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Heat transfer enhancement by metal foam during nucleate pool boiling of refrigerant/oil mixture at a wide range of oil concentration

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Heat transfer enhancement by metal foam during nucleate pool boiling of refrigerant/oil mixture at a wide range of oil concentration

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Nucleate pool boiling heat transfer characteristics of refrigerant/oil mixtures on metal foam covers were experimentally investigated at a wide range of oil concentrations. The refrigerant and oil are R113 and VG68, respectively; and the oil concentration varies from 0% to 40%. The copper foams have pores per inch (ppi) of 10 and 20 and porosity from 90% to 98%. Experimental conditions include a saturation pressure of 101 kPa (14.696 psi), and heat flux from 30 to 137 kW m^{-2} *(2.6417 to 12.064 Btu* s^{-1} ft^{-2}*). The experimental results indicate that the nucleate pool boiling heat transfer coefficients on copper foam covers are larger than those on a plain heating surface by a maximum of 450%; the presence of oil deteriorates the nucleate pool boiling heat transfer on copper foam covers by a maximum of 90%. With the increase of oil concentration, the deterioration effect on high ppi metal foams is more obvious than that for low ppi. A correlation for predicting the nucleate pool boiling heat transfer coefficient of refrigerant/oil mixtures on metal foam covers is developed, and it agrees with 90% of the experimental data within a deviation of ±30%.*

Introduction

Open-cell metal foam is a promising porous material for heat transfer enhancement, thanks to its complex spatial structure, high specific surface area, and high thermal conductivity of metal material. In the past decades, extensive investigations have been carried out for the thermal transport of single-phase flow through metal foam (Bhattacharya et al. 2002; Calmidi and Mahajan 1999, 2000; Zhao et al. 2004, 2005). In recent years, thermal transport of two-phase flow through metal foam has received much attention due to the increase in demand of compact heat exchangers. Research results (Zhao et al. 2009) show that embedding metal foam into the tubes of an evaporator can greatly improve the heat transfer performance for pure refrigerant, and the heat transfer coefficient is two to four times higher than that of smooth tube with the same diameter, indicating that metal foam has the potential to promote the evaporator performance. As the refrigeration product efficiency standards rise, embedding metal foam

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into the tubes of evaporator may improve the efficiency of refrigeration systems. In an actual vapor compression refrigeration system, some lubricant oil for lubricating and sealing the compressor inevitably circulates with the refrigerant to the evaporator, so the heat transfer enhancement effect of metal foam at oil presence condition should be known.

At the refrigerant side of the evaporator, boiling of liquid refrigerant is the primary way for heat transfer. During the refrigerant boiling process, the partial pressure of oil in the vapor phase is negligible (Thome 1996), and oil is considered a non-phase-change fluid. With the continuous evaporation of liquid refrigerant, the concentration of the non-phase-change oil increases, and the local oil concentration can be up to 40% or more (Nidegger et al. 1997; Zurcher et al. 1997; Thome and Phil 1995; Hu et al. 2008). A large amount of oil has significant influence on heat transfer of the refrigerant side (Shen and Groll 2005). The addition of a large amount of oil greatly changes the thermophysical properties of the working fluid; e.g., the surface tension of the refrigerant/oil mixture under 40% oil concentration is approximately ten times higher than that of pure refrigerant. The addition of a large amount of oil also greatly changes the heat transfer characteristics of the heating surface; e.g., the oil-rich layer (Kedzierski 2003) on the fluid–solid interface under a high oil concentration condition can be much thicker than that under a low oil concentration condition. Therefore, in order to apply metal foam into the refrigeration system, it is necessary to know the boiling heat transfer characteristics of the refrigerant/oil mixture on metal foam over a wide range of oil concentrations. As nucleate pool boiling is a basic type of boiling heat transfer, it is necessary to study the nucleate pool boiling heat transfer characteristics of a refrigerant/oil mixture on the metal foam covering the oil concentration from 0% to 40%.

The existing research of nucleate pool boiling heat transfer on the metal foam cover focuses on pure refrigerant (Choon et al. 2006; Xu et al. 2008; Yang et al. 2010a, 2010b) or a refrigerant/oil mixture at low oil concentrations from 0% to 5% (Zhu et al. 2011). Investigation results show that metal foam provides more boiling sites and heat transfer area and greatly promotes heat transfer (Choon et al. 2006; Xu et al. 2008; Yang et al. 2010a, 2010b); oil reduces the nucleate pool boiling heat transfer at low oil concentration conditions (below 5%), and the heat transfer coefficient decreases with oil concentration (Zhu et al. 2011).

There is no published literature about nucleate pool boiling heat transfer characteristics of a refrigerant/oil mixture on a metal foam cover at oil concentrations of more than 5%, and the research on the influence of oil at the concentration of more than 5% is only done on plain surfaces or tubes. The research on plain surfaces or tubes shows that the nucleate pool boiling heat transfer of a refrigerant/oil mixture is obviously affected by the oil concentration; at an oil concentration below 5%, oil slightly enhances or reduces the nucleate pool boiling heat transfer, depending on the heating surface structure (Mohrlok et al. 2001; Kim 2010; Memory 1995a, 1995b); at an oil concentration over 5%, the oil reduces the heat transfer for all cases (Ji et al. 2010). The influence of oil concentration on nucleate pool boiling heat transfer of a refrigerant/oil mixture on plain surfaces or tubes indicates that the oil concentration might also severely affect the nucleate pool boiling heat transfer on metal foam. However, due to the special structure of metal foam, the quantitative relation between the oil concentration and the variation of nucleate pool boiling heat transfer on metal foam might be different from that on a plain surface or tube, and the existing correlation for predicting the nucleate pool boiling heat transfer coefficient on a metal foam cover at low oil concentrations might not be extended to high oil conentration conditions. Therefore, it is necessary to experimentally investigate the influence of oil on nucleate pool boiling heat transfer of refrigerant on a metal foam cover over a wide range of oil concentrations, especially at high oil concentrations, and to develop a correlation to predict the nucleate pool boiling heat transfer coefficient of refrigerant/oil mixture on metal foam covers for both high and low oil concentrations.

