TSF0007

Two-phase flow boiling of R-134a refrigerant in a vertical upward circular mini-channel

Pakorn Wongpromma [1], Sira Saisorn [2,*], and Somchai Wongwises [3]

[1] Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10250, Thailand
[2] Department of Mechanical Engineering, King Mongkut's Institute of Technology Ladkrabang, Prince of Chumphon campus, Chumphon 86160, Thailand
[3] Department of Mechanical Engineering, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand
[*] Corresponding Author: E-mail: sira.sa@kmitl.ac.th, Tel.:+66 7 7506 410

Abstract

Two-phase flow boiling experiment of R-134a refrigerant in a vertical upward circular mini-channel was conducted to investigate flow visualization and heat transfer phenomena. The test section is a stainless steel tube with a diameter of 1 mm and a length of 500 mm. Flow pattern and heat transfer coefficient data were obtained for a mass flux range of 250-820 kg/m^{2}s, a heat flux range of 1-57 kW/m^2 and a saturation pressure range of 8-10 bar. The results indicated five different flow patterns including slug flow, throat-annular flow, churn flow, annular flow and annular-rivulet flow. The flow patterns were found to have strong influence on the heat transfer coefficients. The heat transfer coefficient at low heat flux tends to be independent of mass flux and vapour quality. Increasing of saturation pressure tends to decrease the heat transfer coefficient. In addition, the comparisons of the experimental results with heat transfer prediction methods for small channels were carried out.

***Keywords**:* Flow boiling, Mini-channel, Flow pattern, Heat transfer

1. Introduction

The flow boiling heat transfer in small passages has been rapidly developed for many engineering applications, and hence, research on two-phase flow boiling in micro-scale channel has been needed during the past years. The small passages can be applied to energy and process systems including high-flux compact heat exchangers and cooling devices of equipment such as high-powered lasers, high-performance electronic devices. In micro-channel, surface tension is likely to play an important role for flow boiling mechanisms. In this regard, the flow phenomena of R-134a inside micro-scale channel are significantly different from behaviors taking place in conventional channels. The literature [1-4] indicated discrepancy between micro-scale and macro-scale flows.

The flow boiling experiment in micro-scale channel channel have been mainly reported for horizontal flow as discussed in Kanizawa et al. [5]. However, the flow boiling of R-134a flowing in vertical channel is still needed. The flow boiling in vertical circular mini-channel has been studied by different researchers in literature. For example, Owhaib et al. [6] carried out flow boiling of R-134a in vertical circular tubes having diameters of 1.7, 1.224 and 0.826 mm. The heat transfer coefficient increased with heat flux value and saturation pressure but was less dependent on mass flux or vapour quality. Similar results were reported by Huo et al. [7] which corresponded to the experiment with R-134a flowing in vertical tube with larger diameters (2.01 and 4.26 mm). Lin et al. [8] studied the boiling heat transfer behaviors of R141b refrigerant in a vertical tube with a diameter of 1 mm and reported that the heat transfer mechanisms were dominated by nucleate boiling at low vapour quality while convective boiling contribution was dominant at high vapour quality. Moreover, the heat transfer coefficient can be improved by reducing the channel diameter [6, 7]. Saisorn et al. [9] experimentally studied boiling heat transfer of R-134a flowing in 1.75 mm diameter channel placed in different orientations. The results indicated that vertical flow gave better heat transfer performance in comparison to the horizontal flow. The buoyancy effect was also addressed by Saisorn and Wongwises [10], Kandlikar and Balasubramanian [11], and Wang et al. [12].

Regarding the literature survey, therefore, the aim of this work is to investigate flow visualization and heat transfer phenomena for flow boiling of R134a in a vertical channel having a diameter of 1 mm. The effects of various conditions on two-phase heat transfer phenomena are reported in this work, which has never been seen before.

