Real-Time Determination of the Lubricant Oil Concentration in Refrigeration Systems Using Fiber Optic Sensor Technology[1]

B. Zhou[2,4], D. Nikanpour[2] and J.E.S. Venart[3]

---

[1] Paper presented at the Thirteenth Symposium on Thermophysical Properties, June 22-27, 1997, Boulder, Colorado, U.S.A.

[2] Refrigeration and Heat Pumping Technologies, EDRL-CANMET, 1615 Lionel-Boulet Blvd., Varennes, QC, Canada J3X 1S6

[3] Mechanical Engineering Department, University of New Brunswick, Fredericton, N.B., Canada E3B 5A3

[4] To whom correspondence should be addressed.

ABSTRACT

This paper highlights a fiber optic sensor technology which offers the capability of on-line real-time lubricant oil concentration measurement in refrigeration systems. A prototype probe developed at the CANMET laboratory is described. The experimental results are presented for the probe tested in the mixture of refrigerant R134a and a polyolester oil with concentration up to 5.0 weight percent. The data revealed that the probe is capable of detecting a variation of 0.1% oil concentration. Temperatures for the tests ranged from 20 ºC to 40 ºC. The influence of pressure change on the measurement was examined. The dynamic reliability of the probe was also investigated through the on-line oil concentration measurement on a refrigeration system. The probe was designed and constructed to allow to be easily installed and removed from any refrigeration system.

KEY WORDS: concentration, fiber optic sensor, mixture of POE oil/refrigerant R134a, real time measurement.

1. INTRODUCTION

Compressor lubricant oil is commonly found in the refrigerant lines of vapour compression refrigeration systems due to the miscibility of the oil with refrigerant. The presence of this oil affects the operation of various system components. The oil circulation ratio is, therefore, an important parameter for performance, noise and endurance tests of compressors in the system. On the other hand, in the interest of searching for new, environmentally safer refrigerants, there is a need to evaluate the effect that lubricant oil has on the thermodynamic transport properties of oil/refrigerant mixture and on such fundamental parameters as heat transfer coefficients and pressure drops. All of these effects must be accurately determined as functions of oil concentration.

There are a few techniques that have been reported for real-time lubricant oil concentration measurements in refrigeration systems. For example, the tests using acoustic velocity device, density flowmeter and viscometer for real-time oil/refrigerant mixture concentration measurements have been demonstrated [1, 2, 3]. Suzuki et al. [4] proposed a light absorption technique for the concentration measurements of paraffinic oil in R12 and polyalkylene glycol oil in R134a. More recently, Newell [5] developed an *in situ* optical refractometer for PAG oil in R134a. The configuration and durability of this refractometer, however, needs further improvement. All of these devices have a relatively larger spatial resolution and are not conveniently installed and removed from refrigeration system, especially, when the system is running. Acoustic devices also need recalibration after each replacement [6] because the acoustic path length varies slightly with each new acoustic transducer installation. Some other activities to develop measurement techniques for new refrigerant/oil mixtures are still being conducted upon request and support from ASHRAE.

In recent years, the light transmission properties of optical fiber have also been employed in concentration measurement devices, i.e., fiber optic sensors. Among these sensors, more sensitive, easily constructed and less optically arranged is one based on U shaped refractometer technique [7] as shown in Figure 1. A few local concentration measurements using this

technique have been reported [8,9,10]. Baustian et al. [11] also examined the applicability of this type of sensor for oil/refrigerant concentration measurement

