**Circulating lubricant and its effects on the energetic efficiency of refrigeration circuits: state of the art and perspectives.**

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## *Introduction*

The main purpose of the lubricant in a refrigerating circuit is to promote a safe hydrodynamic lubrication inside the compressor by creating a thin film within the moving parts (pistons, thrust or shaft bearings, etc.) thus reducing the wear generated by the friction.

The oil contributes to electric motor cooling inside hermetic and semi-hermetic compressors.

Furthermore the action of the lubricant is fundamental for the tightness of the stuffing box in open-type compressors and for ensuring a good volumetric efficiency in screw or scroll compressors.

It is important to point out that the lubricant fluid inside the compressor carter, or in the oil separator or in any other volume in the refrigerating circuit, has to be considered as a mixture of oil and refrigerant. So the thermophysical properties must be evaluated according to the actual composition of the mixture: small amount of refrigerant mixed with the oil can reduce markedly the viscosity of the lubricant. Furthermore, constraints may arise for the lubricant return to the compressor.

Accordingly, the circulating refrigerant has not to be considered as a pure fluid but as a mixture of pure refrigerant and some amount of oil. This aspect can affect strongly the efficiency of the heat exchangers (evaporator mainly). Suitable correlations must be adopted for the evaluation of the thermophysical properties of the circulating mixture that, from a thermodynamic point of view, should be treated as a binary zeotropic mixture (Thome, 1995) at least in the temperature and pressure range where the two components, the oil and the refrigerant, are completely miscible.

Qualitatively, refrigeration technicians are used to speak about refrigerant complete miscibility in oil when the liquid phase has a unique composition in thermodynamic equilibrium conditions, at set pressure and temperature. When two separate liquid phases with different composition arise at defined pressure and temperature, we speak about "partial miscibility". If separated liquid phases are present at any temperature, pressure and composition, the two fluids are considered as "un-miscible".

The "solubility" concept is suitable to define the refrigerant amount (on mass or molar basis) mixed in the oil.

The consequence of refrigerant solubility in oil is that some lubricant is discharged by the compressor. The ratio between the lubricant mass flow rate discharged by the compressor and the refrigerant mass flow rate is defined as the Oil Circulation Ratio (OCR). Depending on the circuit lay-out, the oil and the refrigerant type and the operating conditions, the discharged lubricant will distribute with different hold-up in each single component or line. The lubricant hold-up is considered to affect the efficiency of the refrigerating machine.

### *Oil Circulation Ratio (OCR) and components hold-up*

Since the Eightees several investigations have been carried out for the development of in-line OCR measurement techniques. Nowadays, the only technique complying to a Standard is that according to ASHRAE Standard 41.4 – 1984 "Standard method for measurement of proportion of oil in liquid refrigerant". As mentioned in the title, the Standard deals with liquid phase only. When applying this technique, one has to vent at least three samples of liquid withdrawn from the refrigerating circuit. Hence the method is not suitable for "in-line" dynamic measurements.

The sensors proposed in the open literature are based on different transduction principles: e.g. refractive index measurement, viscosity measurement, density measurement, speed of sound measurement, ultraviolet radiation absorption, etc..

As already mentioned, when the oil is discharged by the compressor, a different lubricant hold-up occurs in the circuit components and lines. Prof. Radermacher's group (Cremaschi et al., 2005) measured oil hold-up inside the condenser, the evaporator, the liquid and the suction lines in air conditioning systems with OCR of about 1% and 5% respectively, for different refrigerant mass flow rates. The investigated fluids were R410A/POE, R410A/MO, R22/MO, R134a/POE and R134a/PAG. The reported measurements indicate that the oil hold-up inside the circuit components can be considerable at some OCR values for given refrigerant mass fluxes in vapour-phase lines. The hold-up is linked to oil/refrigerant mixture viscosity and pipes orientation.

The same group proposed the same study on a transcritical $CO_2$ system. The paper is in press ((Hwang et al., 2007).

Wujek and Hrnjak (2006) have considered the effects of a PAG oil in a prototype of refrigerating unit operating with transcritical R744 cycle. Their observations show that increasing the OCR, in absence of separator of oil, the COP of the system tends to decrease: in particular, the Authors observed a decrease in the gas cooler efficiency and higher pressure drop at the evaporator. However the installation of an oil separator caused additional pressure drop in the discharge line. As a consequence the no improvement of the COP was measured even though the OCR was reduced.