Experimental setup and procedure

Experimental setup

Figure 1 shows the experimental equipment for testing the nucleate pool boiling heat transfer characteristics of a refrigerant/oil mixture on metal foam covers. It consists of a copper block, a boiling apparatus, and a condensation loop. The experimental

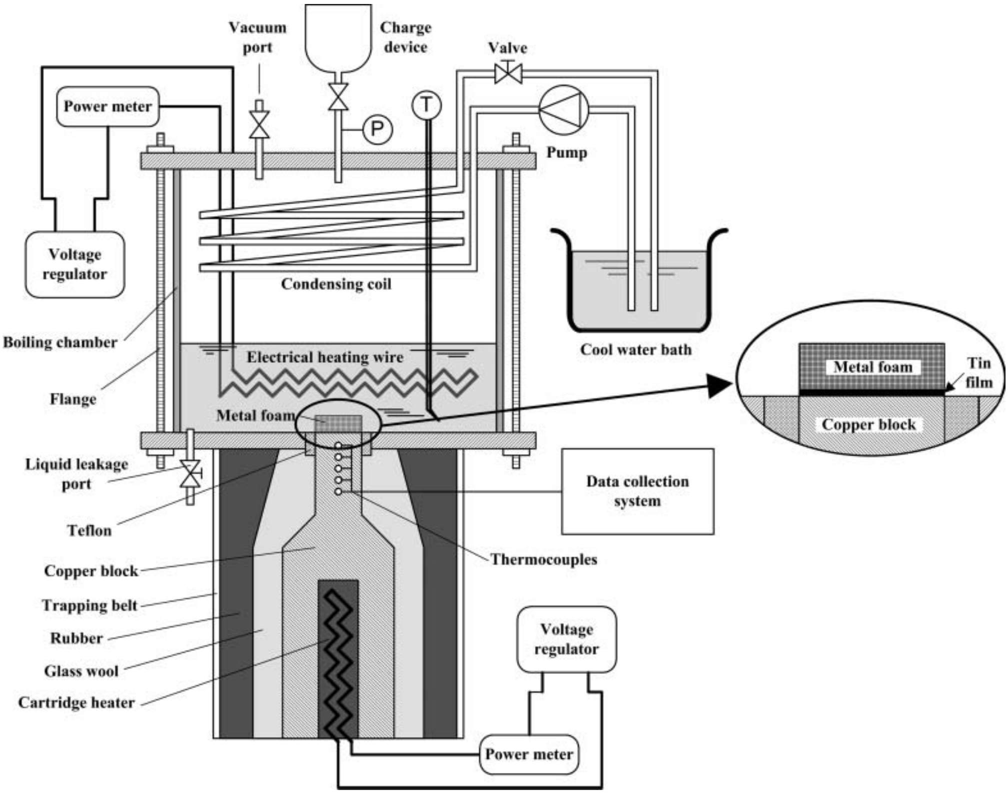
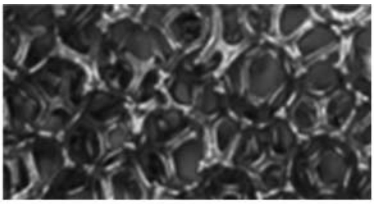


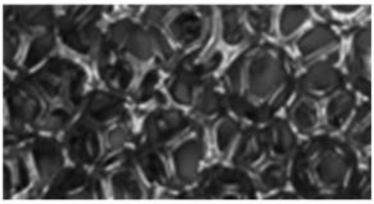
Figure 1. Schematic diagram of experimental setup.

equipment was introduced in detail by Peng et al. (2010) and Zhu et al. (2011), when it was used for testing the nucleate pool boiling heat transfer of a refrigerant/oil mixture with nanoparticles on a plain heating surface and refrigerant/oil mixture on metal foam covers.

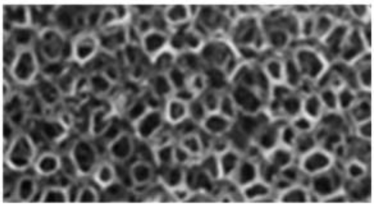
In the experimental setup, a cartridge heater is inserted from the bottom into the copper block to provide the needed heat during the experiments. The cartridge heater connects a voltage regulator in parallel and a power meter in series in order to adjust and display the heating power, respectively. The copper block contains five holes, each of which is plugged in a K-type thermocouple, so that the temperature distribution can be measured. The top surface temperature of the copper block and the heat flux can be calculated based on the temperature distribution. The top surface of the copper block is in the shape of 10.0-mm-diameter (0.394 in.) circle, and it is welded with a copper foam cover. The whole copper block is wrapped by glass wool, rubber, and a trapping belt in sequence to achieve the thermal isolation from the environment. Rubber foam is used for thermal insulation. The trapping belt is used for preventing condensation water from getting into the test section. The boiling apparatus includes a boiling chamber, an electrical heating wire and a charge device for the refrigerant/oil mixture. The boiling chamber consists of transparent plexiglass at four sides and two copper plates at the top and the bottom. At the center of the bottom copper plate, a circular hole of a diameter slightly larger than that of the copper block upper part is drilled, so the copper foam cover can contact the working fluid in the boiling chamber. A ring made of Teflon is used to ensure thermal isolation between the bottom copper plate and the copper block. On the top copper plate, there are seven holes that are used to connect the inlet and outlet of cooling water, the two ends of electrical heating wire, the charge device for refrigerant/oil mixture, a pressure sensor, and a K-type thermocouple. The electrical heating wire is used to maintain the fluid saturation. The pressure sensor and K-type thermocouple are used to monitor



a) Copper foam #1: ppi=10, Porosity=90%



b) Copper foam #2: ppi=10, Porosity=95%



c) Copper foam #3: ppi=30, Porosity=98%

Figure 2. Copper foam sample photos.

the pressure of the boiling chamber and measure the fluid temperature, respectively. The condensation loop consists of a condensing coil, water pump, and cool water bath. It is used to condense the refrigerant vapor, thus keeping the pressure of the boiling chamber.

