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Oil Concentration Measurement In Saturated Liquid Refrigerant Flowing Inside A Refrigeration Machine[*]

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Abstract

An ultrasonic device was calibrated to measure *in situ* and in real time the polyol ester oil (POE) concentration of the refrigerant liquid R 410A. The first part of this paper is devoted to the properties of the mixture, to the effects of the presence of oil on the speed of sound in the liquid phase and to the calibration and validation procedures carried out with a saturated liquid refrigerant. In order to have a number of calibration points that is not too large, it is necessary to maintain the mixture as close as possible to saturation conditions, which constrains the choice of the location of the sensor on the installation investigated. In the second part, the first results obtained on this installation are presented. It appears that the speed of sound in the POE / R 410A mixture is a strong function of the temperature and oil concentration, as was expected, but it also significantly depends on the pressure. Consequently, if the use of a sensor in a sub-cooled area is considered, additional calibration and validation procedures are necessary.

Keywords: ultrasonic sensor, oil concentration, on line measurement, refrigeration, R410A

1. Introduction

Regulations aiming at suppressing refrigerants containing chlorine have been constantly evolving toward greater strictness and, in the short or middle term, toward the prohibition of HCFC. HCFC will ultimately be replaced by substitution fluids, for the most part belonging to the HFC family, which are not threatened by current regulations.

The use of HFC involves the replacement of mineral and alkylbenzene oils used until now, by synthetic polyol ester oils (POE) or, more rarely, by polyalkyleneglycols (PAG) which are the only ones capable of offering satisfactory miscibility properties.

Lubrication of refrigeration compressors is indispensable for limiting abrasive wear and for optimising their efficiency. However, in spite of the presence of efficient separators, it is impossible to prevent a small quantity of oil from escaping from the compressor, which then pollutes the liquid refrigerant. This small quantity of oil may have positive effects (it contributes, for example, to the tightness of the circuit) but it can also be the source of an increase in the ratio between the saturation

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pressure in the condenser (HP) and in the evaporator (LP), which can have a negative impact on the efficiency of the thermodynamic cycle. This increase in the HP / LP ratio is linked to three distinct but simultaneous phenomena:

-An increase in the resistance to thermal transfer in the liquid phase, which is not systematic: a small amount of oil in the refrigerant fluid may have a favorable influence on heat transfer in exchangers (Thome and Phil 1995).

-A modification of the boiling and condensation curves.

-An increase in pressure losses, the viscosity of the oil being greater than that of the liquid refrigerant.

In addition, oil circulation may call into question the validity of experiments by introducing an additional degree of uncertainty in energy balances, and the difficulties related to its presence are aggravated during non-stationery operation.

The consequences of the presence of oil on the operation of a refrigeration machine have not been studied very much from an overall point of view. In general, the authors consider oil as a simple pollutant of the refrigerant fluid, which would only modify the property studied, most often thermal transfer. This point of view is not shared by Thome and Phil (1995) who show that the oil-refrigerant mixture may be assimilated to a zeotropic mixture just as a mixture of refrigerants: this approach allows taking into consideration, in an overall manner, all oil-related effects in the entirety of the cycle.. Grebner and Crawford (1993) also use an overall approach but it is limited to the evaporator alone in the cases of R 12 / mineral oil and R 134a / synthetic oil mixtures.

All these theoretical studies can only be carried out on the basis of reliable data on the thermodynamic and physical properties of oil-refrigerant mixtures. A few studies have been published on this subject (Baustian et al., 1986a and 1986b; Burton et al., 1999*;* Martz et al., 1996*;* Cavestri, 1995; Henderson, 1994; Mermond et al., 1998a, 1998b and 1999). The relatively rapid evolution of refrigerants and oils available on the market makes researching experimental data difficult. It is necessary then to use the mixing rules or the theoretical methods specifically adapted to the calculation of these properties, available in particular in the recent bibliographic studies of Mermond et al. (1998b and 1999). However, we are then confronted with new difficulties linked to the properties of oils: the relations available (Mermond et al., 1998a; Thome and Phil, 1995; Grebner and Crawford, 1993) are often simplistic or else the physical properties are calculated from other characteristics, which are also poorly known. For reasons of confidentiality, few data are made public by the oil manufacturers.

