motion around the bubble
(7) Micro-convection due to the special manner of the bubble collapse
(8) Transferring of heat and kinetic energy by the stable micro-bubble to the bulk flow
(9) Marangoni-force induced micro-convection

The introduced mechanisms of 5,6,7,8 and 9 could count as a comprehensive mechanism of the *turbulence induced by the bubble formation and collapse* because of their similarity in creation of turbulence by inducing micro-convection.

In the present study an attempt was made to investigate the mechanisms of heat transfer in a subcooled boiling condition by analyzing bubble behavior in subcooled boiling flow on a heated rod using the technique of high-speed photography. The bubble behavior at three locations 1, 25 and 45 cm from the beginning of a heated rod were analyzed at different conditions of subcooling temperature, linear power density and flow rate. For the evaluation of the heat transfer shear of different mechanisms in nucleate boiling, and the quantitative calculation of partial heat transfer by each of the introduced mechanisms, a series of bubble parameters was selected from the experimental data provided by high-speed photography of a heated rod having a nucleate boiling regime on its surface.

2. Experimental apparatus and procedure of the High-Speed Photography

Fig. 1 shows the schematic view of the test loop. The subcooled boiling was performed by Joule heating on the middle part of the stainless steel rod, which has high electrical resistance compared to the rest of the rod made by copper. Flow of distilled water was used as the recirculating coolant in the loop. A power between 0~60 kW was supplied from a voltage regulator and a transformer connected to an electrical power line with 200V and 300A electricity current.

The rod diameter and length of the heated surface of the rod are 10 mm 50 cm, respectively. The outer tube of the test section was made of glass having 30mm inner diameter, which was permitted visual observation. In the present experiment, several different conditions were chosen such as different incoming coolant subcooling temperature 25, 50 and 75K, coolant flow velocities 16, 32, 53 cm/sec and imposed linear power densities 100~600, W/cm for the interracial high-speed photography from the heating surface.

High-speed photography was performed using a KODAK EKTAPRO High-speed Motion Analyzer (model 4540), which contains an imager, a processor and a keypad. By using this system photographic pictures were able to be taken from 30 to 40500 frames per second. This system was connected with three other accessories, a computer, a monitor and a video tape recorder. Fig. 2 shows the experimental setup of the high-speed photography.

The high-speed photography was operated at 13500 frames per second in different conditions of subcooled boiling. The taken pictures would cover the cross-section 2.5mm X 2.5mm of the visible test section. This was achieved by using a 100mm telephoto lens (SMC PENTAX-M MACRO 1:4 100mm) with a 180mm extended tube. The slow motion behaviors (10 frames per second) of the bubble for five minutes were recorded on videotape by the video tape recorder for each condition For each condition a minimum of 200 consequential images of the bubble behaviors have been saved in the computer memory. The bubble behaviors were visualized for four different conditions which were in different heights, inlet subcooled temperatures, linear power densities and flow rates.

