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REAL - TIME MEASUREMENT OF THE OIL CONCENTRATION IN 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 POE oil 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 propagation and to the calibration and validation procedures carried out with a saturated liquid refrigerant. Indeed, 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 is constraining for 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 of the 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.

NOMENCLATURE

a	Sound speed	(m/s)	*Subscripts*		
m	Mass	(kg)	l	Liquid	
P	Pressure	(Pa)	m	Mixture	
T	Temperature	(°C)	o	Oil	
x	Oil concentration	(kg/kg)	r	refrigerant	
ρ	Density	(kg/m^3)	v	Vapour	

INTRODUCTION

Regulations aiming at suppressing liquid 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 liquids, for the most part belonging to the HFC family, 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 refrigerating compressors is indispensable for limiting wear and tear 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 of the HP / BP ratio linked to three distinct but simultaneous phenomena :

- An increase in the resistance to thermal transfer in the liquid phase which, however, is not systematic : a certain amount of oil in the refrigerant liquid may have a favourable influence on heat transfer in exchangers (Thome and Phil).
- A displacement of the boiling and condensation curves.
- An increase in pressure losses, the viscosity of the oil being greater than that of the refrigerant liquid.

In addition, oil circulation may call into question the validity of tests and trials by introducing an additional degree of uncertainty in energy balances, and the difficulties related to its presence are aggravated during phases of

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temporary operation.

The consequences of the presence of oil on the operation of a refrigerant cycle have not been studied very much from an overall point of view. In general, authors consider oil as a simple pollutant of the refrigerant liquid which would only modify the property studied : most often thermal transfer. This point of view is not shared by Thome and Phil who show that the oil-refrigerant mixture may be assimilated to a zeotropic mixture just as a mixture of liquid refrigerants : this approach allows taking into consideration, in an overall manner, all oil-related effects in the entirety of the cycle. Grebner and Crawford also use an overall approach but which 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 works have been published on this subject (Baustian *et al.* 1986a and 1986b, Burton *et al.*, Martz *et al.*, Cavestri, Henderson, Mermond *et al.* 1998a, 1998b and 1999) but the relatively rapid evolution of refrigerant liquids and oils available on the market makes researching experimental data difficult. It is necessary then to use the laws of mixtures 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, Grebner and Crawford) are often simplistic or else the physical properties are calculated from other characteristics, 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 in circulation in the refrigerant circuit. In steady state, this information may allow validating or not the theoretical models and calculations. It can also allow quantifying system efficiency optimisation potential, whether this concerns circulating less oil to improve the 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 certain parts of the installation, and in particular at the level of the evaporator.

The work presented here concerns the characterisation of a 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 as an interesting substitute for R 22 for realisations in the future :

- 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 gasses having a greenhouse effect .
- Its performances (in terms of Coefficient of Performance) are equivalent to those obtained with HCFC 22.
- Its volume refrigerant capacity is high, which allows using compressors with a low swept volume.

Today, R 410A is a possible answer to the problem of finding a substitute for chlorinated refrigerant liquids in industrial refrigeration 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 first part of the text presents the most commonly used methods for measuring oil concentration in a refrigerant liquid whereas the second part is devoted to the calibration bench of the ultrasonic sensor that we have used. The first results are presented in the third part.

1. METHODS FOR MEASURING OIL CONCENTRATION

In a refrigeration installation, the circulating mixture appears, depending on its location at a given moment, 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

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or 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 vapour phase of the refrigerant and that another part adheres to the walls of the tubing. In the gaseous phase, two methods of measurement may be implemented :

- Infrared spectrometry 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 extremely expensive.
- A method based on flame ionisation whose validity is uncertain.

These methods, which are carried out by sampling, have all the disadvantages specific to punctual measurements, i.e., it is impossible to use them during phases of transitory operation and it its difficult to affirm that the measurement is representative of the average characteristics of the circulating mixture, all the more so in that the type of flow encountered in the gaseous phase makes the results uncertain. 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. The usual technique is, once again, a punctual method (ANSI/ASHRAE Standart 41.4-1984): it consists in taking samples of the oil-refrigerant mixture ; these samples are then weighed, the refrigerant is evaporated slowly and the residual mass then allows determining the oil concentration. Experiments have shown that this method is laborious, above all in cases where 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 (Baustian *et al.* 1986a and 1988a, de Andrade *et al.*, Meyer and Jabardo., Bayani *et al.*, Suzuki *et al.*, Katsuna *et al.*).

The first method is based on the variation of the density of the mixture (Baustian *et al.* 1988b, Bayani *et al.*). 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 sufficient 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 uses variations in mixture viscosity and also requires the construction of a calibration bench. Trials were carried out by Baustian *et al.* (1988c) with an R 12 / mineral oil couple. The authors announce an accuracy of 1 % at lower concentrations (below 10 %) and of 2% above that level.

