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The determination of superheated layer thickness and wall superheat in vertical tube natural circulation reboiler

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Abstract

The characteristics of incipient boiling for vertical thermosiphon reboiler are studied in detail. The liquid film adjacent to the heating surface, the superheated layers thickness, δ^*, must attain a threshold value so that the critical bubble nuclei with radius r_c can further grow to the point of detachment. Thus, the relation between δ^* and r_c at the threshold of post-critical growth is of primary importance in determining the onset of nucleate boiling. In the present study a semi-empirical equation for wall superheat is proposed which includes the effect of submergence for the experimental data available in the literature. The data for water and organic fluids having wide range of thermophysical properties were correlated with a single correlation having mean absolute deviation of 14.73%. The value of δ^*/r_c for each fluid and unified value have also been also proposed.

Keywords: Incipient boiling; Superheated layer thickness; Phase-change; Submergence

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Nomenclature

a_1, b_1	constant used in equation of Agarwal [16]
a_2, b_2	constant used in equation of Ali and Alam [18]
a_3, b_3	constant used in equation of Kamil et al. [20]
C_1	constant, $(1 + \cos\theta)$
h	heat transfer coefficient, W/m^2 K
h_{fg}	latent of vaporization, J/kg
k	thermal conductivity, W/m K
L	total heated length, m
P	pressure, N/m^2
Pr	Prandtl number
q	heat flux, W/m^2
r	radius, m
R	gas constant, N m/kg K
r_{max}	maximum cavity radius, m
r_{tan}	cavity radius based on the tangency criterion, m
S	submergence, %
T	temperature, °C
ΔT_s	degree of superheat $(T_w - T_s)$, °C
ΔT_{sub}	degree of subcooling $(T_s - T_L)$, °C
y	distance perpendicular to the heated wall, m
Z	distance along the test section, m

Greek symbols

δ^*	superheated layer thickness, m
η	exponent used in Eq. (13)
ρ	density, kg/m^3
θ	contact angle
σ	surface tension, N/m

Subscripts

Pred	predicted
v	vapor
s	saturation
w	wall
B	boiling
L	liquid
b	bubble
c	cavity, critical condition
sub	subcooling
OB	onset of boiling

avg	average
MAD	mean absolute deviation
ONB	onset of nucleate boiling

1. Introduction

Vertical tube closed-loop thermosiphon reboilers used in petroleum, chemical, petrochemical, and nuclear power plants, are usually the most cost effective reboiler system. It is a one-pass heat exchanger in which boiling occurs inside vertical tube. The heat transfer coefficients at the onset of boiling are very high because of the nature of nucleate boiling and the increase in velocity because of the transition from a single-phase fluid to a two-phase mixture. The point at which the two-phase begins is know as point of incipient boiling (IPB), which corresponds to the conditions of minimum degree of wall superheat or heat flux required for the formation and detachment of first vapor bubble from the heated surface. Therefore, information on the conditions required for the onset of nucleate boiling are of paramount importance in the design of two-phase heat transfer equipments. The point of onset of nucleation along the tube length and its required wall superheat depends upon a number of operating parameters. Yin and Abdelmessih [1] and Murphey and Bergles [2] have shown through experimental studies the presence of two incipience boiling points (increasing or decreasing) for the fluorocarbons boiling from commercially finished stainless steel surface. Murphey and Bergles [2] also obtained a relation for the prediction of incipient flow boiling of Freon-113 under chemical potential equilibrium. Similar behavior has been observed with water on a variety of metallic surfaces by Hodgson [3].

