2014

A General Correlation to Predict The Flow Boiling Heat Transfer of R410A in Macro/Mini Channels

Nguyen-Ba Chien
Graduate School, Chonnam National University, San 96-1, Dunduk-Dong, Yeosu, Chonnam 550-749, Republic of Korea, bachien@ejnu.net

Pham-Quang Vu
Graduate School, Chonnam National University, San 96-1, Dunduk-Dong, Yeosu, Chonnam 550-749, Republic of Korea, phamquangvu911273@gmail.com

Kwang-Il Choi
Department of Refrigeration and Air Conditioning Engineering, Chonnam National University, San 96-1, Dunduk-Dong, Yeosu, Chonnam 550-749, Republic of Korea, imcgi@chonnam.ac.kr

Jong-Taek Oh
Department of Refrigeration and Air Conditioning Engineering, Chonnam National University, San 96-1, Dunduk-Dong, Yeosu, Chonnam 550-749, Republic of Korea, ohjt@chonnam.ac.kr

A general correlation to predict the flow boiling heat transfer of R410a in macro/mini-channels

Nguyen-Ba Chien[1], Pham-Quang Vu[1], Kwang-Il Choi[2], Jong-Taek Oh[2*]

[1]*Graduate School, Chonnam National University, San 96-1, Dunduk-Dong, Yeosu, Chonnam 550-749, Republic of Korea*

[2]*Department of Refrigeration and Air Conditioning Engineering, Chonnam National University, San 96-1, Dunduk-Dong, Yeosu, Chonnam 550-749, Republic of Korea*

* Corresponding Author: **Email**: ohjt@chonnam.ac.kr, **Tel**: +82-61-659-7273; **Fax**: +82-61-659-7279

Keywords: Correlation, R410A, boiling heat transfer, Marcro/minichannel

ABSTRACT

This study demonstrated a general correlation to predict the saturated flow boiling heat transfer of R410A in horizontal macro and mini-channels. The experimental data were observed in various tube diameters of 1.5, 3.0, 6.61 and 7.49 mm, mass fluxes of 100 – 600 kW $m^{-2}s^{-1}$ heat fluxes of 10 – 40 kW m^{-2}, saturation temperature of 5 – 15 ºC and vapor quality from 0.2 to 1. The database was compared with numerous well-known correlations. The proposed correlation was based on the superposition model of nucleate boiling and force convective boiling contribution. The new modified-correlation showed a good prediction against our database.

1. INTRODUCTION

R410A, recently, has been widely used in air-conditioning systems due to the phasing out completely of R22 in the near future. To improve the design of the evaporator, studies of boiling heat transfer characteristics as well as developing a suitable heat transfer coefficient (HTC) correlation for R410a are necessary.

Through the development and application in many fields of cooling devices, there are various studies and proposed heat transfer coefficient correlations for both minichannel and (or) macrochannel (Conventional channel) [1-16]. Although, some well-known general correlations are extensively used such as the ones developed by Chen[2]; Shah [7;8],Gungor and Winterton [4], it's still need to develop a more exactly correlation for specific refrigerant since the reviews of Zhang et al. [16], Bertsch et al. [1] demonstrated the large error of existing HTC correlations with other experimental data due to the difference of operation conditions.