It's evident that the mentioned analyses are strictly linked to the investigated system: a different circuit arrangement, different refrigerant, different oil or different mass flow rate of the refrigerant itself may lead to completely different lubricant hold-up in each single component. It is a common belief that the compressor and circuit design should be carried out having the OCR reduction as a target.

### *Effects of the lubricant on heat transfer*

The lubricant type and the related OCR are fundamental for compressor efficiency and strongly affects also the two-phase heat transfer process inside circuit heat exchangers.

Shen and Groll (2005a e 2005b) critically reviewed some of the most outstanding papers available in the open literature dealing with the effects of the lubricant mixed with the refrigerant on the heat transfer coefficient (HTC) and on pressure drop during the boiling process (2005a) and the condensation (2005b).

Both the mentioned works evidenced the high scattering of the experimental data available. The measurement presented by several Authors indicate every possible effect of the oil, both in the direction of a penalization, of an improvement and of a negligible effect of heat transfer, depending on the different testing conditions.

Concerning the “pool boiling”, in the 21 considered works, the greatly different conditions, in terms of oil type, refrigerant type, saturation temperature, heat flux, foaming, led to and extremely large scattering of the results, thus making impossible the implementation of a sufficiently consistent semi-empirical model for HTC prediction. In general, the effect of the lubricant was found to be more penalizing on enhanced microfin surfaces. One of the most interesting theory was proposed by Kedzierski (2001): a lubricant film is formed in direct contact with the heated surface. Kedzierski observed that in presence of small oil mass percentage (typically lower than 0.5% with R134a) the HTC tended to increase, while HTC decreased sharply for higher oil concentrations.

Concerning the “flow boiling” process, Shen and Groll (2005a), through the analysis of 33 different works, inferred that the presence of oil promotes surface wetting, thus promoting the on-set of annular flow pattern. The studied work clearly indicated that it is fundamental to analyze the experimental data with reference to the relevant flow pattern. However, it is worth noting that the oil-refrigerant mixture viscosity is much higher than the pure refrigerant one. So the lubricant layer in direct contact with the heated surface, causes a marked mass transfer resistance.

Also during the “flow boiling” the microfin tubes seem to be more penalized by the presence of oil.

The behaviour of a refrigerant that is not completely miscible in the oil must be considered separately. In fact, in this situation the oil can form a separate phase laying directly on the heated surface. The consequent additional thermal resistance can be particularly penalizing in this situation.

The leading penalization during condensation of refrigerants with oil seems to be related to the high viscosity of the refrigerant/oil mixture if compared with the pure refrigerant (Shen e Groll, 2005b, 16 papers considered). Accordingly, the penalizing effect is by far higher at high vapour quality (incipient condensation). In this situation, the data available in literature indicate that the oil effect is less penalizing in microfin tubes.

Both during evaporation and condensation fluid pressure drops inside the heat exchangers increase because of the presence of oil. As a consequence, as it is well known, the compression work increases and the refrigerating cycle efficiency is reduced. The pressure drop increment is more marked inside minichannels: a review of the data available in the open literature and some comments about the consistency of the available calculation models is presented in Thome and Ribatski (2006) for $CO_2$ evaporation inside tubes. Recently, Field and Hrnjak (2006) measured the pressure drop during two-phase adiabatic flow of carbon dioxide inside a channel with hydraulic diameter of 148.0 μm with R134a and POE ISO 32 oil for different refrigerant mass fluxes and different OCRs. The highest pressure drop increment was observed at high vapour qualities.

The supercritical cooling of carbon dioxide in presence of oil should be considered apart from the “traditional” condensation process. Recently, Dang et al. (2007) measured the effect of PAG oil on R744 “gas cooling” process inside smooth tubes with inner diameter from 1 to 6 mm and working pressure from 8 to 10 MPa, mass fluxes from 200 to 1200 $kgm^{-2}s^{-1}$ and circulating oil mass percentage between 0 to 5%. The Authors pointed out that increasing the OCR also the pressure drops increase while HTC decreases. The effect can be “dramatic” close to the pseudocritical region (with a reduction up to 75% of HTC for the lower diameter tubes). For the higher diameter's tubes, with 1% OCR, the HTC penalization was found to be negligible.