Gibb's equilibrium theory of bubble in the uniformly superheated liquid and the one-dimensional steady or transient heat conduction equation is widely accepted approach for the prediction of incipient boiling. It was postulated that in the liquid film adjacent to the heating surface the superheated layers δ^*, must attain a threshold value so that the critical bubble nuclei with radius r_c can further grow to the point of detachment. Hsu [4] developed analytical expression for the size range of active nucleation sites for constant heat flux at the wall. Han and Griffith [5] proposed an analysis similar to Hsu [4]. Bergles and Rohsenow [6] adopted the Han and Griffith [5] analysis to develop a criterion for the onset of nucleate boiling for a system with a wide range of cavity sizes. Sato and Matsumura [7] proposed an analytical expression equivalent to that of Hsu's [4] for the prediction of incipient nucleate boiling of water at atmospheric pressure. Based on the analysis of Hsu [4], Davis and Anderson [8] derived an equation for the prediction of subcooled incipient boiling of water in forced convection. They concluded that the criterion used in their analysis appears satisfactory for determining an upper limit of the liquid superheat required to initiate nucleate boiling when a wide range of cavity sizes exist. Frost and Dzakowic [9] extended the analysis of Davis and Anderson [8] and derived an equation for the prediction of boiling incipience for a variety of different liquids. They considered their equation to be applicable to both forced and natural convection system. Unal [10] considered the effect of pressure on the boiling incipience under subcooled flow boiling of water in a vertical tube. Further Unal [11] determined the incipient point of boiling for subcooled nucleate flow boiling of water with high-speed photography. Yin and Abdelmessih [12] investigated the phenomenon of liquid superheat during incipient boiling in a uniformly heated forced convection channel. They obtained the experimental data using Freon-11 as the test medium and extended the analysis to obtain an equation for δ^*/r_c. Based on empirical equation of δ^*/r_c they obtained two incipience equations, one for the increasing heat flux and other for decreasing heat flux. Sudo et al. [13] carried out an experimental investigation for the validity of existing correlation. They recommended that the existing Bergles and Rohsenow [6] correlation have a good performance with the error of about 1 K against the lower limits of measured wall superheat. Hino and Ueda [14] found that superheats measured were little affected by mass velocity and liquid subcooling for R-113. Marsh and Mudawar [15] performed experimental study to develop a fundamental understanding of boiling incipience in wavy free-falling turbulent liquid films. Some workers [16–21] experimentally obtained the boiling and non-boiling zones (Z_{OB}/L) for heating surface and wall superheat for incipient boiling in a vertical tube thermosiphon reboiler with wide range of submergence. The submergence which causes the circulation of fluid in closed-loop thermosiphon reboiler is important parameter to keep the circulation velocity to desirable limit. It was maximum liquid head used in their study [16–21] corresponded to the liquid level equal to the top end of the reboiler tube. This condition has been termed 100% submergence. Shamsuzzoha et al. [22–25] have developed a generalized correlation for prediction of superheat including the effect of submergence for different fluids. Zurcher et al. [26] developed model to predict the ONB to differentiate purely convective evaporation from mixed nucleate and convective boiling during evaporation of natural refrigerant ammonia in horizontal flow boiling. The analysis during evaporation with different heat flux ranges showed accurate predictions in terms of the local heat transfer coefficient using this new onset of nucleate boiling criterion. An analytical model has been formulated by Shim et al. [27] for fully-developed turbulent flow and heat transfer in finned annuli using a modified mixing-length turbulence model. The model has been extended to predict the conditions at the onset of nucleate boiling using the criterion of Davis and Anderson [8]. Hapke et al. [28] investigated the heat transfer characteristics during flow boiling in a minichannel. They used the thermographic measuring method and measured axial distribution of the external wall temperature. They also investigated in detail for the ONB and results on a vertical evaporator pipe are presented and in dependence on the mass flux and the heat flux. A summary of previous boiling incipience investigations for natural circulation are given in Table 1.

Thus, it seems that the available literature does not include the effect of submergence in the prediction of δ^*/r_c and degree of wall superheat in vertical thermosiphon reboiler. Therefore, a semi-empirical model has been developed for the prediction of wall superheat, and the value of δ^*/r_c has been proposed, including the effect of submergence. The model prediction was done by experimental data available in literature [16,17,19]. A single value of δ^*/r_c, and unified correlation for wall superheat was proposed for all the data together and compared with existing incipience equations.

2. Analysis

The following assumptions made in the present theoretical analysis are:

(i) The potentially active cavities are of conical shape and the bubble nucleus which forms at such surface cavities has the shape of a truncated sphere.

Table 1
Summary of boiling incipience investigations in natural circulation

Authors	Flow geometry	Heater material	Fluid	Mean velocity ($m\,s^{-1}$)	Pressure [bar (psia)]	Subcooling (°C)	Incipience formula
Frost and Dzakowic [9]	Authors performed analysis using experimental data from prior studies						$q = \frac{k_L \rho_v h_{fg}}{8\sigma T_s}(T_w - T_s)^2 \frac{1}{Pr_L^2}$ Tangency criterion, $y = Pr_L^2 r$ at the point of tangency
Agarwal [16]	Vertical tube	Stainless steel	Water, acetone, ethyl acetate, propanol, toluene	–	Atmospheric pressure	0.9–73.0	$(T_w - T_s)^2 = (a_1 - b_1 q)^2 \frac{2\sigma T_s}{k_L h_{fg} \rho_v} q$
Ali and Alam [18]	Vertical tube	Stainless steel tube	Water, acetone, ethanol, ethylene glycol	–	Atmospheric pressure	0.2–45.5	$(T_w - T_s)^2 = (a_2 - b_2 q)^2 \frac{2\sigma T_s}{k_L h_{fg} \rho_v} q$
Kamil et al. [20]	Vertical tube	Stainless steel tube	Water, methanol, benzene, toluene, ethylene glycol	–	Atmospheric pressure	0.5–11.6	$(T_w - T_s)^2 = (a_3 - b_3 q)^2 \frac{2\sigma T_s}{k_L h_{fg} \rho_v} q$
Shamsuzzoha et al. [24]		Authors performed analysis using experimental data from prior studies [16,17,19] for distilled water, toluene and ethylene glycol					$(T_w - T_s) = (1.8435)\left[\frac{2\sigma T_s q}{k_L \rho_v h_{fg}}\right]^{1/2}(S)^{0.62826}$
Shamsuzzoha et al. (present study)		Authors performed analysis using experimental data from prior studies [16,17,19]					$(T_w - T_s) = (2.1986)\left[\frac{2\sigma T_s q}{k_L \rho_v h_{fg}}\right]^{1/2}(S)^{0.59971}$

(ii) Gibb's equation of bubbles coexisting with a surrounding uniformly superheated liquid can be used as a reasonable first approximation. That is

$$(T_b - T_s) = \frac{RT_bT_s}{h_{fg}} \ln\left(1 + \frac{2\sigma}{r_bP_s}\right) \tag{1}$$

Here T_b is not constant over the bubble surface because temperature gradients are present in the wall region.

