On the Effect of Lubricant on Pool Boiling Heat Transfer Performance

Jung-Tsung Hung
Patech Fine Chemicals Co., Ltd., Changhua County 50741, Taiwan, tzung@patechfc.com.tw

Yu-Kai Chen
Patech Fine Chemicals Co., Ltd., Changhua County 50741, Taiwan, yukai@patechfc.com.tw

Ting-Yang Chen
Department of Mechanical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, g82424@hotmail.com

Shou-Ren Sheng
Department of Mechanical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, x6962173@gmail.com

Chi-Chuan Wang
Department of Mechanical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, ccwang@mail.nctu.edu.tw

On the Effect of Lubricant on Pool Boiling Heat Transfer Performance

Jung-Tsung Hung[1], Yu-Kai Chen[1] , Ting-Yang Chen[2], Shou-Ren Sheng[2], Chi-Chuan Wang[2,*]

[1]Patech Fine Chemicals Co., Ltd., Changhua County 50741, Taiwan

[2]Department of Mechanical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan

*Corresponding Author: ccwang@mail.ntcu.edu.tw

ABSTRACT

This paper presents a brief overview of pool boiling heat transfer performance of refrigerant/lubricant mixtures. Various parameters affecting the heat transfer coefficient, such as viscosity, surface tension are examined. It is known that, during evaporation process, the lubricant accumulates on the surface since the refrigerant is preferential to evaporate. Hence, excess lubricant enrichment on the surface results in a thin lubricant excess layer and a thermal boundary layer, which influence the heat transfer performance, either enhancement or degradation. The effect of lubricant concentration on pool boiling is not consistent due to different working conditions. Some major parameters causing the inconsistency includes surface active components in the oil that changes the surface tension appreciably, such as local variations in concentration and surface tension gradient on growing bubbles; enhanced stirring in the boundary layer detaching bubbles; number of boiling sites; foaming on the heating surface and the like. Generally, increasing the oil concentration continuously degrades the heat transfer performance for highly interrupted surfaces. But the deterioration effect of lubricant on the HTC for plain and integral tubes occurs at a comparatively high oil concentration. At a lower concentration, the HTC can be higher or lower than the oil-free refrigerant, depending on the complex interactions amid surface geometry, lubricant, saturation temperature, heat flux, foaming, etc. Yet a higher viscosity and a lower surface tension of lubricant normally cast positive influence on HTC. It appears that foaming may be beneficial to enhance pool boiling and a higher heat flux or a lower saturation temperature also provide positive influence on HTC of refrigerant lubricant mixtures.

1. INTRODUCTION

Table 1: Thermophysical properties of R113/oil mixture. From Zhu et al. (2012)

	Oil concentration				
Thermophysical properties	0%	5%	10%	20%	40%
Density, kg m^{-3}	1508.2	1464.4	1422.4	1345.9	1215.2
Thermal conductivity, W $m^{-1}K^{-1}$	0.063655	0.064111	0.064672	0.066105	0.0070219
Specific heat, J kg^{-1} K^{-1}	940.37	988.49	1036.6	1132.9	1325.4
Viscosity, Pa s	0.00049040	0.00061451	0.00077001	0.0012091	0.0029809
Surface tension, N m^{-1}	0.014698	0.017388	0.018529	0.020154	0.022468

The heart of compression-based refrigeration and air-conditioning systems is the compressor which circulates refrigerant to proceed heating or cooling. In practice, the compressors require lubricants for essential lubrication of the moving parts. On the other hand, the lubricant provides a seal between the moving parts enabling efficient vapor compression. Gibb et al. (2003) had shown the benefits that introducing more energy efficient refrigeration lubricants can lead to a reduction in energy consumption as high as 15% and indirect reductions in emissions of the greenhouse gas CO_2. With properly designed lubricants, Gibb et al. (2003) estimated that up to 80% of the industrial refrigeration and air-conditioning systems replaced in the next twenty years in the USA could result in annual energy saving up to 200,000 GWh corresponding to 11 million metric tons of carbon in reduced CO_2 emissions. Despite its crucial role in increasing the energy efficiency of compressor, in typical operation of an air-conditioning or refrigeration system, a small amount of oil is carried out of the compressor with the discharge vapor into the circuit of the refrigeration system. Since the oil separator cannot secure the oil in total, it results in the migration of lubricant oil. The tiny amount of lubricant changes the thermodynamics and transport properties of refrigerant mixtures. Among the difference in thermophysical properties, the influence of viscosity is especially imperative since the viscosity of lubricant oil is about two to three orders higher than that of refrigerant. Yet the corresponding surface tension of lubricant is approximately one order higher than that refrigerant. Consequently lubricant oil would impose a significant influence on the heat transfer characteristics. Table 1 tabulated the thermophysical properties of R-113 and VG68 oil with concentration ranging from 0 to 40% from Zhu et al. (2012). Normally, a moderate drop of mixture density subject to the rise of lubricant concentration is seen, accompanied with a slight increase of thermal conductivity and a moderate rise of specific heat and surface tension. The most pronounced change of physical property, as expected, is the viscosity which rises more than six times at a concentration of 40%.

