EFFECT ON SURFACE VIBRATION ON FLOW BOILING HEAT TRANSFER OF R-600A IN A VERTICAL/PARALLEL CIRCULAR TUBE WITH METALLIC POROUS INSERTS

[1]MAO-YU WEN, [2]CHING-YEN HO

[1]Department of Mechanical Engineering, Cheng Shiu University, Kaohsiung 833, Taiwan, ROC
[2]Department of Mechanical Engineering, Hwa Hsia University of Technology, Taipei 235, Taiwan, ROC
E-mail: [1]wmy@gcloud.csu.edu.tw, [2]hcy2126@cc.hwh.edu.tw

Abstract - This study carried out an experiment to investigate the characteristics of sub-cooled flow boiling heat transferof a hydrocarbon refrigerant R600a (isobutane) flowing in a vertical circular pipe within dispersed-copper porous inserts under surface vibration. The experiment was performed at a saturation temperature of 10°C. Vapor qualities were from 0.076 to 0.89, and there was a mass flux of 105 – 1085 kg/m^2s and a heat flux of 12-65 kW/m^2. The effects of surface vibration and the geometries of the inserts (the mean pore diameters, porosity and permeability) on the heat transferof R-600a were presented. In addition, comparisons were made with a horizontal pipe having the same geometry and experimental conditions

Index Terms - R600a,vertical/ parallel flow boiling, heat transfer, surface vibration, dispersed-copper porous inserts sixth term

I. INTRODUCTION

Pulsation or vibration heat transfer has become a topic attracting increasing research attention. Boiling heat transfer is an important research field [1], where the vibrations promote bubble formation delaying the onset of the critical heat flux. For high heat flux applications, porous media has been widely used to effectively enhance heat transfer in cooling channels.A review of the literature on flow boiling associated with ammonia and hydrocarbon refrigerants was undertaken by Thome et al. [2].

The method of intensification of the heat transfer process by applying vibrations to the heating surface is among the promising techniques. Liu et al. [3] investigated the effects of mechanical vibration on the heat transfer characteristics of tubular laminar flow.Lee et al. [4] studied the effects of mechanical vibrations on the CHF at atmospheric pressure in a vertical annulus tube under electrically heated conditions and reported that the vibration intensity increased the CHF up to 16.4%. The vibration amplitude was one of the effective parameters for CHF enhancement. Vibration frequency and mass flux had no significant effect on CHF enhancement.Navruzovet al. and Li et al. [5] experimentally and numerically performed convective heat transfer performance using a vertically-oriented piezoelectric fan in the presence of a channel flow.The effect of the ultrasonic vibrations on the heat transfer enhancement has been reported by several authors [6]. Free convection [7] and boiling [8, 9] were extensively investigated, and the consequences of ultrasound upon these phenomena are well known. Rui and Tao [10] numerically studied both the heat transfer and pressure drop for a static round tube and cosine oscillating tube using the finite volume method.Cavitation and acoustic streaming are physical processes subsequent to ultrasound propagation into a liquid medium, and their impact on heat transfer can be of major importance [11, 12]. Chen et al. [13] utilized an experimental test and empirical correlation development for heat transfer enhancement of a stainless-steel circular heater rod under ultrasonic vibration. The ultrasonic vibration was generated by three transducers with a total power of 150 W and an ultrasonic frequency of 40 kHz attached to the tank bottom. Effects of height, heat flux and liquid subcooling were investigated and analyzed.Dukhanet al. [14] experimentally investigated the heat transfer due to the oscillating water flow in open-cell aluminum-foam subjected to a constant wall heat flux. Liu et al. [15] experimentally studied the effect of the driven frequency on the flow and heat transfer of an impinging synthetic air jet. Deloueiet al. [16] experimentally investigated the effects of ultrasonic vibration and nanoparticles on the pressure drop and heat transfer enhancement of the inlet turbulent flow. The results indicate that ultrasonic vibrations could reduce the negative effect of a pressuredrop and improve the positive effect of heat transfer enhancement caused by nanoparticles up to 15.27% and11.37%, respectively. Although a number of works have reported in-tube evaporative heat transfer enhancement and the associated pressure drop with an internally porous media tube, experimental work on in-tube evaporations with copper porous inserts is sparse and little work exists regarding the effect of dispersed-copper porous inserts on the evaporation of R-600a. In addition, no previous work has addressed the effect of surface vibration on the flow boiling heat transfer of water in a circular tube with perforated-copper porous inserts.

