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Recognition of Net Vapor Generation in Subcooled Flow Boiling

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***Abstract*— Point of net vapor generation (NVG) or onset of significant void flow (OSV) is investigated in a vertical rectangular channel. It is important point in subcooled flow boiling due to the dramatic increase in the amount of vapor. Experimental evidence shows that the onset of significant void (OSV) generally signals of flow instability in a system with pressure driven boundary condition and also influences on the reactivity of the liquid cooled nuclear reactors. Bubble detachment from nucleation site or heated surface was introduced frequently as a triggering mechanism of net vapor generation. However, bubble detachment was observed before point of NVG, in this work. Experimental results are explored in this work and then simple measurable way is proposed to recognize point of NVG in subcooled flow boiling. In this way, net vapor generation is a point that subcooling temperature is equal to excess wall temperature. This is a point that condensation rate is in balance with vaporization rate in subcooled flow boiling, and afterward vaporization exceeds from condensation, significantly.**

Keywords—subcooled flow boiling; void fraction; net vapor generation (NVG); onset of significant void (OSV)

I. Introduction

In describing the process of subcooled boiling in forced convective flow of liquid in a confined channel it has been noted that vapor in various amounts is generated at the heated surfaces in the channel. In the particular case of the design of liquid cooled nuclear reactors information on the void fraction under subcooled conditions is often required because of its influence upon the reactivity of the system. It is frequently postulated that in the representation of subcooled boiling, at first, for high degrees of subcooling the vapor generated remains as discrete bubbles attached to the surface whilst growing and collapsing; voidage in this region is essentially a wall effect. At somewhat lower subcoolings, bubbles detach from the surface, condensing only slowly as they move through the slightly subcooled liquid; voidage in this region is a bulk fluid effect. This point is known as point of net vapor generation (NVG). The void fraction rises sharply with length from the transition point of NVG. Bowring [1] proposed a model for the estimation of void fraction in this region. In addition, simple empirical methods of calculating the void fraction in the subcooled boiling of water have been suggested by several researchers. A simple expression for the void fraction at point of NVG has been suggested by Levy [2] from a consideration of the forces exerted on a vapor bubble attached to the wall and the temperature distribution in the single-phase liquid away from the heated surface. Bowring [1] applied the following criterion to establish this point.

$$\Delta T_{sub,NVG} = \eta \frac{q_w}{G v_f} \quad (1)$$

Where $\Delta T_{sub,NVG}$ is the subcooling at which bubble detachment occurs, η is an empirical factor derived from experimental data for water and found to depend only on the system pressure. He proposed the relationship for water over the pressure range 11 to 138 bar.

Saha and Zuber [3] have proposed a simple method to calculate the point of NVG which can be assumed to be coincident with the point of bubble detachment. At low flow-rates the bubble detachment is assumed to be thermally controlled, occurring at a fixed value of Nusselt number [$q_w D/k_f \Delta T_{sub,NVG}$]. At high flow-rates bubble departure is hydrodynamically induced and occurs at a fixed Stanton number [$q_w/Gc_p \Delta T_{sub,NVG}$].

$$[If \;\; Pe < 70{,}000]\, \Delta T_{sub,NVG} = 0.0022 \frac{q_w D}{k_f} \quad (2)$$

$$[If \;\; Pe > 70{,}000]\, \Delta T_{sub,NVG} = 153.8 \frac{q_w}{Gc_p} \quad (3)$$

Above correlation is simple to use and a recent critical review of models by Lee et at. [4] has shown that it remains the most accurate. However, many observational investigations show the contradictory with the base of NVG models. Before the point of NVG, at the condition close to onset of nucleate boiling (ONB), bubbles tended to be lifted off the wall and collapsed in subcooled bulk liquid, at atmospheric pressure [5-7, 9]. Whilst, under moderate pressure conditions, it was observed that bubbles mostly slid on the heated surface at the incipient boiling point [18]. In the experiments using FC-87 as a working fluid, bubbles departed from nucleation sites and slid on the surface for a long distance [8].

In this paper, experimental investigation was performed in a vertical upward subcooled flow boiling to introduce a new simple way of recognition of point of NVG.

