International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 433

Effect of Lubricating Oil on Refrigerant Distribution in Microchannel Heat Exchangers: A Review

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ABSTRACT

The compactness and good air-side heat exchange of the microchannel heat exchanger make it widely used in residential and automotive air conditioning systems. However, due to the different properties of refrigerant liquid and vapor, there is phase separation in the header and heat exchange tubes of the microchannel heat exchanger, resulting in uneven distribution of the refrigerant in the parallel microchannel tubes, the heat transfer area utilization rate is reduced, and the system performance is reduced. In addition, the presence of lubricants can also affect refrigerant distribution. The conclusion is that a small amount of lubricating oil will make the refrigerant distribution performance worse, and further adding lubricating oil will change the flow pattern, thereby improving the refrigerant distribution performance. This is because foam is formed after a large amount of oil is introduced to make the flow pattern more uniform. For any given lubricant content, at the same mass flow rate, as the quality increases, the distribution becomes worse because there is less liquid in the top pipe. In the case of the same inlet quality, as the mass flow increases, the high-momentum liquid can reach the top of the header, which is easy to be entrained by the top pipe, and the refrigerant distribution is better. However, although the lubricant improves the distribution of the refrigerant in the parallel microchannel tubes, it also significantly reduces the specific enthalpy difference of the working fluid, which is mainly due to its non-evaporative nature. Therefore, the influence of lubricating oil on the pressure drop and heat transfer characteristics of the microchannel heat exchanger after improving the refrigerant distribution is still an unresolved issue.

Keywords: lubricating oil, distribution, microchannel heat exchanger, refrigerate

NONMENCLATURE

Abbreviations	
OCR	oil circulation ratio

1. INTRODUCTION

Extruded aluminum heat exchangers with hydraulic diameters ranging from 3 mm to 0.25 mm are favored by people because of their small size, high heat transfer coefficient, and small refrigerant charge, which can withstand higher working pressures, although Kandlikar[1] defined as micropipes, but these heat exchangers are called "microchannels" by the industry, and these extruded aluminum microchannel heat exchangers have been used in automotive air conditioning and heat pump systems since the early 1990s[2]. Recently, the popularity of microchannel heat exchangers has grown into a disruptive technology for the refrigeration industry that has relied on circular copper tubes with a diameter greater than 6 mm for decades[3]. In automobile and building air conditioning systems, the use of micro-channel heat exchangers has increased. More and more researches are focused on the heat transfer and pressure drop in microchannels and microchannels, especially in two-phase flow. As the channel size decreases, inertia, viscosity and surface tension play a more important role in the microchannel than gravity. However, one of the challenges in using microchannel heat exchangers as evaporators is how to evenly distribute the two-phase refrigerant in parallel microchannel tubes[4]. Due to the large difference in physical properties (such as density, viscosity, etc.), vapor and liquid refrigerants have significantly different inertial momentum, and it is difficult for the vapor-liquid two phases in the evaporator to be evenly distributed in the parallel tubes[5]. Some tubes lacking liquid refrigerant will have larger overheating areas, and the heat transfer area utilization rate is very low. Therefore, the system cooling capacity and COP usually deteriorate[6]. In order to achieve a good design, it is necessary to understand the refrigerant distribution characteristics of the working fluid in the small channel.

In the vapor compression refrigeration system, lubricating oil has the functions of lubricating, sealing and flushing, which can prevent the refrigerant from overheating, prevent wear and friction between matching parts, block contaminants, prevent corrosion, deal with debris generated by wear, and eliminate motors the heat generated by friction and power loss, and reduce noise by foaming, lubricating oil plays an extremely important role in ensuring the reliability and service life of the compressor [7, 8]. However, the lubricating oil in the compressor will inevitably be carried out by the refrigerant vapor and enter the heat exchanger. As the operating conditions of the system change, the mass percentage of lubricating oil flowing with the refrigerant is generally between 0.1% and 8.0%[7]. Because the lubricating oil exceeds the viscosity of the refrigerant and has no phase change in the refrigeration cycle, it will change the thermophysical properties (liquid-gas balance, enthalpy, viscosity, surface tension, etc.)and flow patterns of refrigerants, thereby affecting the heat exchange and The pressure drop characteristics cause certain effects[9, 10], such as increasing the flow resistance of the refrigerant and affecting the heat transfer effect on the refrigerant side. And the circulating oil that disappears from the compressor can form a fairly uniform mixture with the liquid refrigerant, or it can exist as a separate oil film in the tubes and headers of the heat exchanger[11]. Due to the relatively small geometric size and manifold structure of the microchannel heat exchanger, the influence of oil on it is unique, because the oil will block the ports of some microchannels[12]. At present, there is very little literature on the role of oil in small pipe diameters, little is known about the effect of lubricating oil on the distribution of refrigerant in the microchannel evaporator, and its heat transfer and pressure drop characteristics in the heat exchanger are not well defined, the influence of lubricating oil on its heat transfer and transportation characteristics is still an unsolved problem[13]. In addition, few people have studied the effect of oil on the performance of the entire microchannel heat exchanger. These heat exchangers include not only tubes, but also inlet and outlet headers. Therefore, the influence of lubricating oil on the distribution of microchannels is worth exploring. This article reviews the research on the influence of lubricating oil on the distribution of microchannels, and aims to provide support for the design and optimization of microchannel heat exchangers.