Metal foam and characteristic parameters

Three kinds of copper foams with different geometries are selected in this study, as shown in Figure 2.

Porosity (the void volume fraction) and pores per inch (ppi) are two parameters generally used to characterize a metal foam (Calmidi 1995). The copper foam used in the present study have 10 ppi and 20 ppi, porosity from 90% to 98%, and thickness of 10.0 mm (0.394 in.), as listed in Table 1. The copper foam was cut into cylinders with the same diameter as the top surface of the copper block. Parameters of the copper foams are measured with the methods of Bhattacharya et al. (2002), Calmidi and Mahajan (2000), and Zhao et al. (2004), and the results are listed Table 1.

Before the experiment for each copper foam, the copper foam was welded on the copper block with tin in order to ensure small thermal resistance between them. The method is in accordance with the one introduced in Xu et al. (2008) and Yang et al. (2010a). First, the top surface of the copper block was cleaned by methanol, then the copper block was baked in an oven to reach the melting point of tin. Second, the copper block was taken out of the oven and still heated by a cartridge heater, and some tin was laid on the top surface of the copper block, leaving a thin tin film. Finally, a clean copper foam cover was put on the surface of the copper block, then the copper block was cooled down, so the copper foam cover was welded tightly with the copper block.

After each experiment, the copper foam cover was removed from the top surface of the copper block by heating the copper block to the melting point of tin. Then the procedures described in the last section were repeated to weld another copper foam cover on the top surface of the copper block.

Test condition

Test conditions are tabulated in Table 2. In the present study, R113 and VG68 are used as refrigerant and oil, respectively. The use of R113 is based on two considerations: (1) R113 is in liquid state at normal pressure and temperature, so it is easier to prepare the refrigerant/oil mixture with R113 than those with refrigerants that are in vapor state at normal pressure and temperature,

Table 1. Metal foam characteristic parameters.

No.	ppi	Porosity	Pore size, Pore size, mm (in.)	Fiber diameter, mm (in.)	Specific surface area, m^2/m^3 (ft^2/ft^3)
Copper foam #1	10	90%	4.302 (0.1696)	0.85 (0.03351)	1102 (336)
Copper foam #2	10	95%	4.434 (0.1748)	0.80 (0.03154)	808 (246)
Copper foam #3	20	98%	1.823 (0.07188)	0.40 (0.01577)	1331 (406)

Table 2. Test conditions.

No.	Geometry parameters of copper foam (porosity/ppi/thickness), mm (in.)	Oil concentration	Heat flux, kW m^{-2} (Btu h^{-1} ft^{-2})	Saturation pressure, kPa (psi)
Copper foam #1	90%/10 ppi/10 (0.3943)	0%, 5%, 10%, 20%, 40%	30–137 (9514–43,449)	101 (14.7)
Copper foam #2	95%/10 ppi/10 (0.3943)			
Copper foam #3	98%/20 ppi/10 (0.3943)			
Plain surface	—			

and (2) R113 is one kind of refrigerant, and the thermophysical properties between R113 and the other refrigerants (such as R134a) are closer than those between non-refrigerants (such as water) and the other refrigerants, so the results of the present study can be extended to other refrigerants. The oil concentration includes 0%, 5%, 10%, 20%, and 40%. In order to demonstrate the enhancement effect of the metal foam cover on the nucleate pool boiling heat transfer, the test conditions also include a plain surface besides the three copper foam covers.

All signals of temperature and pressure are collected by a data acquisition system and transmitted to a computer after the system reaches steady state.

Data reduction and uncertainties

The nucleate pool boiling heat transfer coefficient h is calculated as

$$h = \frac{q}{T_w - T_{\text{bulk}}}, \tag{1}$$

$$q = -\lambda \left.\frac{dT}{dz}\right|_{\text{w}}, \tag{2}$$

where q is the heat flux, T_w is the test surface temperature, T_{bulk} is the liquid bulk temperature, λ is the copper thermal conductivity, and z is the coordinate perpendicular to the test surface.

In Equation 1, the liquid bulk temperature T_{bulk} changes with the composition of the refrigerant/oil mixture, and it is measured by K-type thermocouples. The liquid bulk temperature under five oil concentrations is listed in Table 3.

In Equation 2, $dT/dz|_w$ is the temperature gradient of test surface. The relationship between T and z can be described as $T = a_1 + a_2 z$, where a_1 and a_2 are constants correlated based on the measured five temperatures on the copper block.

The uncertainty of nucleate pool boiling heat transfer coefficient Δh is calculated as

$$\Delta h = \sqrt{\left(\frac{\partial h}{\partial q}\right)^2 \Delta q^2 + \left(\frac{\partial h}{\partial T_w}\right)^2 \Delta T_w + \left(\frac{\partial h}{\partial T_{bulk}}\right)^2 \Delta T_{bulk}}. \tag{3}$$

By substituting Equation 2 into Equation 3, the relative uncertainty of the nucleate pool boiling heat transfer coefficient is calculated as

$$\frac{\Delta h}{h} = \sqrt{\left(\frac{\Delta q}{q}\right)^2 + \left(\frac{\Delta T_w}{T_w - T_{bulk}}\right)^2 + \left(\frac{\Delta T_{bulk}}{T_w - T_{bulk}}\right)^2}. \tag{4}$$

The maximum relative uncertainty of nucleate pool boiling heat transfer coefficient is obtained at the condition of the smallest test surface temperature and the largest saturated liquid temperature, calculated to be 10.2%.

Table 3. Saturated liquid temperature of R113/oil mixture at atmospheric pressure.