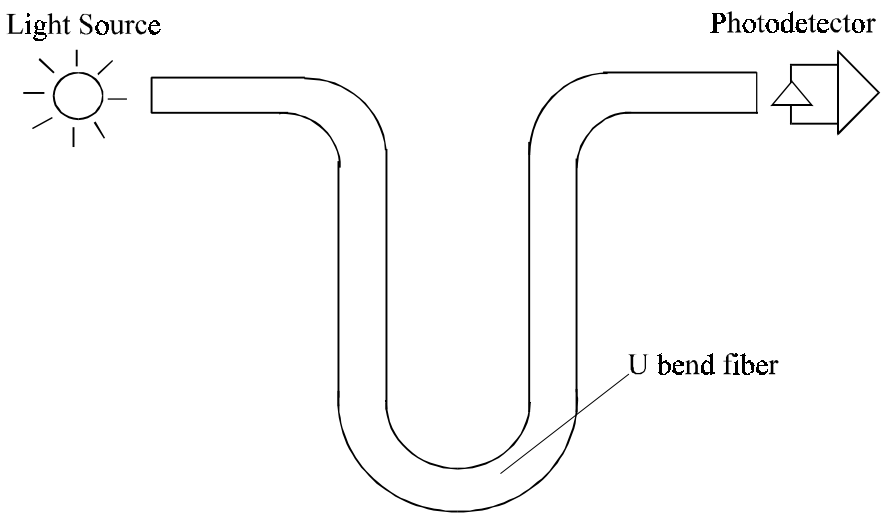

Figure 1 Fiber Optic U Bend

in refrigeration systems. Some problems were, however, encountered that led to discontinuing their work. First, a plastic optical fiber with polystyrene core was employed to make U bend sensor for the mixture of oil/R113 with a good performance. The polystyrene core of the fiber was, however, attacked by the halocarbon refrigerant. Second, there were obstacles in making the U sensing element using plastic-clad silica fiber due to the difficulty in removing the chemically-bonded cladding. Third, A cladding mode element with multiple U bends similar to Harmer's device [12] was made with the use of an all-silica fiber. However, the resulting device was not sensitive to changes in fluid refractive index at the U-bend sensor tip. This was possibly due to large bending radii employed. According to the authors' experience, a cladding mode element with only one U bend could detect the existence of water (the refractive index of water at room temperature is 1.333) if an all-silica fiber with a numerical aperture of 0.275 was used and the bending diameter was less than 1.2 mm. This means that the cladding mode element should also be sensitive to the concentration variation in the mixture of oil/R113 since the

refractive index of R113 is 1.354 (in liquid state at T=25 ^{o}C) and the common lubricant oils in refrigeration systems have refractive indices greater than 1.4. Finally, a glass rod (3 mm diameter) U bend probe was constructed. The probe performance was quite poor due to the temperature sensitivity of optoelectronic components, especially, the output variation of light source with temperature. The fast development of fiber optics technology, however, makes it possible to solve these problems at an acceptable cost. One might ask the following question: since the plastic fiber probe with one U bend and the removal of cladding had a promising performance, why was not an all-silica fiber used to develop a single U bend refractometer but with smaller bending radius. These mentioned issues were in mind when the present research was formulated. A major objective of the work was to improve the U type fiber optic sensor system and re-examine its applicability for real-time oil/refrigerant concentration measurement in refrigeration system.

2. DESIGN PRINCIPLE OF SENSING ELEMENT

A light can be guided along the axis of an optical fiber from one end to another end with little loss due to a total internal reflection occurring. Light attenuation will, however, happen when the fiber is bent. Figure 2 shows an optical fiber which is bent to form a U type,

at a radius R. The cladding of the fiber at the bent section is stripped off. The medium surrounding the fiber, therefore, serves as a cladding. When a light ray, I, which is totally reflected in a straight section of the fiber reaches the bending area, it may still be totally reflected and continues to propagate in the fiber or be attenuated. The ray, I, will be totally reflected in the bent section if it has an incident angle, θ_{co}, greater than a critical angle, θ_{bc} [7]:

$$\theta_{co}>\theta_{bc} \quad (1)$$

where θ_{co} and θ_{bc} are given below [7,12]:

$$\theta_{co}=\arcsin[\cos\alpha*(R+h)/(R+2a)] \quad (2)$$

$$\theta_{bc}=\arcsin(n_m/n_{co}) \quad (3)$$

here α is an angle which the ray, I, makes with the fiber axis, h is a distance from the ray, I, to the fiber core-cladding interface, a is the radius of the fiber, R is the bending radius, n_m and n_{co}

are the refractive indices of the surrounding medium and the fiber core, respectively.