Finally, all the calculations described above are of interest only if it is possible to know, or at least to evaluate, the quantity of oil circulating in the refrigerant circuit. In a steady state, this information may allow validating the theoretical models and calculations. It can also allow quantifying system efficiency optimization potential, whether this concerns circulating less oil to improve the heat exchanges and the compression rate, or circulating more oil to improve compressor efficiency. In the transient state, it can also provide very important information on the conditions of compressor lubrication as well as on possible harmful phenomena of oil accumulation in some parts of the installation, and in particular in the evaporator.

The work presented here concerns the characterization of an R 410A and POE oil mixture. The principal objective was to validate a method of measuring the quantity of oil in circulation in a refrigeration installation. R 410A is a quasi-azeotropic HFC mixture, having no action on the ozone layer. Though little used in refrigeration installations, it is considered an interesting substitute for R 22 for future applications:

-Its potential of action on the greenhouse effect is low (GWP = 1900). In relation to other HFCs like R 404A which have a greater GWP, it will be all the less threatened in the future by the decisions of the Kyoto protocol concerning the reduction of emissions of gases having a greenhouse effect.

-Its performances (in terms of Coefficient of Performance) are equivalent to those obtained with HCFC 22.

-Its volumetric refrigeration capacity is high (up to about 30-40% higher than R 22), which allows using compressors with a low swept volume and reduces the amount of fluid introduced in the installations.

Today, R 410A is a possible answer to the problem of finding a substitute for chlorinated refrigerant liquids in industrial refrigeration and A/C installations. In the longer term, and subject to the development of specific materials, it may be the replacement solution for R 22 in all installations.

The second part of the text presents the most commonly used methods for measuring oil concentration in a refrigerant liquid. The third part is devoted to the calibration bench of the ultrasonic sensor that we have used. The first results are presented in the fourth part.

2. Methods for Measuring the Oil Concentration

In a refrigeration installation, the circulating mixture appears, depending on its location, under different forms which may be liquid, gaseous or biphasic. Oil concentration is measurable in the liquid or the gaseous phase. Measuring in the gaseous phase is difficult to carry out as the structure of the flow at the compressor or oil separator exit is not well known. It is probable that part of the oil circulates in the form of a cloud of droplets dispersed in the vapor phase of the refrigerant and that another part adheres to the pipe walls. In the gaseous phase, two methods of measurement can be implemented:

-A method based on flame ionization whose validity is uncertain.

-Infrared spectrometry, which has the advantage of allowing simultaneous measurement, with a single device, in the gaseous and the liquid phases; it is, however, a solution that is delicate to implement and that is rather expensive.

These methods are carried out by sampling, and thus have all the related disadvantages: it is impossible to use them during phases of transient operation and it is difficult to affirm that the sample is representative of the average characteristics of the circulating mixture. Furthermore, it seems delicate to carry out sampling at the pressure levels that may be reached in a machine using R 410A.

Measuring in the liquid phase is easier to carry out and some results have already been published by other authors (Baustian et al., 1986a, 1986b, 1988a, 1988b and 1988c; Navarro de Andrade et al., 1999*;* Meyer and Jabardo, 1992; Bayani et al., 1995; Suzuki et al., 1993*;* Katsuna et al., 1991). The usual technique is, once again, a sampling method: it consists of taking samples of the oil-refrigerant mixture; these samples are then weighed, the refrigerant is evaporated slowly. The residual mass then allows determining the oil concentration. Experiments have shown that this method is laborious, especially when a large number of measurements have to be taken.

After examination of the bibliography, it seems that there are four methods for measuring, in real time, the liquid phase oil concentration. The first method is based on the variation of the density of the mixture (Baustian et al., 1988b; Bayani et al., 1995). A densimeter is installed on a liquid piping circuit and the measurement is related to the temperature and the concentration. It seems, however, difficult to obtain a satisfactory level of accuracy with this method as the density of the mixture is not, in general, a sufficiently strong function of the oil concentration. Baustian et al. (1988b) have obtained an absolute accuracy of 1% with an R 12 and mineral oil mixture and 2% with two R 22 / mineral oil and R 502 / synthetic oil mixtures. This method requires the construction of a calibration bench.