Numerous general heat transfer correlations proposed were used to evaluate the experimental data in our study. Shah [7] investigated a CHART correlation using about 800 data points of both vertical and horizontal tubes. Four dimensionless parameters, including ψ, Co, Bo, Fr_l, were employed to define the chart. This correlation is recommended for all pure Newtonian fluids except metallic fluid in the reduced pressure ranging from 0.004 to 0.8. Lazarek and Black [12] introduced a new heat transfer coefficient correlation that expressed the Nuttselts number as the function of the liquid Reynolds and boiling number. The data were measured in round tube with an internal diameter of 0.31 cm and using R-113 refrigerant. Since the strong effect of vapor quality on the heat transfer coefficient was observed, the authors concluded that the nucleate boiling was dominant mechanism. Gungor-Winterton [4] investigated a general correlation using 4300 data points of water, refrigerants and ethylene glycol. This correlation was based on the form proposed by Chen [2] in which the heat transfer coefficient mainly consist 2 mechanisms: nucleate boiling and convective boiling. The mean and average deviations were 21.4% and 25%, respectively. Later, Gungor and Winterton (1987) also supported a simpler form of this correlation. Liu and Winterton (1991) developed a flow boiling correlation that based on the method of combining the two contributions suggested by Kutateladze [13] for vertical and horizontal tubes. The authors used the same data as Gungor-Winterton's [4]. Tran et al. [15] investigated a general heat transfer coefficient using small channel boiling heat transfer data with wall super heats > 2.75 ºC for circular and rectangular tubes for R12, R113, and the data from Lazarek and Black [12]. This study reported that the nucleation mechanism was dominant and the Reynolds number was replaced by Weber number to eliminate viscous effects in favor of surface tension. Bertsch et al [1] developed a composite heat transfer correlation including nucleate and convective boiling heat transfer. The effect of bubble confinement was also taken into account. 3889 data points observed in the wide testing range with the hydraulic diameter of 0.16 to 2.92 mm were used in this study. The proposed correlation archived a mean absolute deviation of less than 30%. However, the results discussed later show that none of these correlations can be predicted well our experimental heat transfer coefficient of R410A. In addition, the working fluid performed a significant effect on HTC as proposing by Kandlikar [5-6] that lead to the demand of individual correlation or factor for each working fluid.

Hence, the aim of this study is to develop the boiling heat transfer correlation of R410A in the four kinds of tube diameter of 1.5, 3.0, 6.45 and 7.49 mm. Based on the database of 452 data points of R410A, a new correlation was developed with the good accuracy.

2. DESCRIPTION OF THE HEAT TRANSFER DATABASE

The experimental data were obtained in the following conditions: the mass fluxes ranged from 100 to 600 kg $m^{-2}s^{-1}$, heat fluxes ranged from 10 to 40 kWm^{-2}, saturation temperature ranged from 5 to 15 ºC and vapor quality ranged from 0.2 to 1. Total 452 data points were collected including 61 with D_h > 3.0 mm (macrotube) and 391 with $D_h \leq 3.0$ mm (minichannel). The distribution of data was shown in fig. 1. The flow regime was defined basing on the Reynolds numbers of vapor and liquid phase as: Re < 2300 : laminar (L), Re > 3000: turbulent (T) and 2300 < Re < 3000: transition regime. Fig. 1 depicted that almost data points were observed in laminar-turbulent and turbulent-turbulent regime in the order of 17.48% and 72.35%, respectively. There is no data in the laminar-laminar and turbulent-laminar regime.

3. DEVELOPMENT OF A NEW BOILING HEAT TRANSFER COEFFICIENT CORRELATION OF R410A

In this study, the experimental data were compared with several well-known heat transfer coefficient correlations including: Shah [7], Lazarek and Black, Gungor-Winterton [4], Liu and Winterton [9], Bertsch