It is therefore the objective of the current study to investigate the effect on surface vibration on two-

phase flow and boiling heat transfer characteristics of R-600a in a vertical tube with/without copper porous inserts. In this study, the influences of frequencies and amplitudes of vibration, mass velocity, heat flux, vapor quality and the geometry of the tube having dispersed coppers and pipe angles ($\theta = 0^{\circ}, 90^{\circ}$)on heat transfer characteristics were examined.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

A. Experimental apparatus

The present flow boiling test apparatus (Fig. 1) was illustrated in Wen et al. [17]. A DC servomotor powered

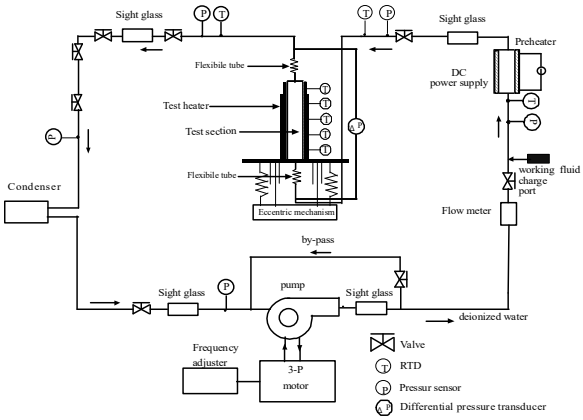


Figure 1.Schematic diagram of flow boiling test apparatus

the drive shaft (its height can be adjusted) carrying two different, rotating bodies at each end, as shown in Fig. 2. The tested surface underwent forced vibrations in the vertical plane. With this system, the oscillation frequency of the surface of the test section, f, could be set in the range of 0.98–10.19 Hz. This placement profile of the oscillating plate was measured by tracking the motion of the plate using an electro-optical displacement follower (accelerometer). This was done in order to assess the accuracy of the drive system in providing sinusoidal motion to the cylinder. The resulting time traces indicated that there was some dwell at the end of the stroke for low oscillation frequencies, ranging from 0.1 to 0.3 Hz. However, this dwell became negligible at higher oscillation frequencies.

The inaccuracy during measurements was deemed sufficiently small, while the motion of the cylinder was adequately sinusoidal for our purposes over the desired range of vibration frequencies. From the time traces, we obtain the surface vibration frequencies in the range of 0.98–10.19 Hz and the relative amplitudes of vibration of the flat surface ranged from 0.5–2.0 mm. Details of the test section are illustrated in Fig. 3. As shown, the section contains a horizontal tube with porous inserts, a surrounding annulus, and sensors for temperature and pressure. The test section is a counterflow, concentric-tube heat exchanger with R-600a present in the inner tube

