Measurements of Absorption Rates of HFC Single and Blended Refrigerants in POE Oils

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Thermophysical properties of refrigerant/lubricant mixtures play an important role in refrigeration and air-conditioning system design. Therefore it is important to have a good understanding of the mixture composition in each system component such as the compressor or evaporator. Because the system operation is dynamic the rates of absorption and desorption become significant parameters. In this paper measured absorption rates of alternative refrigerants in polyolester (POE) oils are reported. An effective online mass gain method was designed and constructed to measure the absorption rates and solubility of refrigerants in lubricants. HFC single refrigerants (R-32, R-125, R-134a, and R-143a), and blended refrigerants (R-404A, R-407C, and R-410A) were tested with POE ISO 68 lubricant under various conditions. The experimental results showed that, at room temperature, R-134a is the most soluble in POE ISO 68 oil among all the refrigerants tested at pressures of 239 kPa (20 psig) to 446 kPa (70 psig). Among the blended refrigerants tested, R-407C was found to be the most soluble at room temperature and pressures of 239 kPa and 446 kPa. Experimental solubility data from this new measurement method were compared with data available in the literature. Good agreement between the two indicates the feasibility of the new method employed in this investigation.

INTRODUCTION

In a vapor compression system, refrigerant vapor encounters the lubricant in the compressor and the refrigerant carries some of the lubricant throughout the system. Therefore, the mixture properties, such as solubility, miscibility, viscosity, and foamability, greatly affect the system performance. Good miscibility results in efficient lubricant return, thereby improving both lubrication and heat transfer. Foaming reduces vibration and noise from the compressor (ASHRAE, 1994). Previous studies (ASHRAE 1994; Cawte 1991; Van Gaalen et al. 1990, 1991; Yanagisawa et al., 1986) have led to understanding mixture properties of chlorinated refrigerants (R-12 and R-22) and the compatible lubricants (alkylbenzene and mineral oil). Recent studies by researchers at Shizuoka University (Fukuta et al. 1993, Fukuta et al. 1995, and Fukuta et al. 1997) have provided an understanding of the transient mixing phenomenon of R-22 in mineral oils coupled with diffusion. These studies have provided experimental and theoretical analyses of apparent diffusion coefficients of R-22 in mineral oils.

Environmental concerns have recently led the air-conditioning and refrigeration industry toward alternative HFC (hydrofluorocarbon) refrigerants. The alkylbenzene and mineral oils are being replaced by synthetic lubricants in which HFC refrigerants are more soluble (Short 1989).

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Researchers are making efforts to measure the thermophysical properties of the mixtures of HFC refrigerants and synthetic lubricants. However, the relevant publications in the literature have reported only equilibrium properties. Chang and Nagashima (1993) measured the viscosity of mixtures of R-134a and polyalkyleneglycol (PAG) with a falling-ball viscometer. The results showed that the viscosity of the mixture was between the viscosity of pure R-134a and that of pure PAG, which differ by four orders of magnitude. That means that a slight change in the mixture fraction could result in a significant change in viscosity. Similar results were reported by Kumagai et al. (1994) who measured viscosity and density of mixtures of R-134a with various types of glycols. Komatsuzaki et al. (1994) studied the lubricity of mixtures of R-134a and polyolester (POE). It was found that the lubricity dropped sharply when the refrigerant ratio in the mixture was over 50% by volume. Foamability also highly depends on the mixture composition. In the experiments conducted by Sibley (1993) and Yanagisawa et al. (1991), it was found that foam height varied with the amount of refrigerant and the maximum height occurred at the volume mixing ratio of about 50%.

From the above studies, it was concluded that properties of the mixture are highly related to mass composition, that can be generally estimated from the solubility data. However, an air-conditioning system operates in a dynamic manner. Therefore, the mixture composition based on the solubility data alone, could be misleading. A more accurate composition can be predicted if the absorption rate is known. The knowledge of absorption and desorption rates at the interface of the refrigerant and the lubricant is also important, because they affect the foaming characteristics. Foaming characteristics affect sound absorption in the compressor and heat transfer in the evaporator. A study of these characteristics has assumed an added importance for the alternative HFC refrigerants and synthetic lubricants since very little foaming occurs between these pairs. For this reason, the objective of the present research was to measure the absorption rates of HFC refrigerants (both single and blended) in synthetic lubricants. A new piece of equipment was specially designed and constructed for this purpose. This new device that employs an online mass gain measurement method, enables the measurement of absorption and desorption rates as well as of the solubility of refrigerants and lubricants at various temperature and pressure conditions.