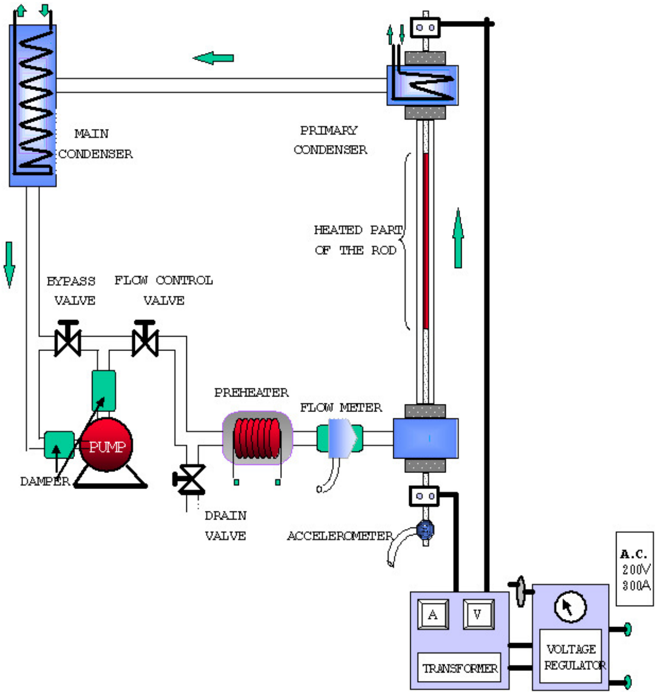

Fig.1: Schematic diagram of the experimental setup

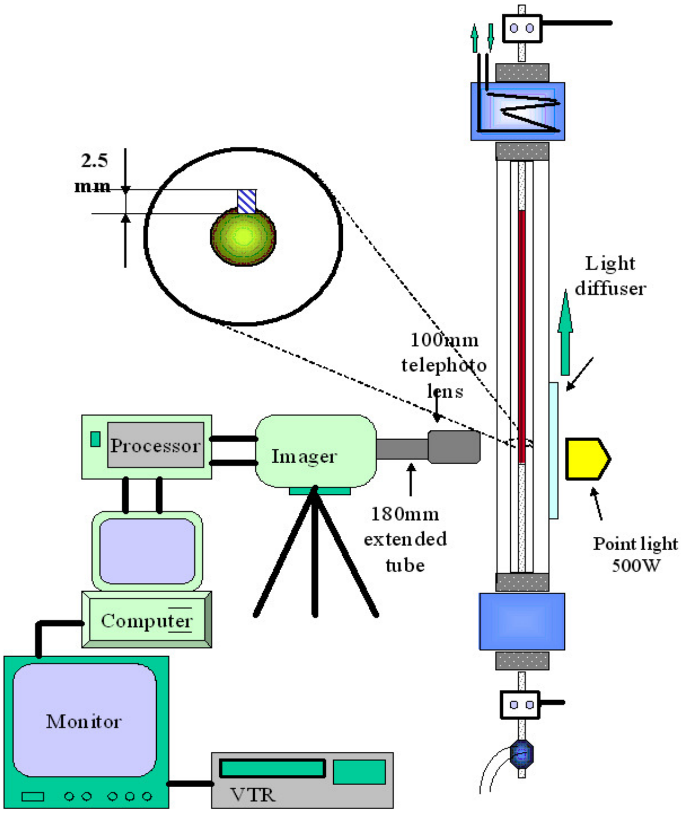

Fig. 4: Experimental setup of high-speed photography

3. Experimental Results

The behavior of bubbles in different conditions of subcooling temperature, linear power density and flow rate was analyzed using high-speed photography. The observed behaviors can be divided into two main categories:

a) General aspects of interfacial behavior of the coolant in subcooled boiling flow
b) Specific aspects of bubble behavior at different subcooled boiling flow conditions.

A brief explanation on the results is presented here.

3.1. General aspects

In all cases in which the bubble formed on the heating surface, a thin shear flow, which looks similar to a dark fluid layer in the photographs, covers the heating surface. The darkness of the thin layer can be explained by the difference in the reflection angle of the back light due to the temperature difference between the subcooled water and the saturated or superheated water. This thin layer disappears in the linear power densities less than that required for the onset of nucleate subcooled boiling flow, and in the low subcooling or in the saturated conditions.

High-speed photography of the bubble ebullition cycle shows that vapor blown from a cavity forms as a bubble with a hemispheric or an elongated hemispheric shape. This process occurs during a short interval between less than 74 μs to around 222 μs, depending on parameters such as linear power density, subcooling, and cavity characteristics. The motion of water in the layer around the bubble causes the bubble to separate from the heating surface. The contact area of the bubble with the wall starts to shrink. This continues until the bubble adheres to the wall at a single point, at which time the bubble becomes similar to a balloon. This process is followed by the ejection of the bubble from the surface. Most of the bubble volume condenses in bulk flow near the surface. The collapse starts from the bottom of the bubble. It appears that the condensation rate from the bottom is much more notable than the bubble top.

