Quantitative Evaluation of Heat Transfer in Bubble Collapse Process in Subcooled Flow Boiling Condition

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Abstract

In this paper an attempt has been made to quantitatively determine the heat transfer contribution of the different mechanisms during the bubble collapse process in subcooled flow boiling condition.

For achieve this objective, the bubble behavior was studied over a vast range of its parameters using the high speed photography results in subcooled flow boiling. The different conditions of inlet subcooled temperature, linear power density (W/cm), flow velocity as well as two heights of a heated rod were considered for heat transfer calculation purpose.

The bubble behavior was analyzed during the subcooled flow boiling on a vertical heating rod with upward coolant water using the results of high-speed photography obtained by Nematollahi in 1999 at Tohoku University.

The heat transfer contributions of the different mechanisms of the subcooled flow boiling were calculated using the applied models in the literature as well as the results obtained from the bubble behavior analysis.

Four mechanisms of superheated layer mixing, turbulence induced by bubble collapse process, latent heat transport and transferring the energy by stable micro bubbles (SMB) (remained after original bubble collapse) were considered to be investigated in different subcooled boiling conditions.

Due to huge number of different-sized bubbles, they are classified against their maximum diameter into the various groups with specified class intervals and then their distribution against bubble maximum diameter is investigated for different experimental conditions.

The heat transfer calculations are conducted using the applied models in the literature as well as the obtained results from the bubble behavior analysis and the results in percentage are evaluated for various conditions of linear power density, inlet subcooling temperature, flow velocity and different heights of the heating rod.

According to the calculated results, the most effective mechanism in the collapse process was nominated to be superheated layer mixing at the moment of bubble departure. Also it was concluded that during the collapse process as bubble starts to shrink an finally collapses in the subcooled liquid at the end of its life, contributes about 18% on the average to heat transferring from the heated rod.

Introduction

Owing to the especial characteristics of subcooled flow boiling, it has been widely used in many technical applications and particularly in high-energy density systems of nuclear reactor power plants. Although nucleation and bubble growth are well studied and frequently investigated in the literature but condensation and bubble collapse process as well as the mechanisms — by which the bubbles transfer energy from a heated wall — are still undeveloped.

The following mechanisms are considered to be investigated in this study for bubble as it starts to shrink and finally collapses at the end of its life in subcooled liquid;

I. Superheated layer mixing at the moment of bubble detachment,
II. Turbulence induced by bubble collapse process,
III. Latent heat transport and
IV. Transferring the heat and kinetic energy by the stable micro-bubbles (SMB) to the bulk flow [1].

The heat transfer contributions of the aforementioned bubble mechanisms were calculated in the present study using the analytical models applied in the literature as well as the subcooled boiling parameters.

The measurement of some parameters including the bubble diameter, active nucleation sites and thickness of the superheated layer formed on the heating surface was conducted through the image processing techniques in MATLAB software. In addition, due to the huge number of the different-sized bubbles, they were classified regarding the bubble maximum diameter with class interval of 0.5 mm.

Table 1. Average and the range of heat transfer contribution of different mechanisms of bubble collapse process during subcooled flow boiling conditions.

	Mechanisms	Heat Transfer Contribution (%)	
		Range	Average
I	Superheated Layer Mixing	2.62 ~ 34.11	9.8
II	Turbulence induced by bubble collapse process	1.18 ~ 11.56	4.12
III	Latent Heat Transport	0.61 ~ 12.23	4.16
IV	Stable Micro-Bubble	0.006 ~ 0.089	0.02
	Total	4.41 ~ 58	18.1

Research Methodology

- **Experimental Data & bubble classification:**

In the present investigation, high-speed photography results of the bubble behavior provided by Nematollahi [1] during subcooled flow boiling are utilized for heat transfer calculations of the bubble mechanisms in the collapse process.

The high-speed photography had been operated over a cross-section of 2.5×2.5mm from the visible test section at 13500 frames per second and for different inlet subcooling temperature of 25, 50 and 75K, upward coolant flow velocities of 16, 32 and 53 cm/sec, linear power densities of 66~360 W/cm and at 1 and 25 cm from the beginning of the heated rod.

This study was performed on over than 4000 frames of the high speed photography. Due to huge number of observed bubbles with various diameters, they were classified relative to the maximum bubble diameter with class interval 0.1 mm according to Dell Valle and Kenning research [2].

- **Evaluation of Heat Transfer Contribution of the Different Mechanisms:**

I. Superheated layer mixing after bubble detachment

Following the bubble departure into the bulk flow some superheated liquid from thermal boundary layer is released periodically into the subcooled bulk flow by the bubble in its wake [3]. Sivagnanam et al. [4] have offered the following model which is obtained from an energy balance as For modeling the influence of this mechanism on the heat transfer from the heating surface;

$$\phi_{SHL} = \delta_{\mathrm{SHL}}\,\pi D^{2}_{m-i}\rho_l C_p (T_w - T_f) N_{B-i} \tag{1}$$

Where, δ_{SHL} is superheated layer thickness. The number of bubbles having the diameter corresponding to ith class is denoted by $N_{B\text{-}i}$.

