Judgement and calculation method research of onset of nucleate boiling under tube outside pool boiling condition

Yanbin Liu, Xiangyu Meng, Xuesheng Wang, Yuyang Yuan

School of Mechanical and Power Engineering, East China University of Science and Technology, Room 637, Building 17,130 Meilong Road, Shanghai 200237, China

Author addresses: lyb2006666@163.com,872026442@qq.com, wangxs@ecust.edu.cn, 124743224@qq.com

Corresponding author’s e-mail address: wangxs@ecust.edu.cn

Abstract. Pool boiling is a common phenomenon and widely utilized to realize the heat transfer process in different fields. In advanced nuclear power plant such as the AP1000 passive safety system, pool boiling is also used to fulfil the residual heat removal function through the Passive Residual Heat Removal Heat Exchanger (PRHR HX). The onset of nucleate boiling (ONB) point is one of the key points during heat transfer mechanism changing process. The judgement and predicted method of the ONB under tube outside pool boiling condition is still a difficulty and needs further investigation. In this paper, the heat transfer characteristic of the ONB point is experimentally studied by combining with high speed camera technology. Base on the observing and calculating results, the ONB point is judged. The applicabilities of different ONB point predicting correlations are estimated and an empirical correlation predicting wall superheat degree more accurately is developed.

1. Introduction

The Passive Residual Heat Removal Heat Exchanger (PRHR HX) is an important equipment of the passive safety system in advanced nuclear power plants such as AP1000. Heat transfer characteristic study of the PRHR HX has received more and more attention. The fundamental heat transfer mechanism of the PRHR HX submerged in the IRWST is heat transfer through the C-shaped tubes in a large volume of water pool.

Large volume boiling is also called pool boiling, which occurs through still liquid heated by the wall of container or the solid interface immersed in the liquid. For example, liquid heated by wire/plate immersed in it, or heated by horizontal or vertical wall inserted in it. K. Cornwell[1] made a definition of tube outside pool boiling, there is no externally imposed liquid velocity in the general potential field around the tube, and it is accepted that, to an observer on the tube surface, the tangential bubbly flow will differ little between pool boiling and boiling with an imposed liquid flow.

ONB point is one of the key parameters during tube outside pool boiling process, it is the transition point from single phase natural convection to subcooled pool boiling. Currently, there a number of definitions of ONB point in literature about pool boiling and forced convection boiling. In most of the definitions, statement of bubble generation or bubble departure is given. Through below definitions, we can see that bubble feature during heating process is important to the investigation of ONB point. In this study, high speed camera is used to photograph bubble feature generating on tube outside wall during heating process.
(1) Yang et al. [2]: the first point where bubble begins generating but does not departs from heating surface in the channel.

(2) Lv et al. [3]: the first point where bubble generates on the wall along flow direction.

(3) Collier et al. [4]: the point where wall superheat is large enough to make vapor phase nucleate on the wall in pool boiling.

(4) Kandlikar et al. [5]: the first point where bubble generates on the wall along flow direction.

(5) Basu et al. [6]: the first point where bubble generates on the wall along flow direction.