The second method has not been implemented very frequently; it is based on variations in mixture viscosity and also requires the construction of a calibration bench. Experiments were carried out by Baustian et al. (1988c) with an R 12 / mineral oil mixture. The authors announce an absolute accuracy of 1% at lower concentrations (below 10%) and of 2% above that level.

The third method is based on infrared (Suzuki et al., 1993) or ultraviolet light absorption (Kutsuna et al., 1991) by the liquid. This method is accurate but requires a complex and costly installation.

Finally, the fourth method that we have used seems to offer the best compromise between cost and accuracy: it is based on the measurement of the speed of sound in the liquid mixture. It has been applied by several authors (Baustian et al., 1988a; Navarro de Andrade et al., 1999; Meyer and Jabardo, 1992). Meyer and Jabardo (1992) have related the oil concentration to temperature and speed of sound in a linear relation:

$$x_{o,l} = A_0 + A_1.a_{sat} + A_2.T \qquad (1)$$

where A_{0-2} are constant coefficients, a_{sat} is the speed of sound in the saturated liquid and *T* is the temperature. Eq. (1) is extremely simple and can be used for a first approximation. However, for better accuracy, it is desirable to use the relation of Baustian et al. (1988a) which accounts for quadratic terms:

$$\begin{aligned} a_{sat} &= b_0 + b_1.x_{o,l} + b_2.T + b_3.x_{o,l}^2 \\ &\quad + b_4.x_{o,l}.T + b_5.x_{o,l}^2.T \end{aligned} \qquad (2)$$

where b_{0-5} are constant coefficients, a_{sat} is the speed of sound in the saturated liquid and *T* is the temperature. Eqs. (1) and (2) are valid only for a saturated liquid. In reality, the speed of sound in the mixture is a function of the oil concentration, of the temperature and of the pressure. The overall trend of the curve of this function is not known but it may be simplified under forms (1) or (2) when temperature and pressure are related by the saturation curve. In the event the measurements are carried out in the subcooled liquid, Meyer and Jabardo (1992) indicate that the speed of sound at saturation state could be approached by a relation of the type:

$$a - a_{sat} = (A_3 + A_4.T)(P - P_{sat}) \qquad (3)$$

where $A_{3\text{-}4}$ are constant coefficients.

However, Eq. (3) has been established and verified for R 134a and R 12 but nothing indicates that it is valid for R 410A. In *Figures 1* and *2*, we have plotted the evolution of the ratio $(a - a_{sat})/(P - P_{sat})$ for subcooling going as far as 20°C, the saturation temperatures being set at 30°C, 40°C and 50°C. Indeed, we notice that this ratio evolves in a quasi-linear way for R 134a (the same trend is observed for CFC 12); however, this is no longer the case for R 410A. These data were obtained from the REFPROP database of the NIST (NIST Thermodynamic Properties of Refrigerants and Refrigerant Mixtures - Standard Reference Data - version 6.01, 1998).

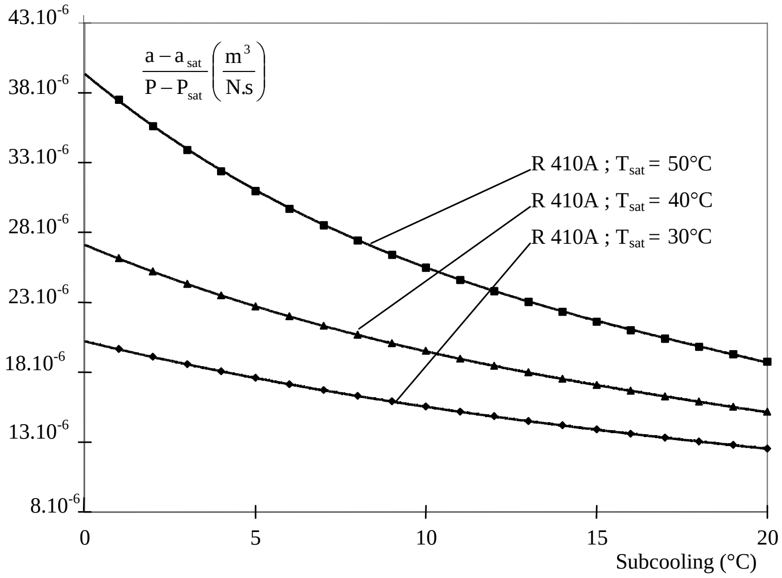

Figure 1. Sensitivity of the speed of sound to subcooling (R 410A)