2. Nomenclature

B_o	=	boiling number, $B_o = q''/Gi_{LG}$
D	=	diameter (m)
G	=	mass flux (kg/m^{2}s)
h	=	heat transfer coefficient (W/m^{2}K)
i	=	specific enthalpy (J/kg)
i_{LV}	=	latent heat of vapourization (J/kg)
L	=	channel length (m)
MAE	=	mean absolute error,

$$\mathrm{MAE} = \frac{1}{N}\sum_{1}^{N}\left(\frac{\left|h_{pre} - h_{exp}\right|}{h_{exp}}\right)\times 100$$

N	=	number of experimental data
q	=	heat transfer rate (W)
q_{loss}	=	heat loss (W)
q''	=	heat flux (W/m^2)
T_{fluid}	=	fluid temperature (K)
$T_{wall,in}$	=	inner wall temperature (K)
W_e	=	Weber number, $W_e = G^2D/\rho\sigma$
x	=	vapour quality
z	=	axis length (m)

Greek symbols

ρ	=	density (kg/m^3)
σ	=	surface tension (N/m)

Subscripts

avg	=	average
exp	=	experimental value
in	=	inner
L	=	liquid phase
loc	=	local
pre	=	predicted value
sat	=	saturation
wall	=	wall surface

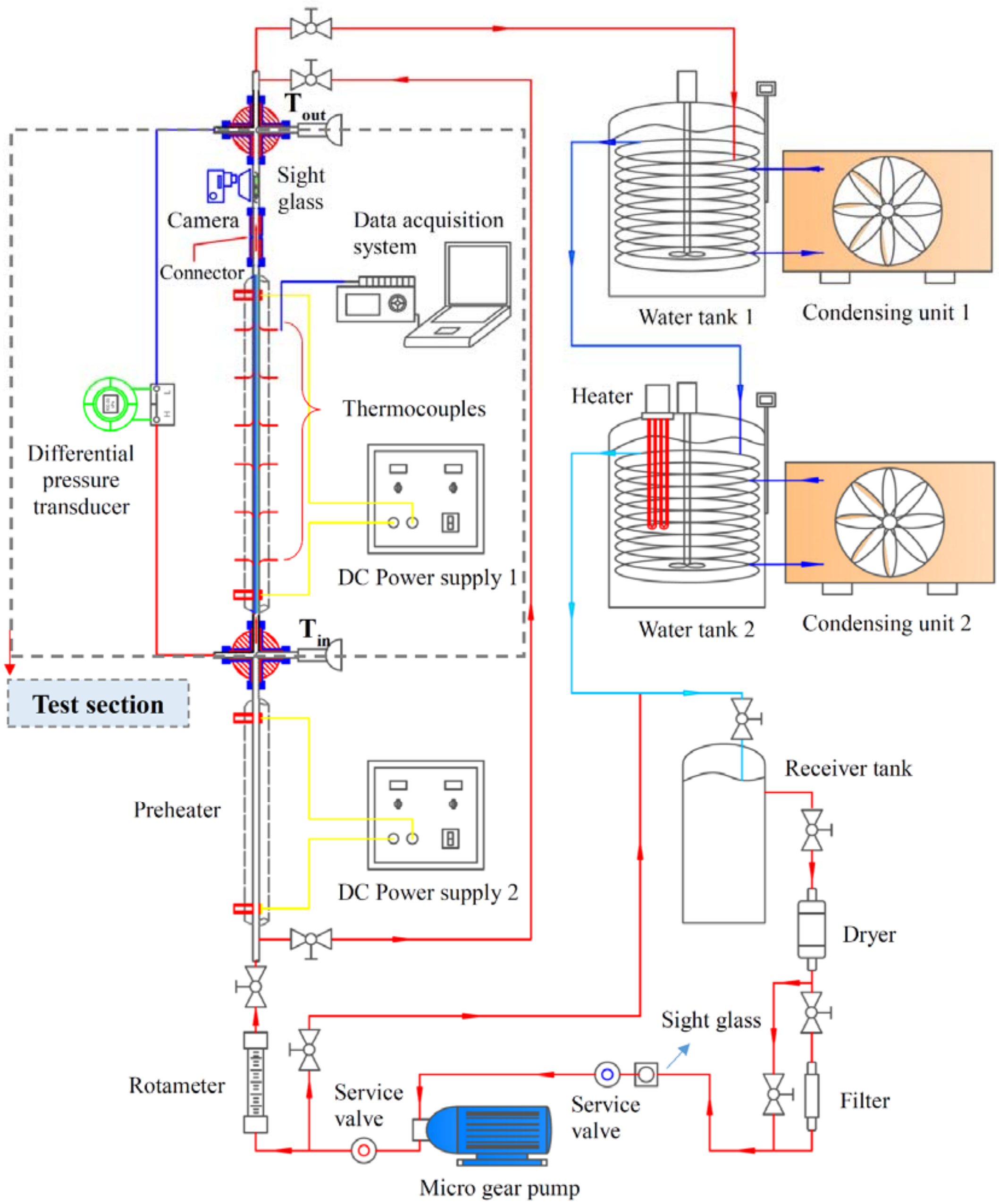

Fig. 1 Schematic diagram of flow boiling apparatus.

3. Experimental Apparatus and Procedure

In this study, the experimental apparatus was designed to investigate flow boiling of R-134a flowing in a vertical mini-channel with a diameter of 1 mm. The main components of the system include a test section, refrigerant loop, sub-cooling loop and a data acquisition system.

Fig.1 shows the schematic diagram of flow boiling apparatus. Liquid refrigerant is pumped by a gear pump which can be regulated by means of an inverter. The refrigerant flows into a filter/dryer and then passes a series of a rotameter, pre-heater, sight glass tube and enters the test section, respectively. The test section is mounted on a platform oriented in vertical direction. Vapour quality before entering the test section is controlled by the pre-heater with a DC power supply (120A, 15V). The test section in this work