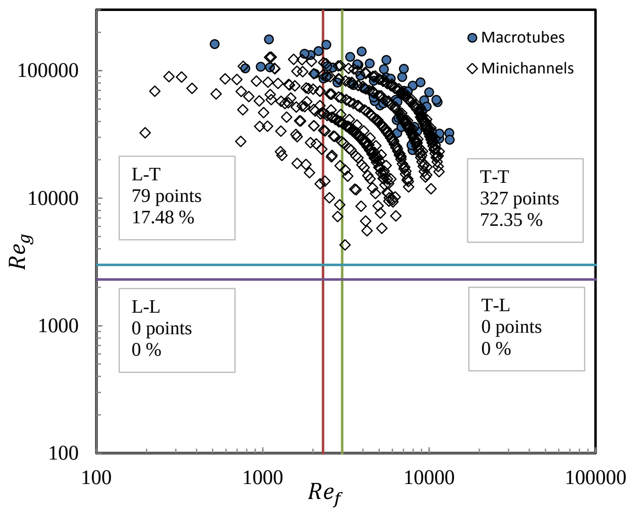

Figure 1. Data distribution

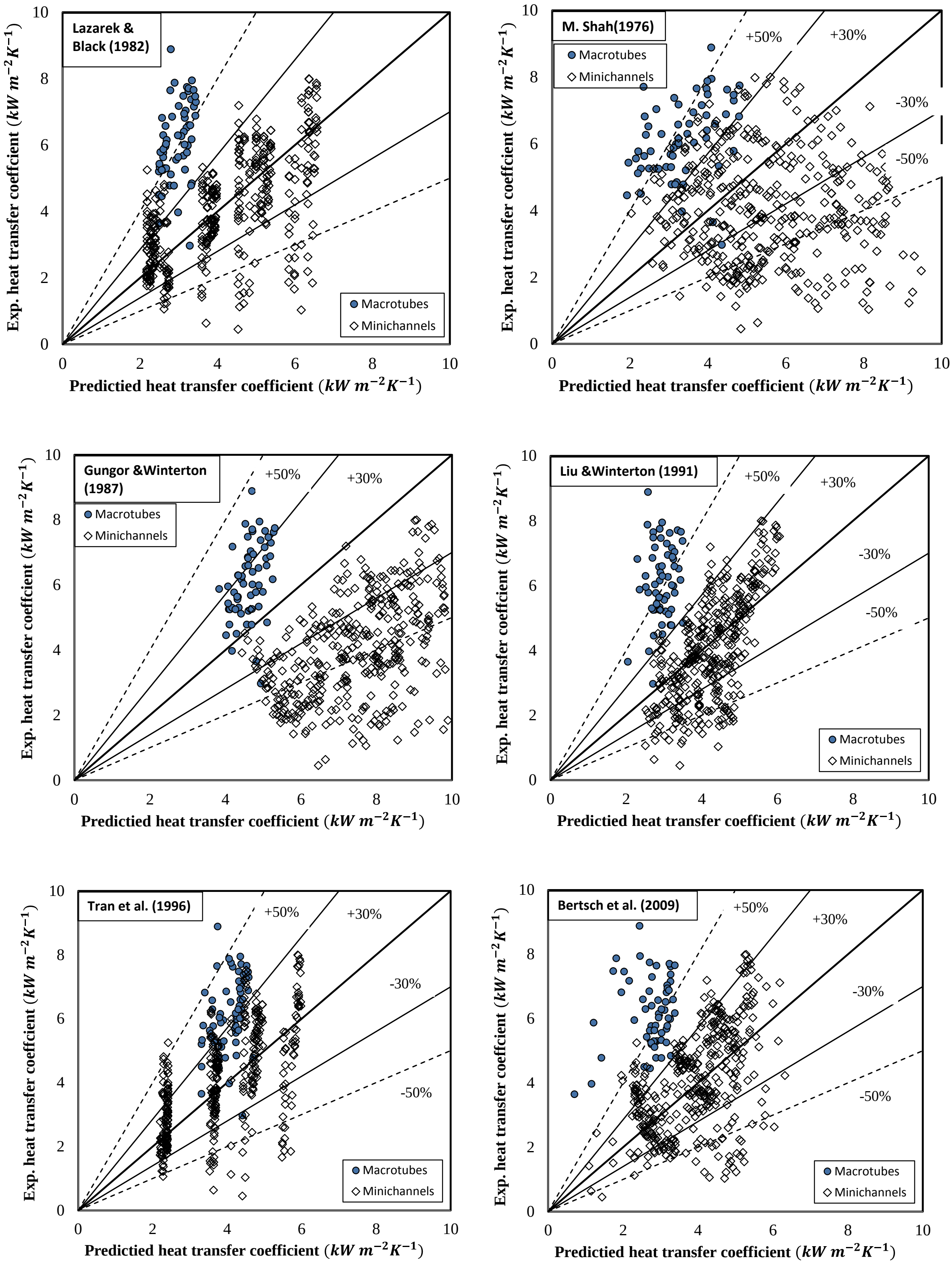

Figure 2. Comparison of experimental data with some existing correlations

et al [1], Tran et al. [15]. The comparison was shown in fig. 2. The summary of the above correlations was demonstrated in table 1. In pre dry-out regime, the heat transfer coefficient mainly consist two mechanisms: nucleate boiling and force convective boiling. Hence, the correlation proposed by Chen [2] that developed based on the superposition model was used as the basis for new proposed correlation. The formula was defined as:

$$h_{tp} = F.h_{lo} + S.h_{pool} \tag{1}$$

Where h_{tp}: two-phase heat transfer coefficient, $F.h_{lo}$: Convective boiling term; $S.h_{pool}$: Nucleate boiling term. F is the enhance factor of convective boiling process due to the increasing of flow velocities when the vapor quality increases. S is the suppression factor of nucleate boiling term to account the decreasing of fluid layer thickness as the vapor quality increases.