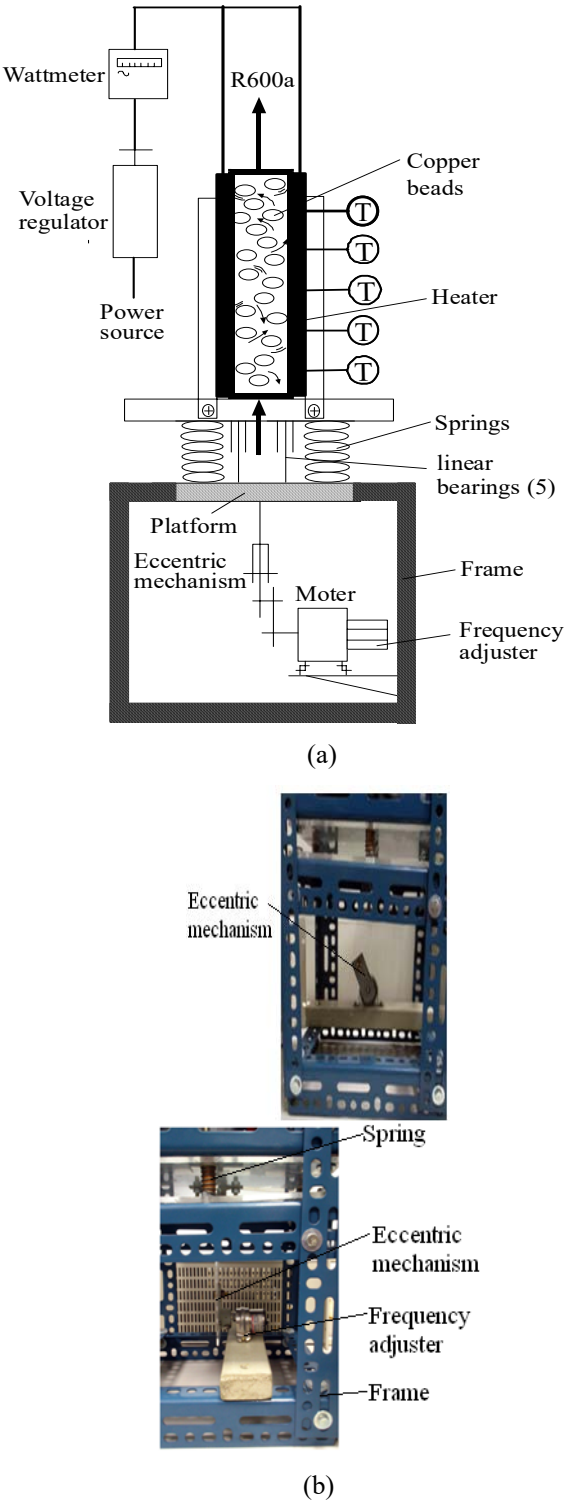


Figure 2. (a) Details of vibration device with test section, (b) picture of the vibration device

and water flowing in the annulus. The test section, working fluids and water loops are well insulated thermally with glass wool. The test tubes are made of oxygen-free high conductivity copper and have the same parameters of 9.5 mm OD, 7.5 mm ID and 500

mm length. The concept of dispersed-copper porous inserts for the present study is uncatchable and isn't brazed prior to be located inside the tube. The channel filled up with copper particles. The inserts should be fixed in the test tube. The physical parameters and dimensions of the porous channels are summarized in Table 1.

Table 1.Physical parameters and dimensions of the porous channels

Tube No	Diameter of copper	Number Percentage of two coppers	Mean Pore Diameter (mm)	Porosity	Permeability (m^2)
	Open tube				
1	D1=6mm		1.012	0.50296	$1.236x10^{-7}$
2	D2=2mm		0.336	0.50211	$1.362x10^{-8}$
3	D1：D2	1：1	0.500	0.49957	$5.3105x10^{-8}$
4	D1：D2	1：2	0.434	0.50425	$5.5645x10^{-8}$
5	D1：D2	2：1	0.606	0.50254	$5.47x10^{-8}$

The porosities of the five samples were measured using the density method [18].According toLurpin and Huntington [19], the mean pore diameter (D_e) and permeability (K_p) are given by:

$$D_e = \frac{2}{3} D_p \left(\frac{\varepsilon}{1-\varepsilon}\right) \quad (1)$$

$$K_p = \frac{D_p^2 \varepsilon^3}{150\,(1-\varepsilon)^2} \quad (2)$$

The uncertainty analysis was designed to consider the error caused by the interpolation procedure of the measuring instruments using a propagation-of-error analysis. Table 2 shows the measurement uncertainties of experimental parameters for the present study.