is a stainless steel tube to which the DC power supply is attached in order to generate a constant surface heat flux condition. Leaving the test section, the refrigerant is then condensed in a water tank 1 with a condensing units 1. The temperature of system is controlled by a water tank 2 with a heater and a condensing unit 2 and then is collected in a receiver tank. The liquid refrigerant returns to the refrigerant pump to complete the cycle. T-type thermocouples are installed at the inlet and outlet of the test section to measure the fluid temperatures. The 12 thermocouples are installed on the top and bottom sides along the tube to measure the wall temperature. The test section is well insulated with rubber foam. A R-134a refrigerant rotameter is installed near the pre-heater and is specially calibrated in the range 0.02 to 0.2 LPM by the manufacturer. The signals from all the thermocouples and pressure transducers are collected and recorded by the data acquisition system.

The thermocouples and pressure transducers as well as all relevant instruments installed in flow boiling apparatus were well calibrated. The two-phase flow experiments were conducted after the validation based on the single-phase flow results which were fairly agree with the fully developed laminar flow theory.

4. Data reduction

The local heat transfer coefficient, h_{loc}, at a given distance is determined by:

$$h_{loc} = \frac{q''}{\left(T_{wall,in}(z) - T_{fluid}(z)\right)} \tag{1}$$

The inner wall temperature of the tube can be determined using the equation for steady-state one-dimensional heat conduction.

The local fluid temperatures, T_{fluid} (z), of two-phase region can be obtained based on the assumption corresponding to a linear variation of the fluid temperature along the test section.