Oil concentration	0%	5%	10%	20%	40%
Bulk temperature, °C (°F)	47.6 (117.68)	48.1 (118.58)	48.8 (119.84)	50.0 (122.00)	53.6 (128.48)

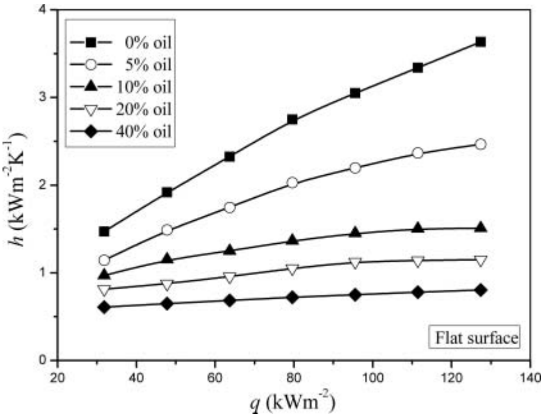


Figure 3. Nucleate pool boiling heat transfer coefficients of R113 and R113/oil mixture on plain heated surface.

Results and discussions

Nucleate pool boiling heat transfer under high oil concentration

Figures 3 and 4 show the variation of the nucleate pool boiling heat transfer coefficient under five oil concentrations as a function of heat flux on plain surface and three copper foam covers, respectively. The heat transfer coefficients on plain surface, as shown in Figure 3, are used for comparing with those on copper foam covers in order to demonstrate the enhancement effect of a copper foam cover on the nucleate pool boiling heat transfer under the same test condition.

It can be seen from Figure 4 that the nucleate pool boiling heat transfer coefficient decreases with the increase of oil concentration under each heat flux, indicating that oil always deteriorates the nucleate pool boiling heat transfer of refrigerant on the metal foam cover. The possible reasons for oil deteriorating the nucleate pool boiling heat transfer on the metal foam cover are (1) the presence of oil increases the surface tension of boiling fluid, leading to the increase of bubble departure diameter and decrease of bubble departure frequency, thus deteriorating the nucleate pool boiling heat transfer; (2) as the refrigerant vaporizes, the non-phase-change oil accumulates on the wet surface, forming an oil-rich layer, thus deteriorating the nucleate pool boiling heat transfer. The forming of an oil-rich layer and its effect on the pool boiling heat transfer is that the refrigerant/lubricant liquid mixture travels to the heated wall, and the refrigerant preferentially evaporates from the surface, leaving behind a liquid phase enriched in lubricant. A balance between deposition and removal of the lubricant establishes the thickness of the excess lubricant at the surface. The refrigerant is forced to diffuse through this excess layer during evaporation (Kedzierski 2003; Peng et al. 2010), so the pool boiling heat transfer is deteriorated.

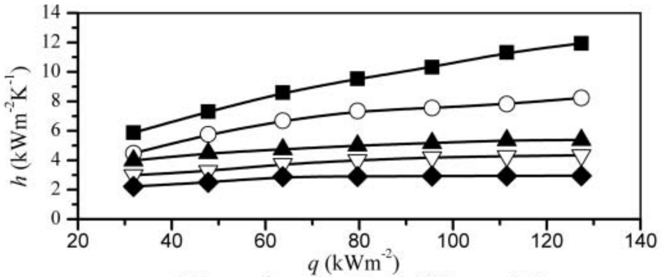
It can also be seen from Figure 4 that the nucleate pool boiling heat transfer coefficient of copper foam #1 is a little larger than that of copper foam #2, and the heat transfer coefficient of both copper foams #1 and #2 are smaller that that of copper foam #3. These phenomena resulted from the following two factors.

1. The effect of nucleation site number—the specific surface areas of copper foams #3, #1, and #2 decrease in sequence, so the cover layer using copper foam #3 provides more nucleation sites than copper foam #1 or #2, thus enhancing the nucleate pool boiling heat transfer on copper foam #3 cover against copper foams #1 and #2. This is a positive influence on the pool boiling heat transfer for metal foam #3.
2. The pore effect on bubble departure—as shown in Figure 1, the pore size of copper foam #3 is much smaller than that of copper foams #1 and #2, so the cover layer using copper foam #3 provides more resistance to bubble departure than that using copper foams #1 and #2, thus deteriorating the nucleate pool boiling heat transfer on copper foam #3 cover against copper foams #1 and #2. This is a negative influence on the pool boiling heat transfer for metal foam #3.

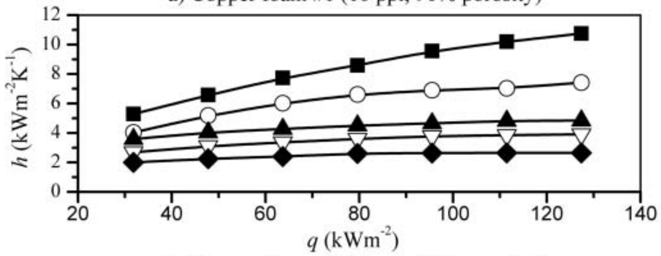
During the nucleate pool boiling process, the first factor is dominant, resulting in the heat transfer coefficient of copper foam #3 being larger than those of copper foams #1 and #2; however, the increase of the heat transfer coefficient of copper foam #3 from copper foams #1 or #2 is not in proportion to the increase of the heat transfer area of copper foam #3 from copper foams #1 or #2.

Effect of metal foam on the nucleate pool boiling heat transfer

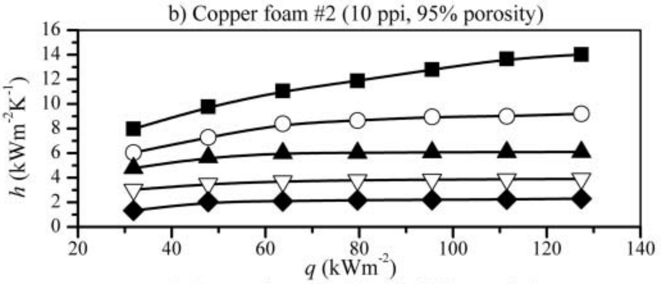
In order to quantitatively analyze the effect of metal foam geometry on the nucleate pool boiling heat transfer of the refrigerant/oil mixture, the metal



a) Copper foam #1 (10 ppi, 90% porosity)



b) Copper foam #2 (10 ppi, 95% porosity)



c) Copper foam #3 (30 ppi, 98% porosity)

Figure 4. Nucleate pool boiling heat transfer coefficients of R113 and R113/oil mixture on copper foam surfaces.

foam enhancement factor EF_{MF} is defined as the ratio of heat transfer of the refrigerant/oil mixture on the metal foam cover to that on the plain heating surface:

$$EF_{MF} = h_{MF}/h_p, \tag{5}$$

where h_{MF} and h_p are the pool boiling heat transfer coefficients of the refrigerant/oil mixture on the metal foam cover and plain heating surface, respectively.