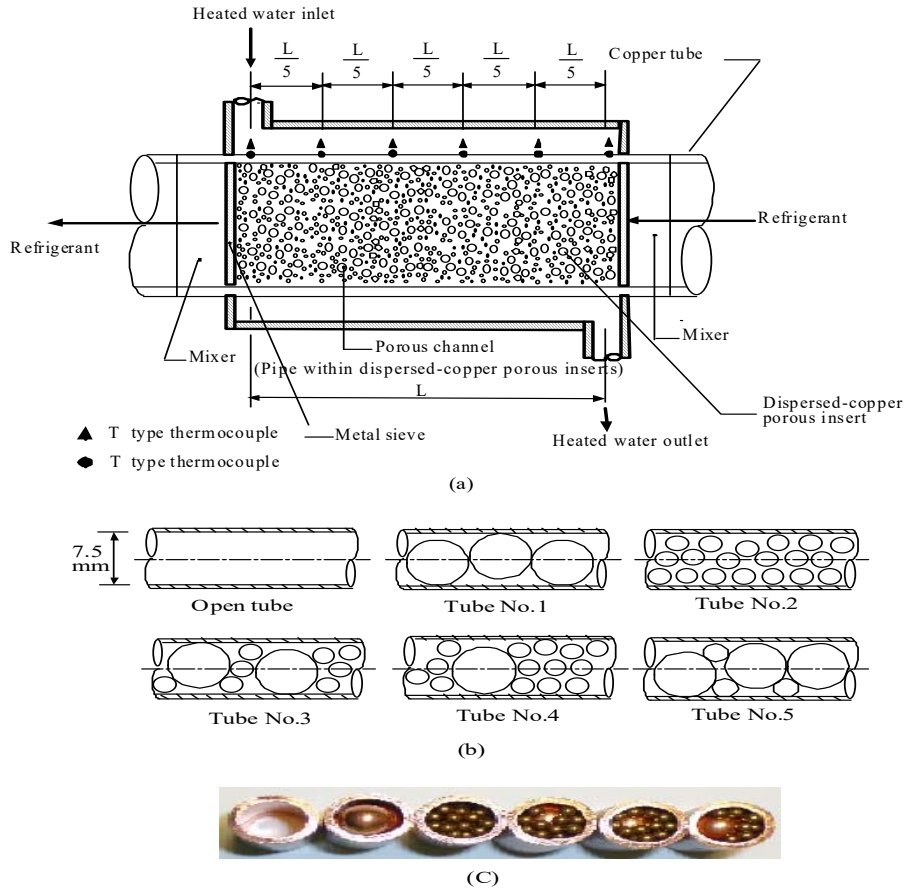


Figure 3. (a) Test channel within dispersed-copper porous inserts, (b) Schematic view of test tubes with inserts, (c) Photographs for side view of test tubes

Table 2.Measurement uncertainties of experimental parameters

Parameters	Uncertainty
Mass velocity, G	±3.1%
Mean heat flux supplied to test section, q	±4.2%
Temperature, T	±0.8%
Local quality in the test section, x	±4.9%
Average heat transfer coefficient, h	±9.2%
Vibration frequency, f	±0.4%
Vibration amplitude, Am	±2.1%

B. Data reduction

The imposed heat flux,q, to the boiling refrigerant in the test section is calculated from an energy balance on the water side. The heat loss, inferred from temperatures monitored in various locations inside the insulation of the test section, did not exceed 0.1% of the transferred heat flux and is assumed to be negligible. The local heat transfer coefficient was calculated from the following equation:

$$h_z = q_z / (T_{wi} - T_s), \qquad (3)$$

where T_{wi} represents the inner wall temperature calculated directly from the measured outer wall temperature by considering one-dimensional heat conduction through the wall. T_s represents the saturation temperature for the refrigerant. The q_z is the local heat flux between two measurement locations calculated from the flow rate and the temperature drop of the water surrounding the test section and flowing counter to the refrigerant flow (Q_z).

The mean heat flux (q) is the averaged local heat flux. The local heat flux, q_z, the local refrigerant quality, x, and xat measurement location zwere given by Hsieh et al. [20] as follows:

$$q_z = \frac{Q_z}{\pi D_i L_H}, \qquad (4)$$

$$q = \frac{Q}{\pi D_i L} \qquad (5)$$

and

$$x_1 = \frac{\pi D_i (z - L_{sc}) q_{1-b}}{AG h_{fg}}, \qquad (6)$$

$$\Delta x_i = \frac{\pi D_i L_H q_{z,i}}{AG h_{fg}} \text{ for } i = 1, 2, \ldots 6 \qquad (7)$$

$$x_{i+1} = x_i + \Delta x_i \qquad (8)$$

where L_{sc} was determined by iteration from the following equation:

$$L_{sc} = \frac{G A C_p (T_s' - T_{in})}{\pi D_i h_{fg}}, \qquad (9)$$

where the specific heat of the working fluid is given by C_p. A is the flow area of the test tube. D_i is the diameterof the test tube. G is the mass fluxof the refrigerant. T_s' and T_{in} are the saturation temperatures at the start of the bulk boiling and the inlet temperature of the refrigerant, respectively. h_{fg} is the latent heat of the refrigerant.