The average heat transfer coefficient for the test section is obtained as seen in Eq. (2)

$$h_{avg} = \frac{q''}{\left(T_{wall,in,avg} - T_{fluid,avg}\right)} \tag{2}$$

where $T_{wall,in,avg}$ is the average value of the inner wall surface temperatures in the test section. The average

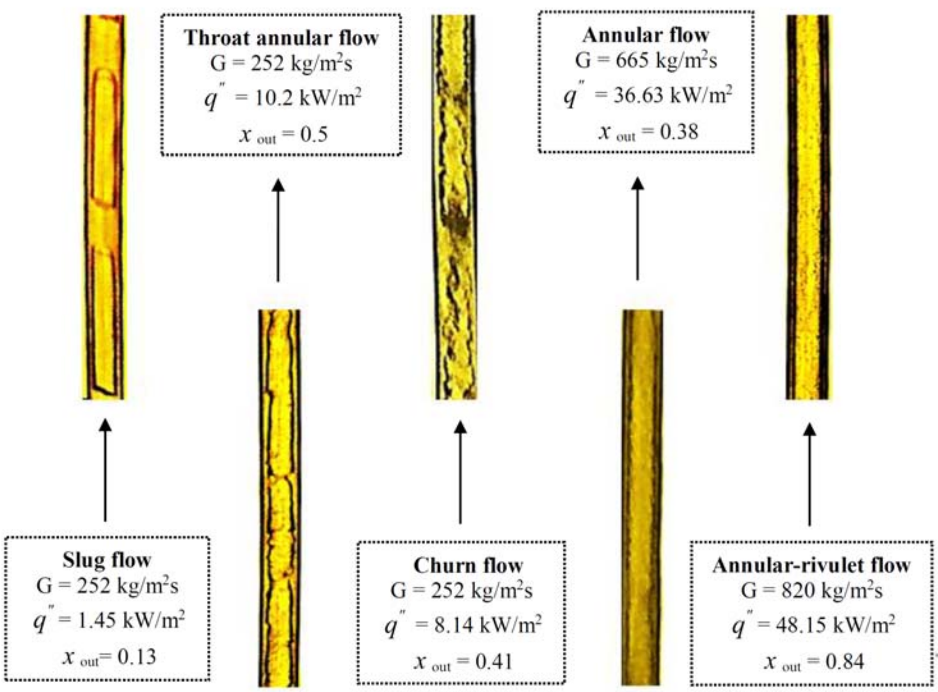

Fig. 2 Flow patterns for vertical upward flow (8 bar).

temperature of R-134a refrigerant, $T_{fluid,avg}$, can be obtained from measurements between thermocouples installed at the inlet and outlet of the test section.

Heat flux, q'', transferred to the test section can be calculated from

$$q'' = \frac{q - q_{loss}}{\pi DL} \tag{3}$$

where q is heat transfer rate based on joule heating method. Heat loss, (q_{loss}), can be estimated based on energy balance and thermal resistance concept

Finally, the local vapour quality of the refrigerant R-134a is determined based on thermodynamic properties as follow

$$x = \frac{i - i_L}{i_{LV}} \tag{4}$$

where i_L is the specific enthalpy of the saturated liquid, i_{LV} represent the latent heat of vaporization and i is the local fluid enthalpy. The range of experimental condition is shown in Table 1.

Table 1 Experimental conditions.

Parameter	**Range**
Diameter (mm)	1
Length (mm)	500
Mass flux (kg/m^{2}s)	250-820
Heat flux (kW/m^2)	1-57
Saturation pressure (bar)	8-10
Vapor quality	0.1-0.98
Test section material	Stainless steel

5. Results and Discussion

5.1 Flow pattern

The observed flow patterns in fig. 2 include slug flow, throat-annular flow, churn flow, annular flow, and annular-rivulet flow. The descriptions of different flow patterns were similar to vertical upward flow results reported in Saisorn et al. [9].

Slug flow is characterized by elongated bubbles that are larger and longer than the tube diameter.

Throat-annular flow occurs collision of two consecutive elongated bubbles, which coalesce a throat-like gas core.

Churn flow is observed distortion of the elongated bubbles.

Annular flow is formed by liquid film at the tube wall and vapour flow in region of the tube core.