Figure 5 shows the variation of EF_{MF} of three copper foam covers as a function of heat flux under five oil concentrations. It can be seen from Figure 5 that the values of EF_{MF} under each oil concentration are all greater than 1 (ranging from 2.2 to 5.5), indicating that metal foam obviously enhances the nucleate pool boiling heat transfer. EF_{MF} of copper foam #1 is always a little larger than that of copper foam #2 under the same oil concentration and heat flux because (1) copper foams #1 and #2 have almost the same pore size, thus having the same resistance to the bubble departure, and (2) the specific surface area of copper foam #1 is a little larger than that of copper foam #2, thus providing more heat transfer area to promote the nucleate pool boiling heat transfer.

It can be seen from Figure 6 that when comparing EF_{MF} of copper foams #1 and #2, EF_{MF} of copper foam #3 is greater under the oil concentrations of 0%, 5%, and 10%, is close under the oil concentration of 20%, and is smaller under the oil concentration of 40%. This phenomena mainly resulted from the increase of oil concentration greatly increasing the bubble departure diameter; thus, the influence of copper foam #3 on bubble departure is more obvious than that of copper foams #1 and

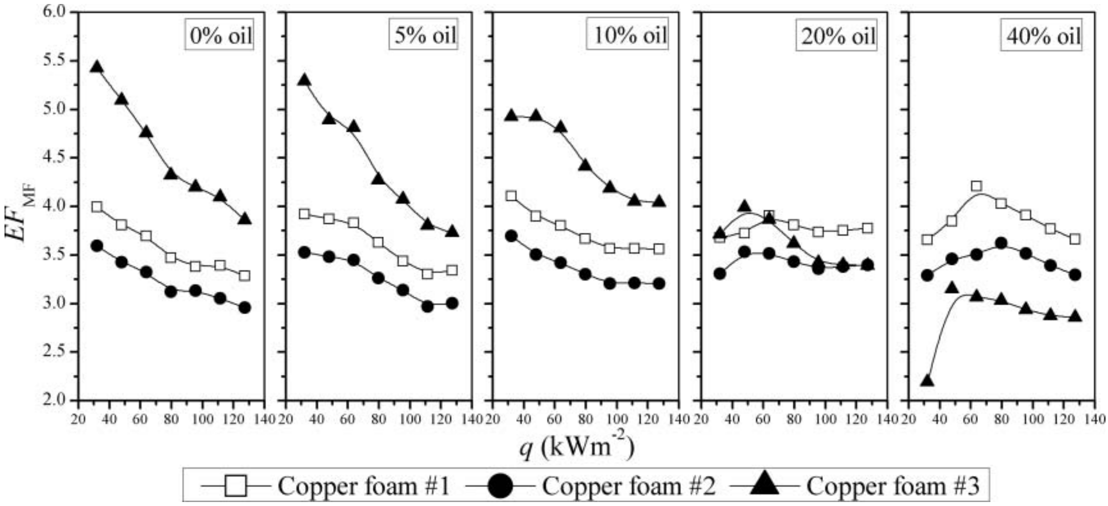


Figure 5. EF_{MF} as a function of heat flux.

#2. According to Fritz correlation (Fritz and Ende 1935), the bubble departure diameter is in proportion to the 0.5 power of surface tension. As the surface tension of the R113/oil mixture at 40% oil concentration is approximately 1.53 times that of pure R113 (see Table 4), the bubble departure diameter of the R113/oil mixture at 40% oil concentration is about 1.3 times that of pure R113. The bubble departure diameter of pure R113 under the present study condition is around 1 mm (0.0394 in.), so the bubble departure diameter of the R113/oil mixture at 40% oil concentration is around 1.30 mm (0.0512 in.). It can be seen from Table 1 that pore size fiber diameters are 1.82 mm (0.0719 in.) and 0.40 mm (0.0158 in.), respectively, so the mean void pore diameter is around 1.40 mm (0.0552 in.), and the diameter of some pores may smaller than 1.30 mm (0.0513 in.). Hence, the structure of copper foam #3 may influence the bubble growth at 40% concentration.

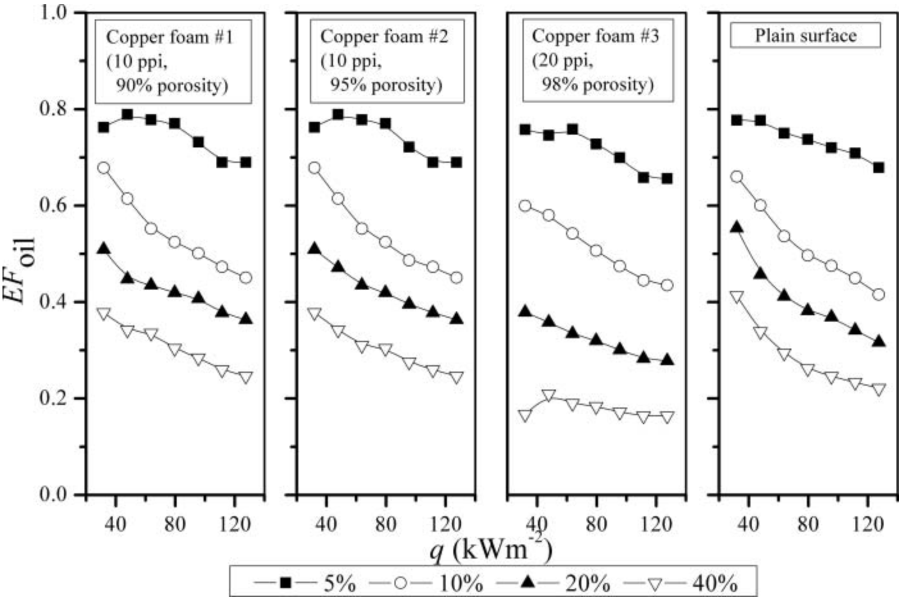


Figure 6. EF_{oil} as a function of heat flux.