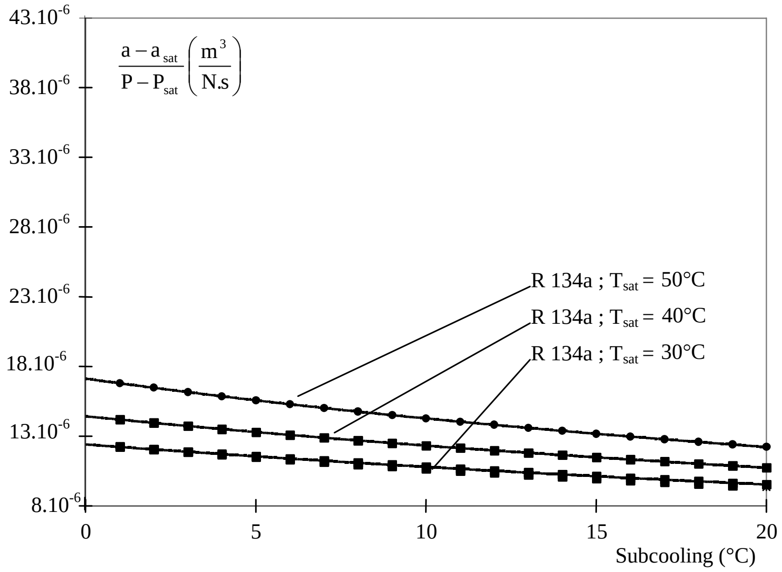

Figure 2. Sensitivity of the speed of sound to subcooling (R 134a)

3. Experimental Means: Calibration Bench

The ultrasound speed sensor must be installed on the piping system in which the R 410A / POE oil mixture circulates in the liquid state. The device available is calibrated for temperatures ranging from 0°C to 50°C and can be used with sufficient accuracy (0.08 m/s) for liquids where the speed of sound exceeds 200 m/s. The device is equipped with a piezoelectric element that emits ultrasonic waves. These waves are directed towards the opposite branch of a U-shaped metallic frame where they are reflected and sent back to the piezoelectric element that then becomes a receiver. The speed of sound thus corresponds to two times the distance between the emitter and the target element divided by the time it takes the wave to cover the distance. As the sound waves' direction is perpendicular to the direction of flow of the liquid mixture, the result of the measurement does not depend on the flow speed (provided that it stays within the manufacturer guaranteed range: 0.05-0.6 m^3/s in our case). For better measurement accuracy, a Pt 100 type thermistor is integrated into the frame whose thermal distortion is taken into account. The calibration bench (*Figure 3*) consists of:

-A tank (1) heated by contact by means of a heating wire (5).
-A volumetric circulation pump (2).
-A sensor for measuring the speed of sound (3).
-An absolute pressure sensor (4).
-Valves and self-sealing couplings.
-An electrical cabinet.

Several authors agree in stating that the quantity of oil occurring in the vapor phase of an oil/refrigerant liquid mixture is negligible (Thome and Phil, 1995; Cavestri, 1995; Henderson, 1994). Consequently, the calculation of the mass of oil to be injected into the calibration bench must be carried out starting from the mass of the liquid phase. The oil concentration in the liquid is defined by its mass fraction $m_o/m_{m,l}$. The oil mass can then be related to the liquid oil concentration $x_{o,l}$:

$$m_o = \frac{x_{o,l}.m_{r,l}}{1-x_{o,l}} \qquad (4)$$

where $m_{r,l}$ is the mass of the liquid refrigerant that depends on the temperature and pressure.