(iii) The liquid temperature within the thermal layer has a linear profile, which is not significantly altered by the presence of a neighboring bubble.

(iv) Bubbles grow and detach from the nucleation sites only when the superheated liquid layer is thick enough so that a net heat flux into the developing bubble is realized.

Fig. 1 shows three different possible bubble nucleus shapes that can exist at the mouth of a cavity as shown by Davis and Anderson [8] and Hsu [4]. These nuclei are assumed to be formed by the residual vapor from the preceding bubble. Bergles and Rohsenow [6] considered the case of hemispherical bubble shape, giving an argument that, once a bubble passed the hemispherical condition of minimum radius, it would continue to grow. Our discussion is concerned with a truncated spherical bubble. It reduces to the hemispherical bubble when the bubble contact angle is 90 °. It is possible that the nucleus will not grow much beyond the hemispherical shape even if the superheat is sufficient, for shear forces acting on the bubble can sweep it from the wall. The hemispherical bubble will have greater stability.

Only the cavities in a narrow size range involved at the onset of nucleate boiling, and the population density of bubbles on the surface just prior to the onset of nucleate boiling are so low that they will not greatly affect the temperature profile in the fluid. Because the bubble nuclei are very small, they are within the laminar sublayer and the thermal conductivity of the liquid is also assumed constant. The heat transport occurs by conduction through the liquid only within the laminar sublayer:

$$T_L = T_w - \frac{qy}{k_L} \tag{2}$$

If δ^* represents the superheated layer thickness

$$T_L = T_s = T_w - \frac{q\delta^*}{k_L} \tag{3}$$

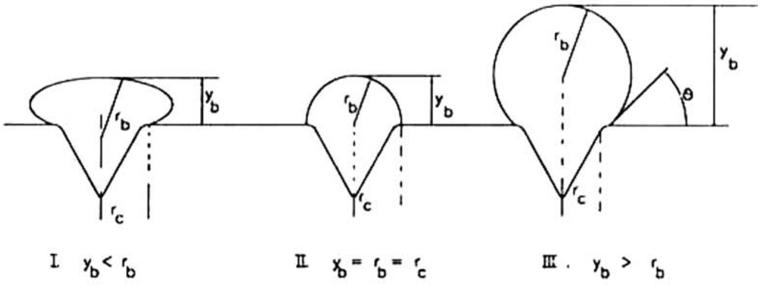

Fig. 1. Possible bubble models.

Bergles and Rohsenow [6] proposed one useful criterion for the initiation of nucleate boiling. The authors suggested that, at a distance $y = r_b$, $T_L = T_b$ (where $T_b > T_s$) as the condition for bubble to grow. It was then postulated that the minimum wall superheat ($T_w - T_s$) required to initiate boiling is determined by the point of tangency of Eq. (1) with Eq. (2); that is,

$$\frac{dT_b}{dr_b} = \frac{dT_L}{dy} \tag{4}$$

The relation between the bubble nucleus height y_b, the bubble nucleus radius r_b and the cavity radius r_c can be obtained by considering the case of a truncated sphere.

$$y_b = r_b(1 + \cos\theta) = C_1 r_b \tag{5}$$

$$r_c = r_b \sin\theta \tag{6}$$

It is convenient to express r_b in superheat equation, Eq. (1) in general terms of bubble height y_b, which is distance from the wall to the top of the bubble, y_b, as defined in Eq. (5). It then follows that:

$$(T_b - T_s) = \frac{RT_bT_s}{h_{fg}} \ln\left(1 + \frac{2\sigma C_1}{y_b P_s}\right) \tag{7}$$

Taking the first derivative of Eqs. (1) and (2), we have,

$$\frac{dT_b}{dy_b} = -\frac{2\sigma C_1 R T_s^2 \left[1 - \frac{RT_s}{h_{fg}} \ln\left(1 + \frac{2\sigma C_1}{y_b P_s}\right)\right]^{-2}}{y_b^2 P_s h_{fg}\left(1 + \frac{2\sigma C_1}{y_b P_s}\right)} \tag{8}$$

and

$$\frac{dT_L}{dy} = -\frac{q}{k_L} \tag{9}$$

Substituting Eqs. (8) and (9) into Eq. (4), we get

$$\frac{q}{k_L} = \frac{2\sigma C_1 R T_s^2 \left[1 - \frac{RT_s}{h_{fg}} \ln\left(1 + \frac{2\sigma C_1}{y_b P_s}\right)\right]^{-2}}{y_b^2 P_s h_{fg}\left(1 + \frac{2\sigma C_1}{y_b P_s}\right)} \tag{10}$$

It is complicated to obtain an explicit solution for y_b from Eq. (10). Therefore, it is important to assume the justified simplification, which causes easy to solve Eq. (10) for the wall superheat. For systems of low surface tension or high pressure, it is possible to write that

$$1 \gg \frac{2\sigma C_1}{y_b P_s}$$

Eq. (10) is then simplified to give as:

$$\frac{q}{k_L} = \frac{2\sigma C_1 T_s}{y_b^2 h_{fg} \rho_v} \tag{11}$$

Rather than imposing specific relations between y_b and δ^* as in previous studies, combining Eqs. (3) and (11) and assuming that $\theta = 90°$, which corresponds to a hemispherical bubbles at the onset of post-critical growth. At $\theta = 90°$, the resulting equation can be further simplified ($C_1 = 1$, $y_b = r_b = r_c$), without sacrificing the accuracy and corresponds to a hemispherical bubble.