CONCEPT OF MEASUREMENT

Conventionally, the refrigerant content in a refrigerant/lubricant mixture is measured according to the ANSI/ASHRAE Standard 41.4-1984 (Bayani et al. 1995). In this method, a refrigerant/lubricant mixture is heated to 150°C in vacuum. Thus, all the refrigerant content is driven off the sample. The sample mass is then measured again. The initial amount of the refrigerant in the mixture can be found by taking the difference between the two mass measurements. Although this method provides accurate measurements of refrigerant concentration, it is not useful when absorption rates are of interest. Numerous samples need to be taken frequently in order to achieve reliable results.

In this research, a new online mass gain measurement method was designed for absorption rate measurements in a pressure vessel. This involved the instantaneous mass change of a lubricant due to absorption/desorption of the refrigerant measured by a force transducer installed inside the pressure vessel.

EXPERIMENTAL FACILITY AND SAMPLES

The experimental apparatus is schematically shown in Figure 1. A pressure vessel was constructed of 0.64 cm (0.25 in) thick iron sheet. Two high-pressure sight glasses that were able to withstand 3.5 MPa (500 psig) were installed on the vessel for visual inspection of the sample during the experiments. The access port was used to evacuate the system, and also to charge the system with refrigerant. The system was sealed by sheet gasket. From the results of a pressure
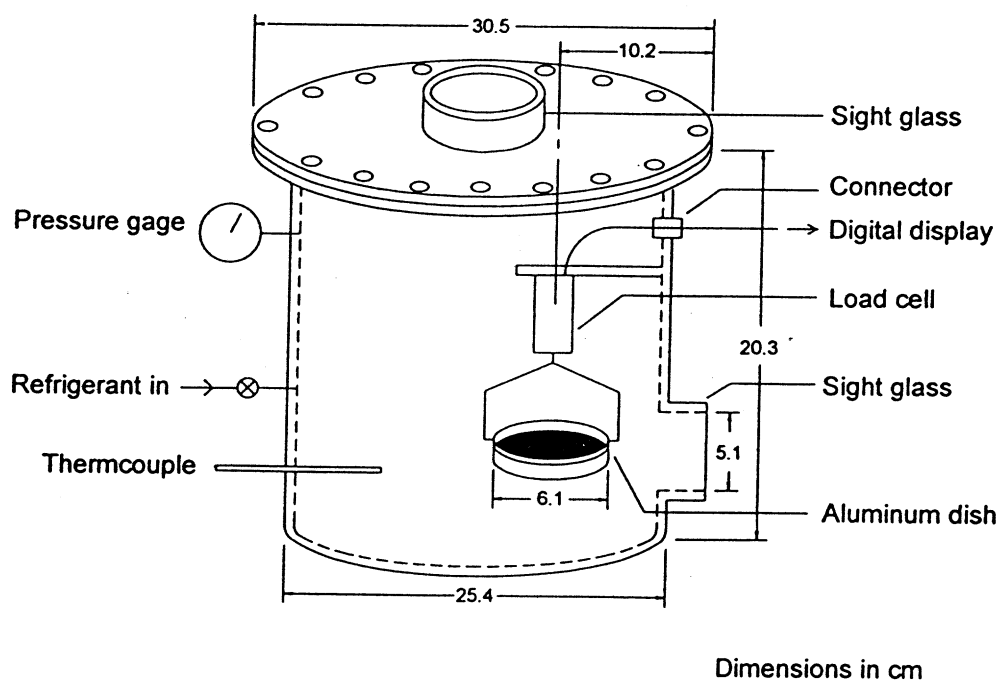
Dimensions in cm

Figure 1. Experimental apparatus for absorption measurements

Table 1. List of Refrigerants and Lubricants Tested for Absorption

HFC Single Refrigerants	R-32
	R-125
	R-134a
	R-143a
HFC Blended Refrigerants	R-404A (44% R-125, 4% R-134a, 52% R-143a)
	R-407C (23% R-32, 25% R-125, 52% R-134a)
	R-410A (50% R-32, 50% R-125)
Lubricant	POE ISO 68

test, the maximum safe working pressure of the vessel was about 791 kPa (100 psig). A lubricant sample can be placed in a shallow aluminum dish suspended from a force transducer. A refrigerant can be introduced in the chamber from a port such that the incoming jet does not affect the lubricant surface.