In convective boiling term, the Distus-Boelter correlation was used to evaluate the heat transfer of liquid only in the tubes:

$$h_{lo} = 0.023\mathrm{Re}_l^{0.8}\,\mathrm{Pr}_l^{0.4}\frac{k_l}{D} \tag{2}$$

With two-phase flow, the heat transfer is normally higher than that in single phase due to the higher velocities and the thinner film layers. The enhance factor F, consequently, is considered under the effect of vapor quality ratio and the density ratio. Chen [2] and Gungor-Winterton [4] defined F as the function of Martinelli parameter X_{tt}. Shah [7] replaced this parameter by convection number C_o since the influence of viscosity ratio was not found. In this study, the correlate analysis also depicted that the Martinelli parameter and convection number showed the similar effects. To simply the calculation, F was chosen as the function of convection number $F=f(C_o)$. The convection number was defined as:

$$C_o = \left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_g}{\rho_l}\right)^{0.5} \tag{3}$$

Using the regression method, the new F factor was proposed that

$$F = 1.061\exp\left(\frac{0.042}{C_o}\right) \tag{4}$$

In the nucleate boiling term, Copper correlation [3] was used to predict the pool boiling heat transfer. Assume that the surface roughness of tubes are 1µm, the Copper correlation was determined as:

$$h_{pool} = 55P_R^{0.12}(-\log_{10}(P_R))^{-0.55}M^{-0.5}q_H^{0.67} \tag{5}$$

Where P_R is the pressure reduction; M is the molecular weight of R410A. Note that, the properties of R410A are obtained using REPROP 8 of NIST.

The suppression factor S of nucleate boiling term was performed with the least square program. After many testing, the final form of S is the function of convection and confinement number. The detail of function was defined as:

$$S = 0.238\frac{C_o^{0.238}}{C_f^{1.11}} \tag{6}$$

The confinement number was defined as:

$$C_f = \frac{1}{D}\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}} \tag{7}$$

Table 1. Flow boiling heat transfer correlations considered in this work	
1. Lazarek and Black correlation[12]:	$h_{tp} = (30\,\text{Re}_{lo}^{0.857}\,Bo^{0.714})(\frac{k_l}{D_h});$ $\text{Re}_{lo} = \frac{GD_h}{\mu_l}; \text{Bo} = \frac{\phi}{Gi_{\lg}}; \phi = 1.4\times10^4 - 3.8\times10^5\ \text{W}/m^2$
2. Shah correlation[7;8]	$\psi = \frac{h_{TP}}{h_l}; \quad Co = \left(\frac{1}{x-1}\right)^{0.8}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}$ $Bo = \frac{q}{Gh_{lv}}; \quad Fr_L = \frac{G^2}{\rho_l^2 gD}$ $h_l = 0.023\,\text{Re}_l^{0.8}\,\text{Pr}_l^{0.4}\left(\frac{k_l}{D_i}\right)$ $h_{tp} = Max(F,S)h_l;$
. 3 Gungor and Winterton correlation [4]:	$h_{tp} = F.h_l + S.h_{nb}$ $h_l = 0.023\,\text{Re}_l^{0.8}\,\text{Pr}_l^{0.4}\left(\frac{k_l}{D_i}\right)$ $F = 1 + 24000Bo^{1.16} + 1.37\left(\frac{1}{X_{tt}}\right)^{0.86}$ $h_{nb} = 55P_r^{0.12}q^{2/3}(-\log_{10} p_r)^{-0.55}M^{-0.5}$ $S = (1+0.55F^{0.1}\,\text{Re}_{lo}^{0.16})^{-1}$ If the tube is horizontal and the Froude number Fr_l is less than 0.05 then F,S should be multiplied by the factor $F.Fr_l^{(0.1-2Fr_l)}; SFr_l^{0.5}$, respectively.
4. Liu and Winterton [9]	$h_{tp} = \left[\left(Fh_l\right)^2 + \left(Sh_{pool}\right)^2\right]^{0.5},$ $\text{h}_l = 0.023\,\text{Re}_{lo}^{0.8}\,\text{Pr}_l^{0.4}\,\frac{k_f}{D_h}; F = \left[1 + x\,\text{Pr}_l\left(\frac{\rho_l}{\rho_v} - 1\right)\right]^{0.35}$ $h_{pool} = 55P_r^{0.12}q^{2/3}(-\log_{10} p_r)^{-0.55}M^{-0.5}; S = \left(1+0.55F^{0.1}\,\text{Re}_l^{0.16}\right)^{-1}$
5. Tran et al. [15]	$h = (8.4x10^{-5})(Bo^2 We_l)^{0.3}\left(\frac{\rho_l}{\rho_v}\right)^{-0.4}$
6. Bertsch et al. [1]	$h_{tp} = S.h_{nb} + F.h_{conv,tp}$ $h_{nb} = 55P_r^{0.12}q^{2/3}(-\log_{10} p_r)^{-0.55}M^{-0.5};$ $h_{conv,tp} = h_{conv,l}.(1-x) + h_{conv,v}.x;$ $S = 1 - x$ $F = 1 + 80.(x^2 - x^6).e^{-0.6C_f}$