### *Perspectives for the future*

Previous considerations clearly indicate the need for refrigerating compressors with low as possible OCR: according to the data available in the open literature, present author believes that OCR lower than 0.5% is advisable. Nevertheless, two interesting alternatives have been recently proposed "offbeat": the use of suitable additives or the use of the so called "nano-lubricants".

*Use of additives*

Oil additives are commonly used in refrigeration technology. The main purposes are usually anti-corrosion, anti-oxidation, anti-wear, anti-seize.

In 1990 a U.S. Patent (n. 4,936,280, 1990) claimed that the use of additives based on sufficiently polar molecules can improve the distribution of the lubricant film over the metallic surface. The consequent reduction of the film thickness promotes a reduction of the mass transfer resistance and of the pressure drop linked to the lubricant film itself characterized, as already mentioned, by viscosity much higher than the pure refrigerant.

Nowadays several polar additives are available. Some manufactures of chillers equipped with flooded evaporators claimed an improvement of more than 30% of the machine efficiency. In the open literature only a few data were obtained systematically. Kedzierski (2007) studied the "pool boiling" of the mixtures R134a/POE and R123/MO with an additive. With R134a/POE the HTC was measured to increase up to 73% with 5 $kW \cdot m^{-2}$ heat flux and even 95% with 22 $kW \cdot m^{-2}$. With R123/MO no improvement was found in pool boiling. On the basis of the mentioned results Kedzierski put forward some hypothesis about the characteristics of the additive for an heat transfer improvement:

- Oil and additive must have "chemically different" molecules, i.e. the structure of the basic molecule or of the molecular chain don't have to be the same in oil and additive: e.g. if the MO is naftenic it is not advisable to use a naftenic based additive molecule;
- The liquid-vapour surface tension of the additive must be higher than lubricant one:
- The viscosity (liquid phase) of the additive must be higher than the lubricant one.

For further details please see the cited paper.

*Use of "nano-lubrificants"*

In the recent year the lubricant industry is dealing with an intense research activity in the field of nanotechnologies with the aim of improving the tribological performance of lubricants (see for example Liu et al. 2004). The results achieved in the industrial applications are extremely encouraging showing very good performances when adding carbon nanotubes or nano particles of copper oxides. Nevertheless several aspects have still to be investigated before making this technology ready for large industrial application.

Only recently few Far East companies have started to experimentally investigate the possibility of using the "nanolubricants" in refrigeration compressors in particular for the compressor typologies, like scroll ones, which efficiency is more affected by the lubricant performance. Lee et al. (2006) investigated the behaviour of the thrust slide-bearing of a scroll compressor with R22 and mineral oil with carbon nano particles added.

The Authors found out experimentally that the nano particles (0.1 mass percentage in oil) increase up to 225% the breaking pressure of the oil film. The cooling performance of the contact surfaces was shown to be by far more efficient than the pure oil. The friction coefficient with pure oil was found to be higher than the one with oil+nano-particles. As an outcome, the wear of the surfaces in contact after several working hours was measured to be lower with the "nano lubricant".

Furthermore, the addition of carbon or copper oxides or aluminium oxides or titanium oxides nano particles to liquids is recognised to improve significantly the single-phase HTC in several applications (the behaviour in two-phase applications is still a much debated question).

The very "intriguing" hypothesis is then: since the addition of nano particles is expected to improve significantly the lubricant performance in terms of compressor reliability and efficiency, should we expect also that the nano particles induce in the lubricant also an improvement in the heat transfer performance, as it happens when adding the same particles to liquids?

If this should occur, the circulating oil could be an opportunity for increasing refrigerating machines efficiency, rather than a source of concerns for the engineers.

### *List of Acronyms*

| | | | |
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| HTC: | Heat Transfer Coefficient | POE | PolyOlEster |
| MO: | Mineral Oil | PAG | PolyAlchilenGlycol |
| OCR | Oil Circulation Ratio | | |

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