The third method is based on infrared (Suzuki *et al.*) or ultraviolet (Kutsuna *et al.*) light ray absorption 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 the accuracy desired : it uses the variations of the speed of sound in the mixture. It has been applied by several authors (Baustian *et al.* 1988a, de Andrade *et al.*, Meyer and Jabardo). Meyer and Jabardo have related the oil concentration to temperature and to pressure in a linear relation :

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

The relation (1) is extremely simple and may be used for a first approximation. However, for greater accuracy, it is desirable to use the relation of Baustian *et al.* (1988a) which calls into play quadratic terms :

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

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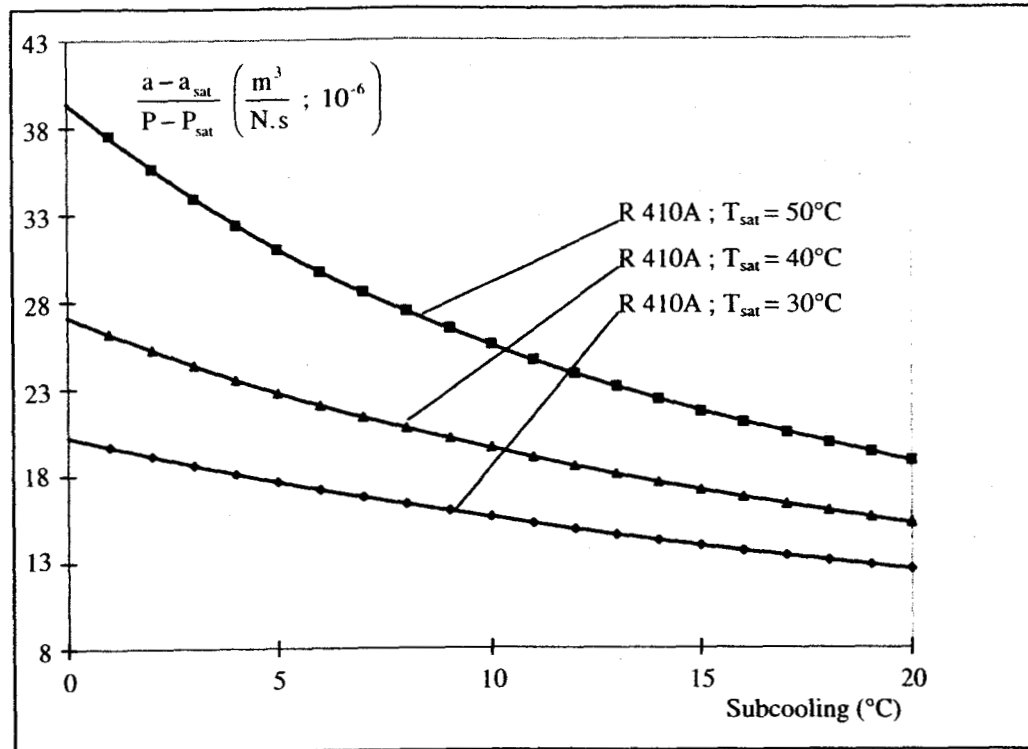Purdue University, West Lafayette, IN, USA – July 25-28, 2000

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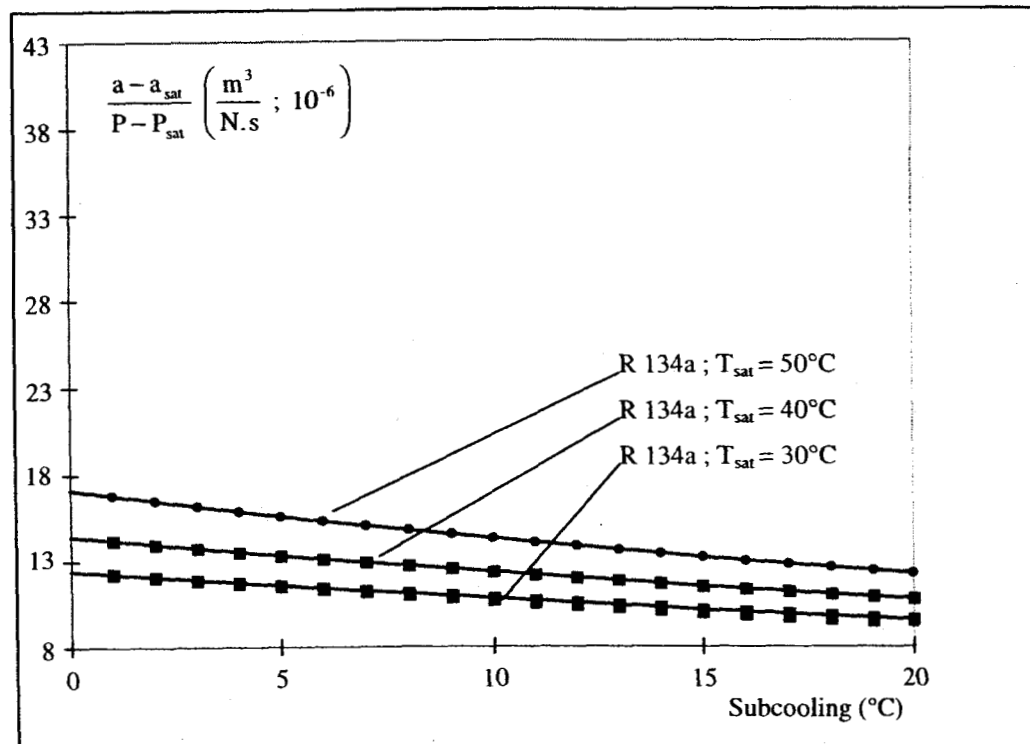**Figure 1 :** Sensitivity of the speed of sound to subcooling (R 410A).