III. RESULTS AND DISCUSSIONS

Flow boiling experiments were conducted initially without surface vibration, and then, the experiments were performed with surface vibrations at different intensities of vibration. The effects of frequency and amplitude of the vibration were investigated. The main variable parameters in the present study are the frequency and amplitude of the vibration, the heat flux, the mass flux, the vapor quality, the porous geometry (size of the inserts, porosity, the mean pore diameters and permeability) and the pipe angles($\theta = 0^\circ, 90^\circ$). The effects of the vibration frequency on the boiling heat transfer at Am=0.5 mm for Tube 2 and the Open tube are shown in Fig. 4. It is observed that heat transfer improves when surface vibration is introduced. Notably, Tube 2 has a relatively higher effect of frequency on the boiling heat transfer coefficient than the Open tube. This is due to the fact that at appropriate vibration frequencies, particles inside the tube can be caused to move in a similar manner to those in the well-known gas-fluidized bed, and they will enhance the heat transfer.This may be attributed to the contribution of the porous structure on the part of forced convection in a partial nucleate boiling region. Moreover, the greater improvement is due to many bubbles moving along the heated surface and a great deal of thermal layer removal. In addition, increasing the frequency beyond 9 Hz does not seem to improve the heat transfer coefficient any further. This is probably because the bubbles cause vibration damping, reducing the heat transfer rate due to the limit of available cross-sectional area for fluid flow. Comparison of the effects of vibration frequency on the average boiling heat transfer coefficients with respect to the vertical pipe under the same experimental conditions as the horizontal pipe shows about 1.41-fold for the Open tube and 1.69-fold for Tube No. 2.

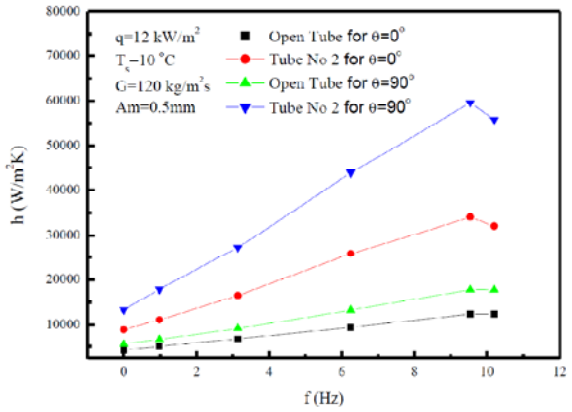


Figure 4. Effect of frequency on heat transfer coefficient

The effect of the amplitude on the boiling heat transfer at f=3.14 Hz for Tube 2 and the Open tube are shown in Fig. 5. It was found that at a lower amplitude (Am<0.5 mm), the effect of enhancement of the heat transfer is strongly increased as the amplitudes increase, and further increase of the amplitudes does not improve the results for the porous structure. In addition, for the Open tube, the heat transfer coefficient quickly increases as the Am increases until the Am equals about 0.5 mm. Then, the heat transfer coefficient slowly increases as the Am increases. The increase in the heat transfer at a low amplitude is attributed to the action of the vibration on a thermal boundary layer. Also, the vibration amplitude creates the flow turbulence which increases the heat transfer. There is also a possibility of change in the bubble dynamics due to surface vibration. The frequency of the bubble formation, bubble departure diameter and bubble growth rate is affected by the intensity of the vibration. It is believed that the bubble evolution rate increases with the surface vibration, increasing the heat transfer rate from the surface. At a higher amplitude, it is possible that the bubbles create a vibration damping that reduces the heat transfer rate.Comparison of the effect of amplitude on the average boiling heat transfer coefficients with respect to the vertical pipe under the same experimental conditions for the horizontal pipe shows about 1.36-fold for the Open tube and 1.66 for Tube No. 2.

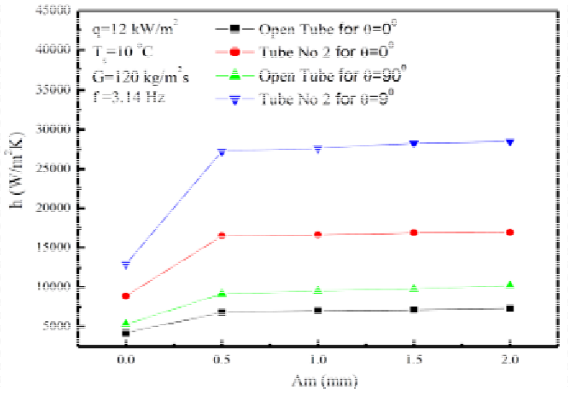


Figure 5. Effect of amplitude on heat transfer coefficient for different pipe inclination