Lubricants used for refrigeration system are classified into mineral and synthetic oils. The mineral oils can be subdivided into paraffins, naphthenics, aromatics and non-hydrocarbons. The synthetic oils that had been introduced for the widely used mineral oils are not miscible, and the HFCs were proposed as substitutes of the CFCs. The synthetic lubricant oils are classified into Polyol Ester (POE), Poly Aklylene Glycol (PAG), Alkyl Benzene (AB), and Poly Alpha Olefin (PAO). Normally additives are added into lubricant to improve its characteristics. Additive types include (1) pour-point depressants for mineral oil, (2) floc-point depressants for mineral oil, (3) viscosity index improvers for mineral oils, (4) thermal stability improvers, (5) extreme pressure and antiwear additives, (6) rust inhibitors, (7) antifoam agents, (8) metal deactivators, (9) disperants, and (10) oxidation inhibitors (ASHRAE 2010). Some additives provide performance advantages in one area but could raise other problems in another. Apparently, the presence of these additives complicates the heat transfer performance of the lubricant oils. There had been many reviews concerning the influences of lubricant oils on the heat transfer characteristics of refrigerant, for instance Filho et al. (2009), Shen and Groll (2005a, 2005b), Wang et al. (2012, 2014), some general behaviors of the lubricants were reported and some controversies still exists. The objective of this study is to give a short overview about the effect of lubricant on the nucleate boiling heat transfer characteristics.

2. TYPICAL RESULTS ABOUT LUBRICANTS ON HTC

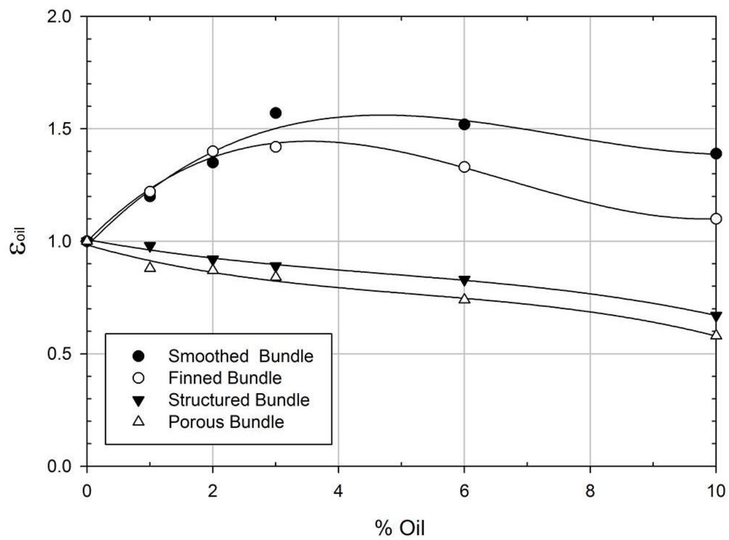


Fig. 1. Effect of oil on heat transfer enhancement ratio ε_{oil} (=$h_{r,o}/h_r$) at 30 kW m^{-2}). From Memory et al. (1995)