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

The relations (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

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the saturation curve. In the event the measurements are carried out in the subcooled liquid, Meyer and Jabardo indicate that the speed of sound at saturation may be approached by a relation of the type :

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

The relation (3) has, however, been established and verified in the case of 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 $\left(a - a_{sat} \right) / \left(P - P_{sat} \right)$ for a subcooling going as far as 20°C, the saturation temperature 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 but that this is no longer the case for R 410A. Furthermore, the correction to be applied to the speed of sound to approach the saturation value is more important for the latter and the values obtained depend to a greater degree on the saturation temperature. The CFC 12 behaves similarly to the HFC 134a.

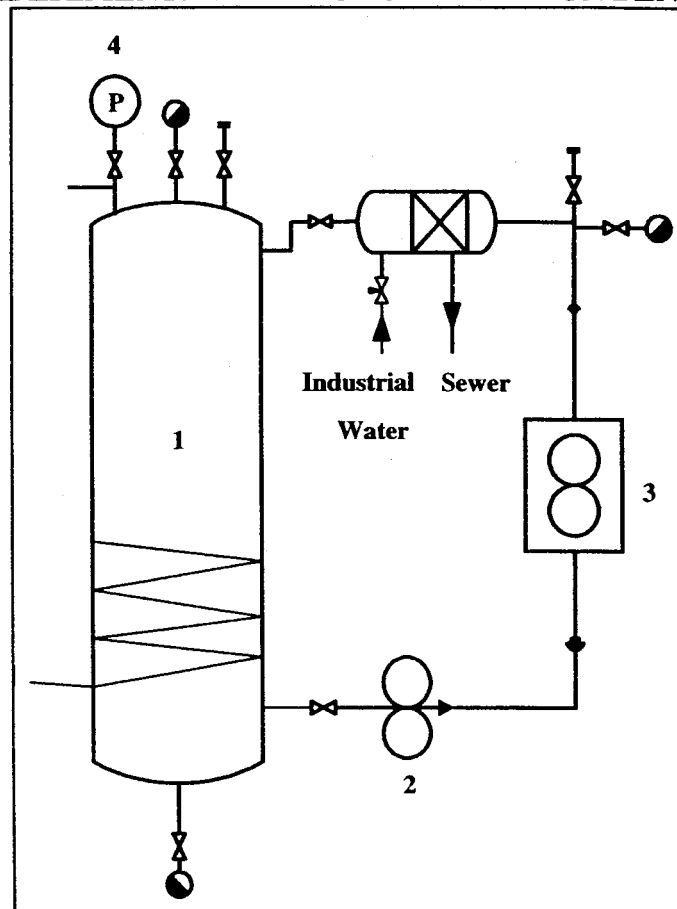## 2. EXPERIMENTAL MEANS : CALIBRATION BENCH

Figure 3 : Calibration bench.

The ultrasound speed sensor must be installed on piping in which the R 410A / POE oil mixture circulates in the liquid state. The device that we have available is calibrated for temperatures ranging from 0°C to 50°C and may 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 at the opposite branch of an U-shaped metallic frame where they are reflected and sent back toward the piezoelectric element which then becomes a receiver. The speed of the propagation of sound thus corresponds to 2 times the distance between the emitter and the target element divided by the time it takes the wave to cover the distance. For greater measurement accuracy, a Pt 100 type temperature probe is integrated into the frame whose thermal distortion is taken into account.