When a surrounding medium is a two component liquid mixture, such as oil and refrigerant, the critical angle will be changed with the concentration of the mixture. On the other hand, when $\theta_{co} \leq \theta_{bc}$, the ray, I, will be transmitted into the surrounding medium through as well as being reflected into the fiber at the interface of the fiber and the medium. The relative amounts of transmitted and reflected light are governed by the Fresnel reflection and transmission coefficients which are related to the refractive index of the surrounding medium or the concentration of a liquid mixture at the bend.

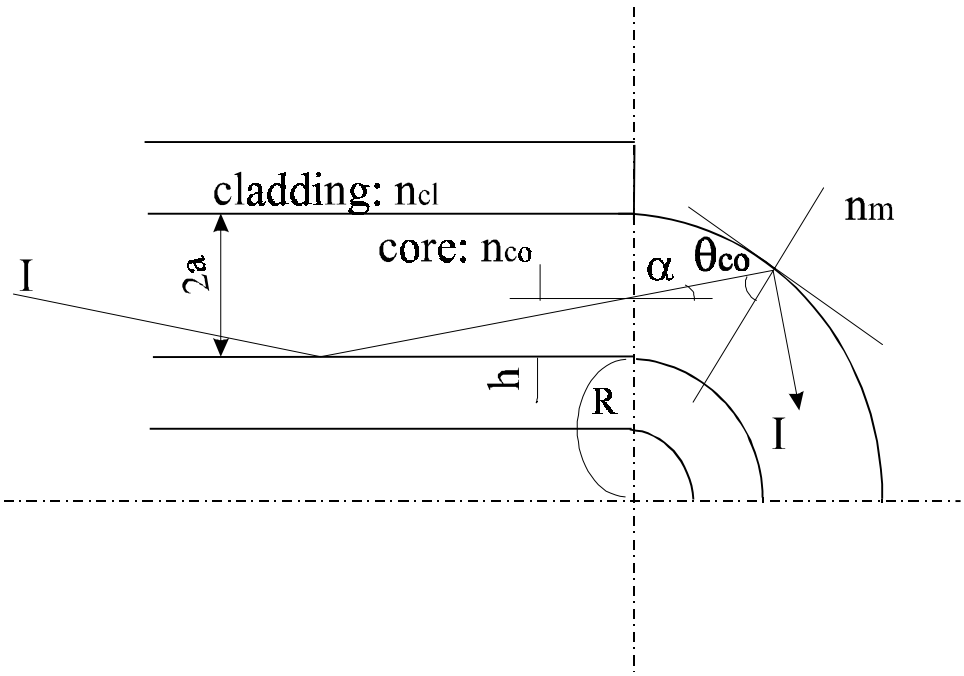

Figure 2 Design Principle of Sensing Element

Based on the above, It can be concluded that the attenuation of light rays in the bent section of optical fiber is affected by the concentration of liquid mixture. If the change of attenuation of light can be measured, an optical fiber with a U bend can be utilized as a concentration sensor for liquid mixtures. This principle was employed in the present study to design a sensing element for POE oil concentration variation detection in R134a. A multimode

all silica glass fiber was chosen to make the sensing element. The coating of the fiber around bending area was removed before the fiber was bent. Because the attenuation of light increases as the bending radius decreases, the reduced radius of the U shaped bend could substantially increase the light loss from the sensing tip, thereby decreasing output signal levels. Selection of the bending diameter was made in order to achieve a suitable trade-off between sensing element miniaturization and signal quality so to meet the desired oil concentration resolution requirement. The bending diameter in this study was chosen to be miniaturized to 0.6 mm. Some of the cladding was removed from the U bend using polishing kit (AMP, 228055), allowing intimate contact between the core and the fluid. The sensing element was made suitable for the detection of POE oil concentration variation up to 10.0% in R134a with a sensitivity of less than 0.1%.