Up to now, there are already a number of studies about the pool boiling heat transfer or forced convective heat transfer. Judd and Merte [7] analyzed the changing tendency of superheat with subcooling at constant heat flux under nucleate pool boiling condition. Surface superheat firstly increased and then decreased as subcooling increased. Merte and Clark [8] investigated the influence of acceleration on pool boiling heat transfer. It was found that none of the correlations mentioned in literature could predict the trends resulting from acceleration of the experimental system well. Ulucakli and Merte [9] continuously studied the effect of acceleration on pool boiling heat transfer through modified experimental facilities. Results showed that for fixed heat flux and acceleration, heater surface superheat increased and then decreased with the increasing of liquid subcooling. Wiebe and Judd [10] conducted a series of experiments and measurements in order to study water boiling on a copper surface, under various combinations of heat flux and subcooling. Increasing heat flux and decreasing subcooling were observed to result in a decreasing extrapolated superheat layer thickness. Sultan and Judd [11] investigated active nucleation sites and bubble flux density through water boiling experiments by using a single copper surface as heater at atmospheric pressure. Results indicated that the active nucleation sites were randomly located and their spatial distribution followed the Poisson distribution, and bubble flux density was non-uniformly distributed even though heat flux was uniform over the heating surface. Hsu [12] proposed a model to define the size range of active cavities as a function of wall temperature or heat flux. It indicated that maximum and minimum size of effective cavities are functions of subcooling, pressure, physical properties and thickness of superheat liquid layer. Bergles and Rohsenow [13] investigated ONB point heat transfer under forced convection condition. An empirical correlation was given. Su et al. [14] conducted a series of experiments to study forced convection boiling heat transfer. Influence factors on ONB point were analyzed and correlation was fitted to predict the heat flux of ONB point in narrow channel. Yang et al. [2] studied subcooled heat transfer in annular channel under natural convection condition. An empirical correlation was developed through analyzing experimental results to predict ONB point. Some other researchers such as Sato-Matsumara [15], Davis-Anderson [16] and Kandlikar [17] also conducted a series of experiments to investigate heat transfer of ONB point and modified formulas were put forward to predict ONB point in their study. Furthermore, Bourdon [18] conducted experimental study on pool boiling heat transfer. Degassed water boiling on surfaces of hydrophilic and hydrophobic cases was performed, the ONB point has been measured and the influence of the wettability has been quantified. Bourdon [19] also conducted a series of experiments of water on smooth glass surfaces under pool boiling condition. Surface wettability was changed by grafting different monolayers. Superheat at the ONB point was measured. A non-linear decrease of the superheat at the onset of boiling was observed with decreasing the wettability of the surface.

Most of above-mentioned studies investigated the occurring condition and modified calculating correlation of ONB in vertical annular channel, horizontal narrow passage or vertical narrow passage under forced convection heat transfer situation. Now available literature has already pointed out that research findings under forced convection and confined space conditions cannot be directly used to predict heat transfer calculation under natural convection subcooled boiling conditions. Judgement of ONB point and applicability of different correlations in literature for tube outside pool boiling heat transfer need further investigation and verification. Furthermore, complexity of pool boiling and predicting accuracy requirement of ONB point push the combination of different research method and technology. In this paper, experimental data, heat transfer calculating results and bubble features photographed by high speed camera are analyzed cooperatively.
2. Experimental setup

Fig. 1 is the photo of experimental setup, the operation interface of data acquisition and high speed camera and the layout of thermocouples.

The experimental setup mainly consists of the C-tube, water tank, electric heater, pump, thermocouples, flowmeter and tank cover etc. The material of the C-tube, water tank is 304 stainless steel. The power of electric heater is 15kW. The outside diameter of the C-tube is 19.05mm and the wall thickness is 1.65mm. 2 Pt100 and 34 J type thermocouples are used to measuring temperature. All thermocouples and other instruments were calibrated before experiment. In order to decrease heat loss during experiment process, insulation layer was installed outside the water tank, oil tank and pipe. A tank cover filled with water was used to cool most of the steam generated during the experiment. As the cover was not tightly sealed with the tank wall, the operation pressure of the water is atmospheric pressure. High speed camera used here was to photograph bubble feature generated outside tube. Table 1 is main performance parameter of the high speed camera.

| Model          | Parameter                  | Value                          |
|----------------|----------------------------|--------------------------------|
| Mikrotron EoSens® | Active pixel @ Max. framerate | 1,280 (H)×1,024 (V) @506 fps  |
| CL             | Max. framerate             | 120,000 fps                    |
|                | Min. shutter speed         | 2 μs~1 s                       |
|                | Power supply               | 8~24 V DC                      |

T-1 and T-2 were separately installed at the inlet and outlet of the C tube to measure oil temperature. Tw-1 to Tw-8 were tube wall temperature measuring points, three thermocouples were equidistantly installed at each point and take an average. Tb-1 to Tb-6 were water temperature measuring points (vertical direction). Tb-7 to Tb-10 were water temperature measuring points (horizontal direction). Tb-7 and Tb-8 were located at L-2 level, and Tb-9 and Tb-10 were located at L-3 level. Two sight glasses for observing bubble feature were installed on tank wall, detail locations are shown in Fig. 1(c). Besides sight glasses, additional fill light holes were opened.

