FLOW PATTERN VISUALIZATION OF REFRIGERANT/LUBRICANT OIL MIXTURES IN FLOW BOILING

Enio Pedone Bandarra Filho, bandarra@mecanica.ufu.br
Oscar Saul Hernandez Mendoza, oscarhm@mecanica.ufu.br
Faculty of Mechanical Engineering, Federal University of Uberlandia (UFU), Av. Joao Naves de Avila, 2160, Bloco 1M, 38400-902, Uberlandia , MG, Brazil.

John Richard Thome, john.thome@epfl.ch
Laboratory of Heat and Mass Transfer (LTCM), Faculty of Engineering (STI), École Polytechnique Fédérale de Lausanne (EPFL), Station 9, Lausanne, CH-1015, Switzerland.

Abstract. *A comprehensive review of flow pattern visualization of refrigerant/lubricant oil mixtures in flow boiling is presented in this paper. The flow patterns of refrigerant/oil mixtures are discussed together with a selection of photo and video images, showing the main characteristics of the flow with small percentages of lubricant oil. In phase change, the flow involving liquid and vapor inside a tube can assume many distinct geometrical configurations between the phases, which are normally known. However, when oil is present, the flow pattern can assume other configuration, mainly associated with the frothing formation and it is possible to notice the difference in frothing formation with respect to the particular refrigerant and tube geometry.*

Keywords*: Flow visualization, mixture, lubricant oil, refrigerant, flow boiling.*

1. INTRODUCTION

In refrigeration, heat pumps and air conditioning systems the presence of oil is unavoidable since the oil is required to lubricate the moving parts for proper functioning of the compressor. Some lubricant oil, depending of each installation, thus flows through all the components of the system, where in heat exchangers the presence of oil can affect the flow pattern and both the heat transfer and pressure drop depending of the concentration. Due a wide variety of refrigeration, heat pump and air conditioning systems, such as domestic, commercial and industrial installations, in general, this amount of lubricant oil circulating in the system can vary from as low as 0.1% up to 8.0% by weight in the refrigerant flow.

In phase change, the flow involving liquid and vapor inside a tube can assume many distinct geometrical configurations between the phases, which are commonly called flow patterns. Numerous studies have been conducted on flow patterns in flow boiling conditions for pure refrigerants, including flow visualization and flow pattern map development. However, there are few studies about flow patterns of refrigerant/oil mixtures. Unfortunately, two phase flow patterns of refrigerant/oil mixtures received lower attention by the scientific community in comparison with pure refrigerants, mainly due to the difficulty of visualization.

The main objective of this paper is to review and analyze the main parameters affected by the oil's presence in flow patterns.

2. EXPERIMENTAL STUDIES WITH VISUALIZATION

Worsøe-Schimidt (1960) was the first one to observe in his visualization section that when oil was added into the refrigerant, the wetted perimeter of the wall was increased in stratified-wavy flows. This behavior could be explained by the surface tension, since the oil has a higher surface tension in comparison with the pure refrigerant. Figure 1 shows the evolution of the flow pattern of a R-12/oil mixture at the inlet (a), middle (b) and outlet (c) of his evaporator. It is possible to note that, as expected, at high vapor qualities the oil effect is more evident, where the local oil mass fraction (ω) is much higher in the remaining liquid phase than the 3.9% at the inlet.

Manwell and Bergles (1990) conducted an experimental study on flow patterns in R-12/oil mixtures inside smooth and microfin tubes. The mass velocities of the tests varied from 45 to 430 kg/s.m^2 and oil concentrations, ω, from 0%, 2%, 5% and 10% of (300 SUS naphthenic mineral oil). It is possible to see in Fig. 2 that the foaming formation increased with the oil concentration. Fig. 2 (a) depicts a stratified wavy flow pattern without bubbles while in Fig. 2 (b), (c) and (d) the formation of foam is more evident throughout the liquid phase. In Figure 3 (a), (b) and (c), a different kind of foaming formation is observed in microfin tube, occurring only at the interface. It is important to note the size of these bubbles is larger than those obtained in the smooth tube (Fig. 2 d), basically at same conditions, but with 5% of oil concentration.