The total volume of the bench is filled by the liquid mixture and by the gaseous refrigerant fluid:

$$V_{tot} = \frac{m_{m,l}}{\rho_{m,l}} + \frac{m_{r,v}}{\rho_v}$$
$$\Leftrightarrow \; V_{tot} = \frac{1}{1-x_{o,l}}\frac{m_{r,l}}{\rho_{m,l}} + \frac{(m_{m,l} - m_{r,l})}{\rho_v} \qquad (5)$$

The mixing rule most commonly used to calculate density assumes that the total volume of the liquid mixture is strictly equal to the sum of the volumes of each of the two components:

$$\rho_{m,l} = \frac{1}{\dfrac{x_{o,l}}{\rho_o} + \dfrac{1-x_{o,l}}{\rho_{r,l}}} \qquad (6)$$

Eq. (6) is, nevertheless, to be used with care since Baustian (1986a) and Conde (1996) have pointed out that it is, on occasion, necessary to use a correction factor. However, the lack of reliable information adapted to the mixture used led us to use Eq. (6) without modification. From it, the value of the oil mass to be injected into the calibration bench is deduced:

$$m_o = \frac{x_{o,l}}{1-x_{o,l}} \frac{V_{tot} - \dfrac{m_{m,l}}{\rho_v}}{\dfrac{1}{(1-x_{o,l})\rho_{m,l}} - \dfrac{1}{\rho_v}} \qquad (7)$$

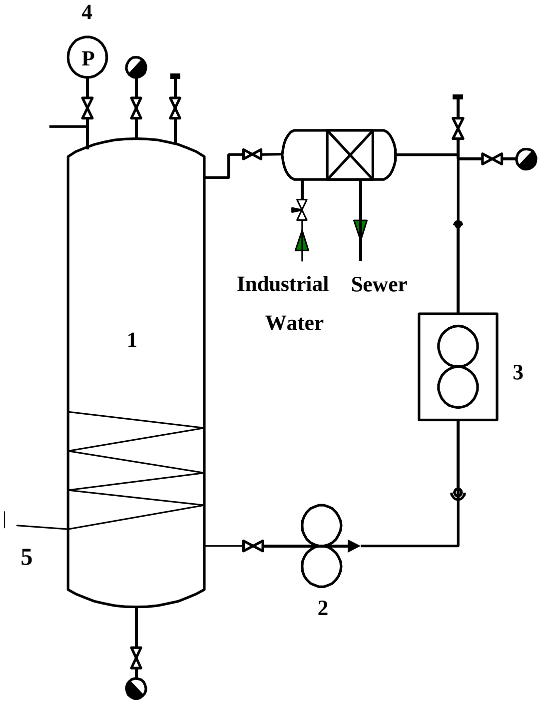

Figure 3. Calibration bench

Finally we want to obtain a relation between the temperature, the liquid speed of sound and oil concentration. Hence, we have, keeping the concentration constant, caused the temperature to change and have thus obtained a network of curves a=f(T) for different oil concentrations. Depending on the liquid vapor equilibrium reached in the mixture tank, different amounts of oil, which depend on the temperature, must be injected in order to maintain a given concentration. The calibration procedure is then based on an increase in the oil mass inside the calibration bench so that it is never necessary to remove any amount of mixture from it.

To validate the hypotheses leading to Eq. (7), a sample of liquid mixture was taken from the calibration bench after the end of the calibration procedure, while the total amount of oil and refrigerant introduced corresponded to a 14.91% oil mass fraction. The sample concentration, measured after evaporation of the refrigerant, was 14.65%, which represents a relative error of 1.7% in relation to the preceding value. This good result on the one hand validates the hypotheses made for the calculation of the oil concentration and, on the other hand, verifies the absence of a leak related to the operation of the bench and to the oil injection procedures.

4. Accuracy, Results

Error concerning the measurement of the concentration of the circulating oil-refrigerant mixture is linked to the uncertainty regarding the quantity of oil injected in the calibration bench and also to the uncertainty regarding the concentration value $x_{o,l}$ calculated from Eq. (2). An error calculation shows that, for temperatures varying from 29.3°C to 43.7° C and for oil concentrations up to 15%, absolute accuracy is ±0.7%. By working with more restricted concentration ranges, it is possible to refine the calculation of coefficients b_0, b_1... b_5 of Eq. (2) and, therefore, to increase the measurement accuracy. Thus, for a concentration range between 0% and 5%, absolute accuracy is ±0.5%.