$$(T_w - T_s) = \left(\frac{\delta^*}{r_c}\right)\left[\frac{2\sigma T_s q}{k_L \rho_v h_{fg}}\right]^{1/2} \tag{12}$$

In a vertical thermosiphon reboiler, the effect of inlet liquid subcooling and submergence on heat transfer, circulation rate, and boiling incipience have been investigated by some researchers. Perhaps most of the studies pertaining to boiling incipience are for flow boiling, whereas the present analysis is for a natural circulation thermosiphon reboiler. In case of a natural circulation reboiler, the induced flow rate is established due to the differential head existing between the cold and hot legs. The hydrostatic head in the cold leg (down-flow pipe) of a thermosiphon reboiler depends upon the liquid submergence, the maximum value of which equals to the liquid level corresponding to the top end of the test section, as 100% submergence ($S = 100\%$). The cold liquid head could be varied independently by maintaining the submergence at 75%, 50%, and 30%. The rate of circulation, therefore, depends upon liquid submergence, heat flux, inlet liquid subcooling, vapor fraction and all those parameters which are involved in the frictional resistance of the circulation loop. At a given submergence, the liquid head in the cold leg remains the same while increase in heat flux shifts the boiling incipience nearer to the heating surface-inlet and the saturated boiling occupies a longer length of the tube resulting in the higher vapor fraction in the tube. As the submergence is lowered, the liquid head decreases, whereas the vapor fraction increases due to the enhanced effect of saturated boiling in the tube. However, the differential head that causes circulation becomes smaller than that at higher value of submergence. A detailed description of the effect of submergence on induced flow has been discussed earlier by Kamil et al. [29] and Khalid et al. [30]. Hence from the aforementioned literature, it is clear that submergence has an important effect on boiling incipience in the case of a natural circulation reboiler. Yin and Abdelmessih [12] have also investigated the effect of velocity on δ^*/r_c. Therefore, it is important to include the effect of submergence in the prediction of the degree of superheat along with the superheated layer thickness. Thus after incorporating the effect of submergence in Eq. (12), it was modified as:

$$(T_w - T_s) = \left(\frac{\delta^*}{r_c}\right)\left[\frac{2\sigma T_s q}{k_L \rho_v h_{fg}}\right]^{1/2}(S)^{\eta} \tag{13}$$

Eq. (13) is the general expression for incipient boiling and several interesting observations can be made from this equation, which involves only the superheat that is easy to measure directly and right hand side as a whole can be evaluated with reasonable accuracy from the measurable quantities.

3. Results and discussion

3.1. Wall- and liquid-temperature profiles along the heated test section

Fig. 2 shows the variation of wall temperature for ethylene glycol with heat flux as a parameter along the test section. The wall temperature, T_w increases with heating length Z. It drops sharply

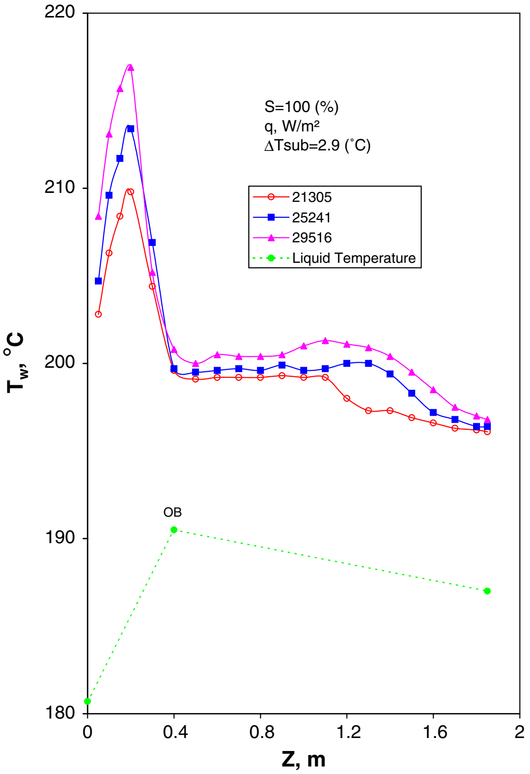

Fig. 2. Wall- and liquid-temperature profiles along the test section with heat flux as parameter for ethylene glycol.

near the position of incipient point and become approximately constant in the down stream region of nucleate boiling. The shape of the curve is almost similar for other heat fluxes and approximately the same inlet liquid subcooling. However, the curves at higher heat fluxes get shifted to higher wall temperatures. The typical behavior, as observed above, remains the same for other test liquids. The values of wall temperature, location of peak values and the lengths of various zones are different for different liquids. This kind of plot has been also reported by Yin and Abdelmessih [12] and Hino and Ueda [14] for their fluorocarbon and R-113 forced convection data respectively. The variation of liquid temperature along the tube length has been shown in Fig. 2 corresponding to the lower most curve of wall temperature only. The liquid temperature increases linearly with the distance along the tube length till it attains the saturation value which itself decreases linearly as the liquid moves upwards due to the reduction of the hydrostatic head [19–21].