II. Experimental Description

Since the experimental facilities and procedures were extensively described elsewhere [9-11], brief explanation is given here. The thermal-hydraulic test loop and the vertical rectangular test section that were used in this study are depicted schematically in Fig. 1. Prior to the experiment, filtered and deionized tap water was kept boiling at least for an hour in a storage tank containing heaters for degassing. The loop was then vacuumed to deliver the degassed water from the storage tank by means of pressure difference. As shown in Fig. 1b, a part of one side of the rectangular test section was heated using two cartridge heaters embedded in a copper block to produce boiling in the rectangular flow channel of 10 x 20 mm. In the test section, the two measuring sections with sight glasses were designed to acquire movie data. The positions of the measuring sections were 100 and 300 mm from the lower end of the heated section. In this study, visualization was performed at the upper measuring section using a high speed camera and the thermal flow parameters such as the flow rate and fluid temperatures were recorded using a data acquisition system.

In this study, pressure and mass flux was used as a main experimental parameter. Pressure P set to around 1 bar and, mass flux G is in range of 400, 460 and 530 kg/m^{2}s. In each series of experiment, the values of pressure P, mass flux G and heat flux qw were kept fairly constant and the liquid subcooling at the inlet ΔT_{sub} was decreased step by step. The range of ΔT_{sub} was set to cover the condition of ONB and that close to saturation boiling. According to specification of instruments, the measurement accuracies of P, ΔT_{sub} and G were estimated less than 10kPa, 2 K and 10 kg/m^{2}s, respectively.

The optical void probe is used to obtain local time-averaged void fraction. The position of void probe tip can be adjusted from the close to the heated surface toward center of channel using micrometer. Thus, to attain lateral void distribution, local time-averaged void is measured in the position close to the heated surface toward center channel step by step until no signal is detected by the probe.

III. Experimental Results and Discussion

The temperature difference between the vapor in a bubble and the surrounding liquid is the driving factor for heat transfer between the two phases. When the liquid is at a lower temperature than the bubble, heat will be transferred from the bubble into the liquid, causing some of the vapor inside the bubble to condense and the bubble to collapse eventually. If subcooling is relatively low, the bubble collapse period will be longer and the process will be controlled by the heat transfer at the interface. When the liquid is at a higher temperature than the bubble, heat will be transferred from the liquid to the bubble, causing the bubble to grow and rise to the top under the influence of buoyancy. Therefore, the treatment of the bubble in subcooled flow boiling, particularly in a heat-transfer controlled regime, is a very complex phenomenon.

