Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

Development of Empirical Correlation to Evaluate Effects of Included Angle on Pool Boiling Heat Transfer of V-Shape Tubes

Myeong-Gie Kang *
Department of Mechanical Engineering Education, Andong National University
388 Songchun-dong, Andong-city, Kyungbuk 760-749
**Corresponding author: mgkang@anu.ac.kr*

1. Introduction

One of the most effective ways to improve current pressurized water reactors is the adoption of passive decay heat removal systems. These systems cool down decay heat of nuclear reactors without any external power supply and operator action [1,2]. The most important facility is a passive heat exchanger that transfers core decay heat to the cold water in a water storage tank.

In general, pool boiling is generating on the surface of a heat exchanging tube. Since heat transfer is related to the conditions of a tube surface, bundle geometries, and a liquid type, lots of studies have been carried out for the combinations of those parameters [3,4]. Summarizing the previous results, heat transfer coefficients (h_b) are highly dependent on the tube geometry and the heat flux of a lower tube (q_L'').

The passive condensers adopted in SWR1000 and APR+ has almost V-shape tube bundles [1,2]. Recently, Kang[5-7] studied the effects of the included angle (δ) and the heat flux of the lower tube on enhancement in heat transfer of the upper tube, arranged one above the other in the same vertical plane. According to Kang [7], the heat transfer coefficient of the upper tube is dependent on not only the included angle but also the inclination angles (α and β, Fig. 1) of the individual tubes.

Since the exact evaluation of the heat transfer is essential for the thermal design of a heat exchanger, an empirical correlation is newly developed.

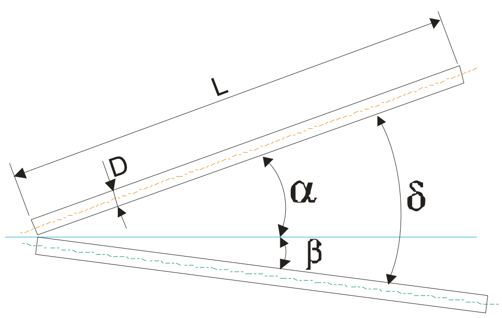


Fig. 1. Schematic of tubes in V-shape arrangement.

2. Correlation of Experimental Data

Table 1 lists the details of the 744 data points used for the correlation development. Figure 2 shows the plot of the experimental data. The data are gained from the smooth stainless steel tubes and the saturated water at atmospheric pressure. There is much difference among the data for the same heat flux because of the inclination angles and the heat flux of the lower tube. The maximum heat transfer coefficient (9.97kW/m^2-°C) is 84% larger than the minimum one (5.43kW/m^2-°C) when the heat flux of the upper tube (q_T'') is 50kW/m^2.

Table 1. Experimental Data for Correlation Development

Reference	α deg	β deg	q_L'' kW/m^2	q_T'' kW/m^2	Number of data
[5]	1	1	0,10,30,60,90,q_T''	10-120	72
	3	3	0,30,60,90,q_T''	10-120	60
	5	5	0,30,60,90,q_T''	10-120	60
	7	7	0,30,60,90,q_T''	10-120	60
	9	9	0,30,60,90,q_T''	10-120	60
[6]	2	0	0,60,q_T''	10-120	36
	6	0	0,60,q_T''	10-120	36
	10	0	0,60,q_T''	10-120	36
	14	0	0,60,q_T''	10-120	36
	18	0	0,60,q_T''	10-120	36
	24	0	0,60,q_T''	10-120	36
[7]	0	2	0,60,q_T''	10-120	36
	0	6	0,60,q_T''	10-120	36
	0	10	0,60,q_T''	10-120	36
	0	14	0,60,q_T''	10-120	36
	0	18	0,60,q_T''	10-120	36
	0	24	0,60,q_T''	10-120	36

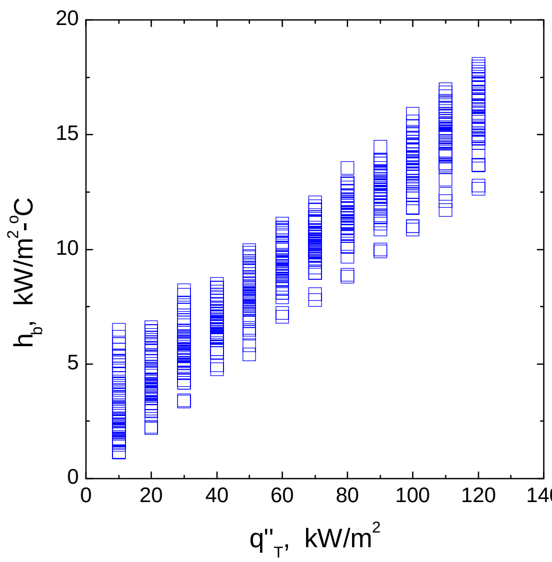
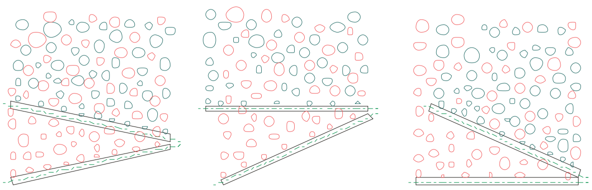


Fig. 2. Plots of experimental data.