| Table 2 Summary of the experimental working condition |
|---------------------------------|-------------------|-------------------|
| Oil flow rate(m³/h)             | Oil inlet temperature(℃) | Water initial temperature(℃) |
| I                               | 2.0               | 178.5             | 35.0              |
| II                              | 2.0               | 167.5             | 35.0              |
| III                             | 2.0               | 156.0             | 45.0              |

Before experiment, non-condensable gas was discharged after the water adding process. The degassing process finished until all the water in tank was boiling. During the process, continuously collected experimental data and photographed bubble features outside the c-tube. When all water in tank
boiling for a period of time, experiment was finished. Table 2 is summary of the experimental working condition.

3. Experimental data processing method

During experimental process, directly obtained data included thermal oil inlet and outlet temperature, tube wall temperature, tank water temperature and thermal oil flow rate. Experimental data was calculated through heat balance equation and Newton cooling law:

$$Q = M c_{pf} \Delta T = qA = hA \left(T_e - T_f\right)$$  \hspace{1cm} (1)

In formula (1), $Q$ is heat transfer rate through tube wall, W; $M$ is mass flow rate, kg/s; $c_{pf}$ is specific heat, J/(kg·℃); $\Delta T$ is temperature difference between oil inlet and outlet, ℃; $q$ is heat flux through tube wall, W/m²; $A$ is effective heat transfer area of C tube, m²; $h$ is tube outside heat transfer coefficient at corresponding measuring point, W/(m²·℃); $T_e - T_f$ is the difference of tube outside wall temperature and tank water temperature at corresponding height, ℃.

In the experiments, direct measurement error was calculated based on instrument specification, and indirect measurement error was analyzed through the method introduced in literature[20]. The errors of thermal oil temperature, tank water temperature, tube wall temperature, thermal flow rate, heat transfer rate, heat flux and heat transfer coefficient are separately ±0.51 ℃, ±0.40 ℃, ±0.46 ℃, ±0.02 m³/h, 1.6%, 2.7% and 3.5%.

4. Result and discussion

4.1. Judgment of ONB point of tube outside pool boiling

In this paper, space observation method is adopted to obtain tube outside bubble generation and movement phenomenon of the centers of upper horizontal and vertical sight glasses.

4.1.1. Wall temperature, water temperature, heat transfer coefficient and bubble feature analysis of the upper horizontal observation sight glass center.

Fig. 2(a) is the trends of tube outside wall temperature, corresponding tank water temperature and heat transfer coefficient with time at the central position of the upper horizontal observation point. Tube wall temperature reaches saturation temperature of liquid water at $t_1$, water temperature reaches saturation temperature at $t_3$. At $t_2$ (9620s) between $t_1$ and $t_3$, an obvious turning point occurs on heat transfer coefficient curve and the slope of the curve begins increasing obviously. Wall temperature and water temperature are still rising steadily. Fig. 2(b) is bubble feature outside tube at the center of the upper horizontal observation point at $t_2$. Bubbles uniformly generate on tube outside surface but rarely depart, a few bubbles depart from the surface may because micro convection in tank water caused by density difference. Based on above analysis, bubble feature is in good agreement with the definitions in former studies.

![Fig. 2 The trends of important parameters and the bubble feature outside the horizontal tube](image)
4.1.2. Wall temperature, water temperature, heat transfer coefficient and bubble feature analysis of the vertical observation sight glass center. Fig. 3(a) is the trends of tube outside wall temperature, corresponding tank water temperature and heat transfer coefficient with time at the central position of the vertical observation point. Similar to Fig. 2(a), wall temperature and water temperature separately reach saturation temperature at t1 and t3. At t2 (11675s), heat transfer coefficient begins rising rapidly. Fig. 3(b) is the bubble feature outside tube at the center of the vertical observation point at t2. Likewise, bubbles uniformly generate on tube outside surface but rarely depart. It also agrees well with the definitions in most literature. After t2, more and more bubbles detach from tube outside wall, enhance heat transfer and promote temperature rising.