2. THE INFLUENCE OF LUBRICATING OIL ON REFRIGERANT DISTRIBUTION CHARACTERISTICS

The compactness and good air-side heat exchange of the microchannel heat exchanger make it widely used in residential and automotive air conditioning systems[14]. However, due to the different liquid-vapor properties of the refrigerant, there is phase separation in the header and heat exchange tubes of the microchannel heat exchanger, resulting in uneven distribution of the refrigerant in the parallel microchannel tubes[4, 15, 16]. Due to the low cooling capacity, the superheated refrigerant vapor will cause areas with low mass flow and/or high inlet quality to dry up. This will lead to uneven temperature distribution on the surface of the heat exchanger and low utilization of the effective heat transfer area. Since the single-phase heat transfer coefficient is much lower than the heat transfer coefficient of the two-phase flow, the heat transfer coefficients of the refrigerant side and the air side are both lower than the heat transfer coefficient of the two-phase flow surface. In addition, as the temperature of the refrigerant increases, the temperature difference between the air and the refrigerant decreases. Therefore, the uneven distribution of refrigerant will result in a great decrease in heat exchanger performance[17]. The presence of lubricants will also affect the refrigerant distribution, which is the result of the combined effect of the oil effect in the header and the microchannel tube. In summary, the presence of lubricating oil in the microchannel heat exchanger will affect the distribution of refrigerant in two ways [18]: (1) The addition of lubricating oil can change the flow resistance of each microchannel tube to varying degrees, thereby affecting the mass flow of refrigerant distribution between parallel tubes. Lubricating oil affects the flow resistance by changing the heat transfer and pressure drop characteristics of the working fluid. (2) Adding lubricating oil will change the flow pattern in the intake header, thereby affecting the distribution of refrigerant quality.

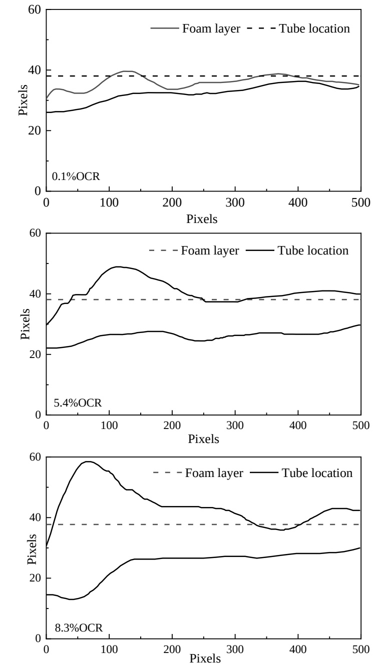

Fig 1 Quantitative flow regimes in the inlet header with different OCRs [18]