Table 4. Thermophysical properties of R113/oil mixture.

	Oil concentration				
Thermophysical properties	0%	5%	10%	20%	40%
Density, kg m^{-3} (lb ft^{-3})	1508.2 (94.112)	1464.1 (91.360)	1422.4 (88.758)	1345.9 (83.984)	1215.2 (75.828)
Thermal conductivity, W m^{-1} K^{-1} (Btu h^{-1} ft^{-1} °F^{-1})	0.063655 (0.036780)	0.064111 (0.037043)	0.064672 (0.037368)	0.066105 (0.038196)	0.070219 (0.040573)
Specific heat, J kg^{-1} K^{-1} (Btu lb^{-1} °F^{-1})	940.37 (0.22497)	988.49 (0.23648)	1036.6 (0.24799)	1132.9 (0.27103)	1325.4 (0.31708)
Viscosity, Pa s (lbf s ft^{-2})	0.00049040 (0.023480)	0.00061451 (0.029423)	0.00077001 (0.036868)	0.0012091 (0.057892)	0.0029809 (0.14273)
Surface tension, N m^{-1} (lbf ft^{-1})	0.014698 (8.39278*e*–5)	0.017388 (9.92881*e*–5)	0.018529 (1.05803*e*–4)	0.020154 (1.15082*e*–4)	0.022468 (1.28296*e*–4)

Effect of oil on the nucleate pool boiling heat transfer

In order to quantitatively analyze the effect of oil on the nucleate pool boiling heat transfer on metal foam, oil enhancement factor EF_{oil}, defined as the ratio of heat transfer of refrigerant/oil mixture to that of pure refrigerant, is used:

$$EF_{oil} = h_{r,o}/h_r, \tag{6}$$

where $h_{r,o}$ and h_r are the pool boiling heat transfer coefficient of the refrigerant/oil mixture and pure refrigerant, respectively.

Figure 6 shows the variation of EF_{oil} of the three copper foam covers as a function of heat flux under five oil concentrations. It can be seen from Figure 6 that EF_{oil} of the three copper foams are all smaller than 1 (ranging from 0.1 to 0.8), indicating that the presence of oil always deteriorates the nucleate pool boiling heat transfer on the metal foam cover. The nucleate pool boiling heat transfer coefficient decreases by a maximum of 90% under the working conditions of the present study.

It can also be seen from Figure 6 that EF_{oil} of the three copper foams decreases with the increase of heat flux under each oil concentration condition. The reason might be that under the oil presence condition, there is an oil-rich layer on the heating surface, and the refrigerant is forced to diffuse through this excess layer when evaporating. With the increase of heat flux, the evaporation mass flux of refrigerant increases, and the block effect of the oil-rich layer on refrigerant evaporation is more obvious than that under low heat flux.

Figure 6 also demonstrates that EF_{oil} of the three copper foams are almost the same under oil concentrations of 5% and 10%, ranging from 0.5 to 0.8, indicating that the deterioration of oil to the nucleate pool boiling heat transfer on the three copper foam covers is the same. At oil concentrations of 20% and 40%, EF_{oil} of copper foam #3 ranges from 0.1 to 0.4, which is obviously smaller than that of copper foams #1 and #2, indicating that the deterioration of oil to the nucleate pool boiling heat transfer on copper foam #3 is stronger than that on copper foams #1 and #2 under high oil concentration conditions.

Nucleate pool boiling heat transfer coefficient correlation for refrigerant/oil mixture with high oil concentration on metal foam covers

Predictability verification of existing correlation to refrigerant/oil mixture on metal foam cover under high oil concentration conditions

Until now, there has been no nucleate pool boiling heat transfer correlation for the refrigerant/oil mixture on the metal foam cover under high oil concentration conditions.

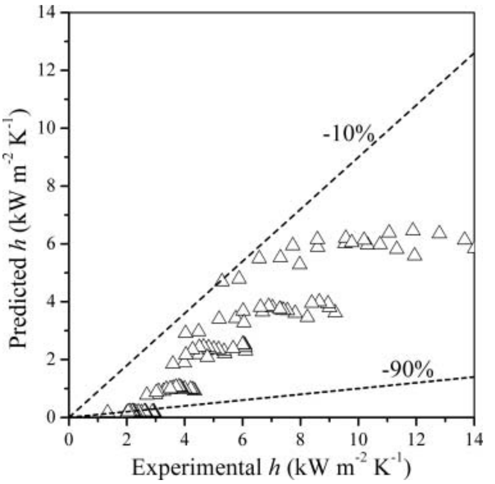


Figure 7. Comparison of the experimental data of present study with the predicted values obtained by Zhu et al.'s (2011) correlation.

In the experimental investigation of nucleate pool boiling heat transfer of the refrigerant/oil mixture on metal foam covers under low oil concentration conditions, Zhu et al. (2011) proposed a correlation for predicting the nucleate pool boiling heat transfer coefficients of refrigerant/oil mixtures on metal foam covers under low oil concentration conditions (0%–5%). Although Zhu et al.'s correlation can predict the nucleate pool boiling heat transfer coefficients of refrigerant/oil mixtures on metal foam covers under low oil concentration conditions, it is not certain that the correlation is fit for high oil concentration conditions. Therefore, the predictability of Zhu et al.'s correlation to the experimental data of the present study is uncertain and should be investigated.