Fig. 3 shows the plot of wall temperature T_w versus tube length Z with liquid submergence as a parameter for water. The location of wall-temperature peak get shifted towards the tube inlet and the curves move to lower values of T_w as the liquid submergence is reduced from 98% to 54%. For a submergence of 98% and 75%, the three regimes of heat transfer single-phase convection, surface and saturated boiling as shown in Fig. 3 are present, while at lower submergence of 54% the initial portions of curves before their peaks are absent.

The typical variation of wall and liquid temperatures as observed indicates that there exist different regimes of heat transfer in a reboiler tube. The linear rise in the temperature of liquid as it

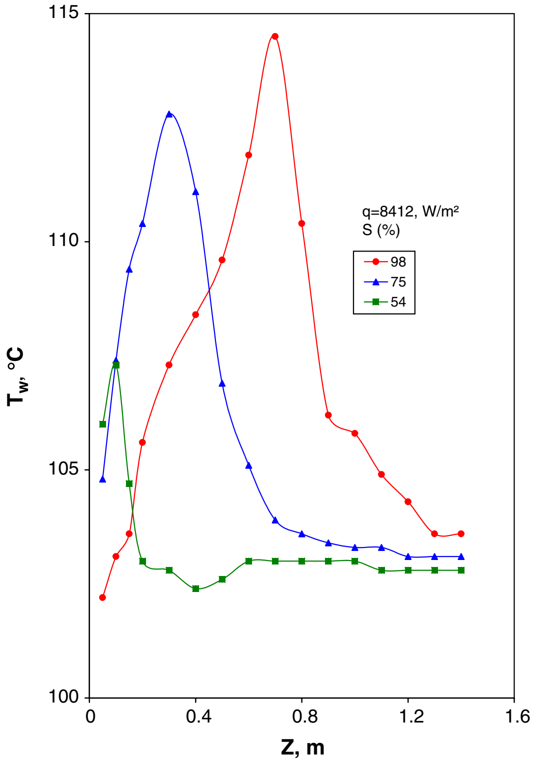

Fig. 3. Wall-temperature profiles along the test section with submergence as parameter for water.

moves upwards through the tube results from sensible heating under uniform heat flux. When the minimum required wall superheat is attained, the bubbles start nucleating at the surface but collapse due to the presence of subcooled liquid core. The onset of subcooled boiling thus creates additional turbulence at the surface. This explains why the linearly increasing wall temperature corresponding to convective heat transfer starts varying at a decreasing rate, eventually becoming zero at peak values in Figs. 2 and 3. Once the bulk-liquid temperature attains saturation value, the bubbles generated at the surface grow to their maximum size and get detach, resulting in the existence of vapor phase in the tube. All of the heat supplied gets absorbed as latent heat of vaporization, converting the liquid to vapor. Thus the two-phase flow goes upward through the tube with an increasing quantity of vapor and hence changing flow patterns. This corresponds to saturated boiling regime, as exhibited by the slowly decreasing wall- and liquid-temperature profiles.

As the value of heat flux is raised, the wall temperature also increases to provide a temperature difference adequate for transferring the additional heat. In convective mode of heat transfer, this should be almost in the same ratio as that of heat flux change. But in nucleate boiling, this is not so, because the increased heat flux enables larger number of nuclei for bubble generation to become active, and thus enhance the heat transfer coefficient and requires a small temperature difference. This explains the shifting of the wall-temperature curves with heat flux as observed in Figs. 2 and 3. The shifting of the saturated boiling to a lower level in the tubes as the submergence is reduced from 100% is probably due to the change in circulation rates. The decrease in the value of liquid submergence reduces the driving force for liquid circulation and hence the flow rate of the liquid through the reboiler tube. At a lower rate of liquid circulation, the rate of change of temperature with tube length becomes higher, and the saturation temperature is attained at a much smaller length from the inlet.

3.2. Boiling incipience in vertical thermosiphon reboiler

The analysis for the prediction of boiling incipience in vertical tube is based on Gibb's equilibrium theory, which is widely used in the literature. The proposed equation (13) is the general model for wall superheat and δ^*/r_c calculation, which can be used for the ONB for low surface tension, and wide range of cavity sizes and submergence.

Figs. 4 and 5 show the heat flux versus wall superheat curve for water and toluene respectively. For water at a submergence of around 74–88%, majority of the data points lie within ±15% of the correlation line. Above figures show that the predicted values of wall superheat are in good agreement with the experimental data. The ranges of parameters covered in developing and validating the correlation are given in Table 2 for all nine systems. The incipient boiling superheat was also calculated from other investigator's correlation and is plotted in the same figure. A similar trend