4. ACCURACY ANALYSIS OF NEW PROPOSED CORRELATION

Fig.3 showed the comparison of mean deviation of present correlation with others. The new proposed correlation has the mean deviation of 20.66% and 21.06 % for macro and mini-channel, respectively. Among others, Gungor-Winterton correlation determined the best deviation for the macro channel (25% of MD) but failed in predicting the heat transfer coefficient of minichannel. In the other case, Tran correlation [15] showed the mean deviation of around 30% for both macro and minichannel. The mean deviation was determined as following:

$$MD = \frac{1}{N}\sum\frac{\left|h_{pred} - h_{\exp}\right|}{h_{\exp}}\times 100\% \tag{8}$$

The comparison of experimental heat transfer coefficient and predicted one was shown in figure 4.

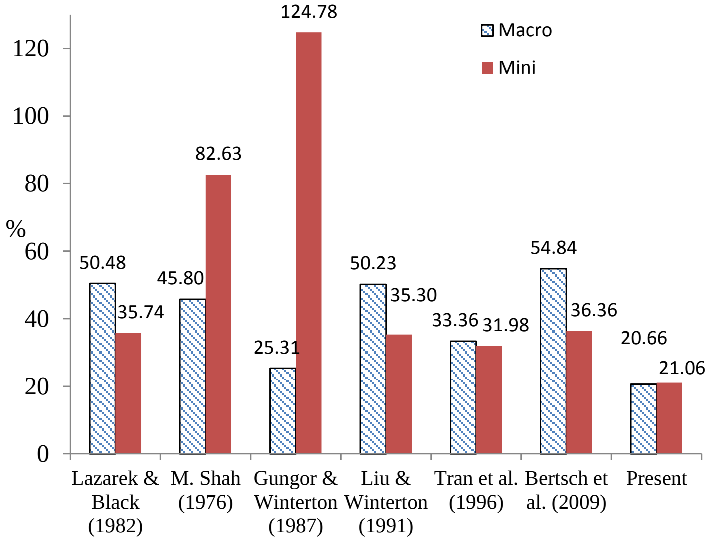

Figure 3. Comparison of mean deviations

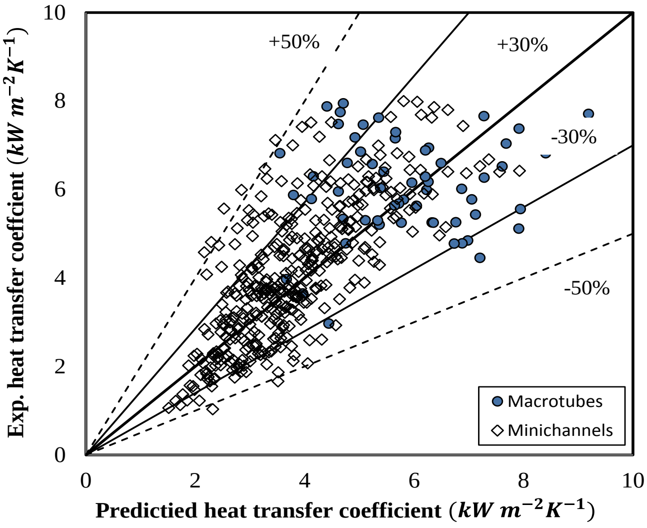

Figure 4. Comparison between experimental and predicted heat transfer coefficient

5. CONCLUSIONS

A new correlation for two-phase flow boiling heat transfer of R410A was developed. The proposed correlation was based on the superposition model of nucleate boiling and force convective boiling contribution. The mean deviation for both macro and mini-channels was achieved at about 20%.

ACKNOWLEDGEMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2013R1A1A2013476).

REFERENCES

[1]. Bertsch, S. S., Groll, E. a., & Garimella, S. V. (2009). A composite heat transfer correlation for saturated flow boiling in small channels. International Journal of Heat and Mass Transfer, 52(7-8), 2110–2118.

[2]. Chen, J.C., 1966. A correlation for boiling heat transfer to saturated fluids in convective flow. Ind. Eng. Chem. Process Des. Dev. 5, 322–329.

[3]. Cooper, M.G., 1984. Heat flow rates in saturated nucleate pool boiling–a wide-ranging examination using reduced properties. Advances in Heat Transfer 16, 157 – 239 (Academic Press).

[4]. Gungor, K., & Winterton, R. (1986). A general correlation for flow boiling in tubes and annuli. International Journal of Heat and Mass Transfer, 29(3), 351–358.