Of special interest for studies pertaining to the effect of the vibration frequency on heat transfer performance augmentation is the question of how much the heat transfer performance of the tube with porous inserts is increased relative to the tube without porous inserts under the same conditions for different vibration frequencies. The effect of the porous insert on the heat transfer coefficients can be further quantified by forming a ratio of the heat transfer coefficient for the tube with porous inserts to the value for the tube without any inserts, i.e. enhancement factor, $E = h_a / h_s$. Figure 8shows the effect ofporous inserts, i.e. tube number on Eunder a heat flux of12 kW/m^2, a mass flux of 120 kg/m^{2}s, $\theta = 90°$ and $T_s = 10°C$ for different vibration frequencies. This indicates that as the vibration frequency increases, the enhancement factor becomes greater. Moreover, comparison of the heat transfer coefficients with respect to the tube without an insert under the same experimental conditions with f=0-10.19 Hz for the test tubes are about 1.9-fold (Tube 1), 2.9-fold (Tube 2), 2.4-fold (Tube 3), 2.8-fold (Tube 4) and 2.2-fold (Tube 5), respectively. It was also found that Tube 2 has the best E, followed by Tubes 4, 3, 5 and 1, respectively. Notably, Tubes 2 and 4 have relatively higher E values than the other test tubes. This is due to the fact that these two tubes have the lowest mean pore diameter, porosity and permeability levels (see Table 1), more tunnels connected to the refrigerant by regularly spaced pores and lower resistance with regard to heat transfer. The effect of vibration frequency on the heat transfer is the same as the vibration amplitude on the heat transfer. As a result, the E values increase as the frequency (f) increases until f equals about 9 Hz; then, the heat transfer coefficient slowly increases as f increases.

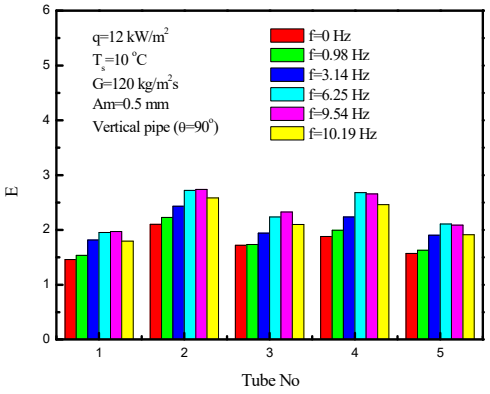


Figure 6.Effect of frequency on enhancement factor (E) vs. Tube No.

CONCLUSIONS

The effect of surface vibration on the sub-cooled flow boiling heat transfer of R600a in a tube with porous inserts was studied. The influences of surface

vibration, mass flux, refrigerant quality and the sizes of the inserts (the porosity, mean pore diameters and permeability) on the boiling heat transfer and pressure drop characteristics were examined and discussed. The main findings yielded from the experimental results are as follows:

1) Tubes with a surface vibration significantly increase the flow boiling heat transfer compared to the tubes without vibration. The frequency and amplitude of the vibration have significant effects on heat transfer enhancement.
2) The heat transfer coefficient is apparently insensitive to the change in pipe inclination (horizontal and vertical pipes). Comparison of the effects of the vibration frequency on the average boiling heat transfer coefficients with respect to the vertical pipe under the same experimental conditions as the horizontal pipe shows about 1.41-fold for the Open tube and 1.69-fold for Tube No. 2.
3) As the vibration frequency increases, the average enhancement factor (E) becomes greater. The E values for Tubes No. 1, 2, 3, 4 and 5 atf=0-10.19 Hz under the same conditions are about 1.9-fold (Tube 1), 2.9-fold (Tube 2), 2.4-fold (Tube 3), 2.8-fold (Tube 4) and 2.2-fold (Tube 5), respectively.
4) Tube 2 has the best E, followed by Tubes 4, 3, 5 and 1, respectively. Notably, Tubes 2 and 4 have relatively higher E values than the other test tubes. This is due to the fact that these two tubes have the lowest mean pore diameter, porosity and permeability levels, and they have more tunnels connected to the refrigerant by regularly spaced pores and a lower resistance with regard to heat transfer.

ACKNOWLEDGEMENT

The study was supported by the Ministry of Science and Technology of the Republic of China through Grant No. MOST 106-2221-E-230-013. Special thanks are due to Mr. C.-H. Yeh for his assistance in obtaining the experimental data.

REFERENCES

[1] M. Legay, B. Simony, P. Boldo, N. Gondrexon, S. Le Person, A. Bontemps, Improvement of heat transfer by means of ultrasound: Application to a double-tube heat exchanger, UltrasonicsSonochemistry 19 (2012) 1194-1200.