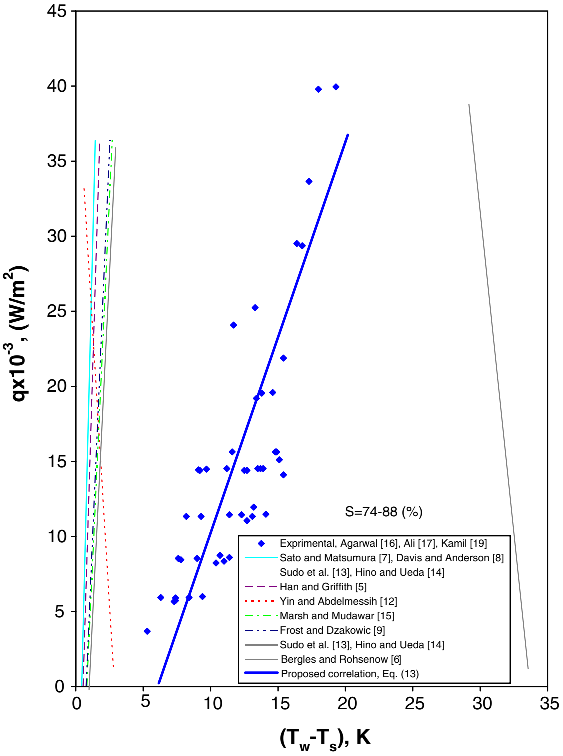

Fig. 4. Heat flux versus degree of superheat at boiling incipience for water.

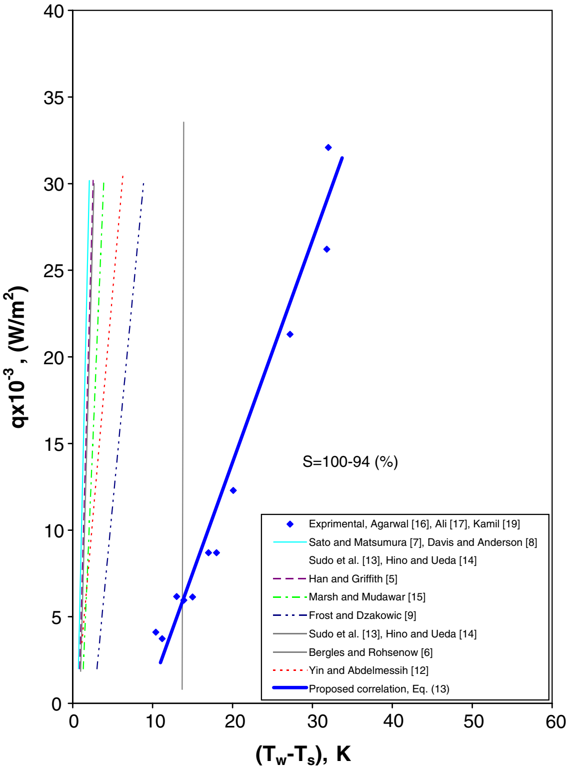

Fig. 5. Heat flux versus degree of superheat at boiling incipience for toluene.

Table 2
Ranges of parameters, maximum % error, value of exponent η used in Eq. (13), and δ^*/r_c

Systems	Submergence (%)	ΔT_{sub} (°C)	Heat flux (W/m^2)	Exponent η (Eq. (13))	Maximum error (%)	δ^*/r_c
Acetone	30–100	0.2–45.5	3548–15 115	0.78086	±20	1.9148
Methanol	30–100	1.0–3.7	4105–21 305	0.50663	±16	6.1586
Ethyl acetate	28–97	2.5–44.5	3548–14 500	1.0053	±12	0.4251
Ethanol	30–100	1.1–21.6	3800–21 884	0.7081	±11	2.0148
Benzene	30–100	0.7–3.6	4106–29 225	0.5269	±17	3.093
Propanol	39–97	1.2–54.2	3342–21 765	0.45647	±14	4.4293
Water	30–100	0.2–73.0	3486–43 373	0.60402	±16	2.0553
Toluene	30–100	1.9–68.3	2042–32 085	0.56127	±15	2.3667
Ethylene glycol	30–100	3.25–15.8	15 115–33 654	0.62584	±18	1.5524

has been shown for other test liquids. For low heat flux, the submergence has less effect on incipient boiling than for high heat flux. For a fixed submergence, low superheat is required for the low heat flux, and high superheat is required for higher heat flux for incipient boiling. None of the correlations predict the data well, and generally most of the correlations under predict the superheat values for different systems. But Sudo et al. [13] and Hino and Ueda [14] correlations for

Table 3
Comparison of proposed model, Eq. (13), with other correlations

Systems	Acetone	Methanol	Ethyl acetate	Ethanol	Benzene	Propanol	Water	Toluene	Ethylene glycol
**Mean absolute deviation (MAD)*									
Sato and Matsumura [7]	95.93	95.49	91.59	94.97	91.16	93.32	92.60	91.5	90.37
Bergles and Rohsenow [6]	90.67	89.24	87.70	89.19	87.99	86.86	84.19	88.73	88.13
Han and Griffith [5]	95.02	94.48	89.70	93.84	90.40	91.82	90.94	89.59	88.21
Davis and Anderson [8]	95.93	95.49	91.59	94.97	91.16	93.32	92.60	91.50	90.37
Frost and Dzakowic [9]	86.59	77.03	47.46	54.00	63.36	22.69	87.05	63.71	76.43
Yin and Abdelmessih [12]	88.87	89.29	78.92	87.17	83.04	82.50	82.22	80.78	86.52
Hino and Ueda [14] and Sudo et al. [13], $r_{\tan} < r_{\max}$	95.93	95.49	91.59	94.97	91.16	93.32	92.60	91.50	90.37
Hino and Ueda [14] and Sudo et al. [13], $r_{\tan} > r_{\max}$	56.71	58.43	37.09	51.43	36.04	37.36	209.0	25.63	69.83
Marsh and Mudawar [15]	92.39	91.57	84.27	90.60	85.35	87.51	86.16	84.09	81.99
Proposed correlation, Eq. (13)	17.53	13.57	9.73	8.07	14.06	11.04	12.46	11.77	15.61

* MAD = Mean absolute deviation, $\mathrm{MAD} = \left[\frac{1}{N}\sum_{i=1}^{N}\left|\frac{\Delta T_{\mathrm{pred}} - \Delta T_{\mathrm{exp}}}{\Delta T_{\mathrm{exp}}}\right| \times 100\right]$, where N is the number of experimental data points.