(a)


(b)

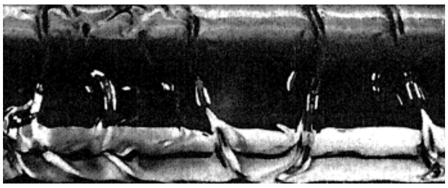
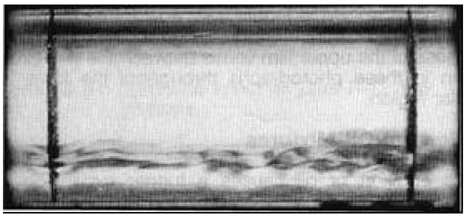
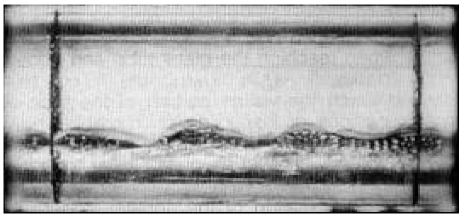

(c)

Figure 1. Visualization by Worsoe-Schimidt (1960), showing the evolution of the flow pattern of R-12/oil mixtures at the inlet **(a)**, middle **(b)** and outlet **(c)** of his evaporator. Conditions: Saturation temperature of -30 ^oC, mass velocity of 60 kg/s.m^2 and 3.9% of oil.


(a)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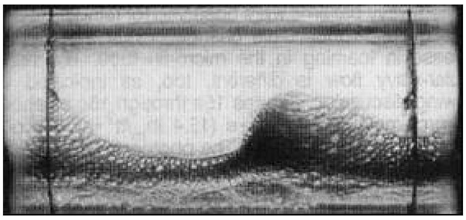
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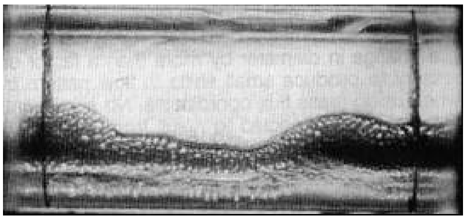
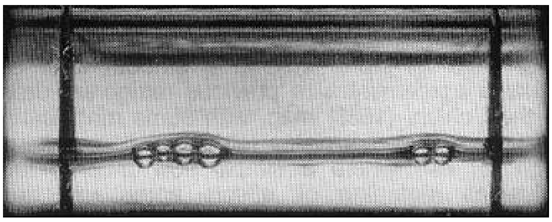
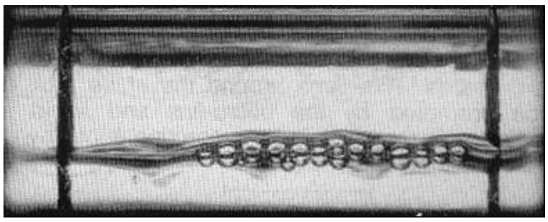

(d)

Figure 2. Visualization at the exit of smooth tube by Manwell and Bergles (1990), showing the comparison of the flow pattern of R-12/oil mixtures varying the concentration: **(a)** pure R-12, **(b)** ω = 1%, **(c)** ω = 2% and **(d)** ω = 5%. Conditions: Saturation temperature between 1 and 2 ^oC, mass velocity of 80 kg/s.m^2 and vapor quality of 13%.


