

Using Density to Calculate the Oil Circulation Ratio of a PAG Oil in R134a

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ABSTRACT

Automotive air-conditioning systems employ a refrigerant as the working fluid; however, a portion of oil is discharged from the compressor as part of the compression process and also circulates through the system. This small amount of parasitic fluid needs to be determined for proper design of heat exchange equipment and connection piping. It is desired to be able to measure the small concentrations of oil circulating as a component of the working fluid online in real time. The oil in circulation as a fraction of the total fluid flow rate is termed the oil circulation rate or oil circulation ratio (OCR). A method for determining the OCR online with a coriolis type density meter is discussed.

INTRODUCTION

Oil, which is needed to lubricate the compressor, is carried with the refrigerant throughout the system. Oil affects fluid properties such as enthalpy, thermal conductivity, and viscosity and can impact the ability to accurately measure heat exchanger and system performance. Fluid property and flow maps have been developed for various refrigerant-oil mixtures; in combination with these maps the ability to accurately measure OCR online may prove to be a powerful tool in quickly measuring, analyzing, and improving system performance (1, 2). Without this ability to accurately measure the oil circulation rate over the range of operating conditions, it is impossible to create accurate thermodynamic balances based entirely on the properties of the refrigerant portion of the working fluid.

The refrigerant-lubricant mixture selected for this study is a commonly used mixture for automotive air-conditioning systems: R134a with a 46 cSt PAG oil which is commonly marked as ND-8 oil. In a typical air conditioner, utilizing R134a with PAG oil, a single phase exists only in subcooled portions of the condenser and the liquid line. Therefore, the experiments were conducted at typical automotive air-conditioner condenser discharge conditions: between 20 °C and 45 °C, pressures ranging from the saturation pressure up to 1800 kPa, and a fixed mass flux of nominally 300

kg/m²s. The working fluid ranged from pure refrigerant to 16% oil, by mass,

As described by Gibb's Phase Law, for a single phase fluid comprised of two components, it is necessary to measure three independent intensive fluid properties to completely describe its state. Since the temperature and pressure are easily obtainable and generally measured in experimental air-conditioning systems, only one additional fluid property needs to be measured. It is believed that density, which is the inverse of specific volume, can be used to provide the additional independent intensive fluid property. The accuracy and precision of calculating the OCR with these measurements is compared analytically and experimentally.

Oil circulation ratio, or oil circulation rate, (OCR) is a measure of the fraction of oil flowing within the working fluid of the system. OCR is defined by Equation 1 and equals the mass flow rate of oil divided by the total mass flow rate of the combined refrigerant and oil.

$$OCR = \frac{\dot{m}_{oil}}{\dot{m}_{refrigerant} + \dot{m}_{oil}} \quad (1)$$

It should be noted that OCR is neither a measure of the overall concentration of oil in the system, nor a measure of the local oil concentration at a specific point in the system. The local oil concentration changes throughout the system; some points, such as the compressor sump, have large local concentrations of oil but little circulation.

Currently the measurement standard for determining the concentration of miscible oils in refrigeration systems is described by ASHRAE Standard 41.4 (3). This standard has the virtue of being very accurate for traditional air-conditioning systems with miscible oils and significant refrigerant charges; however it requires the taking of a sample from an operating system which can then lead to a change in the operation of that system and is not suitable for online, real time analysis. ASHRAE Standard 41.4 involves thoroughly cleaning and evacuating a suitably sized sample cylinder, the cylinder's evacuated weight is recorded and the cylinder

is connected to the liquid line of the system. When an OCR measurement is desired, a valve is opened allowing the refrigerant oil mixture into the sample cylinder. The cylinder is then closed and removed from the system and weighed. The refrigerant, in its vapor phase, is allowed to slowly escape and a vacuum is applied to remove any dissolved refrigerant from the liquid lubricant. The cylinder is then weighed again and using the differences in weights the ratio of oil circulating in the liquid refrigerant stream is determined. The cylinder must then be cleaned prior to the next OCR measurement. In order to maintain system charge, the appropriate amount of oil and refrigerant must be added back to the system to replace what was removed by the sample procedure. As can be seen, many tedious steps must be completed in order to calculate a single OCR.