Wang et al. (2014) had summarized experimental data regarding to the influence of lubricant on the nucleate boiling heat transfer subject since 1980 from a total of 34 literatures. The associated surface, operation condition, lubricant concentration, heat flux, and major findings were summarized. From their summary, it appears that the test results about lubricant on HTC are quite inconsistent. Depending on the lubricant, refrigerant, concentration, tube geometry, saturation temperature and supplied heat flux, the HTC can be augmented or impaired and it lacked some conclusive trend upon the lubricant addition. Normally the increase of HTC occurs only at a comparative low oil concentration. Figure 1 depicts test results from Memory et al. (1995). They conducted measurements of pool boiling heat-transfer coefficients in pure R-114 and R-114-oil mixtures having a bundle of smooth tubes and three enhanced tube bundles (finned, structured and porous). Each bundle contained 15 electrically heated tubes in a staggered triangular-pitch layout. With addition of oil, the performance of the smooth and finned tube bundles peaks at a specific oil concentration before dropping off slightly. For the structured and porous bundles, oil addition leads to a steady decrease in performance, especially for the porous bundle at high heat fluxes. Analogous results were reported by Ji et al. (2010) who performed R-134a/PVE lubricant for plain, integral fin and four enhanced tubes. Their test results also reveal a more pronounced drop with lubricant concentration especially for enhanced tube geometries. In short, most studies depicted that the presence of oil would jeopardize nucleate boiling heat transfer performance especially for a highly structured surface than a smooth one. However, it should be noted that some investigators had reported a consistent decrease of heat transfer coefficient with oil concentration for plain and structured surfaces (eg. Chongrungreong and Sauer (1980a), Bell et al. (1987), Webb and McQuade (1993)), indicating some complex behaviors amid lubricant, refrigerant, and heating surfaces.

3. TYPICAL THEORIES ABOUT LUBRICANTS ON HTC

During boiling of refrigerant and lubricant mixture, the more volatile component refrigerant evaporates preferentially and leaves the less volatile component (lubricant) at the heating surface and around the bubble, forming an oil-rich layer. This was suggested from some prior researches, such as Jensen and Jackman (1984) and Mitrovic (1998). A schematic of the idealized configuration about the oil-rich layer is shown in Fig. 2. In addition, due to the preferential evaporation of the refrigerant, an oil-rich layer and a steep oil concentration gradient forms around the bubble so that the liquid-gas surface tension is likely to increase. The rise of surface tension requires more work for evaporation and deteriorates the HTC accordingly. However, this may lead to a reduction in bubble size and an increase in bubble frequency. In addition, the he high oil viscosity induces a thicker thermal boundary layer at the heated surface,which can increase the number of active nucleation sites, and enhance the heat transfer performance.

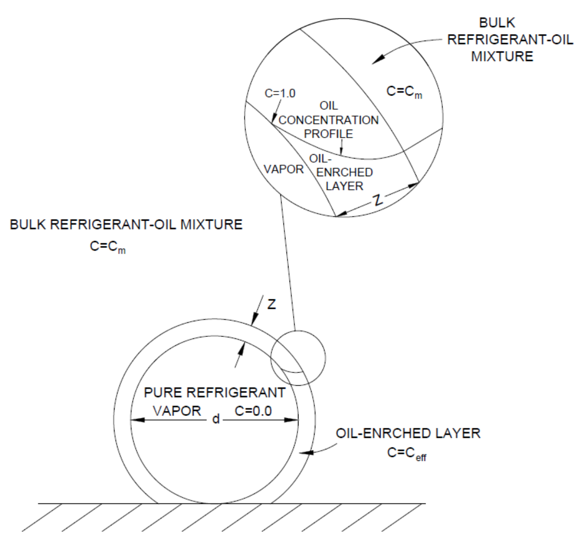


Fig. 2. Schematic of the bubble growth in association with oil-rich layer. (From Jensen and Jackman, 1984)

Wang et al. (1999) also examined the influence lubricant oil (3GS, 5GS) on the heat transfer performance for plain tube at saturation temperatures of 20 °C, 4.4 °C, and -5 °C with oil concentration being 0.75, 1.5, 3.6, and 7%, respectively. At a higher saturation temperature of 20 °C, the heat transfer coefficients are decreased with increase of oil concentration. However, for a saturation temperature of -5 °C, the effect of lubricant oil on the heat transfer coefficients is reversed. This reversed trend of lubricant on the HTC at various saturation temperature for smooth tube is also reported by Mohrlok et al. (2001) in boiling R-507 refrigerant mixture. The heat transfer coefficients with oils are higher than those of pure refrigerants over the range of ω = 0~3%. A maximum increase of 20~30% of heat transfer coefficient is observed near ω = 1.5%. There are several possible explanations of this unusual characteristic. Firstly, it is attributed to the influence of the most influential physical properties, surface tension and viscosity. For the influence of viscosity, based on the pool boiling correlation developed by Stephan and Abdelsalam (1980) where:

$$Nu = 207\left(\frac{qd_B}{k_f T_s}\right)^{0.745}\left(\frac{\rho_g}{\rho_f}\right)^{0.581}\left(\frac{\nu_f}{\alpha_f}\right)^{0.533} \tag{1}$$