(a)


(b)

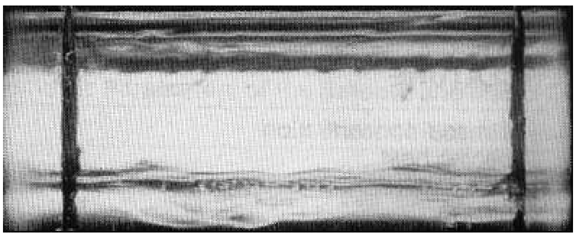
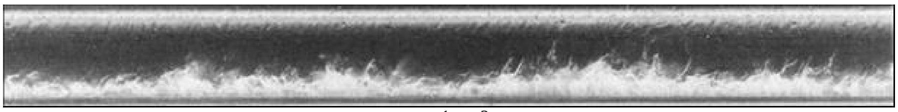
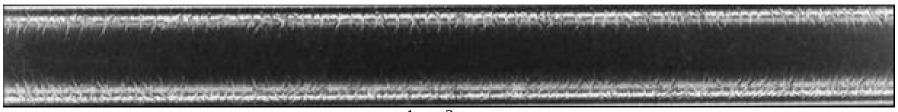

(c)

Figure 3. Images at the exit of microfin tube by Manwell and Bergles (1990), showing the comparison of the flow pattern of R-12/oil mixtures: **(a)** and **(b)** ω = 5% and vapor quality of 13%, **(c)** ω = 3% and vapor quality of 23%. Conditions: Saturation temperature between 1 and 2 ^oC and mass velocity of 75 kg/s.m^2.

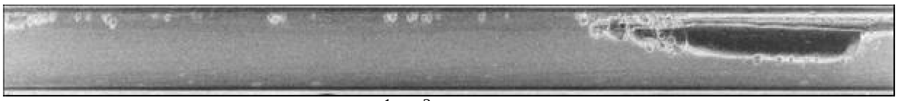
Wongwises et al. (2002) conducted a visual study of R-134a/oil (PAG) mixtures inside a horizontal tube with a diameter of 7.8 mm with an oil concentration of 5%, varying the mass velocity from 150 to 590 kg/s.m^2. The flow patterns observed at different mass velocities and vapor qualities are shown in Figure 4. It is interesting to note the strong presence of froth in the flow patterns and they concluded that the frothing increased wall wetting and the transition from the stratified wavy to annular flow pattern came earlier.



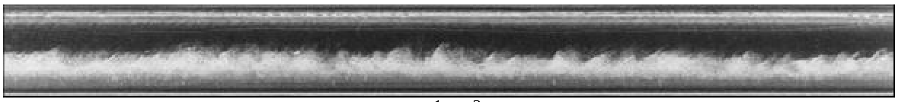
Wavy/Annular flow – G = 150 kg s^{-1} m^{-2}, ω = 5% and vapor quality 15%.



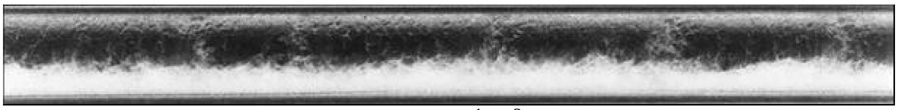
Annular flow – G = 150 kg s^{-1} m^{-2}, ω = 5% and vapor quality 70%.



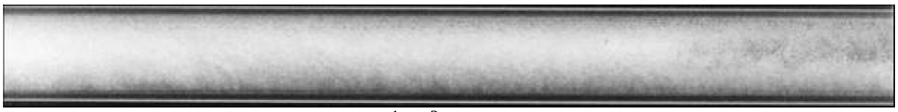
Plug flow – G = 295 kg s^{-1} m^{-2}, ω = 5% and vapor quality 0.1%.



Wavy/Froth flow – G = 295 kg s^{-1} m^{-2}, ω = 5% and vapor quality 7%.



Froth/Wavy/Annular flow – G = 490 kg s^{-1} m^{-2}, ω = 5% and vapor quality 50%.



Froth flow – G = 490 kg s^{-1} m^{-2}, ω = 5% and vapor quality 25%.

Figure 4 – Flow patterns observed by Wongwises et al. (2002).