Figure 7 shows the deviation of the nucleate pool boiling heat transfer coefficients predicted by Zhu et al.'s (2011) correlation under the working condition of the present study to the present experimental data. It is shown that the deviation is within –10% to –90%.

From the predictability verification of Zhu et al.'s (2011) correlation, it can be concluded that their correlation is not fit for the working conditions of the present study. The potential reasons for this follow.

1) The effect of oil on the nature of the heating surface–fluid combination is not considered. The nature of heating surface–fluid combination is reflected by the coefficient C_{sf} in Zhu et al.'s (2011) correlation. C_{sf} is considered as constant, for the correlation is for low oil concentration conditions, and the influence of oil on the value of C_{sf} is negligible. In the present study, as the oil concentration is much higher (up to 40%), the interaction between the heating surface and refrigerant/oil mixture can be different from that under low oil concentration conditions; for example, the oil rich layer is thicker with an increase of oil concentration (Kedzierski 2003). Therefore, for high oil concentration, C_{sf} is not appropriate as a constant as in Zhu et al.'s correlation but should be a function of oil concentration.
2) The effect of metal foam cover thickness on the nucleate pool boiling heat transfer is not reflected. The thickness of the metal foam cover is used for calculating the wet surface area, thus affecting the nucleate pool boiling heat transfer coefficient; but the nucleate pool boiling heat transfer coefficient does not vary linearly with the thickness of the metal foam cover, as the metal foam cover has a temperature gradient through the thickness direction. In the study of Zhu et al. (2011), the thicknesses of the metal foam covers are all the same, so Zhu et al.'s correlation does not reflect the temperature gradient of the metal foam cover through the thickness direction on the nucleate pool boiling heat transfer. In the present study, the thickness of the metal foam covers are different from those in Zhu et al. (2011), leading to large errors when using Zhu et al.'s correlation to predict the nucleate pool boiling heat transfer coefficient of the present study. In order to reflect the effect of the thickness of the metal foam cover, cover thickness (H) should be added to the exponent of A_{wetted}/A_{plain}, and the new correlation should be fitted by the experimental data of both Zhu et al. (2011) and the present study.

Development of a new nucleate pool boiling heat transfer correlation for refrigerant/oil mixture on metal foam covers under high oil concentration conditions

In the present study, a new correlation for predicting the nucleate pool boiling heat transfer coefficient correlation for refrigerant/oil mixture on metal foam covers under high oil concentration conditions is developed based on the modification of Zhu et al.'s (2011) correlation, which was developed based on experimental data under low oil concentratrion conditions and does not reflect the effect of oil on the nature of the heating surface–fluid combination and the effect of metal foam cover thickness on the nucleate pool boiling heat transfer.Therefore, two modifications are made to Zhu et al.'s correlation to predict the nucleate pool boiling heat transfer of the refrigerant/oil mixture on the metal foam cover under low and high oil concentration conditions: introducing oil concentration into C_{sf} and introducing H into the effect factor of metal foam (EF_{MF}).

In the new correlation, the heat transfer coefficient on metal foam cover ($h_{MF,r,o}$) is expressed as the production of the effect factor of metal foam (EF_{MF}) and the heat transfer coefficient on a plain heating surface ($h_{plain,r,o}$), as in Zhu et al. (2011), shown in Equations 7–9. The two modifications are that C_{sf} is expressed as a function of oil concentration, as shown in Equation 10, and the thickness of metal foam covers (H) is introduced as an exponent coefficient of the term EF_{MF}, as shown in Equation 11:

$$h_{MF,r,o} = EF_{MF} \times h_{plain,r,o}, \tag{7}$$

$$h_{plain,r,o} = {}^{q}\!/_{\Delta T_b}, \tag{8}$$

$$\Delta T_b = \frac{C_{sf} h_{fg}}{c_{p,r,o}} \left[\frac{q}{\mu_{r,o} h_{fg}} \sqrt{\frac{\sigma_{r,o}}{g(\rho_{r,o} - \rho_g)}} \right]^{0.33} \times \left(\frac{c_{p,r,o} \mu_{r,o}}{\lambda_{r,o}} \right)^n, \tag{9}$$

$$C_{sf} = a + b\omega, \tag{10}$$

$$EF_{MF} = \left(\frac{A_{wetted}}{A_{plain}} \right)^{c+dn+e\varepsilon+fH+gq}, \tag{11}$$

where q is the heat flux; ΔT_b is the temperature difference; A_{plain} is the top surface area of the copper block; A_{wetted} equals the sum of the top surface area and the product of the metal foam volume and specific surface area; H is the thickness of the metal foam cover; h_{fg}, $c_{p,r,o}$, $\mu_{r,o}$, $\sigma_{r,o}$, and $\lambda_{r,o}$ are the latent heat, specific heat, kinetic viscosity, surface tension, and thermal conductivity of refrigerant/oil mixture, respectively; $\rho_{r,o}$ and ρ_g are the densities of the refrigerant/oil mixture and refrigerant vapor, respectively; and g is the local gravity acceleration. The properties of the refrigerant/oil mixture needed for the calculation are presented in the Appendix, and the results are listed in Table 4.

Parameters of n, a, b, c, d, e, f, and g in Equations 9, 10, and 11 are fitted based on 108 pieces of data under high oil concentration in the present study and 96 pieces of data under low oil concentration in Zhu et al. (2011), covering the heat flux from 10 to 137 kW m^{-2} (0.88055 to 12.064 Btu s^{-1} ft^{-2}), oil concentration from 0% to 40%, metal foam ppi from 10 to 20, porosity from 90% to 98%, and thickness from 5 to 10 mm (0.1971 to 0.3943 in.).