While this system works well for the miscible combinations for which it was designed, a large uncertainty is experienced when using immiscible combinations (4). When immiscible combinations were measured in this fashion, the standard deviation in OCR was as high as approximately 20% of the measured OCR. It is hoped that the method described in this paper can also be used with immiscible refrigerant oil combinations, which would require the assumption that that both liquid phases travel together, homogeneously.

Due to the numerous difficulties of the sampling technique it is desirable to create a technique for measuring OCR online. Since oil concentrations vary throughout the system, OCR should be measured in a location where oil holdup is minimal thus ensuring that all oil contained within the working fluid is in circulation at the sample location. Additionally, only in single phase regions can OCR be readily determined since vapor-liquid phase slip may occur when different phases are present. Since the only location where single phase conditions typically exist is in the subcooled regions of the condenser and in the liquid line, ASHRAE 41.4 specifies that the OCR measurement be taken in the liquid line as locations within the condenser are typically difficult to access. A pressure-enthalpy diagram showing the phases present in a traditional air conditioning system can be seen in Figure 1.

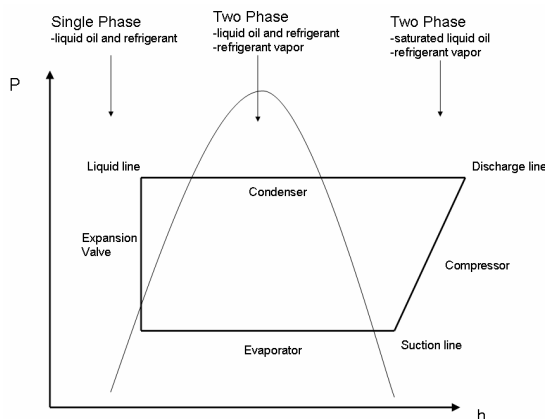


Figure 1: Phases present in a traditional air-conditioning system

Baustian, Pate, and Bergles suggested several different fluid properties which could be used to measure OCR online (5). Their work was done with paraffinic, naphthenic, and alkylbenzene oils with R113. They listed the pros and cons of a wide range of fluid property measurements which they believed could be used for measuring OCR online. Their main focus was on the properties which were most disparate between pure refrigerant and oil and which could be accurately measured with a simple, low cost meter. They believed that some of the most promising results could be obtained from measuring density, index of refraction, ultra-violet light absorption, speed of sound, and electrical capacitance of the refrigerant oil mixture. Since that time, several devices have been developed, and are currently marketed, to measure the OCR online. Newell Instruments produces a device which measures the critical angle at which light is reflected, this is a measure of the index of refraction. This device has been shown to measure the concentration of PAG oil in R134a with a great degree of accuracy (6). Japan Spectroscopic markets an ultra-violet absorption meter. Anton-Parr manufactures a device to measure the speed of sound in the bulk liquid. However, all of these devices add further complexity to experimental systems. These devices also add, a sometimes substantial, cost to experimental setups. Coriolis type flow meters, such as those produced by Micromotion and Siemens, are often installed in the liquid line of experimental systems to measure the mass flow rate. These devices are also able to measure the density of the working fluid by measuring the period at which the tubes inside the flow meter oscillate.

EXPERIMENTAL SETUP

To cover the range of conditions experienced in normal air-conditioning operation, it was necessary to construct a system capable of independently varying temperature, pressure, and OCR. The experimental apparatus was located within an environmental chamber which was capable of controlling the temperature over the range of test conditions. The air temperature in the chamber was slowly changed in order to decrease transient and local effects.

A schematic of the test setup can be seen in Figure 2. The working fluid was circulated by a magnetically driven gear pump. The speed of the drive motor was set to provide a flow rate of approximately $300 \text{ kg/m}^2\text{s}$ (approximately 30 g/s). This pump was selected since no oil was needed for lubrication and the drive did not incorporate a shaft seal thus allowing pure refrigerant test conditions at high pressures. After the pump, a length of clear nylon tube allowed for flow visualization, so that when the pressure dropped to the saturation pressure, bubbles could be easily seen.