Poiate Jr. and Gasche (2006) reported an experimental investigation on a R-12/mineral oil mixture with foam formation in a horizontal tube with internal diameter of 3.22 mm. Their tests were conducted at a temperature of 30^{o}C and the main objective was to improve the understanding of the physical phenomena of the mixture flashing, to be used in simulation of lubricating and leakage processes inside refrigeration compressors. Figure 5 presents the flow visualization of the oil-rich mixture, with foam formation through small channels and depicts foam formation for high void fraction values. It is important to emphasize that this type of flow pattern is not found in conventional two-phase flows, mainly because the high oil concentration.

Bandarra Filho et al. (2007) conducted a flow boiling visualization study of R-407C/oil mixtures. They tested a smooth copper tube with an internal diameter of 10.92 mm, mass velocity varying from 100 to 300 kg/s.m^2, saturation temperature of 4^{o}C and oil concentration varied from 0.5% to 5.0%. In Fig. 6 (a), (b), (c) and (d) it is possible to see at G = 100 kg/s.m^2 the behavior of the flow pattern with the increase of the oil concentration and the value of the local heat transfer coefficient. It is interesting to note that with 0.5% and 3.0% oil there appears a thin layer of oil on the wall and at 5% a wavy flow pattern with high amplitude appears, with apparently a highly viscous liquid film that greatly reduces heat transfer.

When mass velocity was higher, G = 200 kg/s.m^2, and for high vapor qualities, Fig. 7 shows the main flow pattern observed was annular flow, and as expected the value of heat transfer coefficient is high, 5700 W/m^2.K for pure R-407C in Fig. 7 (a). In Figure 7 (b) with 1.0% oil and a vapor quality of 94%, they observed a much lower value of the heat transfer coefficient, h = 185 W/m^2.K, even though the wall was still wetted by a thin layer of oil rich liquid. Increasing the oil concentration to 3.0% and vapor quality of 84% in the Fig. 7 (c), it is possible to see the annular flow pattern with a high concentration of froth, mainly in the lower region of the tube. In this case, the value of the heat transfer coefficient is 2178 W/m^2.K. At the same condition, but about 15 seconds later, Fig. 7 (d) shows some droplets of oil flowing in the core of tube, an evidence of the flow instabilities observed in the flow boiling tests. In the sequence, increasing vapor quality, but keeping constant the oil concentration and mass velocity, it is interesting to observe the thin layer of oil rich liquid on the wall and the lower value of heat transfer coefficient, h = 319 W/m^2.K, reflecting the effect of the now laminar film.