A sensitive force transducer, with a capacity of 30 g and rated uncertainty of ±45 mg, was used to measure the mass gain of the lubricant sample that was due to the absorption of refrigerant. A T-type thermocouple probe was used to monitor the temperature of the test environment. The pressure was indicated by a pressure gage with an uncertainty of ±3.4 kPa (0.5 psi). The refrigerant and lubricant samples tested are listed in Table 1.

EXPERIMENTAL PROCEDURE

Two grams (±10 mg) of POE ISO 68 lubricant sample were placed on an aluminum weighing dish hanging from the force transducer. For the purposes of this research, only the absorption effect was of interest, so thin layers of lubricant samples (depth-to-area ratio of 0.0026 m/m^2) were used in the experiments in order to minimize the diffusion effect. The system was then

sealed and evacuated to a pressure of about 3.4 kPa (29 in Hg vacuum). The refrigerant was charged until the test pressure was reached. The charging process took between 15 seconds to 1 minute, depending upon the pressure. The absorption for each refrigerant, except R-134a, was measured at 239, 446, and 584 kPa (20, 50, and 70 psig). For R-134a, the maximum test pressure was 446 kPa (50 psig) because its saturation pressure at room temperature was low, about 469 kPa (68 psig). In general, the refrigerant charge was withdrawn through the vapor valve on the refrigerant tank; however, when a blended refrigerant was used, the refrigerant charge was withdrawn through the liquid valve in order to obtain a better composition of the blend.. Throughout the experiments, the room temperature (24°C) was maintained within ±1°C. Experimental data, including mass gain of the sample, temperature, and pressure, were recorded every 5 minutes. The experiment was stopped when the mass gain stabilized to a constant value.

ANALYTICAL METHOD

Based on the measurements obtained from the experiments, the absorption of refrigerant in the lubricant was calculated in terms of the mass composition as

$$x = \frac{m_r}{m_r + m_l} \times 100 \tag{1}$$

The uncertainty in x was obtained as

$$w_x = \left[\left(\frac{\partial x}{\partial m_r} w_r \right)^2 + \left(\frac{\partial x}{\partial m_l} w_l \right)^2 \right]^{1/2} \tag{2}$$

where

w_r = uncertainty in the measurement of the mass gain, ±45 mg
w_l = uncertainty in the measurement of the lubricant sample, ±10 mg

Taking the partial derivatives of Equation (1) and substituting them into Equation (2), the uncertainty in the calculated absorption w_x was found to be within ±2%.

For a thin layer of the lubricant, the absorption rate is assumed to be linearly proportional to the difference between the solubility, which is the absorption limit, and the present mass composition,

$$\dot{x} = k(X - x) \tag{3}$$

The initial condition applied to the above differential equation is:

$$x = 0, \quad t = 0 \tag{4}$$

and the steady state condition is:

$$x = X, \quad t = \infty \tag{5}$$

Solving the above equation yields:

$$x = X(1 - e^{-kt}) \tag{6}$$

Curve fitting the experimental data with Equation (6) gives the values of X and k, which are the solubility and absorption rate constant of the refrigerant in the lubricant, respectively. The initial absorption rate, which is as important as the solubility in a dynamic system, can be written as

$$\dot{x}_o = kX \tag{7}$$

The numerical results of the analysis are presented in detail in the following section.

RESULTS AND DISCUSSION

The absorption measurements of HFC refrigerants in POE are plotted in Figures 2 to 8. The results of curve-fitting the experimental data with Equation (6) are also plotted in these figures, while the values of X and k are summarized in Table 2. The time period for complete absorption was typically between 90 minutes and 2 hours. The results show that both the initial absorption rate and the solubility increased with pressure. Among all the refrigerants tested, R-134a had the highest initial absorption rate and solubility in POE under the test conditions. For the blended refrigerants, the differential solubility of individual refrigerant component depended on its partial pressure and its vapor pressure. Among the blended refrigerants tested, R-407C was the most soluble. This is consistent with the fact that R-407C contains the largest amount of R-134a (52%). It is speculated that among the components of R-407C (R-134a, R-32, and R-125), R-134a is absorbed in POE in greater proportion. However, the exact refrigerant composition dissolved could not be determined by the existing experimental setup. The effect of pressure on the absorption rate constant is not clear from the data. Although the values vary with the pressure, the effect of these k values on the variation in x [Equation (6)] is less than the uncertainty in measurement of x, which is $\pm 2\%$.