3. MEASUREMENT APPARATUS

A prototype fiber optic probe for concentration measurement of POE oil/R134a mixture was developed at the laboratory. Because the refractive index of liquid mixture changes with temperature as well as concentration, temperature must be monitored when concentration needs to be determined by refractometry. A stainless steel insulated thermocouple (type K, 0.1 ^{o}C resolution) was embedded into the probe and used to monitor temperature. Pressure change may also affect the refractive index of mixture, local pressure was, therefore, also monitored.

When the sensing element was embedded into a support tube, a layered bond around the element was avoided to eliminate a possible poor connection between each two layers of bonding materials.

The probe was designed for application in a temperature range from -20 ^{o}C to +40 ^{o}C and a pressure range of 0 - 3500 kPa. The probe diameter was miniaturized as 3.9 mm. The probe could be installed on machines by using most mechanical connectors.

The instrumentation system associated with the fiber optic probe is shown in Figure 3. Apart from the probe, it also includes a light source, photodetectors and a data acquisition system. A light emitting diode with a peak emission at 830 nm was used as the light source.

Because environment temperature affected output of the light source (LED), hence resulting in a measurement error, one measure was taken to reduce this error by monitoring output of the light source and reading a ratio of the signal outputs from the sensor and the light source. This was done in this study through the use of a 1X2 optical fiber coupler. PIN photodiodes with internal operational amplifier which allows a direct conversion from light to voltage were used to detect optical signal outputs from the sensor and the light source. All of the signal outputs from the photodetectors and the thermocouple were recorded by data acquisition system.

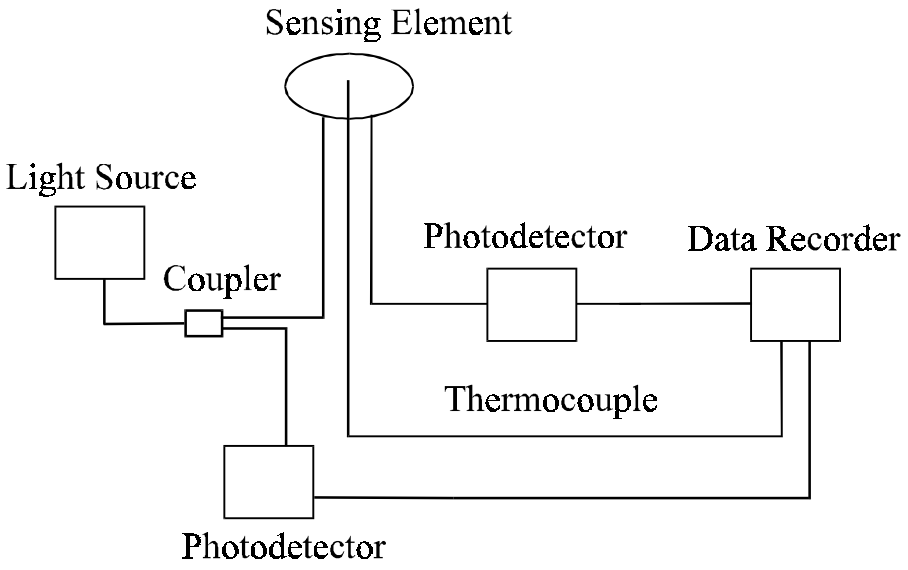

Figure 3

Instrumentation System Associated with the Fiber Optic Probe

4. LABORATORY NON-FLOW TEST

Major considerations during the test were sample preparation of POE oil/R134a mixtures and control of temperature and pressure for probe calibration purposes. The characterizations of the probe were also examined.

A group of the POE oil/R134a mixtures with known concentrations were prepared and examined by the probe to obtain the relation between the signal output and the concentration

of the POE oil in R134a. The probe was inserted into the sample cylinders which were filled with the mixtures of oil/R134a with different concentrations, and the data were collected by data acquisition system. The temperatures of the sample cylinders were maintained constant by the use of a constant temperature bath during the data collections. The signal output variation with oil concentration is shown in Figure 4. The data indicate that the probe has a resolution of 0.1% in oil concentration measurement.