4.1.3. Relationship between heat transfer coefficient and wall superheat $\Delta T_w$. Heat transfer and wall superheat are important parameters during heat transfer process. Relationship between heat transfer coefficient and wall superheat $\Delta T_w$ can help analyzing heat transfer changing regularity. Fig. 4(a) is the variation tendency of heat transfer coefficient with the increase of $\Delta T_w$ at the central position of the upper horizontal observation point. Before 9620s, rise speed of heat transfer rate is low. After 9620s, an obvious increasing of curve slope occurs. Fig. 4(b) is the variation tendency of heat transfer coefficient with the increase of $\Delta T_w$ at the central position of the vertical observation point. Changing tendency is similar to the curve in Fig. 4(a). The turning point is 11675s. accompanied with the analysis above, 9620s and 11675s are ONB points for pool boiling heat transfer outside the central positions of upper horizontal and vertical observation points.
4.2. Analysis of predicting method for $\Delta T_{sat}$

Experimental data under No. I working condition is analyzed in above content. In order to study the predicting accuracy of correlations in different studies, Hsu correlation[12], Sato-Matsumara correlation[15], Kandlikar correlation[17] and Bergles-Rohsenow correlation[13] are chosen to compare with experimental calculated results. Experimental data under No. I–III working condition are used in the following analysis. Fig. 5(a) is comparison of $\Delta T_{sat}$ between experimental calculated and empirical correlation predicted value at the central position of the upper horizontal and vertical observation point. For ease of analysis, ±20% deviation lines are drawn in four pictures.

In Fig. 5(a), 21 of the 24 points distribute beyond the ±20% deviation line. Thus, these correlations cannot predict $\Delta T_{sat}$ accurately. It also indicates that heat transfer mechanism and calculating method of ONB point of pool boiling are different from those of forced convection boiling.

4.3. New predicting method for $\Delta T_{sat}$

Pool boiling heat transfer is different from forced convection heat transfer which has been illustrated in former investigation and above experimental study. Flow pattern is no longer judged by Reynolds number. Grashof number is commonly used dimensionless parameter in the judgement of natural convection flow pattern. Refer to previous studies, here tube outside wall superheat $s_{atT} \Delta T_{sat}$ is proposed as a function of Grashof number and heat flux $q_{ONB}$, $\Delta T_{sat} = f(Gr, q_{ONB})$, $\Delta T_{sat} = T_w - T_{sat}$.

$$\Delta T_{sat} = CGr^m (q_{ONB})^n$$  (2)

In formula, C, m, n are experience factors, obtained by fitting with experimental data. Non line fitting method is adopted to deal with experimental data, and the result is: C=17.9, m=-0.193, n=0.0373. So the relation between $\Delta T_{sat}$, Gr, and $q_{ONB}$ is:

$$\Delta T_{sat} = 17.9Gr^{-0.193} (q_{ONB})^{0.0373} \quad \text{(Scope: } 4.525 \times 10^6 \leq Gr \leq 1.27 \times 10^{10}, \, 3.04^\circ C \leq \Delta T_{sat} \leq 5.91^\circ C)$$  (3)

Fig. 5(b) is comparison of $\Delta T_{sat}$ between experimental calculated and fitted empirical correlation predicted value at the central position of the upper horizontal and vertical observation points. The maximum error is 14.2%, the minimum error is 5.9%, and the average error is 10.5%.

5. Conclusion

The main conclusions are as follows:

(1) Through analyzing of the trends of wall temperature, water temperature and heat transfer coefficient, combining with pictures photographed by high speed camera, the ONB point is preliminary
estimated. It is further verified by the changing tendency of heat transfer coefficient with the increase of $\Delta T_{sat}$.

(2) Predicting accuracy of $\Delta T_{sat}$ calculated by four correlations in literature is estimated by comparing with experimental calculating results. Predicted results exceed acceptable error lines. It further indicates that heat transfer mechanism and calculating method of ONB point of pool boiling are different from those of forced convection boiling.