Table 2. Experimental Results of Absorption of HFC Single and Blended Refrigerants in POE Lubricant at Room Temperature

| Refrigerants	Pressure, kPa/psig	Solubility X, %	Absorption rate constant k, min^{-1}	Initial absorption rate, %/min^{-1}
R-32	239/20	1.597	0.063	0.101
	446/50	2.718	0.049	0.133
	584/70	6.697	0.061	0.405
R-125	239/20	7.281	0.066	0.483
	446/50	10.6	0.046	0.484
	584/70	15.36	0.052	0.799
R-134a	239/20	8.063	0.056	0.449
	308/30	12.52	0.051	0.638
	446/50	21.09	0.066	1.396
R-143a	239/20	2.125	0.051	0.108
	446/50	5.233	0.029	0.152
	584/70	7.514	0.038	0.285
R-404A	239/20	2.200	0.021	0.047
	446/50	6.74	0.028	0.189
	584/70	10.99	0.033	0.361
R-407C	239/20	4.926	0.017	0.082
	446/50	11.58	0.058	0.673
	584/70	21.49	0.089	1.905
R-410A	239/20	2.936	0.161	0.474
	446/50	7.070	0.078	0.552
	584/70	16.30	0.169	2.755
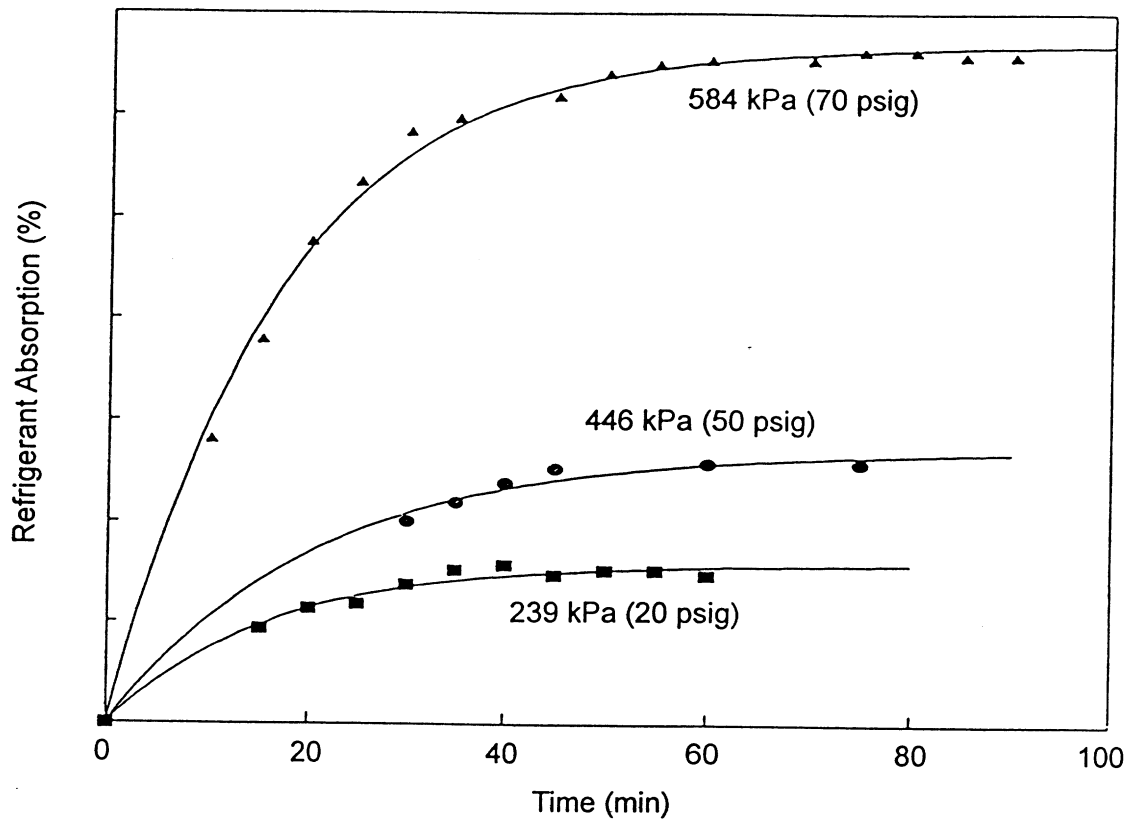
Figure 2. Absorption of R-32 in POE ISO 68 at room temperature
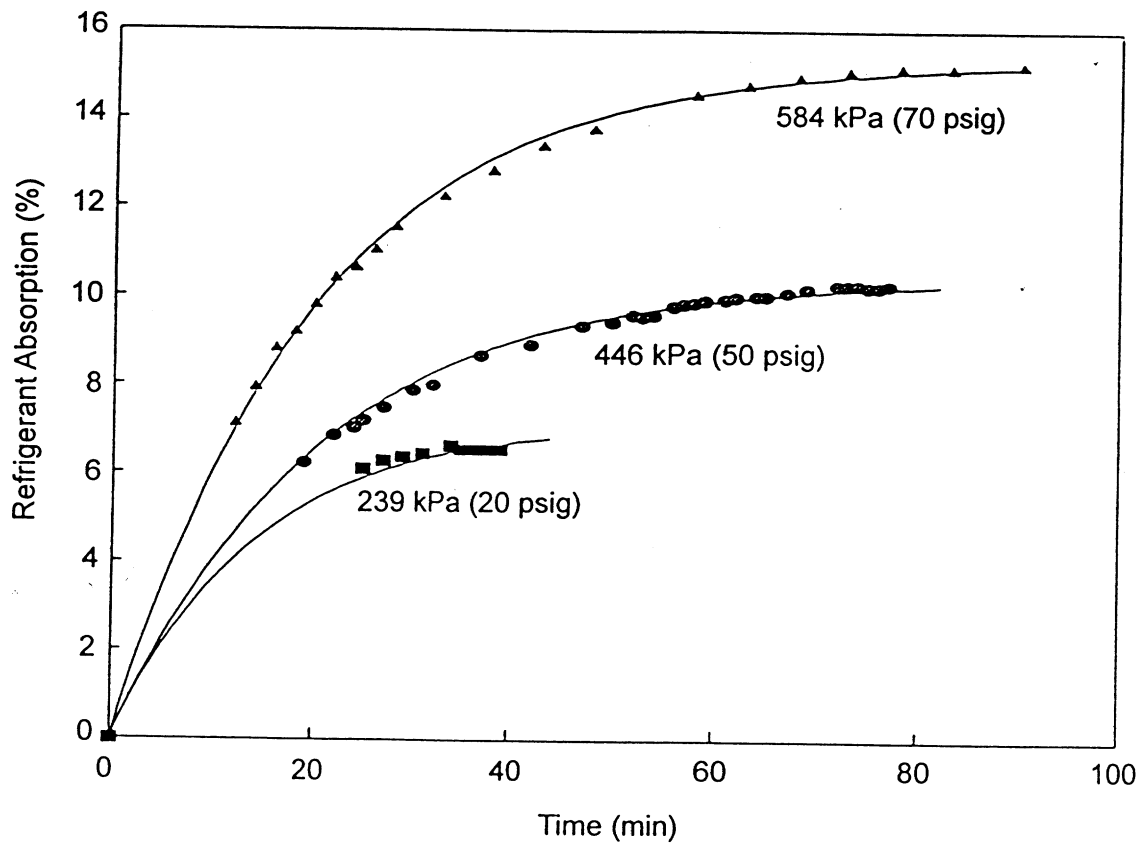