Figure 3 shows the movement of bubbles around the tubes. When α = β, the upper tube is affected by the lower tube through the tube length. However, part of the upper tube is not directly affected by the lower one for the asymmetry cases as shown in Fig. 3(b) and (c). If α ≠ β, the projected length of a tube onto the other one is not the same. Since the flow generated by the lower tube moves upward, the non-overlapped length is not fully contributing to the heat transfer of the upper tube. This discrepancy leads to the difference in heat transfer [7].



(a) α = β (b) α < β (c) α > β

Fig. 3. Schematic of bubble movement around tubes.

Table 2. Summary of Published Correlations

Reference	Correlation
Kang [8]	$h_r = \frac{h_b}{h_{b,q''_L=0}} = Aq_L''^{(B/q''_T)}$ $A = \frac{(P/D)^{-0.04\theta}}{1.0448-0.092\phi}$ $B = \frac{(P/D)^{0.248\theta}}{0.7569+0.0003e^{8.216\phi}}$ h_r: bundle effect P: pitch θ: azimuthal angle ϕ: inclination angle of tube bundle
Cornwell et al. [9]	$Nu_b = C_{tb} Re_b^{2/3}$, $Nu_b = \frac{h_b D}{k_f}$, $Re_b = \frac{q''}{h_{fg}}\frac{D}{\mu_f}$ C_{tb}: constant h_{fg}: enthalpy of vaporization k_f: thermal conductivity of liquid q'': heat flux μ_f: liquid viscosity
Cooper [10]	$h_b = 55 p_R^{(0.12-0.2\log_{10}\varepsilon)}(-\log_{10} p_R)^{-0.55} M^{-0.5} q''^{0.67}$ p_R: reduced pressure M : molecular weight ϵ: surface roughness
Rohsenow [11]	$q'' = \mu_f h_{fg}\left[\frac{g(\rho_f-\rho_g)}{\sigma}\right]^{\frac{1}{2}}\left(\frac{C_{pf}\Delta T_{sat}}{h_{fg}\Pr_f^s C_{sf}}\right)^3$ C_{sf}: constant g: gravitational acceleration $\Pr_f$: Prandtl number of saturated liquid s: constant ΔT_{sat}: superheating of heated surface ρ_f: density of saturated liquid ρ_g: density of saturated vapor σ: surface tension

The experimental data are compared with the calculated results of the published correlations (Table 2) to investigate the applicability of them to this study. The correlations, except Kang [8], are well-known and frequently accepted in design and analysis of thermal systems. The results of the statistical analyses on the ratios of the measured ($h_{b,exp}$) and the calculated ($h_{b,cal}$) heat transfer coefficients (i.e., $h_{b,cal}/h_{b,exp}$) have been performed and shown in Fig. 4. The calculated heat transfer coefficients by the correlations much under predict the present experimental data. Since the published correlations do not have the parameter designating the included angle, this becomes one of the major causes of the discrepancy. Therefore, the new correlation is including a new geometric parameter.

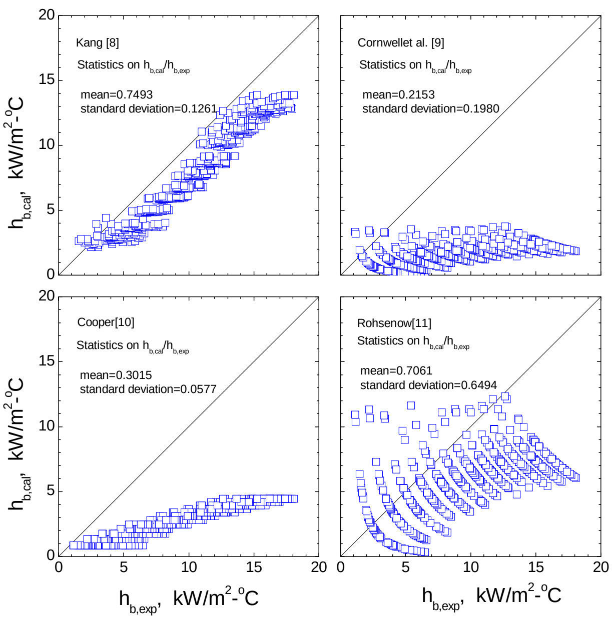


Fig. 4. Comparison of experimental data with published correlations.

A simple correlation is considered to evaluate the effects of the included angle and the heat fluxes. As a result, an empirical correlation has been obtained using present experimental data and the statistical analysis computer program (which uses the least square method as a regression technique) as follows:

$$h_b = \left(0.259 - 0.115\alpha + 0.012\beta + \frac{0.28 q_L''^{0.87}}{q_T''^{1.4}}\right) q_T''^{0.86} \quad (1)$$

In the above equations, h_b and q'' (i.e., q''_L and q''_T) are the heat transfer coefficient and the heat flux and the units are kW/m²-°C and kW/m², respectively. The dimension for α and β is radian. The new correlation is valid for the data ranges shown in Table 1.