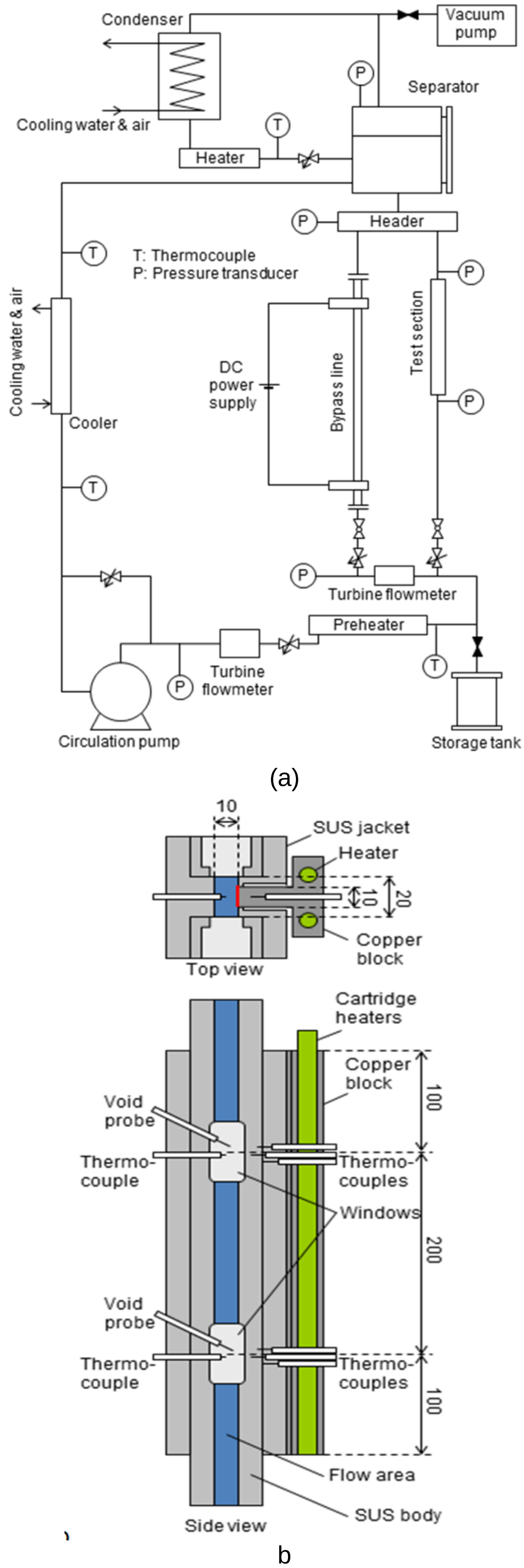

Fig. 1. *Schematic diagram of the experimental facility; (a) experimental loop and (b) test section*

Although, the evaporation and condensation rate is generally assumed to be controlled by the internal and external thermal resistances and the temperature, however, it can be affected by many parameters. It is well understand that the nucleated bubble size is influenced by pressure and mass flux of the flow [18]. According to Fig. 2, large portion of big nucleated bubbles expose with subcooled liquid and small portion is in the superheated layer. Contrary, for small bubble a small portion is in the subcooled liquid, where the condensation process is reduced by the small thermal gradient between the liquid and the vapor phase. Therefore, collapse rate is different owing to bubble size. Moreover, the size of bubbles can affect bubble behavior: Lift off for big bubbles and sliding for small bubbles [9]. Due to acting forces on bubble or collapsing rate of bubble, lift-off bubble may return to heated surface after migration and then grows faster [10]. At high injection frequencies, a bubble might enter into the wake of the previous one, thus changing both the flow and temperature external fields [11]. Hence, a comprehensive theoretical analysis that would take into account all the parameters and possibilities seems to be impossible at this stage. Due to this complexity, many theoretical models have been developed which address a few phenomena in a narrow range of parameters while neglecting others [12,13].

A. *Heat Transfer in Rectangular Channel*

All the former studies neglected the void between ONB and NVG and proposed their void model after PNVG. For the rectangular channel with cross area (W×H) and heated surface (w×z), finding out the relation between void fraction α and thermal-equilibrium vapor quality x_{eq} (or heat flux q_w) to mechanistically investigate void development, is a main goal of this study. Thermal-equilibrium vapor quality can be express as:

$$x_{eq} = \frac{1}{h_{fg}}\left(\frac{q_{net,ev}w}{GWH}z - c_p\Delta T_{sub}\right) \tag{4}$$

Where z is axial distance from the start of activated heated surface. Therefore

$$\frac{\partial x_{eq}}{\partial z} = \frac{q_{net,ev}w}{Gh_{fg}WH} \tag{5}$$

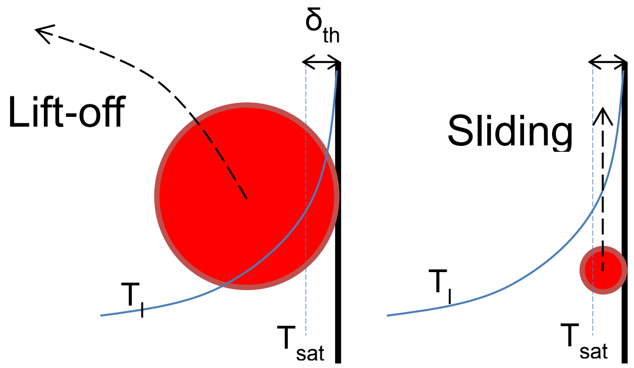

Fig. 2. *Bubble behaviors in subcooled flow boiling; lift-off from surface (left) and sliding on the surface (right)*

In the other hand, conservation of mass of vapor phase is expressed as:

$$\frac{\partial}{\partial t}(\alpha\rho_g) + \frac{\partial}{\partial z}(\alpha\rho_g u_g) = \Gamma_g = \Gamma_v - \Gamma_c \tag{6}$$

where Γ_g is the net vapor generation rate per unit mixture volume, which is difference between vapor generation rate Γ_v, and condensation rate Γ_c. Net vapor generation rate is determined by the heat flux, and the manner that heat flux is partitioned between absorption by the subcooled liquid and the evaporation processes should be determined. Therefore, calculation of Γ_g is difficult.