II. Turbulence induced by bubble collapse process

The special manner of bubble collapse and perturbation in the shape of its boundary layer that is ascribed to the work of surface tension [1], causes the bulk liquid to flow toward the heating surface and thereby enhances the local heat transfer coefficient. Mayinger [5] by using the high speed holographic interferometry method described the heat transfer through this phenomenon in terms of Nusselt correlation;

$$Nu = 0.185\,(\mathrm{Re}_{bub})^{0.7}(\mathrm{Pr}_{liq})^{0.5} \tag{2}$$

All transport properties in the Reynolds and Prandtl number are referred to the liquid state. The characteristic diameter in the Reynolds and Nusselt number has been expressed by the bubble maximum diameter (i.e. the diameter at the moment of bubble departure). Therefore the heat transfer contribution of the bubbles, as a result of this phenomenon, in each bubble diameter class could be obtained by;

$$Q_{SM-i} = \frac{\pi}{4} h_{f-i} N_{B-i} D_{m-i}^{3} t_L (\Delta T_{sat} + \Delta T_{sub}) \tag{3}$$

Where, $h_{f\text{-}i}$ is the heat transfer coefficient related to bubble with diameter $D_{m\text{-}i}$. Since the bubble collapse period is usually much longer than the bubble growing time, the bubble life time (growing time + collapse time) is considered as the duration of this mechanism in the present investigation.

III. Latent heat transport

This latent heat transfer is occurred in the thermal boundary layer around the bubble and eventually causes the bubble to collapse. The heat content of the departing bubbles is obtained from an energy balance as;

$$Q_{lat-i} = \frac{\pi}{6} D^{3}_{m-i}\rho_{g-i} h_{fg} N_{B-i} \tag{4}$$

Where, $\rho_{g\text{-}i}$ is the vapor density of the bubble having maximum diameter corresponding to the ith class. Also, h_{fg} is the latent heat of evaporation related to the bubble with its maximum diameter.

IV. Transferring the energy by stable micro-bubbles (SMBs)

Following the collapse process, only a very small volume of the bubble remains which is much more stable in comparison with the original one. It is called "stable micro-bubble" or in brief "SMB" [1] as a result of its relative long lifetime (10~60 times the original bubble's life time).

Immediately after SMBs formation, they escape quickly from their location toward the bulk flow. Three heat transfer mechanisms for SMBs have been reckoned by Nematollahi [1] as follows;

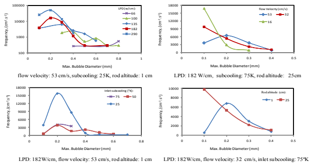
a) Transferring the kinetic energy by SMBs.
b) Latent heat transport due to SMBs.
c) Heat transfer enhancement due to the liquid agitation induced by SMBs in bulk flow.

For simplicity, the SMB motion was assumed to be symmetrical in three dimensions of x, y and z. Therefore the kinetic energy of SMB was calculated as follows:

$$E_k = \frac{\pi}{4}\left[\rho_{SMB} . D^{3}_{SMB} . v_{SMB\_x}^{2}\right] \tag{5}$$

Where, ρ_{SMB} is the vapor density inside the SMB, D_{SMB} is the diameter and v_{SMB_x} is the linear velocity of SMB in each direction. For latent heat transport due to condensation of SMBs, the following relation was used;

$$E_{lat} = \frac{\pi}{6} D^{3}_{SMB}\,\rho_{SMB}\,h_{fg} \tag{6}$$



flow velocity: 53 cm/s, subcooling: 25K, rod altitude: 1 cm

LPD: 182 W/cm, subcooling: 75K, rod altitude: 25cm

LPD: 182W/cm, flow velocity: 53 cm/s, rod altitude: 1 cm

LPD: 182W/cm, flow velocity: 32 cm/s, inlet subcooling: 75°K

Fig. 2 Bubble distributions against maximum bubble diameter.

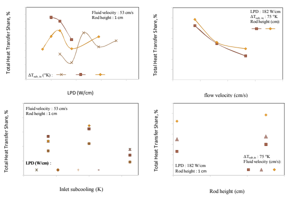


Fig. 3 Heat transfer contribution of superheated layer mixing mechanism in different subcooled flow boiling conditions.