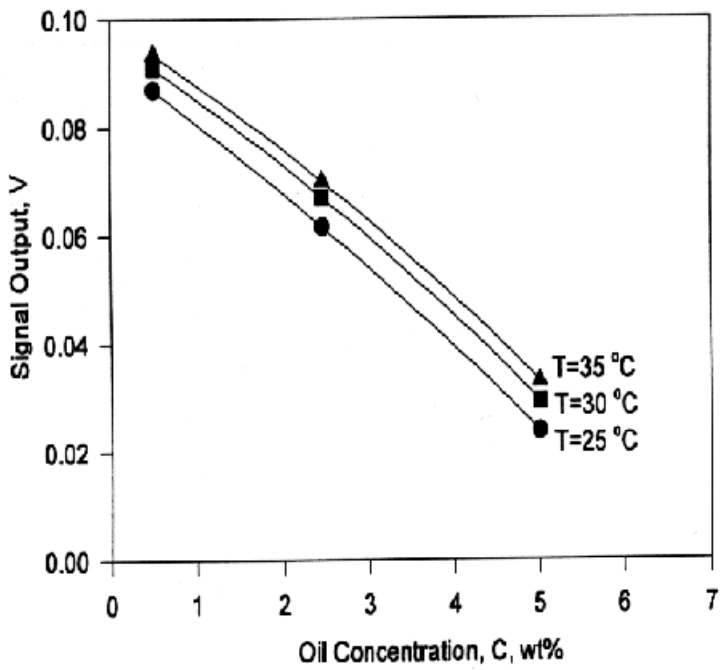

Figure 4 Signal Output Variation with Concentration

To minimize the possible measurement error due to difficult handling of POE oil/R134a mixture samples, a group of standard optical liquids with known refractive indices (R.P. Cargille series AAA) were used as a reference during the tests. An excellent repeatability of the probe was demonstrated by inserting the probe into these liquids and comparing the signals over a long time period. On the other hand, the probe may need recalibration over time for many

reasons. The standard optical liquids were also used for this purpose.

It is known that a temperature change will lead to a change of refractive index of liquid and a change of physical properties of the optical fiber. The probe, therefore, must be calibrated at different temperature levels. The influence of temperature variation on the signal output is shown in Figure 5. The signal output decreases as the liquid temperature decreases. It can be seen that the probe is very sensitive to temperature variation. A signal output variation due to a temperature rise of 1 ^{o}C is equivalent to that caused by an oil concentration decrease of 0.1%. This means that a precise temperature measurement during both probe calibration and on-line concentration measurement is necessary.