(3) A new empirical correlation is non-linear fitted to predict wall superheat $\Delta T_{sat}$ under tube outside pool boiling condition.

References

[1] K. Cornwell, S.D. Houston. Nucleate pool boiling on horizontal tubes: a convection-based correlation [J]. International Journal of Heat and Mass Transfer, 1994, 37(1): 303-309.

[2] R.C. Yang, Y.W. Wang, H. Tang, R. Situ. Experimental study on onset of subcooled boiling and point of net vapor generation[J]. Journal of Engineering Thermophysics. 2001, 22(2): 229-232.

[3] J.F. Lv, Y.X. Wu, Z.H. Li, Q. Song, R.C. Yang. Gas-liquid two-phase flow and boiling heat transfer[M]. Beijing: Science Press. 2017.

[4] J.G. Collier, J. R. Thome. Convective boiling and condensation, third edition[M]. New York, NY: Oxford University Press. 1996.

[5] S.G. Kandlikar. Heat transfer characteristics in partial boiling fully developed boiling, and significant void flow regions of subcooled flow boiling[J]. Journal of Heat Transfer. 1998, 120(2): 395-401.

[6] N. Basu, G.R. Warrier, V.K. Dhir. Onset of nucleate boiling and active nucleation site density during subcooled flow boiling[J]. Journal of Heat Transfer. 2002, 124(4): 717-728.

[7] R.L. Judd, H.J. Merte, M.E. Ulucakli. Variation of superheat with subcooling in nucleate pool boiling[J]. Journal of Heat Transfer. 1991, 113: 201-208.

[8] H.J. Merte, J. A. Clark. Pool boiling in an accelerating system[J]. ASME Journal of Heat Transfer. 1961, 83(3): 234-242.

[9] M.E. Ulucakli, H.J. Merte. Nucleate boiling with high gravity and large subcooling[J]. ASME Journal of Heat Transfer. 1990, 112(2): 451-457.

[10] J. Wiebe, R.L. Judd. Superheat layer thickness measurements in saturated and subcooled nucleate boiling[J]. ASME Journal of Heat Transfer. 1971, 73(4): 455-461.

[11] M. Sultan, R.L. Judd. Spatial distribution of active sites and bubble flux density[J]. ASME Journal of Heat Transfer. 1978, 100(1): 56-62.

[12] Y.Y. Hsu. On the size range of active nucleation cavities on a heating surface[J]. Journal of Heat Transfer. 1962, 84(3): 207-216.

[13] A.E. Bergles, W.M. Rohsenow. The determination of forced convection surface boiling heat transfer[J]. Journal of Heat Transfer. 1964, 86(3): 365-372.

[14] S.Y. Su, X.M. Wang, S.Y. Huang. Investigation of subcooled boiling incipience in flow boiling heat transfer through narrow channels[J]. Journal of Thermal Science and Technology. 2004, 3(2): 104-107.

[15] B.T. Sato, H. Matsumara. On the conditions of incipient subcooled boiling with forced convection[J]. Bulletin of JSME. 1964, 7(26): 392-398.

[16] E.J. Davis, G.H. Anderson. The incipience of nucleate boiling in forced convection flow[J]. AIChE Journal. 1966, 12: 774-780.

[17] S.G. Kandlikar, V. Mizo, M. Cartwright, E. Ikenze. Bubble nucleation and growth characteristics in subcooled flow boiling of water[C]. National Heat Transfer Conference, ASME, HTD342. 1997, 11-18.

[18] B. Bourdon, P.D. Marco, R. Rioboo, M. Marengo, J.D. Coninck. Enhancing the onset of pool boiling by wettability modification on nanometrically smooth surfaces[J]. International Communications in Heat and Mass Transfer. 2013, (45): 11-15.
[19] B. Bourdon, E. Bertrand, P.D. Marco, M. Marengo, R. Rioboo, J.D. Coninck. Wettability influence on the onset temperature of pool boiling: experimental evidence onto ultra-smooth surfaces[J]. Advances in Colloid and Interface Science. 2015, 221: 34-40.

[20] Y. Zhang, D.Y. Li. Experiment of college physics, 4th edition. Beijing: Science Press. 2014.