Condensation of the bubble and the work due to surface tension cause a balloon type bubble to change into a micro-bubble with a diameter around one fiftieth of that of the original bubble. Immediately after its formation, the micro-bubble escapes very rapidly from its location towards the bulk flow. A micro-bubble has a relatively high kinetic energy. In addition to this, a simple theoretical calculation shows that the inside pressure and temperature of the micro-bubble are both relatively much higher than the original bubbles height. These states can keep micro-bubbles much more stable. Due to this stable characteristic of micro-bubbles, the authors call it "stable micro-bubble" or in brief "SMB". A general bubble behavior in subcooled boiling flow is shown in Fig. 3.

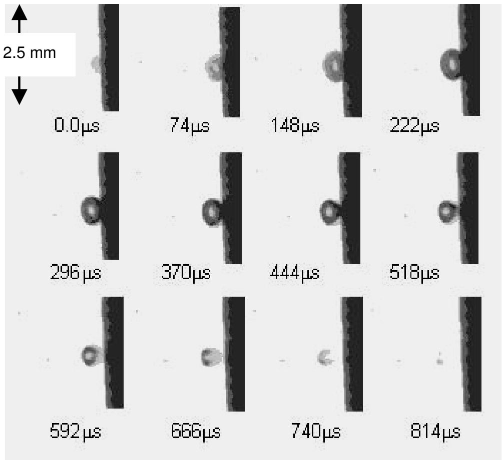

Fig. 3: Typical bubble ebullition cycle in subcooled boiling flow

Table 1: The summery results of the bubble behavior in three subcooled temperatures of the 75, 50 and 25K in fixed LPD 182W/cm at the 1, 25 and 45cm

Degree of Sub-cooling	Attitude	Bubble sites number in 2.5 mm	Bubble growing-time (µs)	Bubble life time (µs)	Bubble max-diameter (µm)	Bubble emission frequency (H z)	Super-Heated-Layer Thickness (µm)
75K	1	3	74~148	148~370	125~435	135~1555	60
	25	4	74~148	148~370	125~280	135~1350	100
	45	5	~148	148~444	156~625	205~540	130
50K	1	4	~148	148~444	94~375	205~945	85
	25	6	~148	148~519	218~500	270~340	115
	45	8	148~222	296~519	155~685	135~475	135
25K	1	6	~148	296~1111	250~685	135~880	55
	25	8	~148	444~889	315~685	205~475	?no
	45	9	148~222	740~1481	440~500	405~610	no

Table 2: The summery results of the bubble behavior in the LPDs of the 182, 290, 430 and 600W/cm in fixed subcooled temperature 75K at the 1, 25 and 45cm

LPDW/cm	Attitude (cm)	Bubble sites number in 2.5 mm	Bubble growing-time (µs)	Bubble lifetime (µs)	Bubble max-diameter (µm)	Bubble emission frequency (Hz)	Super-heated-layer thickness (µm)
600	1	many	? (<<74)	?(<74)	-	-	115
	25	Film Boiling					230~315
	45						285~360
430	1	20	<74	148~222	185	405~880	85
	25	Film Boiling					200~285
	45						215~300
290	1	6	74~148	148~222	125~280	270~1015	70
	25	10(4)	74~148	148~296	95~280	270~945	140~170
	45	12(2)	~74	148~222	65~185	205~610	140~200
182	1	3	74~148	148~370	125~435	135~1555	60
	25	4	74~148	148~370	125~280	135~1350	100
	45	5	~148	148~370	156~625	205~540	130

Table 3: The summery results of the bubble behavior in the flow velocities of the 16, 32 and 53cm/s in fixed LPD of the 182W/cm and subcooling 75K at the 1, 25cm