Annular-rivulet flow is characterized the flowing of a rivulet-like liquid stream on the tube wall.

The results were similar to those reported by Martin-Callizo et al. [13]. The different flow patterns are due to the interactions of flow inertia, buoyancy, gravitational force and surface tension.

5.2 Heat Transfer

The experiments of two-phase heat transfer are presented for R-134a during flow boiling in a vertical upward flow.

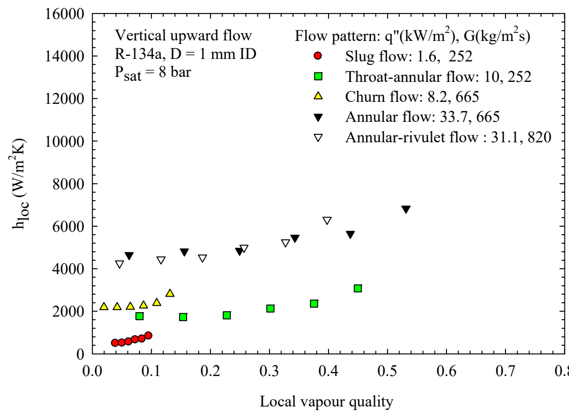

Fig. 3 Local heat transfer coefficient data for various flow patterns.

In Fig. 3, the local heat transfer coefficients for different flow pattern data are presented. It is found that gas-core flows such as annular flow and annular-rivulet flow appear with the high heat transfer coefficient. The experimental results also show that heat transfer coefficient increases with increasing heat flux but is less affected by vapour quality. In addition, the effects of such parameters as heat flux, mass flux, and saturation pressure on the average heat transfer coefficient are illustrated as follows.

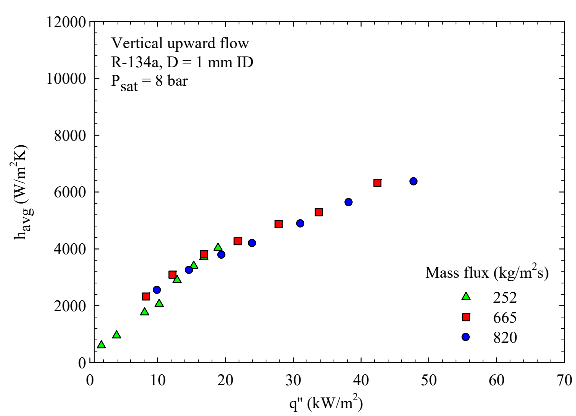

Fig. 4 Heat flux versus heat transfer coefficient for different mass flux values.

In fig. 4, the average heat transfer coefficient increases with increasing heat flux but is less dependent on mass flux. The two-phase heat transfer mechanisms seem to be nucleate boiling contribution. Similar observations were also reported by Owhaib et al. [6] and Huo et al. [7].

Fig. 5 shows the effect of saturation pressure on the heat transfer coefficient. Based on uncertainty analysis under the saturation pressures ranging from 8 to 10 bar, the heat transfer coefficient tends to decrease with increasing the saturation pressure. This may be attributed to the fact that, when the saturation pressure is increased (the latent heat of vapourization is reduced), which causes lower liquid viscosity, the liquid film on the tube wall tends to break easier than the film flowing at lower saturation pressure region. This result also agrees with previous researchers such as Choi et al. [14], Kaew-on and Wongwises [15], and Saisorn et al. [9].

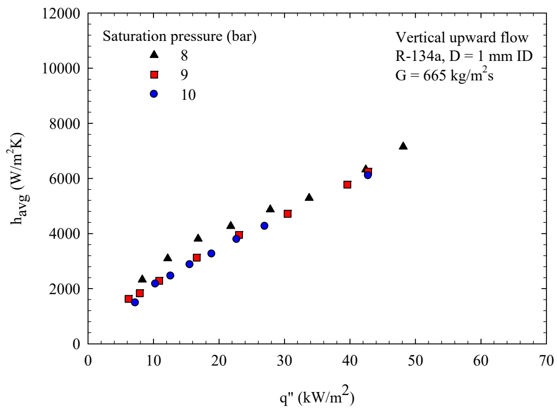

Fig. 5 Heat flux versus heat transfer coefficient for different saturation pressures.