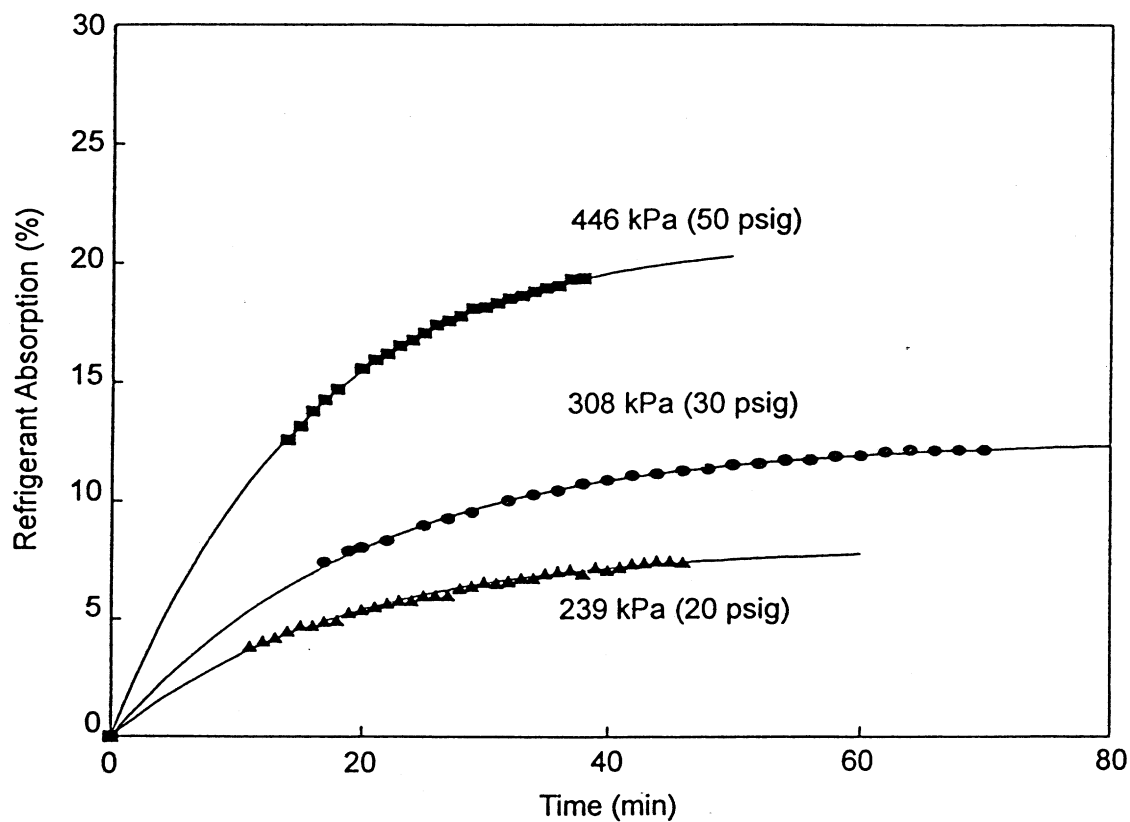**Figure 3. Absorption of R-125 in POE ISO 68 at room temperature**