Flow Rate	Attitude (cm)	Bubble sites number in 2.5 mm	Bubble growing-time (µs)	Bubble lifetime (µs)	Bubble max-diameter (µm)	Bubble emission frequency (Hz)	Super-heated-layer thickness (µm)
53 cm/s	1	3	74~148	148~370	125~435	135~1555	60
	25	4	74~148	148~370	125~280	135~1350	100
32 cm/s	1	4	~148	222~593	~250	135~745	85
	25	6(1)	74~148	~370	80~315	~540	100
16 cm/s	1	4	~148	296~740	59~780	135~745	100
	25	7(1)	~148	~296	80~280	205~475	115

1. The density of active nucleation sites increased with increasing linear power densities and decreasing subcooled temperature.
2. The average bubble maximum diameter decreased with increasing linear power density and subcooled temperature.
3. The bubble emission frequency depends upon the sites.

However, it increased with increasing linear power density and subcooling.

4. Bubble growth time varies between 74μs and 222μs. For large bubbles the results show that increasing boiling length and decreasing linear power density, subcooled temperature or the flow rate will slightly increase bubble growth time.
5. Shorter growth time occurred in lower subcooling temperatures and higher linear power densities.

For a typical bubble the main parameters for linear power density 182 W/cm are listed in Table 4.

Table 4 Typical bubble parameters extracted from the experimental results for linear power density 182 W/cm

Average cavity diameter	Bubble growing time	Bubble life time	Bubble maximum diameter
59 (μm)	148(μs)	500(μs)	555(μm)

3.3. Evaluation of Heat Transfer Shear of Different Mechanisms

In this research the following mechanisms are considered as the most important because of their higher portion in the heat removal from the heating surface:

1. Quenching
2. Super heated layer mixing
3. Latent heat transfer
4. Single-phase heat transfer
5. Turbulent induced by bubble formation and collapse

The quantitative heat transfer portion in percentage for each of the above first four mechanisms was calculated for a typical bubble parameter presented in Table 5. Based on the available models in the literature, there was no exact model for the calculation of the turbulent induced by bubble formation and collapse. Therefore the portion percentage of the turbulent mechanism was calculated by subtracting the summation of the four other mechanisms portion percent from one hundred percent. The evaluated heat transfer shears of the different mechanisms are presented in Table 5.

Table 5. The evaluated heat transfer shear of the different mechanisms

MECHANISMS TYPE	PORTION
Quenching [4,5,6]	(20.5~40)%
Super Heated Layer Mixing [6]	(12~17)%
Latent Heat Transfer [6,7,8,11]	(6~15)%
Single-Phase Heat Transfer [6,9,10,11]	(3~5)%
Turbulent Induced by Bubble Formation And Collapse	(23~58.5)%
Total	100%

As can be seen from Table 5, because of using a different model for calculation of the heat transfer percentage of the four first mechanisms, the portion percentages are expressed in

ranges. The calculated portion percentage for the turbulent induced by the bubble formation and collapse is estimated to be between 23~58%.
The results show that *turbulence induced by the bubble formation and collapse* play a very considerable role in nucleate boiling heat transfer by inducing micro-convection in the different manners of:

(1) induced micro-convection due to evaporation of the entrapped water from the cavity
(2) induced micro-convection due the boundary layer motion around the bubble
(3) Micro-convection due to the special manner of the bubble collapse
(4) Transferring heat and kinetic energy by the stable micro-bubble to the bulk flow
Marangoni-force induced micro-convection

4. Conclusion
The results show that the mechanisms of quenching and turbulent induced by bubble formation and collapse, have between 20.5~40% and 23~58.5% the portion percentage in heat transfers from the heating surface to the bulk flow, respectively. According to the present results, the portion of other mechanisms such as latent heat transfer, super heated layer mixing and single-phase heat transfer are between 6~15%, 12~17%, and 3~5%, respectively. Therefore, it can be concluded that the *quenching* and the *turbulence induced by the bubble formation and collapse* mechanisms play the most important role in nucleate boiling heat transfer by vapor/liquid interchange and inducing micro-convection, respectively.

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