H. Li et al.[13] studied the first lubricating oil effect by simulation, and the results showed that its effect is very limited. This study only focuses on the influence of oil in the intake header, which is considered to be the main factor affecting the distribution. Due to the changes in physical properties, especially the increase in surface tension caused by refueling, the fluid state in the head of the microchannel heat exchanger is very different from that of pure refrigerant. Bowers and Hrnjak[19] observed a huge difference in the fully developed two-phase flow regime of pure R134a and R134a/PAG oil mixtures in the horizontal inlet header. Zou and Hrnjak[20] observed the influence of lubricating oil on refrigerant distribution, and the flow pattern of R134a and PAG46 oil mixture in the vertical intake header. They found that a small amount of lubricating oil would make the refrigerant distribution performance worse. Adding lubricating oil will change the flow pattern, thereby improving the refrigerant distribution performance. This is because foam is formed after introducing a large amount of oil (2.5% and 4.7%) to make the flow pattern more uniform. The study by H. Li et al.[18] showed that the addition of lubricating oil will significantly affect the flow state in the horizontal inlet header. When the OCR is 0.1%, a very small amount of foam is formed, and most of the pipe inlet is exposed to the vapor phase, especially when the minimum liquid level is reached. With the increase of OCR, the foam layer gradually thickens, filling the gap between the nozzle and the liquid level. When OCR is 5.4% and 8.3%, most of the pipe is immersed in the foam layer. The influence of OCR on the average immersion distance of the pipeline is shown in Fig.1. The shorter the distance, the more likely the pipe inlet is to be exposed to the vapor phase. A negative distance means that the foam is located on average below the pipe entrance. At high OCR (>5%), the pipe inlet is immersed in the foam layer most of the time, which can prevent a large amount of steam from flowing through the pipe at the beginning of the intake header. At low OCR (<3%), the tube inlet is likely to be exposed to the gas phase due to relatively little foam formation. This state creates an opportunity to distribute a large amount of steam at the beginning of the inlet header, thus making the distribution worse. Although the lubricant improves the distribution of the refrigerant in the parallel microchannel tubes, it also significantly reduces the specific enthalpy difference of the working fluid, which is mainly due to its non-evaporative nature. Hrnjak et al.[21] believe that the quality distribution is uneven, although it is also affected by the pressure drop in the heat exchanger, but it is mainly the result of the flow pattern in the header. In the stirred flow, the gas-liquid mixing is more uniform and the distribution is more uniform. However, in the separation flow, only a small part of the header is located between the liquid separation height (the blue line in Fig.2 indicates the position where the liquid film separates from the wall) and the liquid arrival (the red line in Fig.2 and Fig.3 indicates the highest liquid level). The tubes there have more chances to receive liquid than other tubes, which causes uneven distribution of high quality. The flow pattern in the header is affected by the inlet conditions. As the quality of the intake air increases, the flow pattern transitions from agitation to separation, so the distribution becomes worse. When oil is present, although the flow pattern is usually still agitated flow or separated flow, the details of the flow pattern in the header have changed. For example, in Fig.2, the flow state of pure R134a is agitated flow at low quality. When OCR=0.5%, the oil has little effect on the flow state of the header, and when the OCR is increased to 2.5% and 4.7%, there will be too many small bubbles or bubbles in the header sometimes, and it is difficult for even light to pass through[22]. This makes the two-phase flow more uniform and the distribution more uniform. At the high quality in Fig.3, the flow pattern of pure R134a is separated flow. When OCR=0.5%, the flow pattern in the header is similar to that of pure R134a. When OCR=2.5% and 4.7%, the liquid film on the wall is thicker, the local stirring flow is larger, and there are a large number of small bubbles in the area, which is conducive to vapor-liquid mixing and expands the stirring flow area. Therefore, the distribution is also improved.

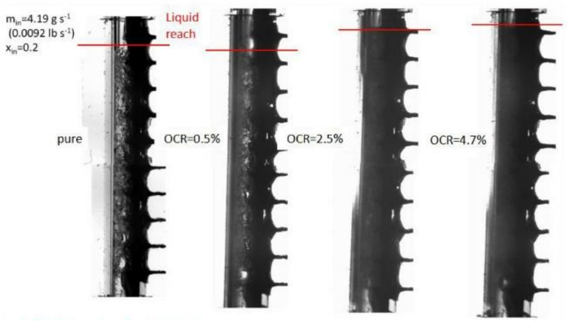

Fig.2 Oil effects on churn flow in the heade [21]

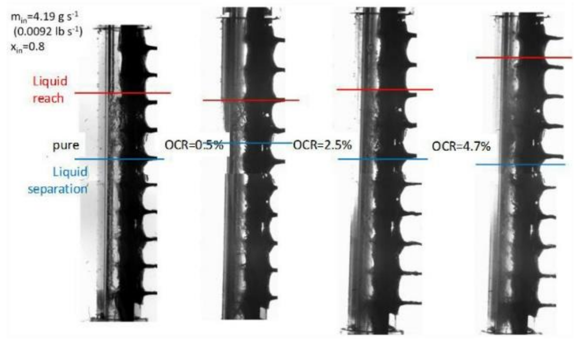

Fig.3 Oil effect on separated flow in the header [21]