The first results were obtained on the calorimetric bench, a simplified diagram of which is presented in *Figure 4*. The ultrasound sensor was placed at the exit of the bottle of liquid so that the refrigerant would be as close as possible to saturation conditions. It is, however, essential for the liquid to be slightly subcooled to avoid the occurrence of gas bubbles: in practice, a theoretical subcooling ranging from 0.7°C to 1.3°C was always measured. The installed compressor is of the piston type, with a swept volume of 13 m^3/h. All trials were carried out following standard ISO 917. The data acquisition started once the steady state was obtained and lasted one hour. The values indicated in TABLE I are, therefore, the mean values recorded for each trial. The samples were taken at the middle of each data acquisition interval.

With respect to the expected accuracy, the results of the TABLE I allow validating the ultrasonic measurement method that was implemented on the calorimetric test installation. The data collected do not allow establishing any correlations between the quantity of oil circulating in the installation and the characteristics of the operating point. The high degree of efficiency of the oil separator was, however, noticeable. Several trials were carried out in the subcooled liquid (in that case, the ultrasound sensor was placed after the subcooler) but, as was expected, the results could not be used.

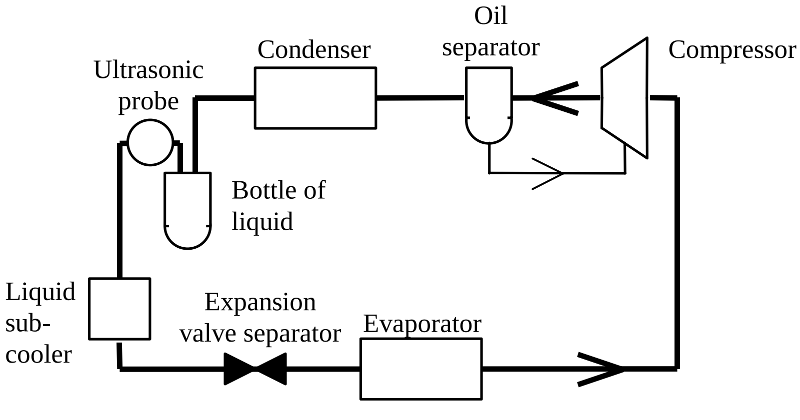

Figure 4. Simplified diagram of the calorimetric installation.

TABLE I. RESULTS OBTAINED WITH AND WITHOUT (W/o) OIL SEPARATOR; COMPARISON WITH SAMPLES.

Oil separator	With	W/o	With	W/o	W/o	With	W/o	W/o	With	W/o
Evaporation T (°C)	12.9	11.5	9.51	5.73	6.03	-15.44	-15.45	-14.52	-24.39	-24.98
Condensation T (°C)	42.8	34	47.25	42.20	42.44	27.96	28.04	48.96	28.41	28.43
Subcooling (°C)	nm	nm	0.72	0.81	0.78	0.84	0.81	1.28	1.04	1.05
$x_{o.l}$ u.s. sensor(%)	0.04	0.21	0	0.125	0.278	0.024	0.199	0.182	0.043	0.375
$x_{o.l}$ by sampling (%)	0.039	0.28	0	0.16	nm	0	0.16	0.33	0.03	0.34

5. Conclusions

The method of ultrasonic measurement allows understanding, with a high degree of accuracy, the phenomena of oil circulation in an installation. However, since the speed of sound in the oil-refrigerant mixture depends on the nature of both the refrigerant and oil, this method will always require time-consuming calibration. After extending the calibration to the subcooled state, it will be possible to set the ultrasound sensor everywhere on the liquid line between the bottle and the expansion valve. Then, due to the short response time of the ultrasound sensor, we will be able to study the circulation of oil in transient states. Finally, as the quantity of circulating oil depends, among other things, on the type of the compressor, complementary measurements will be carried out with a scroll compressor.

Nomenclature

a	Speed of sound (m/s)
A_{0-4}	Coefficients in Eqs. (1) and (3)
b_{0-5}	Coefficients in Eq. (2)
m	Mass (kg)
P	Pressure (Pa)
T	Temperature (°C)
V	Volume (m^3)
x	Oil concentration (kg/kg)
ρ	Density (kg/m^3)

Subscripts

l	Liquid
m	Mixture
o	Oil
r	Refrigerant
sat	Saturation state
v	Vapor

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