By assuming steady state condition and ρ_g and u_g=const. we can drive following equation from two last relations as:

$$\frac{\partial \alpha}{\partial x_{eq}} = \frac{h_{fg}GWH}{w\,\rho_g u_g}\frac{(\Gamma_v - \Gamma_c)}{q_{net,ev}} = C\,\frac{(\Gamma_v - \Gamma_c)}{q_{net,ev}} \tag{7}$$

According to above equation and experimental approach changing void fraction, the influence parameters are Γ_g and heat flux while other parameters do not change significantly (C=const.).

Net vaporization heat flux is $q_{net,ev} = q_v - q_c$. The net vapor generation is due to two terms: evaporation (source term) and condensation (sink term). During subcooled boiling, part of the heat flux goes into raising the mean liquid temperature and part goes into vapor formation. This latter term is a balance between the vapor generated at the wall and that condensed by the subcooled fluid (Fig. 2). Void fraction increase as well as equilibrium quality raise-up. Therefore, evaporation term should be higher than condensation term and particularly after NVG. Evaporation and condensation heat rate are obtained as following:

$$Q_v = h_{fg}A_{fg}(T_w - T_{sat}) = h_{fg}A_{fg}\Delta T_w \tag{8}$$

$$Q_c = h_{fg}A_{fg}(T_{sat} - T_\infty) = h_{fg}A_{fg}\Delta T_{sub} \tag{9}$$

Where A_{fg} is the interfacial area and h_{fg} is the interfacial heat transfer coefficient. Ranz and Marshall (1952) propose following correlation for calculating h_{fg}:

$$h_{fg} = \frac{k_l}{d_b}Nu = \frac{k_l}{d_b}\left(2 + 0.6\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}\right) \tag{10}$$

For the sake of simplicity, steam is assumed to be at saturation condition. Within the subcooled liquid (T_l< T_{sat}) steam is condensing with the mass transfer rate per unit volume:

$$\Gamma_c = \max\left(\frac{Q_c}{H_{fg}}, 0\right) \tag{11}$$

Where, H_{fg} is latent heat enthalpy. With superheated liquid, fluid is evaporating at the rate:

$$\Gamma_v = \max\left(\frac{Q_v}{H_{fg}}, 0\right) \tag{12}$$

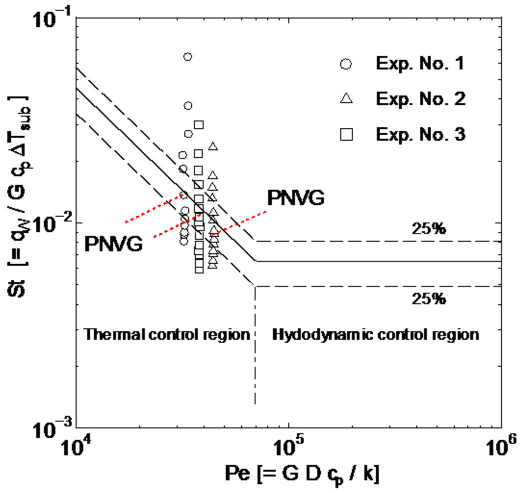

Fig. 3. *Three series of experimental results in 1 bar pressure and mass flux G in range of 400, 460 and 530 kg/m^{2}s, comparison with Saha and Zuber correlation*