The uneven distribution of refrigerant in the evaporator will produce unwanted superheated areas. Due to the low heat transfer coefficient of superheated steam, the temperature difference between the refrigerant and the air is small, resulting in lower heat transfer in the superheated area than in the two-phase area. The cooling capacity of the heat exchanger and the system COP are usually lower than the case of uniform distribution[18, 23]. When Tuo and Hrnjak[24] used flash gas bypass to improve distribution, the COP increased by 55%. Therefore, uneven distribution of lubricating oil and refrigerant in the microchannel heat exchanger is a very important problem. Some studies have focused on the impact of uneven refrigerant distribution on the performance of heat exchangers and systems. Kulkarni et al.[25] simulated the uneven distribution of R410A caused by the pressure drop of the horizontal header. The cooling capacity of the microchannel evaporator is reduced by 20%. Brix et al.[26, 27] simulated the uneven distribution of R134a and R744 in the two microchannel tubes, and the calculated cooling capacity was reduced by 23% and 18%, respectively, compared with the uniform case. Tuo and Hrnjak[24] found that for R134a mobile air-conditioning systems, uneven distribution of quality can result in up to 18% of cooling capacity and 7% of COP reduction. Zou et al.[28] simulated and calculated that the uneven distribution of R410A in the two-way microchannel heat exchanger resulted in a cooling capacity reduction of about 5%. Zou et al.[28] used a heat pump as the experimental object, passing through the outdoor micro-channel heat exchanger twice, the uneven distribution of cooling capacity of R410A and R134a decreased by 30% and 5%, respectively. Byun and Kim[29] proposed that in the heat pump mode, the distribution of R410A in the two-pass outdoor microchannel heat exchanger is uneven, resulting in a 13.4% reduction in cooling capacity compared to the uniform distribution.

H. Li et al.[13] conducted a model analysis on the influence of lubricating oil on the distribution of two-phase refrigerant in a parallel flow microchannel evaporator. By considering the thermodynamics and transport characteristics of the refrigerant-lubricating oil mixture and its influence on the boiling heat transfer and pressure drop characteristics, that is, on the basis of the pure refrigerant correlation, substituting the physical properties of the refrigerant-lubricating oil mixture for the physical properties of the pure refrigerant, a microchannel evaporator model is proposed. The working pair chooses R134a and PAG oil. This model is used to study the influence of viscosity effect and OCR effect on refrigerant distribution. The results show that: high viscosity is not conducive to refrigerant distribution. The literature[30] and the literature[31] have also reached the same conclusion; in the range of 0.1% to 3% oil content, As the oil content increases, the distribution performance deteriorates. But at higher oil content, the distribution performance is improved. Therefore, when the OCR is increased from 3% to 10%, the rich steam pipe will receive more liquid and the rich liquid pipe will receive less liquid, which means that the distribution is improved. The improved distribution at high OCR is because the lubricating oil produces a layer of foam at the vapor and liquid interface. This layer of foam increases the size of the local agitated flow area. Synthetic oils, such as PAG oil, usually contain some surface-active additives (i.e. surfactants). Foam is inherently unstable, and if left still, it tends to collapse into a liquid (this is the lowest energy state). Surface active additives tend to stay on the walls of the foam to prevent the collapse of the foam. The agitation or mixing of vapor and liquid in the header also helps to maintain foam at the vapor-liquid interface. The generation and stability of foam are affected by viscosity, dynamic surface tension, Gibbs elasticity, interfacial shear and expansion viscosity. Among these parameters, the Gibbs elasticity related to the surface tension gradient and Maragnoni effect is considered to be the most important. The distribution of surface-active additives creates a surface tension gradient in the liquid layer, where some locations have high surface tension, while others have low surface tension. When the diffusion rate of the surfactant is just right, the thin spots (possible burst points) in the foam wall can be repaired.