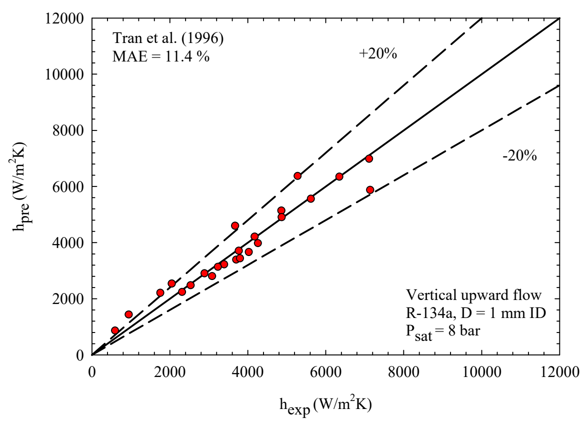

Fig. 6 Comparison between measured and calculated heat transfer coefficient using Tran et al. correlation [16].

The experimental results are also compared with the existing correlations. Only the best prediction method is illustrated in this paper.

Tran et al. [16] modified the correlation suggested by Lazarek and Black [17] which associated with flow boiling in circular and rectangular mini-channels. The prediction method was developed based on the nucleate boiling mechanisms. The heat transfer coefficient can be predicted by

$$h = (8.4\times10^{5})(B_o{}^{2}We)^{0.3}\left(\frac{\rho_L}{\rho_V}\right)^{-0.4} \quad (5)$$

$$\mathrm{MAE} = \frac{1}{N}\sum_{1}^{N}\left(\frac{\left|h_{pre}-h_{\exp}\right|}{h_{\exp}}\right)\times 100 \quad (6)$$

where B_o is Boiling number, We is Weber number, ρ_L is density of liquid, ρ_V is density of vapour, and MAE is mean absolute error.

In fig. 6, the comparison results are presented regarding the average heat transfer coefficient data. The mean absolute errors (MAE) calculated using eq. (6) is 11.4%. The predicted data fall within ±20% error band. As a consequence of the comparisons, the correlation proposed by Tran et al. [16] can well predict the experimental data. This implies that the heat transfer phenomena in a 1 mm diameter tube during vertical upward flow are governed by nucleate boiling contribution.

6. Conclusion

In this work, the flow boiling experiment of R-134a in a vertical upward flow was carried out in a 1 mm diameter tube. The test section was a stainless steel tube. Flow visualization and heat transfer behaviors were reported and the conclusions can be drawn as follows:

1. The observed flow patterns include slug flow, throat-annular flow, churn flow, annular flow and annular-rivulet flow.
2. The heat transfer coefficient increases with increasing heat flux but is less dependent on mass flux as well as vapour quality.
3. The increase in saturation pressure may reduce the heat transfer coefficient.
4. The comparisons with the prediction methods indicate the nucleate boiling mechanisms which are dominant over the entire range of the operating conditions.
5. The present data can be used to develop the thermal device using micro-scale channel, especially oriented in vertical direction.

7. Acknowledgement

The authors would like to express their appreciation to the Thailand Research Fund and KMITL Research Fund for providing financial support for this study.

8. References

[1] Ong, C.L. and Thome, J.R. (2011). Macro-to-microchannel transition in two-phase flow: Part 1 – Two-phase flow patterns and film thickness measurements, *Experimental Thermal and Fluid Science*, vol.35(1), January 2011, pp. 37-47.

[2] Tibiriçá, C.B. and Ribatski, G. (2013). Flow boiling in micro-scale channels – Synthesized literature review, *International journal of refrigeration*, vol.36(2), March 2013, pp. 301-324.