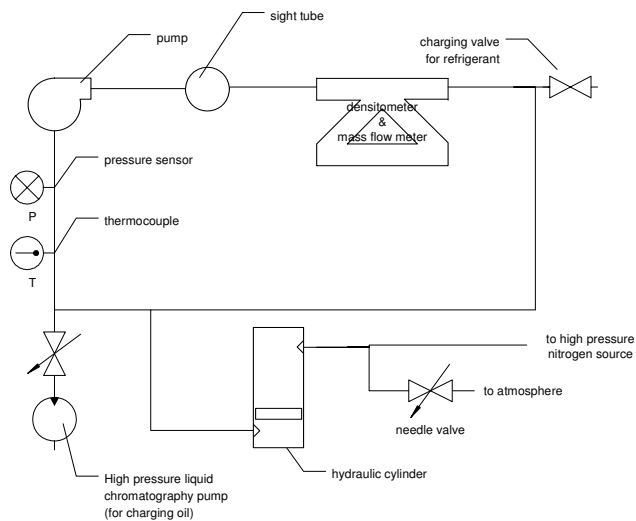


Figure 2: Schematic of experimental setup

A Micromotion CMF-25 allowed for mass flow rate and density to be measured based on the Coriolis Effect. The CMF-25 was connected to the data logger via a Micromotion RFT-9739 transmitter; according to the manufacturer, the combination of transmitter and coriolis meter will yield a density accurate to within 0.2 kg/m^3 . The internal volume of the CMF-25, at roughly 32 cm^3 , is less than the internal volume of most automotive liquid lines. If for testing purposes it is desired to maintain the refrigerant charge of an automotive system, it will be necessary to modify the lengths and diameters of the lines connected to the flowmeter. The pressure drop across the flowmeter can be compensated for by having a less restrictive expansion device.

A Parker hydraulic cylinder with an internal volume of 475 cm^3 was used to vary the internal volume of the system in order to create a subcooled liquid. Slight changes in internal volume caused by the movement of the piston can create large changes in the pressure of the working fluid. The temperature was measured with an Omega type-T immersion thermocouple (accuracy $0.3 \text{ }^\circ\text{C}$) and the pressure was measured by a Sensotec TJE pressure transducer with an accuracy of 10.5 kPa . Refrigerant is added gravimetrically via a charging port to within 0.2 grams . A photograph of the test stand can be seen in Figure 3. Some addition instruments which could also be used for measuring oil concentration were incorporated into the loop can be seen in the photograph. Results from these instruments are outside of the scope of this paper.

All measurement instruments in the loop were connected to an HP 75000 data logger. Data acquisition software from Agilent was used to read the signals from the data logger and to write data to Microsoft Excel. Data analysis was conducted with a combination of Excel and MathWorks Matlab.

Precise quantities of oil were incorporated into the working fluid with a Beckman-Coulter Model 110a high pressure liquid chromatography pump. The mass of oil

delivered per piston stroke of this chromatography pump was determined to be $0.156 \text{ grams per stroke}$. This number was based on calibration tests conducted prior to experimentation by weighing with an electronic balance the amount of oil filled into a beaker with a hundred piston strokes. This calibration was conducted three times to ensure accuracy. The accuracy of the scale used for the calibration was 0.2 grams .



Figure 3: Photograph of experimental apparatus

The experimental method was consistently performed in a way which covered the entire test matrix. The initial test was conducted with pure R134a. When tests were run, the chamber began at room temperature. The working fluid was circulated with a gear pump to help ensure uniformity. The pressure was increased to above the 1800 kPa high pressure limit of the experiment by compressing the hydraulic cylinder with nitrogen gas. While recording data, the pressure was slowly decreased by releasing some of the nitrogen charge through a needle valve. Data continued to be recorded until the bubble point was reached. The temperature was gradually increased in the chamber. At the new chamber temperature, the pressure was again applied and released while recording data. The pattern of slowly increasing temperature and recording data while the pressure was released was repeated until the upper temperature limit of the experiment $45 \text{ }^\circ\text{C}$ was exceeded. After all data with pure refrigerant was collected, a small, known amount of oil was added and the entire temperature and pressure cycle was repeated. Once all required data was recorded for a given OCR, additional oil was added and the cycle was repeated. The OCR was incrementally increased until it reached 0.16 .

The temperatures, pressures, and OCRs of the recorded data points can be seen in Figure 4. It should be noted that more than 19,000 unique data points were recorded in this study. The curve formed by the two phase region can clearly be seen in the figure. The final oil