A comparison between the heat transfer coefficients from the tests and the calculated value by the developed correlation is shown in Fig. 5. To confirm the validity of the correlation a statistical analyses on the ratios of the calculated and the measured heat transfer coefficients (i.e., $h_{b,cal}/h_{b,exp}$) have been performed. The mean and the standard deviation are 1.0006 and 0.0823, respectively. The newly developed correlation predicts the present experimental data within ±8 %, with some exceptions. The scatter of the present data is acceptable and of similar size to that found in other existing pool boiling data.

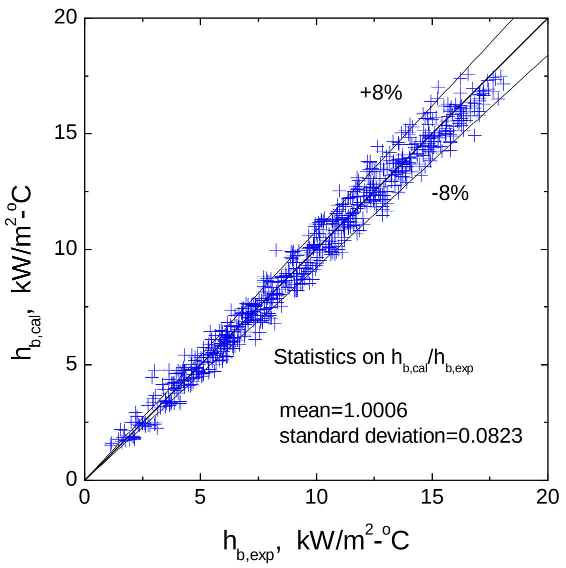


Fig. 5. Comparison of experimental data to calculated heat transfer coefficients by developed correlation.

3. Conclusions

A new empirical correlation including the included angle and the heat fluxes is suggested to evaluate the pool boiling heat transfer coefficient of V shape tubes. Through the survey of published results, 744 data points for the tubes submerged in the saturated water at atmospheric pressure were obtained and the nonlinear least square method was used as a regression technique. The newly developed correlation well predicts the experimental data within ±8%, with some exceptions.

REFERENCES

[1] A. Schaffrath, E. F. Hicken, H. Jaegers, H.M. Prasser,, Operation Conditions of the Emergency Condenser of the SWR 1000, Nuclear Engineering and Design, Vol. 188, p. 303, 1999.
[2] B. U. Bae, B. J. Yun, S. Kim, K. H. Kang, Design of Condensation Heat Exchanger for the PAFS (Passive Auxiliary Feedwater System) of APR+ (Advanced Power Reactor Plus), Annals of Nuclear Energy, Vol. 46, p. 134, 2012.
[3] L. Aprin, P. Mercier, L. Tadrist, Local Heat Transfer Analysis for Boiling of Hydrocarbons in Complex Geometries: A New Approach for Heat Transfer Prediction in Staggered Tube Bundle, Int. J. Heat Mass Transfer, Vol. 54, p. 4203, 2011.
[4] A. Swain, M. K. Das, A Review on Saturated Boiling of Liquids on Tube Bundles, Heat Mass Transfer, Vol. 50, p. 617, 2014.
[5] M. G. Kang, Effects of Included Angle on Pool Boiling Heat Transfer of V-shape Tubes in Vertical Alignment, Int. J. Heat Mass Transfer, Vol. 108, p. 901, 2017.
[6] M. G. Kang, Variation in Pool Boiling Heat Transfer due to Included Angle of Tube Array Having Horizontal Lower Tube, Trans. Korean Soc. Mech. Eng. B, Vol. 42, p 533, 2018.
[7] M. G. Kang, Pool Boiling Heat Transfer of V-Shape Tubes Having Horizontal Upper Tube, Transactions of Korean Nuclear Society Spring Meeting, Jeju, Korea, May 17-18, 2018.
[8] M. G. Kang, Development of an Empirical Correlation to Evaluate the Bundle Effect in Saturated Pool Boiling of Water, Trans. Korean Soc. Mech. Eng. B, Vol. 41, p. 1, 2017.
[9] K. Cornwell, R. B. Schuller, R. B., and J. G. Einarsson, The Influence of Diameter on Nucleate Boiling Outside Tubes, Proc. of the 7th International Heat Transfer Conference, Munchen, Germany, 1982.
[10] M. G. Cooper, Heat Flow Rates in Saturated Nucleate Pool Boiling - A Wide Ranging Examination Using Reduced Properties, Advances in Heat Transfer, Vol. 16, pp. 157-239, 1984.
[11] W.M. Rohsenow, A Method of Correlating Heat-transfer Data for Surface Boiling of Liquids, ASME J. Heat Transfer, Vol. 74, pp. 969-976, 1952.