[3] Mahmouda, M.M. and Karayiannis, T.G. (2013). Heat transfer correlation for flow boiling in small to micro tubes, *International Journal of Heat and Mass Transfer*, vol.66, November 2013, pp. 553-574.

[4] Kim, S.M. and Mudawar, I. (2014). Review of databases and predictive methods for heat transfer in condensing and boiling mini/micro-channel flows, *International Journal of Heat and Mass Transfer*, vol.77, October 2014, pp. 627-652.

[5] Kanizawa, F.T., Tibiriçá, C.B., and Ribatski, G. (2016). Heat transfer during convective boiling inside microchannels, *International Journal of Heat and Mass Transfer*, vol.93, February 2016, pp. 566–583.

[6] Owhaib, W., Martín-Callizo, C., and Palm, B. (2004). Evaporative heat transfer in vertical circular microchannels, *Applied Thermal Engineering*, vol.24(8-9), June 2004, pp. 1241-1253.

[7] Huo, X., Chen, L., Tian, Y.S., and Karayiannis, T.G. (2004). Flow boiling and flow regimes in small diameter tubes, *Applied Thermal Engineering*, vol.24(8-9), June 2004, pp. 1225-1239.

[8] Lin, S., Kew, P.A., and Cornwell, K. (2001). Two-phase heat transfer to a refrigerant in a 1 mm diameter tube, *International journal of refrigeration*, vol.24(1), January 2001, pp. 51-56.

[9] Saisorn, S., Kaew-On, J., and Wongwises, S. (2013). An experimental investigation of flow boiling heat transfer of R-134a in horizontal and vertical mini-channels, *Experimental Thermal and Fluid Science*, vol.46, April 2013, pp. 232–244.

[10] Saisorn, S. and Wongwises, S. (2015). Adiabatic two-phase gas–liquid flow behaviors during upward flow in a vertical circular micro-channel, *Experimental Thermal and Fluid Science*, vol.69, December 2015, pp. 158–168.

[11] Kandlikar, S.G. and Balasubramanian, P. (2005) An experimental study on the effect of gravitational orientation on flow boiling of water in 1054 × 197 μm parallel minichannels, *Journal of Heat Transfer*, vol.127, August 2005, pp. 820-829.

[12] Wang, C.C., Chang, W.-J., Dai, C.-H., Lin, Y.-T., and Yang, K.-S. (2012). Effect of inclination on the convective boiling performance of a microchannel heat sink using HFE-7100, *Experimental Thermal and Fluid Science*, vol.36, January 2012, pp. 143-148.

[13] Martín-Callizo, C., Palm, B., Owhaib, W., and Ail, R. (2010). Flow boiling visualization of R-134a in a vertical channel of small diameter, *Journal of Heat Transfer*, vol.132, March 2010, pp. 1-8.

[14] Choi, K.I., Pamitran, A.S., and Oh, J.T. (2007). Two-phase flow heat transfer of CO_2 vaporization in smooth horizontal minichannels, *International journal of Refrigeration*, vol.30(5), August 2007, pp. 767–777.

[15] Kaew-On, J., and Wongwises, S. (2009). Experimental investigation of evaporation heat transfer coefficient and pressure drop of R-410A in a multiport mini-channel, *International journal of Refrigeration*, vol.32(1), January 2009, pp. 124–137.

[16] Tran, T.N., Wambsganss, M.W., and France, D.M. (1996). Small circular- and rectangular- channel boiling with two refrigerants, *International journal of Multiphase Flow*, vol.22(3), June 1996, pp. 485-498.

[17] Lazarek, G.M., and Black, S.H. (1982). Evaporative heat transfer, pressure drop and critical heat flux in a small diameter vertical tube with R-113, *International Journal of Heat and Mass Transfer*, vol.25(7), July 1982, pp. 945-960.