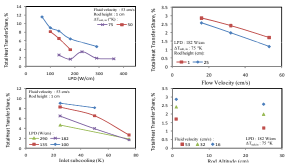


Fig. 4 Heat transfer contribution of "micro-convection due to special manner of bubble collapse" in different subcooled flow boiling conditions.

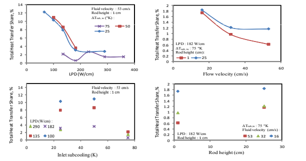


Fig. 5 Effect of different subcooled boiling conditions on total heat transfer contribution of latent heat transport mechanism.

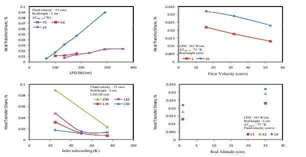


Fig. 6 Total heat transfer contribution of stable micro-bubbles in different subcooled flow boiling conditions.

Results

The effect of each condition on bubbles distribution has been studied among any of the four subplots in Fig. 2. As shown in this figure, in each subplot only one condition was considered to be varied while other conditions were kept constant. The results show that with increase of linear power density (LPD) or at higher parts on the heated rod, the bubble generation rate becomes large in such a way that the small bubbles are more produced while the larger ones are slightly disappeared. Therefore the distribution of bubbles against their maximum diameter as well as the average bubble size are shifted toward the smaller values of the bubble diameter. This is also in agreement with Bergles and Rohsenow ([6]).

The increase in the bulk temperature at higher parts of the heated rod causes the surface temperature to slightly increase and therefore makes more small-sized cavities to be activated as well as ceases the larger active sites from nucleation.

The calculated heat transfer contribution of the different mechanisms (i.e. superheated layer mixing, special manner of bubble collapse, latent heat transfer and transferring energy by stable micro-bubbles to the bulk flow) based on the afore-mentioned approaches are shown in Figs. 3 to 6 for various experimental conditions.

The contributions of the different bubble collapse mechanisms to total heat flux are listed in Table 1 either as the range or average value as well as the total heat transfer percentage of bubble collapse process as it starts to shrink and finally collapses at the end of its life in subcooled liquid.

The contributions of superheated layer mixing mechanism to total was calculated 1.29~17.2% with average value of 9.59%, turbulence induced by bubble collapse 1.18~11.56% and with average value 4.12%, latent heat transfer mechanism 0.61~12.23% and with mean value of 4.16%.

The kinetic energy of an ordinary microbubble was calculated 10^{-10} J. Considering the density of the bubbles in this study, ranging from 1351 to about 9×10^{4} $\mathrm{cm^{-1}s^{-1}}$, the heat transfer contribution of the kinetic energy mechanism of SMBs to total heat flux was obtained around 0.001%. Also, the latent heat mechanism of SMB contributed about 0.03% on the average. Nevertheless, SMBs contributed totally 0.006~0.089 % with mean value of 0.02% to total heat flux. Therefore in contrary of the earlier researches no significant amount of heat could be transferred as a result of the SMBs motion into the bulk liquid.

Consequently the most effective bubble mechanism for transferring heat during the collapse process was nominated to be superheated layer mixing at the moment of bubble detachment. Also it was concluded that during the collapse process as bubble starts to shrink an finally collapses in the subcooled liquid at the end of its life, contributes about 18% on the average to heat transferring from the heated rod.

Furthermore, an inverse dependence on flow velocity is also demonstrated by the heat transfer contribution of all mechanisms. With increase of LPD or liquid subcooling, as to be expected, the total number of bubbles, being mostly small bubbles, are increased but the small bubbles incapacity for heat transferring leads to a reduction in the total heat transfer contribution of latent heat transport and turbulence mechanism as well. Also, it was concluded that the heat transfer contribution of the superheated layer mixing mechanism varies not linearly with change of LPD.

Conclusion

An investigation was made in this paper for quantitative evaluation of the heat transfer contribution of the different bubble mechanisms during the bubble collapse process in subcooled flow boiling condition.

To achieve this objective, the bubble behavior was analyzed through high speed photography results obtained by Nematollahi during the subcooled flow boiling on a vertical heating rod with upward coolant water using the results of high-speed photography.

The heat transfer calculations were conducted using the applied models in the literature as well as the obtained results from the bubble behavior analysis and the results in percentage were evaluated for various conditions of linear power density, inlet subcooling temperature, flow velocity and different heights of the heating rod.

The most effective bubble mechanism for transferring heat during the collapse process was nominated to be superheated layer mixing with average contribution of around 10%. Also it was concluded that the bubbles contributed around 18% on the average during the collapse process. In addition, in contrary of the earlier researches no significant amount of heat could be transferred by SMBs into the subcooled bulk liquid as a result of their small size compared with the original bubbles.

The aim of this study was mainly to improve the comprehension of the highly complicated phenomena influencing the heat transfer process in the collapse process in subcooled flow boiling.

References

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