[2] J.R. Thome, L. Cheng, G. Ribatski, L.F. Vales, Flow boiling of ammonia and hydrocarbons: A state-of-the-art review, Int. J. of Refrigeration 31 (2008) 603-620.

[3] W. Liu, Z. Yang, B. Zhang, P. Lv, Experimental study on the effects of mechanical vibration on the heat transfer characteristics of tubular laminar flow, International Journal of Heat and Mass Transfer 115 (2017) 169–179.

[4] Y.H. Lee, D.H. Kim, S.H. Chang, An experimental investigation on the critical heat flux enhancement by mechanical vibration in vertical round tube, Nucl. Eng. Des. 229 (2004) 47–58.

[5] X.-J. Li, J.-z. Zhang, X.-M. Tan, An investigation on convective heat transfer performance around piezoelectric fan vibration envelope in a forced channel flow, International Journal of Heat and Mass Transfer 126 (2018) 48–65.

[6] Legay M., Gondrexon N., Le Person S., Boldo P., Bontemps A., Enhancement of heat transfer by ultrasound: review and recent advances, Int. J. Chem. Eng. (2011). doi:10.1155/2011/670108.

[7] Kim H.Y., Kim Y.G., Kang B.H., Enhancement of natural convection and pool boiling heat transfer via ultrasonic vibration, Int. J. Heat Mass Transfer 47 (2004) 2831e2840.

[8] Bonekamp S., Bier K., Influence of ultrasound on pool boiling heat transfer to mixtures of the refrigerants R23 and R134A, Int. J. Refrig. 20-8 (1997) 606e615.

[9] Bartoli C., Baffigi F., Effects of ultrasonic waves on the heat transfer enhancement in subcooled boiling, Experimental Thermal and Fluid Science 35 (2011) 423-432.

[10] L. Rui, H. Z. Tao, Numerical investigation of heat transfer and flow inner tube with periodically cosine oscillation, International Journal of Heat and Mass Transfer 127 (2018) 1082–1091.

[11] Lee S.Y., Y.D. Choi, Turbulence enhancement by ultrasonically induced gaseouscavitation in the CO2 saturated water, KSME Int. J. 16-2 (2002) 246e254.

[12] Hyun S., Lee D.-R., Loh B.-G., Investigation of convective heat transferaugmentation using acoustic streaming generated by ultrasonic vibrations, Int. J. Heat Mass Transfer 48 (2005) 703e718.

[13] S.-W. Chen, F.-C. Liu, H.-J. Lin, P.-S. Ruan, Y.-T. Su, Y.-C. Weng, J.-R. Wang, J.-D. Lee, W.-K. Lin, Experimental test and empirical correlation development for heat transfer enhancement under ultrasonic vibration, Applied Thermal Engineering 143 (2018) 639–649.

[14] Dukhan N., Bagci Q., Kavurmacioglu L A., Effect of frequency on heat transfer due to oscillating water flow in open-cell metal foam: An experimental study, Experimental Thermal and Fluid Science 66 (2015) 97-105.

[15] Liu Y.-H., Tsai S.-Y., Wang C.-C., Effect of driven frequency on flow and heat transfer of an impinging synthetic air jet, Applied Thermal Engineering 75 (2015) 289-297.

[16] A. A. Delouei, H. Sajjadi, M. Izadi, R. Mohebbi, The simultaneous effects of nanoparticles and ultrasonic vibration on inlet turbulent flow: An experimental study, Applied Thermal Engineering 146 (2019) 268–277.

[17] M.-Y. Wen, K.- J. Jang, C.-. Ho, The characteristics of boiling heat transfer and pressure drop of R-600a in a circular tube with porous inserts, Applied Thermal Engineering 64 (2014) 348-357.

[18] E. Scheidegger, The physical of flow through porous media, p10. University of Toronto Press, Toronto, Ontario (1963).

[19] J.L. Turpin, R.L. Huntington, Prediction of pressure drop for two-phase, two-component concurrent flow in packed beds, AIChE Journal 13 (1967) 1196-1202.

[20] S.-S. Hsieh, J.-J. Jang, M.-T. Huang, Evaporative heat transfer and enhancement performance of serpentine tubes with strip-type inserts using refrigerant-134a, ASME J. Heat Transfer 121 (1999) 725-757.

★★★