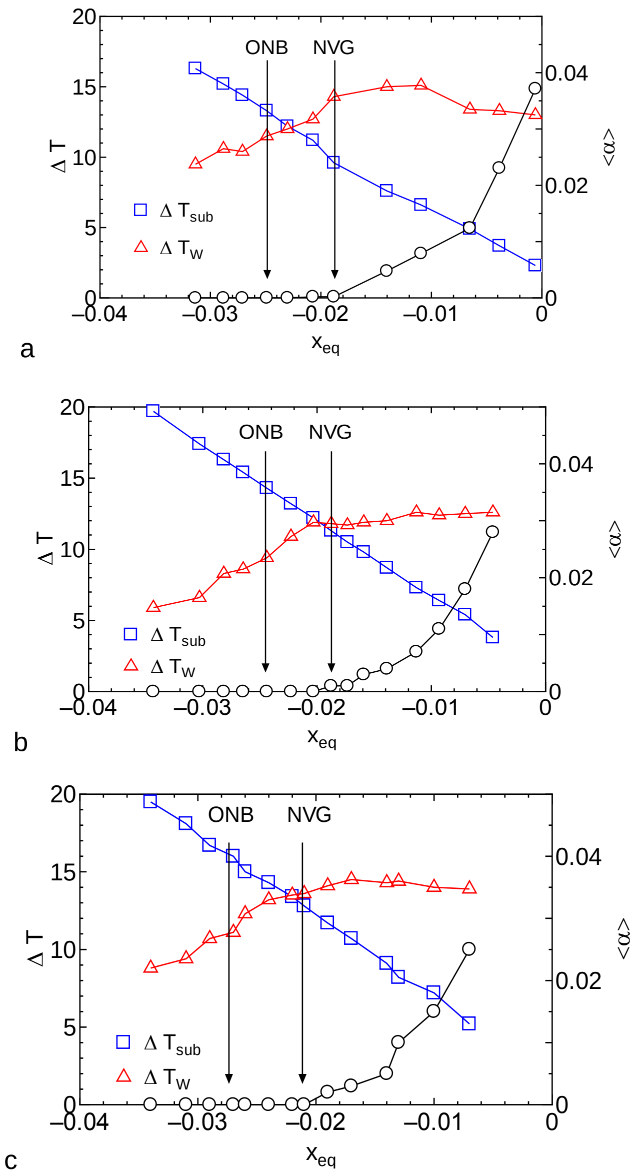

Fig. 4. *Dependence of the mean void fraction<α>, excess wall temperature ΔT_w and subcooling temperature ΔT_{sub} on the thermal-equilibrium vapor quality; (a) G=400 kg/m^{2}s; (b) G=460 kg/m^{2}s; (c) G=530 kg/m^{2}s*

B. *Experimental Results*

Three experimental series at atmosphere pressure with different mass flux G in range of 400, 460 and 530 kg/m^{2}s were completed and demonstrated in Fig. 3 as Exp. No. 1 to 3. The experiments compared with Saha and Zuber correlation which is plotted in this figure with 25% tolerance. Furthermore, in Fig. 4 average cross-sectional void fraction is shown against thermal-equilibrium vapor quality for three experiments to determine point of NVG. For all experiments, point of NVG is depicted in Fig. 3 by arrow and it is found good agreement with Saha and Zuber correlation.

It can be evidently assumed while $\Gamma_C \geq \Gamma_V$ the void fraction cannot increase in the channel. In subcooled flow boiling, there is a point that vaporization rate is in balance with condensation rate and afterward evaporation rate exceed from condensation rate. This point can be assumed as point of NVG.

For simplicity, if we assume same interfacial area and same interfacial heat transfer coefficient for both condensation and vaporization transport phenomena, in according to Eq. 11 and 12 it can be said that the ratio of $\Delta T_w/\Delta T_{sub}$, denotes the vaporization rate to condensation rate, Γ_V / Γ_C . Figure 4 demonstrates trend changes of ΔT_w and ΔT_{sub} versus thermal-equilibrium vapor quality. The interesting result of all experiments is that in proximity of point of NVG the curve of ΔT_w crosses the curve of ΔT_{sub}. In the other word, the ratio of $\Delta T_w/\Delta T_{sub}$ is around unity at the point of NVG and afterward exceed from unity parametrically. It may seem a simple result but it is very important and useful to detect point of NVG. This shows that at NVG the amount of condensation is in balance with vaporization rate, which was calculated in our previous work [10, 11].

IV. Conclusion

Experimental investigation in subcooled flow boiling was performed to find a simple way to determine point of net vapor generation. Net vapor generation is a point that vaporization rate is significant that void fraction in the channel is increased drastically. Bubble detachment from active nucleation site was introduced frequently as a triggering mechanism of NVG. But we observed that bubble detachment, lift-off from heated surface or sliding on the surface, occurs before NVG at the incipience of boiling. In subcooled flow boiling mass transport phenomena by vaporization and condensation are coincide. However, there is a point that vaporization rate Γ_v is in balance with condensation rate Γ_c and afterward vaporization is exceeded from condensation rate. Here, Γ_v and Γ_c is related to excess wall temperature ΔT_w and subcooling temperature ΔT_{sub}. Experimental results show that point of NVG is when ΔT_w is equal to ΔT_w.

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