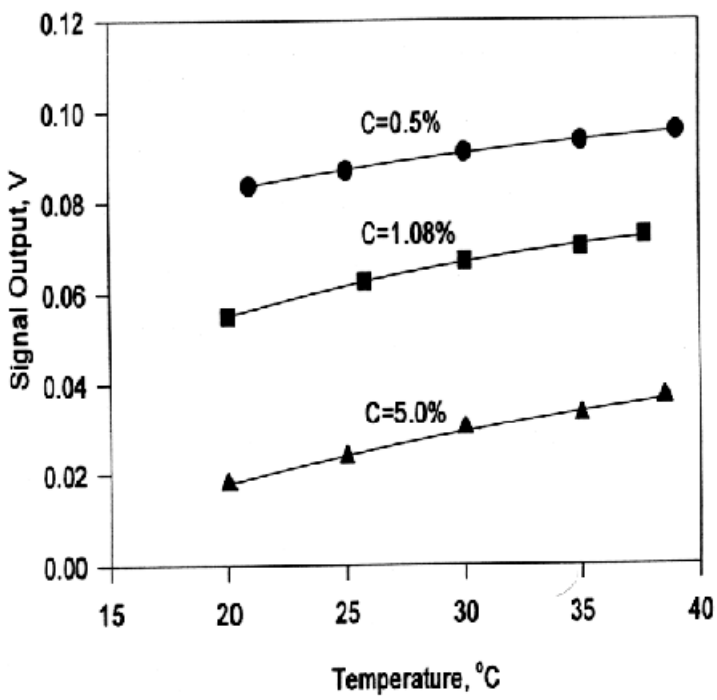

Figure 5 Signal Output Variation with Temperature

The influence of pressure change on the oil concentration measurement by this probe was also investigated. Figure 6 shows that the signal output decreases as the pressure increases. The data indicate that a signal output variation due to every 1000 kPa pressure increase is

equivalent to that caused by an oil concentration increase of 0.022%. This influence may be neglected during concentration measurement. However, a signal output variation due to pressure change in differtent refrigeration systems may need to be compensated if a precise oil concentration measurement is required or a system measurement error needs to be evaluated.

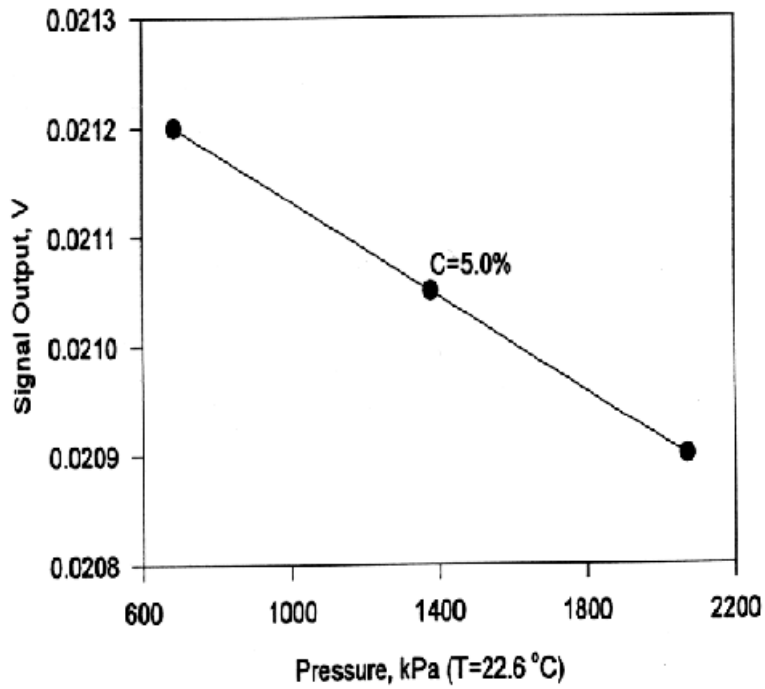

Figure 6 Signal Output Variation with Pressure

The output variation of light source with environment temperature was indeed found during the tests which directly affected the sensor signal output. Reading the ratio of the signals from the sensor and the monitored light source was demonstrated to be an effective measure to reduce the measurement error.

5. ON-LINE MEASUREMENT

The concentration probe was installed on a refrigerator running with R134a to monitor POE oil circulation. It was located on a section of pipeline after condenser. At this location, the

POE oil/R134a mixture was in the liquid phase and the oil in the refrigerant was dissolved when the compressor was running. The probe was inserted into the pipeline through vacuum/charge access and reached the fluid stream. Figure 7 shows the transient oil concentration profile measured by the probe. To investigate dynamic measurement reliability of the probe, some tests were conducted. First, the data from the probe were continuously recorded by the data acquisition system. Second, on-line sample of the oil/R134a liquid mixture near the probe was collected. Third, the oil concentration value of the sample was obtained by vaporizing R134a and measuring weight of the removed part. Finally, this concentration value was compared by those obtained from the probe. It was found that the oil concentration value measured by the probe was in good agreement with that determined by analyzing the on-line sample. With these tests, the probe was verified to have a good performance under a dynamic condition with temperature and pressure variations.