$$d_B = 0.851\beta_0\sqrt{\frac{2\sigma}{g(\rho_f - \rho_g)}} \tag{2}$$

$$\beta_0 = 35° \tag{3}$$

where ν_f is the kinematic viscosity of the liquid phase of refrigerant and α_f is the thermal diffusivity. As seen in Eq. (1), the heat transfer coefficient is proportional to kinematic viscosity $\nu_f^{0.533}$. Hence, it explains in part that a much higher viscosity of lubricant oil at a lower saturation may promote the heat transfer. The experimental data of Sauer et al. (1980b) also indicated that a lower viscosity lubricant added to R-11 refrigerant causes a much stronger decline of heat transfer coefficient than an oil with high viscosity. Secondly, for the influence of surface tension, Mitrovic (1998) argued that it is possible that the oil-rich film reduces the liquid-gas interface surface tension. This is possible when the oil contains some surface-active component. Mitrovic (1998) reached an expression that connects the temperature, oil concentration, and the size of the bubble in equilibrium with the mixture:

$$\frac{h}{h_o} = \frac{-\sigma_o}{\sigma}\frac{r}{r_o}\frac{x}{\ln(1-x)} \tag{4}$$

Where h and r denote the heat transfer coefficient and equilibrium bubble radius, respectively. The subscript o refers the state of lubricant mixtures. By using this expression, adding lubricant oil to a refrigerant can facilitate the bubble formation and improve the heat transfer. For this to occur, the oil must contain some surface active components.

For refrigerant oil mixtures, a higher wall temperature is required to accommodate the same nucleation site density as compared to the pure refrigerant. This leads to a decrease of HTC at constant heat flux condition. With addition of oil, a greater gradient of the surface tension around the bubble may enhance the Marangoni convection. However, at a higher oil concentration, the positive effect of oil on heat transfer associated with change of surface tension is expected to be offset by mass transfer.

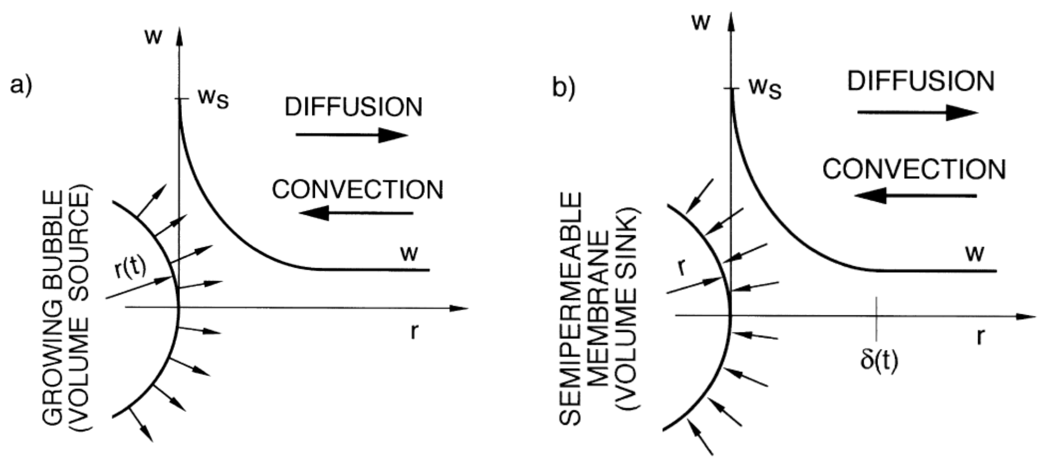
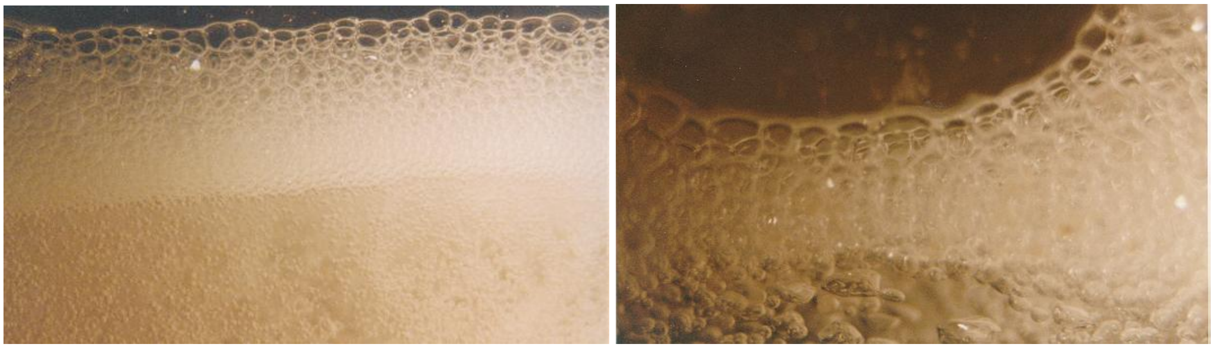


Fig. 3. Schematic illustration of mass transfer during the bubble growth in a refrigerant-oil mixture (a) Expanding bubble surface filters the mixture resulting in an oil accumulation around the bubble. (b) Motionless semipermeable membrane representing the bubble surface the liquid flows radially towards the membrane.