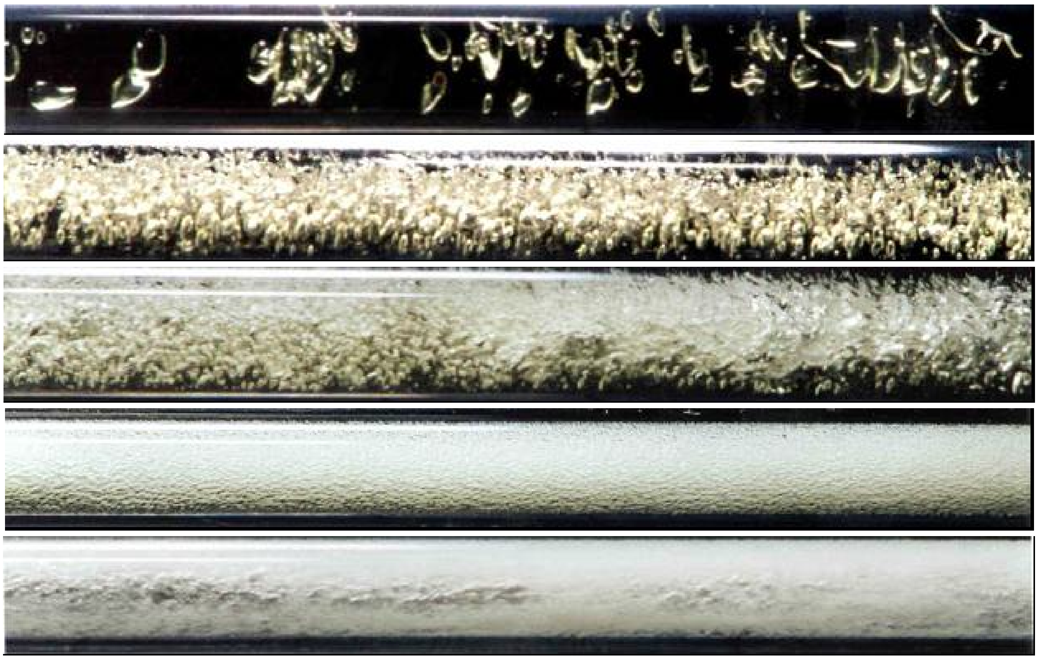


Figure 5. Flow patterns observed by Poiate Jr. and Gasche (2006), illustrating flow of a refrigerant oil-rich mixture with foam formation. Inlet temperature: 30^{o}C, Reynolds number: 4300 and oil concentration: 54%.

(a) Pure R-407C with G = 100 kg/s.m^2, vapor quality=76% and h = 915 W/m^2.K.

(b) R-407C with ω=0.5% G = 100 kg/s.m^2, vapor quality=70% and h = 1229 W/m^2.K .

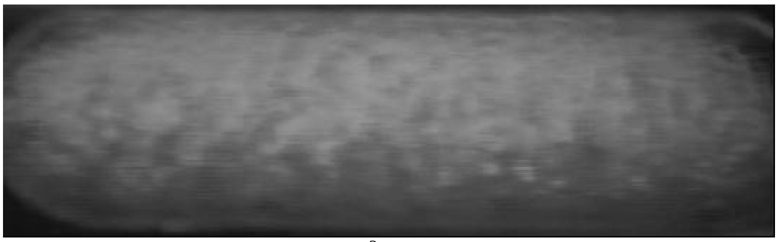
(c) R-407C with ω=3.0%, G = 100 kg/s.m^2, vapor quality=76% and h = 758 W/m^2.K.

(d) R-407C with ω=5.0%, G = 100 kg/s.m^2, vapor quality=80% and h = 85 W/m^2.K.

Figure 6. Flow patterns observed by Bandarra Filho et al. (2007), illustrating the effects of the oil concentration on the flow structure and heat transfer coefficient.

(a) Pure R-407C with G=200 kg/s.m^2, vapor quality =88% and h=5700 W/m^2.K.

(b) R-407C with ω=1.0%, G=200 kg/s.m^2, vapor quality =94% and h=185 W/m^2.K.



(c) R-407C with ω=3.0%, G=200 kg/s.m^2, vapor quality =84% and h = 2178 W/m^2.K.

(d) R-407C with ω=3.0%, G=200 kg/s.m^2, vapor quality =84% and h = 2178 W/m^2.K.

(e) R-407C with ω=3.0%, G=200 kg/s.m^2, vapor quality =91% and h = 319 W/m^2.K.

Figure 7. Visualization of the flow patterns by Bandarra Filho et al. (2007), showing some intrinsic characteristics with the oil concentration and vapor quality variation.

3. DISCUSSION AND ANALYSIS

Many flow pattern maps for predicting two-phase flow regimes inside tubes have been proposed since the 1950's. These are generally two-dimensional graphs with transition criteria to separate the areas corresponding to the various flow regimes. Most flow pattern maps have been developed for adiabatic conditions: that of Baker (1954) is based in air-water and oil/water flows, that of Taitel and Dukler (1976) is based in non dimensional parameters such as the Froude number and Martinelli parameter, and the Hashizume (1983) and Steiner (1993) flow maps for horizontal flow are primarily for refrigerants, just to name a few. Regarding diabatic flow pattern maps, apparently the earliest one is that of Kattan et al. (1998), which was developed according to their experimental observations for five refrigerants (R-134a, R-123, R-402A, R-404A and R-502) under evaporating conditions. Their flow map was then the basis of their flow boiling heat transfer model for evaporation in horizontal tubes in the fully stratified, stratified-wavy, intermittent and annular flow regimes and for annular flow with partial dryout at the top of the tube. Physically, it is connected to the local heat transfer characteristics and mechanisms by use of simplified two-phase flow structures to account for any dry perimeter predicted to occur, and may be applied to both adiabatic and diabatic conditions. Since then, this map has been updated using additional fluids such as R-407C, R-22, R-410A, ammonia (R-717) and CO_2 (R-744) under evaporation and/or condensation conditions.