Figure 4. Absorption of R-134a in POE ISO 68 at room temperature
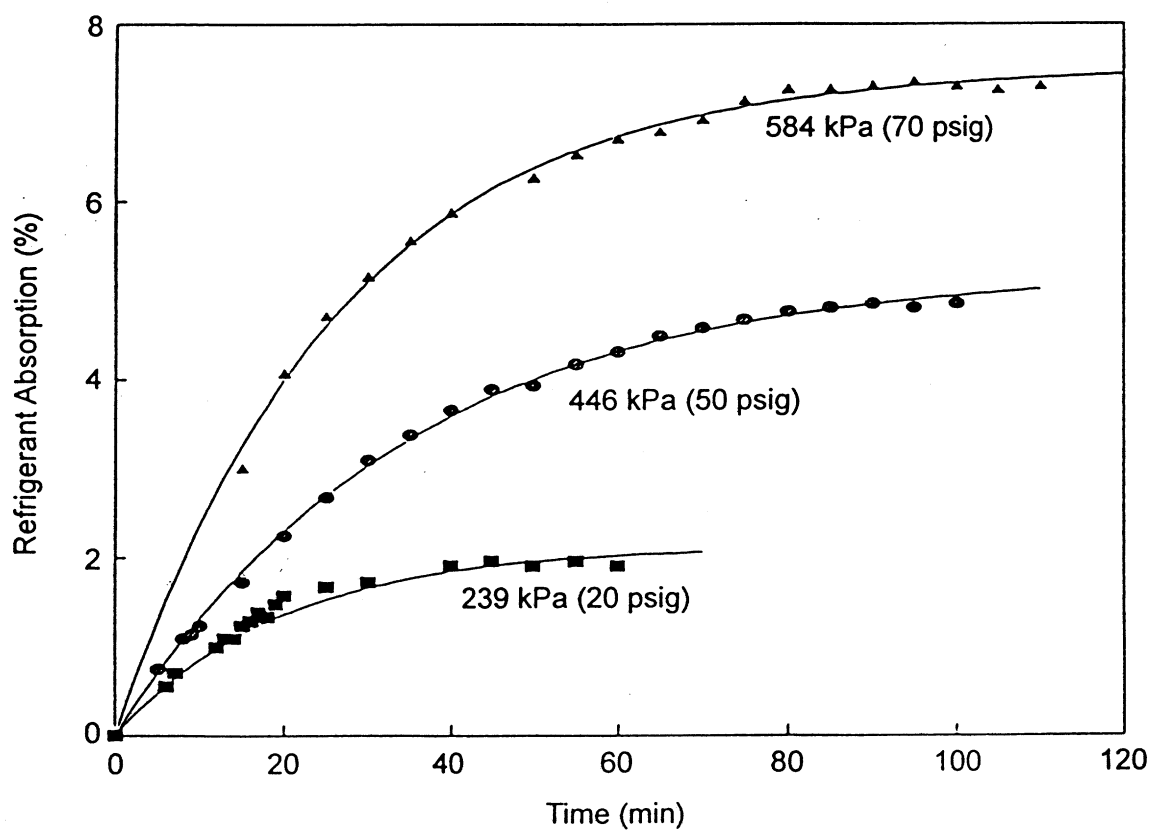