Further elaboration about the effect of mass transfer resistance in the presence of lubricant is given by Mitrovic (1998) as shown in Fig. 3. Since the oil is non-volatile and the vapor in the bubble is the pure refrigerant, the expanding interface of a growing bubble, allows only refrigerant molecules to pass through the bubble vapor space. Hence,oil would arrive and accumulate at the interface steadily via convective transport of oil molecules through the help of refrigerant molecules during expansion. Yet the oil molecules at the interface also tend to diffuse the oil molecules to the bulk. The two mechanisms: the diffusion tends to lower, yet the convection may increase or decrease the oil concentration at the interface depending on the mass fluxes as time passes.

Thirdly, the foaming characteristics subject to lubricant oil at saturate temperature may pose extra augmentation. Figure 4 illustrated the foaming characteristics by Wang et al. (1999) for R-22/3GS oil at saturation temperature of

20 °C and -5 °C. For the same oil concentration, the depth of the foaming increases when the saturation temperature is decreased. The size of the foaming is increased as the saturation temperature is decreased due to a lower pressure. When oil added to the refrigerant an intensive foaming is produced as heat flux is increased. Several investigators had postulated that the increase of heat transfer coefficients at low oil concentration is related to the foaming process (eg. Stephan (1963), Udomboresuwan and Mesler (1986)).



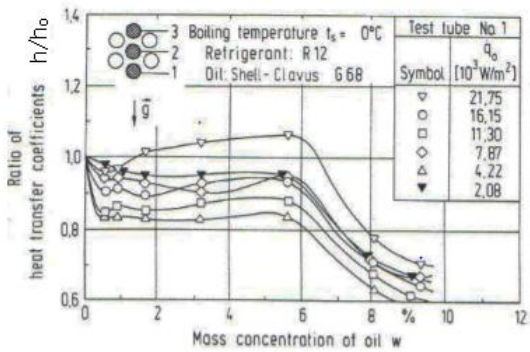
$q = 58\ kW/m^2$, $T_S = 20°C$, $\omega = 0.75\%$ $\quad$ $q = 50.4\ kW/m^2$, $T_S = –5°C$, $\omega = 0.75\%$

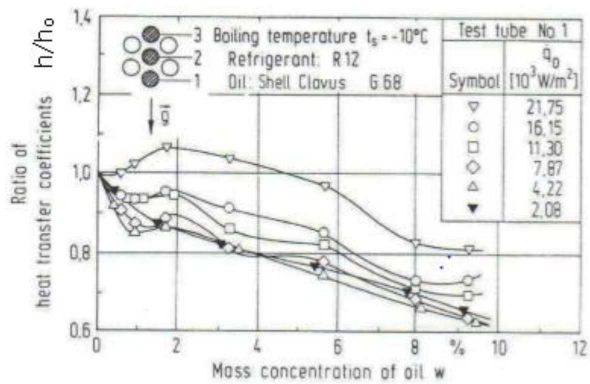
Fig. 4. Photos of foaming characteristics of R-22/3GS mixture at different saturation temperatures. (From Wang et al. (1999).