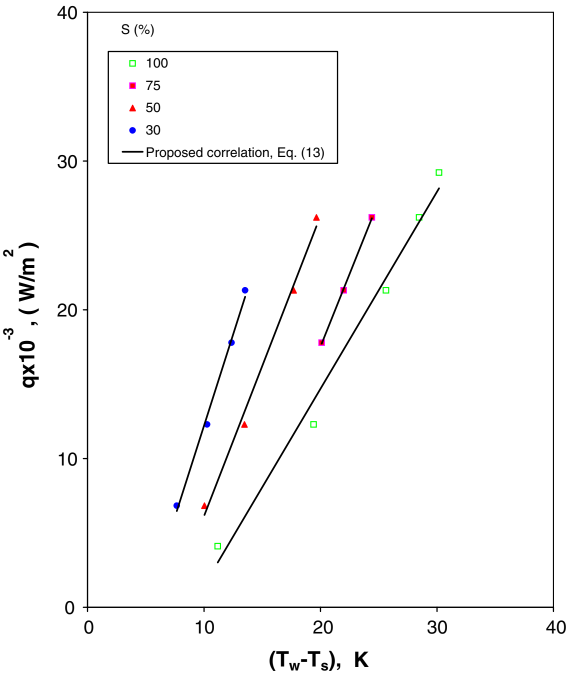

Fig. 6. Heat flux versus degree of superheat at boiling incipience for benzene.

$r_{\tan} > r_{\max}$ criteria overpredicts the superheat value for the fluids, namely water and ethylene glycol at different submergence. A comparison of the proposed model with other investigations is

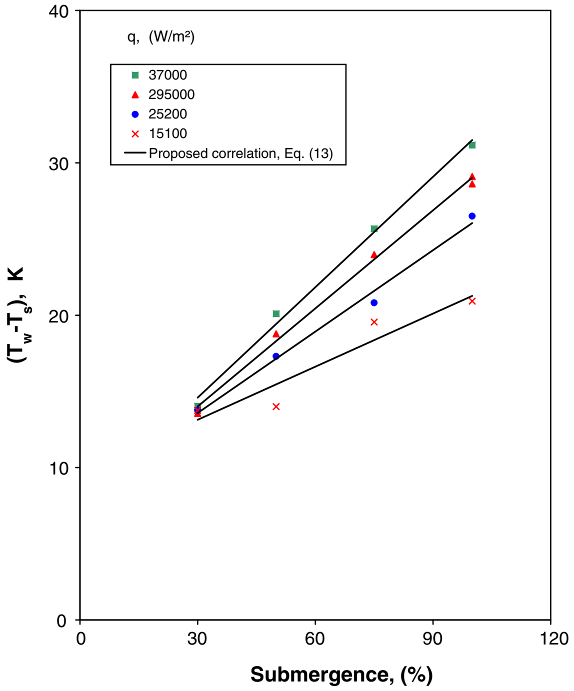

Fig. 7. Degree of superheat versus submergence for ethyl acetate.

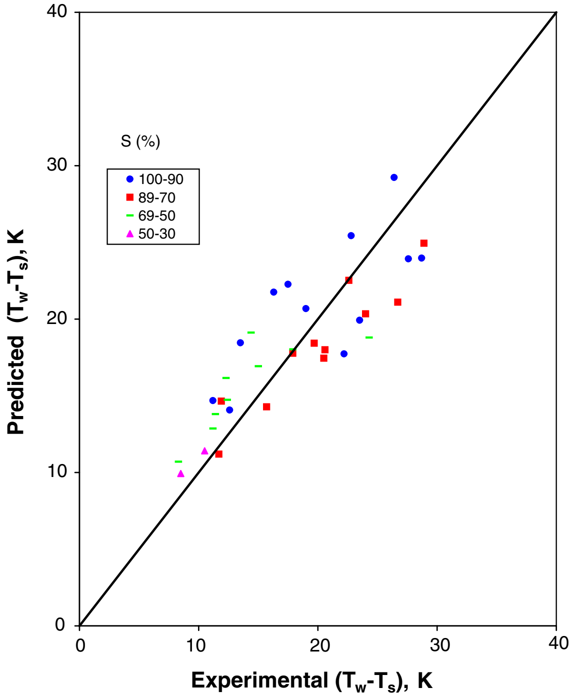

Fig. 8. Comparison between experimental and predicted values of superheat for acetone.

shown in Table 3, giving MAD of the proposed model and other investigators' correlations. The values of δ^*/r_c and exponent η in Eq. (13) with maximum errors (%) are given in Table 2.

Fig. 6 shows the heat flux versus wall superheat computed from Eq. (13), for benzene. The effect due to submergence is evident. The predicted results agree well with experimental data at constant submergence. This figure also shows that at a fixed submergence, there are different predicted lines.