Zürcher et al. (2002) included a new onset of nucleate boiling criterion according to their flow boiling results for R-134a, R-407C and R-717 (ammonia). Wojtan et al. (2005) extended the Kattan flow map to include a new dryout region, new mist flow regime transition and subdivided the stratified-wavy regime into three subregimes based on their observations and dynamic void fraction measurements for R-22 and R-410A.

Cheng et al. (2005) recently developed a new CO_2 heat transfer model and map for evaporation using the model of Wojtan et al. (2005) as their starting point. The method includes new correlations for the nucleate boiling heat transfer coefficients and a new boiling suppression factor based on the annular film thickness. In addition, new dryout inception and completion vapor quality correlations were proposed for CO_2 and a heat transfer correlation for the dryout region was obtained. Most of the sharp changes in heat transfer trends of CO_2 were captured by the new heat transfer model through its map.

In the case of flow patterns of refrigerant/oil mixtures, few studies have been conducted so far and the most verified change is in the transition from stratified wavy to annular flow by the effect of oil. It has been noted that this transition occurs earlier than without oil, which may be caused by an increase of the surface tension of mixture. Another interesting observation is about foaming. Some researchers found a lot of foam formed at the liquid-vapor interface while others observed only a small quantity of foam at the interface. It should be mentioned here that each oil and refrigerant combination has its own particular physical properties that can be associated with foaming characteristics.

In general, the addition of oil in a refrigerant can affect flow boiling heat transfer positively or negatively, depending on many parameters such as mass velocity, vapor quality, miscibility, physical properties of the refrigerant/oil and the oil concentration. There are many studies but fundamental studies are still necessary to further examine the physical phenomena and also to propose prediction methods for refrigerant/oil mixtures in the future. To do so, more fundamental experiments should be performed to establish the actual mechanisms activated and/or affected by the presence of oil.

Finally, it is should be mentioned that flow boiling of refrigerant/oil mixtures in small and micro-channels is encountered in air-conditioning, refrigeration and heat pump systems. For example, micro-channel evaporators are expected to be used in the near future for CO_2 automobile air-conditioning systems. Refrigerant/oil mixtures in these evaporators may also create maldistribution of the flow, which may greatly affect the thermal performance of the evaporator. The oil also greatly increases two-phase pressure drops in micro-channel evaporators and this has a significant effect on the local saturation temperature and thus LMTD (log mean temperature difference). All these aspects pose new challenges to be resolved. Therefore, more fundamental studies on the oil effect on flow boiling, flow patterns and two-phase pressure drops of refrigerant/oil mixtures in micro-channels should be performed in the future.

4. CONCLUSIONS

A state-of-the-art review on the flow patterns of refrigerant/lubricant oil mixtures in flow boiling was presented in this paper. Some images of actual flows of refrigerant/oil mixtures were also presented. It was possible to observe the differences on froth formation according to distinct refrigerants (R-12, R-134a and R-407C). It is also important to note that research on the effects of oil on flow pattern transition, the flow structure and void fraction are still rare but need to be done. According to this review, important research directions related to flow pattern in flow boiling of refrigerant/lubricant oil mixtures have been identified as:

⇒ New experiments in flow boiling of refrigerant/lubricant oil mixtures should be further emphasized to investigate better the physical mechanisms of the oil on the process.

⇒ Study of flow pattern maps of refrigerant/lubricant oil mixtures should be conducted in the future, focusing on the transition between the flow patterns.

⇒ Further investigate froth formation and its effect on the heat transfer process.

⇒ Experiments of flow boiling of refrigerant/lubricant oil mixtures should be carry out in mini and micro channel to verify the effects.

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