The presence of foaming gives rise to more phase interface area through which the latent heat of evaporation is transferred. For a growing bubble, the temperature of the phase interface is decreasing. Heat is transferred at lower temperature differences and with higher heat transfer coefficients. On the other hand, there is an oil-rich layer next to the heating surface and foam. The foam inhibits the flow of liquid refrigerant to the heating surface, giving rise to a high local oil concentration. The foaming phenomenon becomes more pronounced with higher heat fluxes and higher oil concentrations. Several investigators (Memory et al. (1995a, 1995b), Udomboresuwan and Mesler (1986)) also claimed that the effect of foaming for refrigerant-oil mixtures may significantly increase the heat transfer characteristics. Udomboresuwan and Mesler (1986) reported significant enhancement in pool boiling heat transfer in the presence of foam. They assumed two possible enhancement effects caused by the foaming, including (1) a thin liquid film was created between the foam and the heated surface which results in a very large heat transfer coefficient; and (2) secondary nucleation caused by the bubble leaving the surface which bursting into the neighboring liquid-vapor region. Notice that a further increase of heat flux may result in significant increase of the depth of the foaming. In addition, the size of the foaming is getting finer as heat flux is increased. A close examination of the foaming shows that the size of the foaming can be roughly classified into coarse and fine one. The coarse one is on the top of the fine one. In summary of the foregoing observations, it is concluded that the effect of foaming are more evident in higher oil concentration, lower saturation temperature, and a higher supplied heat flux. The presence of foaming may explain partially the sharp bounce of heat transfer coefficient of Zheng et al.'s data (2008) when oil concentration is raised from 5% to 10% at a saturation temperature of 7.2 °C whereas this phenomenon is not seen at a higher saturation temperature of 23.3 °C. Similar test results about an appreciable increase of heat transfer coefficient with a higher supplied heat flux were also reported by some investigators (e.g. Stephan and Mitrovic (1981) and Spindler and Hahne (2009)). Some of their representative data are showed in Fig. 5. In essence, the foaming effect casts a positive role in augmentation of heat transfer. Hsieh and Weng (1997) also postulated that foaming promotes secondary motion in pool boiling and is helpful in moving the oil out of the heated surface. The foregoing explanation about the effect of foaming may also be confirmed with the data of Stephan and Mitrovic (1981, 1982) who showed the HTC is increased by raising heat flux and HTC could be slightly higher than pure refrigerant at a small range of ω. Moeykens et al. (1995) and Moeykens and Pate (1996) examined the spray evaporation performance of R-134a/340-SUS (POE) and R-22/300-SUS (alkyl-benzene) on single tube as well as on tube bundles. Foaming was observed due to the oil dissolved in the refrigerant and appreciable enhancements were observed. In essence, the foaming effect casts a positive role in augmentation of heat transfer.

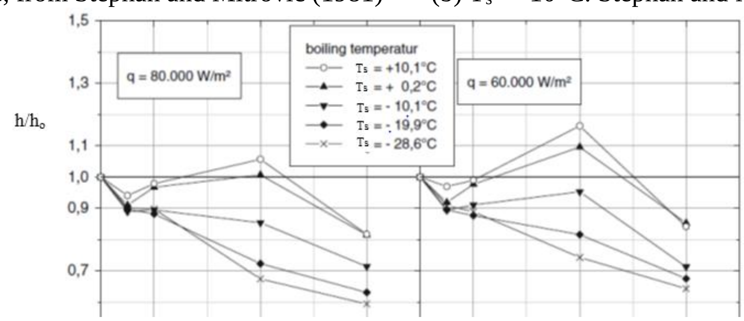
In addition to the foregoing explanations of the influence of lubricant on the HTC, Kedzierski attributed the pool boiling mechanism to the variations of bubble size and bubble number. Kedzierski (2000) attempted to explain the pool boiling mechanism of refrigerant-oil mixtures by introducing the concept of an oil excess (oil rich) layer at the heated surface. Shen and Groll (2005a) had summarized three possible reasons of Kedzierski's study for lubricant enhancing pool boiling:

1. The oil excess layer is able to reduce the solid-liquid interaction. Then the solid-liquid oil-rich layer leads to a reduction in bubble size and an increase in bubble frequency.
2. The high oil viscosity induces a thicker thermal boundary layer at the heated surface. The thicker thermal boundary layer can increase the site density to activate the bubbles.
3. The oil partial miscibility might contribute to the enhanced boiling. When a partial miscible refrigerant-oil mixture boils at the temperature close to the critical solution temperature, there are two liquid films enveloping the bubble, an oil-rich film and a refrigerant-rich film. The interface of the two films has a large curvature gradient, which leads to a great film pressure gradient. The superheated liquid may be moved to the bubble side by the pressure gradient.





(a) T_s = 0 °C, from Stephan and Mitrovic (1981) (b) T_s = -10°C. Stephan and Mitrovic (1981)



(c) Mass concentration from 1-5, taken from Spinder and Hahne (2009)

Fig. 5. Heat transfer performance of refrigerant-lubricant mixtures from representative studies.