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The calibration bench (figure 3) is composed of :

- A tank heated by contact by means of a heating cable (1).
- A volumetric circulation pump (2).
- A device for measuring the speed of the propagation 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 present in the vapour phase of an oil/refrigerant liquid mixture is negligible (Thome and Phil, Cavestri, Henderson). 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. We have assumed that the vapour titre of the refrigerant was not modified by the presence of oil. The quantity of oil necessary is, therefore :

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

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

$$V_{tot} = v_m \cdot m_m + v_v \cdot m_{r,v} \quad \Leftrightarrow \quad V_{tot} = \frac{1}{1-c} \cdot \frac{m_{r,l}}{\rho_m} + \left(m_m - m_{r,l} \right) \cdot v_v$$ (5)

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

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

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

$$m_o = \frac{x_{o,l}}{1 - x_{o,l}} \cdot \frac{V_{tot} - m_m \cdot v_v}{\dfrac{1}{\left(1 - x_{o,l} \right) \rho_m} - v_v}$$ (7)

We would like to obtain a relation between temperature, the speed of sound and the oil concentration of the liquid. In order to do so, we have, keeping the concentration constant, caused the temperature to evolve and have thus obtained a network of curves a=f(T) for different concentrations. Depending on the liquid vapour equilibrium which is reached in the mixture tank, different quantities of oil, which depend on the temperature, must be injected in order to maintain a given concentration. The experimental plan is then based on oil injections of increasing mass so that it is never necessary to remove any from the calibration bench.

The thermodynamic and physical properties of R 410A were obtained from the REFPROP database of the NIST (NIST Thermodynamic Properties of Refrigerants and Refrigerant Mixtures - Standard Reference Data - version 6.01). To validate the hypotheses leading to the relation (7), a sample of liquid mixture was taken from the calibration bench while the oil and the liquid refrigerant masses introduced corresponded to a theoretical oil concentration of 14,91 %. 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 allows on the one hand

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validating the hypotheses made for the calculation of the concentration and, on the other, verifying the absence of a leak related to the operation of the bench and to the oil injection procedures.

3. ACCURACY, RESULTS

Error concerning the measurement of the oil concentration of the mixture in circulation is linked to the uncertainty regarding the quantity of oil injected and also to the uncertainty regarding the concentration value $x_{o,l}$ obtained from (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 a_0, b_1... b_5 of the equation (2) and therefore to increase measurement accuracy. Thus, for a concentration range running from 0% to 5% absolute accuracy is ± 0,5%.

The first results were obtained on the calorimetric bench of which a simplified diagram 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 allow for the taking of measurements: in practice, a subcooling ranging from 0,7°C to 1,3°C is measured at the level of the sensor. The installed compressor is of the piston type, with a swept volume of 13 m³/h. All trials were carried out following standard ISO 917 and the acquisition time was one hour, once the stationery regimen was established. The values indicated in table (1) are, therefore, the mean values recorded for each trial. The samples were taken at the middle of each acquisition interval.

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

Table 1 : Results obtained with and without (W/o) oil separator ; comparison with samplings.

With respect to the expected accuracy, the results of the table (1) allow validating the ultrasonic measurement method which was implemented on the calorimetric test installation. The data collected thus far do not allow establishing any correlation whatsoever 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 subcooled mode (in that case, the ultrasound sensor was placed after the subcooler) but, as was expected, the results could not be used.
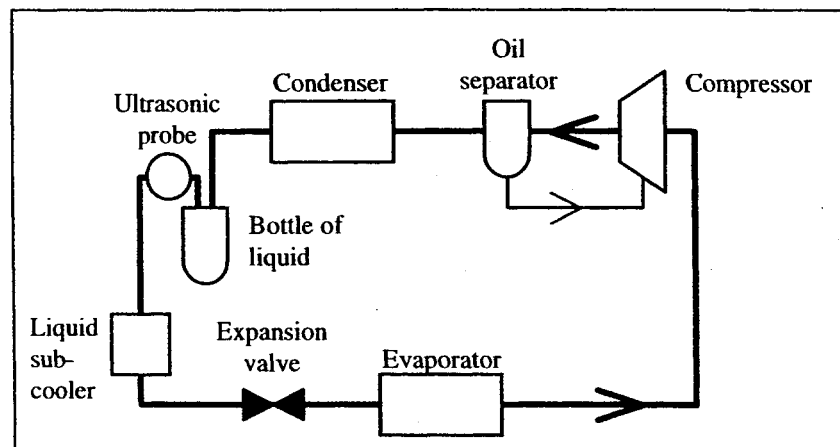

Figure 4 : Simplified diagram of the calorimetric installation.

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5. CONCLUSION

This method of ultrasonic measurement allows grasping, with a high degree accuracy, phenomena of oil circulation in an installation, but since it is dependent on the nature of the refrigerant / oil couple, it requires time-consuming calibration. After taking into account the phenomenon in the subcooled zone, the ultrasound sensor will be able to supply indications as to the influence of oil on the performances of the installation and the compressor. Thanks to the short response time of the sensor, it allows, in addition, studying the circulation of oil in transient states. Finally, as the quantity of oil in circulation is dependent, among other things, on the type of the compressor, complementary measurements will be carried out with a Scroll compressor.

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