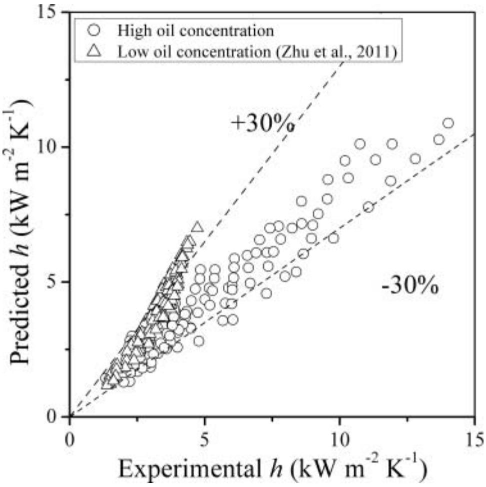


Figure 8. Comparison of the predicted values of the correlation with the experimental data.

By the non-linear programming solution method, the five coefficients of n, a, b, c, d, e, f, and g can be obtained as 0.458, 0.0748, 0.675, –0.294, –0.00815, 1.03, –5.05, and –0.000754, respectively. Therefore, the nucleate pool boiling heat transfer coefficient of the refrigerant/oil mixture with high oil concentration on metal foam covers can be predicted by Equations 7–11. Figure 8 shows the validation of the new correlation. It can be seen that the predicted values of the new correlation can agree with 90% of the experimental data within a deviation of ±30% for both low and high oil concentration conditions.

Conclusion

By investigating the nucleate pool boiling heat transfer characteristics of a refrigerant/oil mixture with a high oil concentration on a metal foam cover, the following conclusions are obtained.

1) The presence of metal foam always enhances the nucleate pool boiling heat transfer of a refrigerant/oil mixture, and the nucleate pool boiling heat transfer coefficient increases by a maximum of 450%. EF_{MF} (the ratio of heat transfer of the refrigerant/oil mixture on a metal foam cover to

that on a plain heating surface) is in the range of 2 to 5.5 under the present working conditions.

2) The presence of oil always deteriorates the nucleate pool boiling heat transfer on a metal foam cover, and the nucleate pool boiling heat transfer coefficient decreases by a maximum of 90%. EF_{oil} is always smaller than 1, ranging from 0.1 to 0.8 under the present working conditions.
3) At an oil concentration of 10% or less, EF_{oil} of high and low-ppi metal foams is almost the same, ranging from 0.5 to 0.8; while at an oil concentration of more than 10%, EF_{MF} of high-ppi metal foams ranges from 0.1 to 0.4, and EF_{MF} of low-ppi metal foams ranges from 0.3 to 0.43. It is indicated that with the increase of oil concentration, the deterioration of oil to the nucleate pool boiling heat transfer on high-ppi metal foam is more obvious than that on low-ppi metal foam.
4) A new correlation for predicting the nucleate pool boiling heat transfer coefficient of a refrigerant/oil mixture on metal foam covers is developed, and the correlation is suitable for both low and high oil concentration conditions.The new correlation can agree with 90% of the experimental data of both low and high oil concentration conditions within a deviation of ±30%.

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Nomenclature

A = heat transfer surface area, m^2 (ft^2)
c_p = isobaric specific heat, J kg^{-1} K^{-1} (Btu lb^{-1} °F^{-1})
EF = effect factor, dimensionless
g = local gravity acceleration, m s^{-2} (ft h^{-1})
h = heat transfer coefficient, W m^{-1} K^{-1} (Btu h^{-1} ft^{-1} °F^{-1})
h_{fg} = latent heat of condensation, J kg^{-1} (Btu lb^{-1})
q = heat flux, W m^{-2} (Btu h^{-1} ft^{-2})
T = temperature, °C (°F)
s = specific gravity, $s = \rho/\rho_{water}$, dimensionless
V = volume, m^3 (ft^3)

Greek symbols

λ = thermal conductivity, Wm^{-1} K^{-1} (Btu h^{-1} ft^{-1} °F^{-1})
μ = dynamic viscosity, Pa s (lbf s ft^{-3})
ρ = density, kgm^{-3} (lb ft^{-3})
ω = oil concentration

Subscripts

base = base surface
plain = plain heating surface
L = liquid
MF = metal foam cover
O = oil
R = refrigerant
Rohsenow = Rohsenow correlation
sat = saturated
W = heating surface
wetted = wetted surface

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Appendix

Appendix. Correlations for thermophysical properties of oil and R113/oil mixture.

Fluid	Property	Correlation to calculate thermodynamic properties
Oil	Density, kg m^{-3}	$\rho_o = 973.86 - 0.69147 \times T$ (T, unit °C [°F])
Oil	Specific heat, J kg^{-1}K^{-1}	$c_{p,o} = 4186[\frac{0.388 + 0.00045(1.8T + 32)}{\sqrt{s}}]$($T$, unit: °C [°F])
Oil	Thermal conductivity, W m^{-1}K^{-1}	$\lambda_o = 0.1172\,(1 - 0.0054T)\big/s$($T$, unit: °C [°F])
Oil	Viscosity, Pa s	$\mu_o = \rho_o(7.586 + 0.61 \times T)^{-2.765}$($T$, unit:°C [°F])
Oil	Surface tension, N m^{-1}	$\sigma_o = 2.9 \times 10^{-2} - 4.0 \times 10^{-5} \times T$($T$, unit: °C [°F])
R113/oil	Density, kg m^{-3}	$\rho_{r,o} = (\frac{\omega}{\rho_o} + \frac{1-\omega}{\rho_r})^{-1}$
R113/oil	Specific heat, kJkg^{-1}K^{-1}	$c_{p,r,o} = c_{p,r}(1-\omega) + c_{p,o}\omega$
R113/oil	Thermal conductivity, W m^{-1}K^{-1}	$\lambda_{r,o} = \lambda_r\,(1-\omega) + \lambda_o\omega - 0.72\omega\,(1-\omega)\,(\lambda_o - \lambda_r)$
R113/oil	Viscosity, Pa s	$\mu_{r,o} = e^{(\omega \ln \mu_o + (1-\omega)\ln \mu_r)}$
R113/oil	Surface tension, N m^{-1}	$\sigma_o = \sigma_r + (\sigma_o - \sigma_r)\,\omega^{0.5}$