4. CONCLUSIONS

The effect of lubricant on the nucleate boiling heat transfer performance is briefly summarized in this study. As noted in the existing literatures, the heat transfer performance in association with lubricants reveals quite inconsistent behaviors. Some major parameters causing the inconsistent trend includes surface active components in the oil that changes the surface tension appreciably, local variations in concentration and surface tension gradient on growing bubbles; enhanced stirring in the boundary layer of detaching bubbles; number of boiling sites; foaming on the heating surface and the like. Some more conclusive trends about the influence of lubricant on the HTC are summarized as follows:

(1) Generally, increasing the oil concentration continuously degrades the heat transfer performance for highly interrupted surfaces. But the deterioration effect of lubricant on the HTC for plain and integral tubes occurs at a comparatively high oil concentration. At a lower concentration, the HTC can be higher or lower than the oil-free refrigerant, depending on the complex interactions amid surface geometry, lubricant, saturation temperature, heat flux, foaming, etc.

(2) Normally a higher viscosity and a lower surface tension lubricant will improve the heat transfer performance.

(3) Some investigators speculated that foaming are beneficial to enhance pool boiling.

(4) Some test results suggested that higher heat flux and lower saturation temperature provides positive influence on HTC of refrigerant lubricant mixtures.

NOMENCLATURE

C	oil concentration	(kg/kg)
C_p	isobaric specific heat	(J kg^{-1} K^{-1})
Q	heat flux	(W m^{-2})
Nu	Nusselt number	(-)
T	temperature	(°C)
s	specific gravity	(-)
h	heat transfer coefficient	(W $m^{-1}K^{-1}$)
ν_f	kinematic viscosity	(m^2 s^{-1})

Symbol

α	thermal diffusivity	(m^2 s^{-1})
β	Contact angle	(degree)
ρ	density	(kg m^{-3})
ε_{oil}	$= h_{r,o}/h_r$	(-)
λ	thermal conductivity	(W $m^{-1}K^{-1}$)
ω	oil concentration	(-)
μ	dynamic viscosity	(Pa s)
σ	surface tension	(N m^{-1})

Subscript

f	liquid phase
g	vapor phase
o	oil
r	refrigerant
r,o	mixture
s	saturation

REFERENCES

ASHRAE (2010), Lubricants in refrigeration system, in ASHRAE Handbook of refrigeration 2010; chapter 12, pp. 12.1-12.31, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta.

Bell, K.I., Hewitt, G.F., & Morris, S.D. (1987). Nucleate pool boiling of refrigerant/oil mixtures. *Experimental Heat Transfer 1987*, *1*, 71-86.

Chongrungreong S, & Sauer, H.J. Jr. (1980) Nucleate boiling performance of refrigerants and refrigerants-oil mixtures. *Journal of Heat Transfer*, *102*, 701-705.

Filho, E. P. B., Cheng, L., & Thome, J. R. (2009). Flow Boiling Characteristics and Flow Pattern Visualization of Refrigerant/Lubricant Mixtures, *International Journal of Refrigeration*, *32*, 185-202.

Gibb P, Randles S, Millington M, & Whittaker A. (2003). Lubricants for sustainable Cooling. In*: Proceedings of the 2003 CIBSE/ASHRAE Conference*, Edinburgh, United Kingdom.

Hsieh, S., & Weng, C., (1997). Nucleate Pool Boiling Heat Transfer Coefficients of Distilled Water (H_2O) and R-134a/oil Mixtures From Rib-roughened Surfaces, *Journal of Heat Transfer*, vol. 119, pp. 142-151, 1997.

Jensen M.K., & D.L. Jackman, D. L. (1984). Prediction of nucleate pool boiling heat transfer coefficients of refrigerant-oil mixtures. *ASME*, *Journal of Heat Transfer*, *106*, 184-190.

Ji, W.T., Zhang, D.C., Feng, N., Guo, J.F., Numata, M., Xi, G., & Tao, W.Q. (2010). Nucleate pool boiling heat transfer of R134a and R134a-PVE lubricant mixtures on smooth and five enhanced tubes. *Journal of Heat Transfer, 132*, 111502-1-8.

Kedzierski, M.A. (2000). Refrigerant/lubricant mixture boiling heat transfer research at NIST. *Sixteenth National Convention of Mechanical Engineers and All India Seminar on Future Trends in Mechanical Engineering*, Research and Development, Dept. of Mech. and Ind. Eng., Sept. 29-30, UOR, Roorkee.