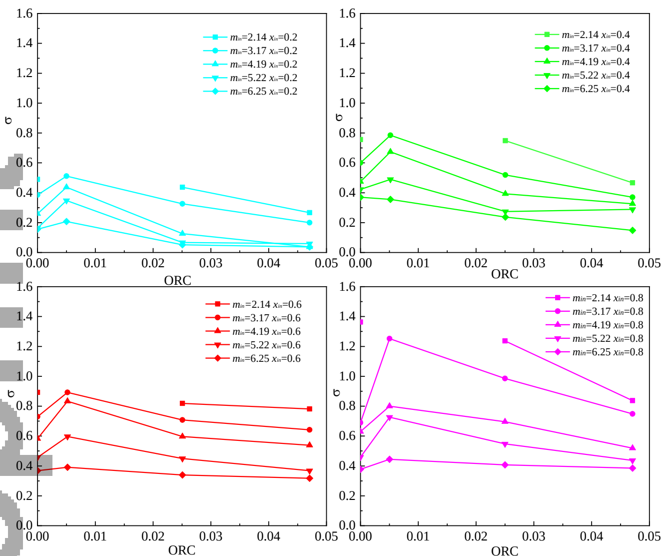

Fig 4 Oil effect on distribution (R134a,PAG 46 oil).a)x_{in}=0.2,b)x_{in}=0.4,c)x_{in}=0.6 ,d)x_{in}=0.8.

Zou and Hrnjak[20] studied the effect of oil on the distribution of refrigerant in a vertical intake header. The results show that for any given lubricating oil content, at the same mass flow rate, as the quality increases, the distribution becomes worse because there is less liquid in the top pipe. In the case of the same inlet quality, as the mass flow increases, the high-momentum liquid can reach the top of the header, which is easy to be entrained by the top pipe, and the refrigerant distribution is better [23, 32, 33]. In addition, when a small amount of oil (OCR=0.5%), due to the low liquid content of the top pipe, its distribution is worse than that of pure R134a, because the high viscosity makes it more difficult for the liquid to reach the top of the header. When the OCR increases to 2.5% and 4.7%, the distribution becomes better and better due to the liquid return from the jacking pipe. This is because a sufficient amount of oil will produce a large number of small bubbles/droplets and foam layers at the gas-liquid interface, which will make the two phases mixed and unified, and expand the liquid phase area[21, 34]. This trend has been observed whether it is low imported quality or high imported quality, as shown in Fig.4. However, at low quality, the improvement is more significant: at OCR of 5% and 4.7%, the distribution is even better than pure R134a. In addition, when the OMF is increased from 0wt% to 10wt%, the pressure drop on the refrigerant side increases by 300% due to the higher viscosity of the refrigerant and oil mixture. However, after replacing the refrigerant with non-evaporating lubricating oil, the evaporator capacity decreases by 19.5 %.

CONCLUSION

In automobile and building air conditioning systems, the use of micro-channel heat exchangers has increased. More and more researches are focused on the heat transfer and pressure drop in microchannels and microchannels, especially in two-phase flow. As the channel size decreases, inertia, viscosity and surface tension play a more important role in the microchannel than gravity. However, one of the challenges in using microchannel heat exchangers as evaporators is how to evenly distribute the two-phase refrigerant in parallel microchannel tubes. In addition, the presence of lubricants can also affect refrigerant distribution. Therefore, this article reviews the research on lubricant distribution to refrigerant in microchannel heat exchangers and draws the following conclusions.

(1) A small amount of lubricating oil will make the refrigerant distribution performance worse, and further adding lubricating oil will change the flow pattern, thereby improving the refrigerant distribution performance. This is because foam is formed after a large amount of oil is introduced to make the flow pattern more uniform.

(2) For any given lubricant content, at the same mass flow rate, as the quality increases, the distribution becomes worse because there is less liquid in the top pipe. In the case of the same inlet quality, as the mass flow increases, the high-momentum liquid can reach the top of the header, which is easy to be entrained by the top pipe, and the refrigerant distribution is better.

(3) Although the lubricant improves the distribution of the refrigerant in the parallel microchannel tubes, it also significantly reduces the specific enthalpy difference of the working fluid, which is mainly due to its non-evaporating nature. Therefore, the influence of lubricating oil on the pressure drop and heat transfer characteristics of the microchannel heat exchanger after improving the refrigerant distribution is still an

unresolved issue. In future research, the heat transfer and pressure drop characteristics of lubricating oil after improving refrigerant distribution should be comprehensively analyzed.

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