[5]. Kandlikar, S. (1990). A general correlation for saturated two-phase flow boiling heat transfer inside horizontal and vertical tubes. Journal of Heat Transfer, 112(February 1990).

[6]. Kandlikar, S., & Steinke, M. (2003). Predicting heat transfer during flow boiling in minichannels and microchannels, 1–9.

[7]. Shah, M. (1976). A new correlation for heat transfer during boiling flow through pipes. ASHRAE Trans, 82, 66–86.

[8]. Shah, M. M. (1982). Chart correlation for saturated boiling heat transfer: equations and further study. ASHRAE Trans.;(United States), 88(1), 185–196.

[9]. Liu, Z., & Winterton, R. (1991). A general correlation for saturated and subcooled flow boiling in tubes and annuli, based on a nucleate pool boiling equation. International Journal of Heat and Mass Transfer, 34(11), 2759–2766.

[10]. Kew, P., & Cornwell, K. (1997). Correlations for the prediction of boiling heat transfer in small-diameter channels. Applied Thermal Engineering, 17, 705–715.

[11]. Kim, S.-M., & Mudawar, I. (2013). Universal approach to predicting saturated flow boiling heat transfer in mini/micro-channels – Part II. Two-phase heat transfer coefficient. International Journal of Heat and Mass Transfer, 64, 1239–1256.

[12]. Lazarek, G., & Black, S. (1982). Evaporative heat transfer, pressure drop and critical heat flux in a small vertical tube with R-113. International Journal of Heat and Mass Transfer, 25(7).

[13]. S. S. Kutateladze. (1961). Boiling heat transfer. Heat and Mass Transfer, 4, 31–45.

[14]. Saitoh, S., Daiguji, H., & Hihara, E. (2005). Effect of tube diameter on boiling heat transfer of R-134a in horizontal small-diameter tubes. International Journal of Heat and Mass Transfer, 48(23-24), 4973–4984.

[15]. Tran, T., Wambsganss, M., & France, D. (1996). Small circular-and rectangular-channel boiling with two refrigerants. International Journal of Multiphase Flow, 3(4), 485–498.

[16]. Zhang, W., Hibiki, T., & Mishima, K. (2004). Correlation for flow boiling heat transfer in mini-channels. International Journal of Heat and Mass Transfer, 47(26), 5749–5763.