Moeykens, S.A., & Pate, M.B., (1996a). Effect of lubricant on spray evaporation heat transfer performance of R-134a and R-22 on single tube. *ASHRAE Transactions*, *102*(1), 111-123.
Moeykens, S.A. & Pat, M.B., (1996b). Effect of lubricant on spray evaporation heat transfer performance of R-134a and R-22 in tube bundles. *ASHRAE Transactions*, *102*(1), 410-426.
Mitrovic, J. (1998). Nucleate boiling of refrigerant-oil mixtures: Bubble equilibrium and oil enrichment at the interface of a growing vapour bubble. *International Journal of Heat & Mass Transfer*, *41*, 3451-3467.
Mohrlok, K., K. Spindler, & Hahne, E. (2001). Influence of a low viscosity oil on the pool boiling heat transfer of the refrigerant R507. *International Journal of Refrigeration*, *24*, 25-40.
Sauer, Jr., H.J., Davidson, G.W., & Chongrungreong, S. (1980). Nucleat boiling of refrigerant-oil-mixture from finned tubing, ASME paper Bo-HT-111.
Shen, B., & Groll, E. A. (2005a). Critical Review of the Influence of Lubricants on the Heat Transfer and Pressure Drop of Refrigerants, Part I: Lubricant Influence on Pool and Flow Boiling, *International Journal of HVAC&R Research*, *11*, 511–526.
Shen, B., & Groll, E. A. (2005b). Critical Review of the Influence of Lubricants on the Heat Transfer and Pressure Drop of Refrigerants, Part II: Lubricant Influence on Condensation and Pressure drop, *International Journal of HVAC&R Research*, *11*, 341–360.
Stephan, K. (1963). Influence of oil on heat transfer of boiling Freon 12 (Refrigerant 12) and Freon 22 (Refrigerant 22), *Proc. of the XIth Int. Congress of refrigeration 1*, Munich, 369-380.
Stephan, K. & Abdelsalam M. (1980). Heat-transfer correlations for natural convection boiling. *Int. J. of Heat and Mass Transfer*, *23***,** 73-87.
Stephan,K., & Mitrovic, J. (1981). Heat transfer in natural convective boiling of refrigerant and refrigerant-oil mixtures in bundles of T-shaped finned tubes. ASME HTD *18*, 131-146.
Stephan,K., & Mitrovic, J. (1982). Heat transfer in natural convective boiling of refrigerant-oil mixtures. *Heat Transfer 1982, paper PB12,* 73-87.
Udomboresuwan A. & Mesler R. (1986). The enhancement of nucleate boiling by foam. Heat Transfer 1986, San-Francisco, *6***,** 2939-2944.
Wang, C.C., Chong, H.D., Lin, Y.T., Hu, Y.Z.R. (1999). Some observations of the foaming characteristics in the nucleate boiling performance of refrigerant-oil mixtures. *ASHRAE Transactions*, *105*(1), 469-477.
Wang, C.C., Hafner, A., Kuo, C.S., & Hsieh, W.D. (2012), An overview of the effect of lubricant on the heat transfer performance on conventional refrigerants and natural refrigerant R-744. *Renewable & Sustainable Energy Reviews*, *16*, 5071–5086.
Wang, C.C., Hafner, A., Kuo, C.S., & Hsieh, W.D. (2014). Influence of lubricant on the nucleate boiling heat transfer performance of refrigerant – a review. *Heat Transfer Engineering, 35*, 651-663.
Webb, R.L., & McQuade, W.F. (1993). Pool boiling of R-11 and R-123 oil-refrigerant mixtures on plain and enhanced tube geometries. *ASHRAE Transactions*, *99*(1), 1225-1236.
Memory S.B., Sugiyama, D.C., & Marto, P.J. (1995a). Nucleate pool boiling of R-114 and R-114-oil mixtures from smooth and enhanced surfaces—I. Single tubes. *Int. J Heat Mass transfer, 38*, 1347-1361.
Memory S.B., Sugiyama, D.C., & P.J. Marto. 1995b. Nucleate pool boiling of R-114 and R-114-oil mixtures from smooth and enhanced surfaces—II. Tube bundles. *Int. J Heat Mass transfer 38*,1363-1376.
Zheng, J., Chyu, M.-C., & Ayub, Z. H. (2008) Boiling of Ammonia/lubricant Mixture on a Horizontal Enhanced Tube in a Flooded Evaporator With Inlet Vapor Quality, *International Journal of Refrigeration*, *3*, 564-572.
Zhu, Y. Hu, H., Ding, G.L., Zhuang, D., & Peng, H. (2012). Heat transfer enhancement by metal foam during nucleate pool boiling of refrigerant/oil mixture at a wide range of oil concentration, *HVAC&R Research*, *18*, 377-389.

ACKNOWLEDGEMENT

The final author wishes to acknowledge partial financial support from Ministry of Science and Technology, Taiwan under contract 104-2221-E-009 -184 -MY3.