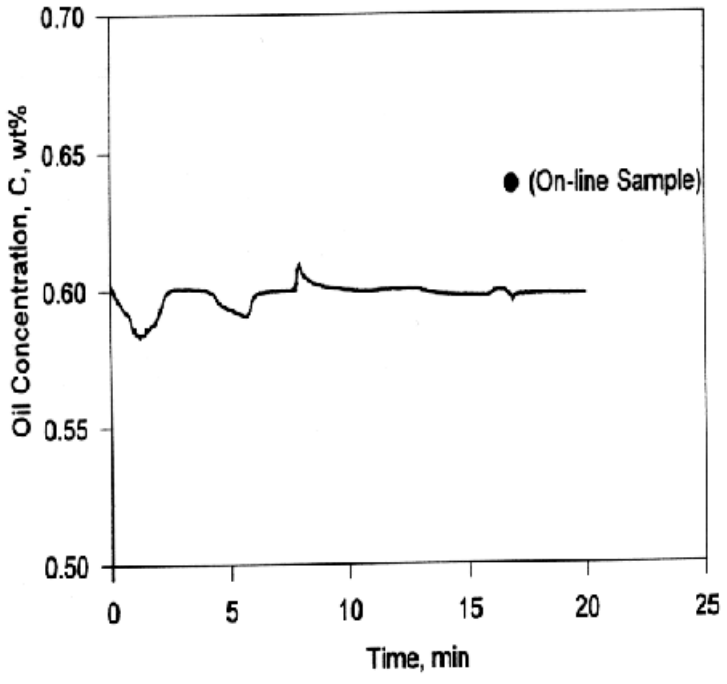

Figure 7 Oil Concentration Profile in a R134a Refrigeration System

6. CONCLUSION

A fiber optic refractometer technique for oil concentration measurement in refrigeration system has been demonstrated. The data were taken for POE oil/R134a liquid mixture. The probe showed a good performance and has proved to be reliable for on-line measurement through the dynamic tests on the refrigeration machine. This technique may also be useful to investigate the influence of oil on heat transfer performance of evaporator, aided by the probe miniaturization and its easy installation on machine.

ACKNOWLEDGMENTS

The authors would like to thank Natural Resources Canada for laboratory facility and Gas Technology Canada for co-funding the project.

REFERENCES

1. J.J. Baustian, M.B. Pate and A.E. Bergles, ASHRAE Transactions, Vol. 94(2): 571 (1988).
2. J.J. Baustian, M.B. Pate and A.E. Bergles, ASHRAE Transactions, Vol. 94(2): 588 (1988).
3. J.J. Baustian, M.B. Pate and A.E. Bergles, ASHRAE Transactions, Vol. 94(2): 602 (1988).
4. S. Suzuki, Y. Fujisawa, S. Nakazawa and M. Matsuoka, ASHRAE Transactions, Vol. 99(1): 413 (1993).
5. Ty A. Newell, HVAC&R Research, Vol. 2, No. 3: 247 (1996).
6. J.J. Meyer and J.M. Saiz Jabardo, Int. J. Refrig., Vol. 17, No. 7: 482 (1994).
7. T. Takeo and H. Hattori, Japanese J. of Applied Physics, Vol. 21, No. 10: 1509 (1982).
8. T.L. Bergman, F.P. Incropera and W.H. Stevenson, Rev. Sci. Instrum., Vol. 56, No. 2: 291 (1985).
9. B. Zhou, J.E.S. Venart and S. Hinata, Fluid Phase Equilibria, Vol. 79: 175 (1992).
10. J. Kamoshida, Y. Suzuki and N. Isshiki, Prepr. Of JSME, Thermal Engineering Conference’93, No. 930-76: 183 (1993).

11. J.J. Baustian, M.B. Pate and A.E. Bergles, Heat Transfer Laboratory Report, Department of Mechanical Engineering, Iowa State University, Ames, Iowa, No. HTL-48, ISU-ERI-Ames-88199: 199 (1987).

12. A.L. Harmer, IEE Conference Publication, No. 221: 104 (1983).