Fig. 7 shows the plot of degree of superheat versus submergence for ethyl acetate. From the plots, it is clear that the superheat increases linearly with increase in submergence for a constant heat flux. As the value of heat flux is decreased, the lines shift to a lower level as exhibited in Fig. 7. Therefore, it is clear that submergence has a strong affect on the condition of the onset of nucleate boiling.

Figs. 8 and 9 show the comparison of the experimental degree of wall superheat with predicted superheat (Eq. (13)) for acetone, and water. The majority of data points lie within considerable error limits.

An effort was also made to obtain unified correlation of all nine systems together with 350 data, covering wide ranges of heat flux, submergence and ΔT_{sub}. The correlation for the incipient boiling superheat was obtained as:

$$(T_w - T_s) = (2.1986)\left[\frac{2\sigma T_s q}{k_L \rho_v h_{fg}}\right]^{1/2} (S)^{0.59971} \tag{14}$$

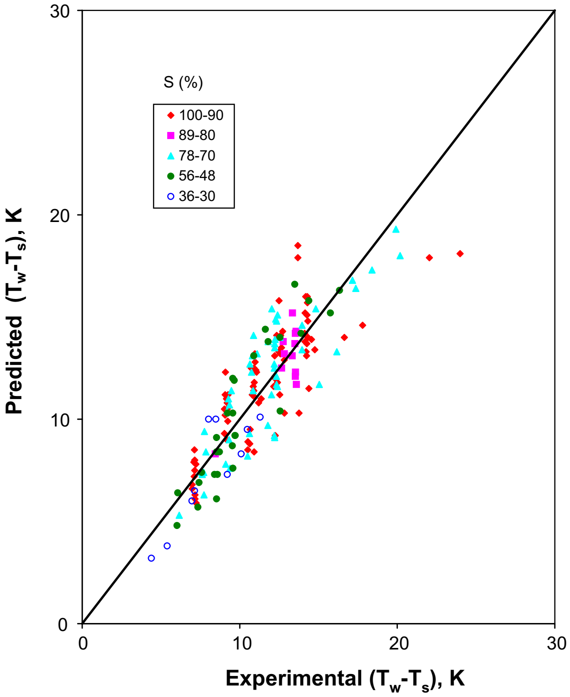

Fig. 9. Comparison between experimental and predicted values of superheat for water.

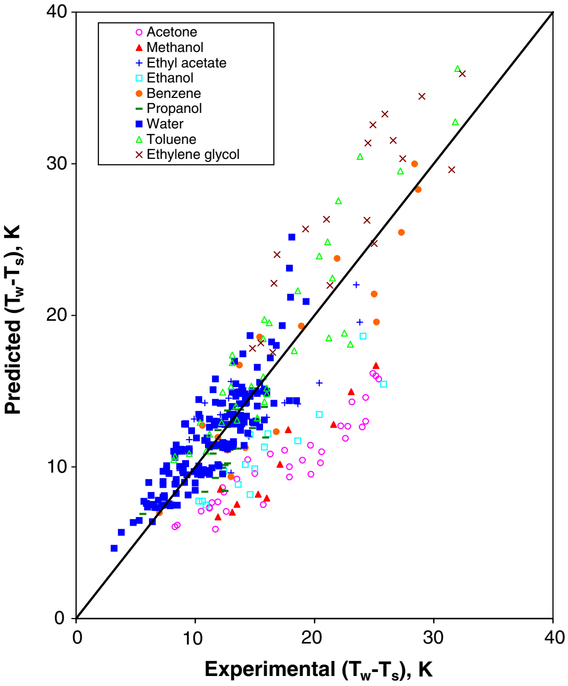

Fig. 10. Comparison of experimental with predicted degree of superheat by proposed correlation, Eq. (14), for all test liquids.

Fig. 10 shows the plot of comparison of experimental data with the predicted wall superheat by the proposed correlation covering all the data. The ranges of parameters covered in developing and validating the correlation is given in Table 2. It is observed that majority of the data points of the present study is within the maximum error of ±19% and a MAD of 14.73%.

4. Conclusions

The following important conclusion can be drawn from the present study:

The value of superheated layer thickness δ^*/r_c has been proposed for water and other organic fluids. The proposed unified value of $\delta^*/r_c = 2.1986$ is in clear agreement with the earlier reported values of δ^*/r_c by other investigators. Based on the theoretical analysis and experimental data available in literature, Eq. (13), has been proposed, which can predict the wall superheat required for onset of boiling at a given heat flux, submergence, and using the thermophysical properties of test liquids. The value of δ^*/r_c and exponent η has been proposed for wide range of cavity size and tabulated in Table 2 with maximum % errors. The data may also be correlated by a single equation (Eq. (14)) for all of the fluids. The majority of data points lie within a maximum error limit of ±19%. The criterion shows that the onset of fully-developed boiling requires a minimum degree of wall superheat for a given liquid and heat transfer surface. At constant submergence as the heat flux increases, the wall superheat required for incipient boiling increases. The superheat increases linearly with submergence for a constant heat flux. At a low value of heat flux, the role of submergence has lesser effect than for high heat flux. The comparisons made from various correlations clearly show that submergence is an important parameter in the prediction of ONB in a vertical thermosiphon reboiler.

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