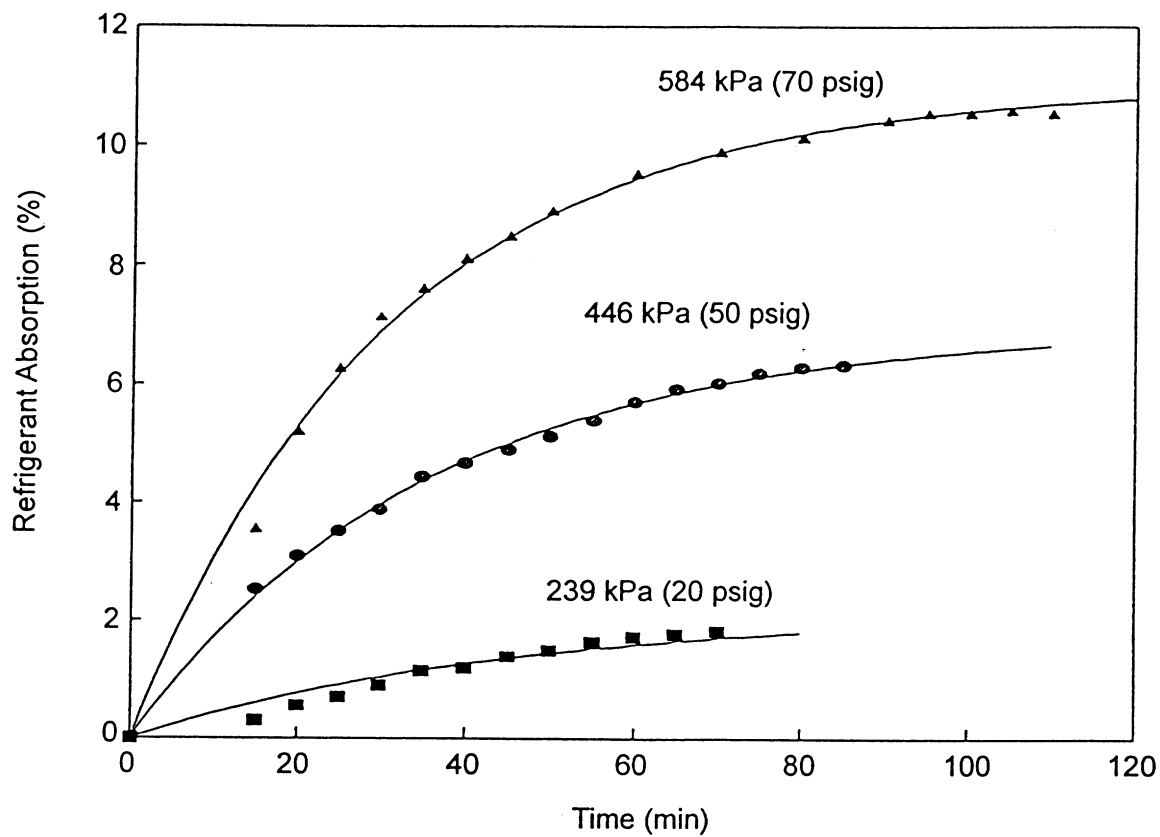Figure 5. Absorption of R-143a in POE ISO 68 at room temperature

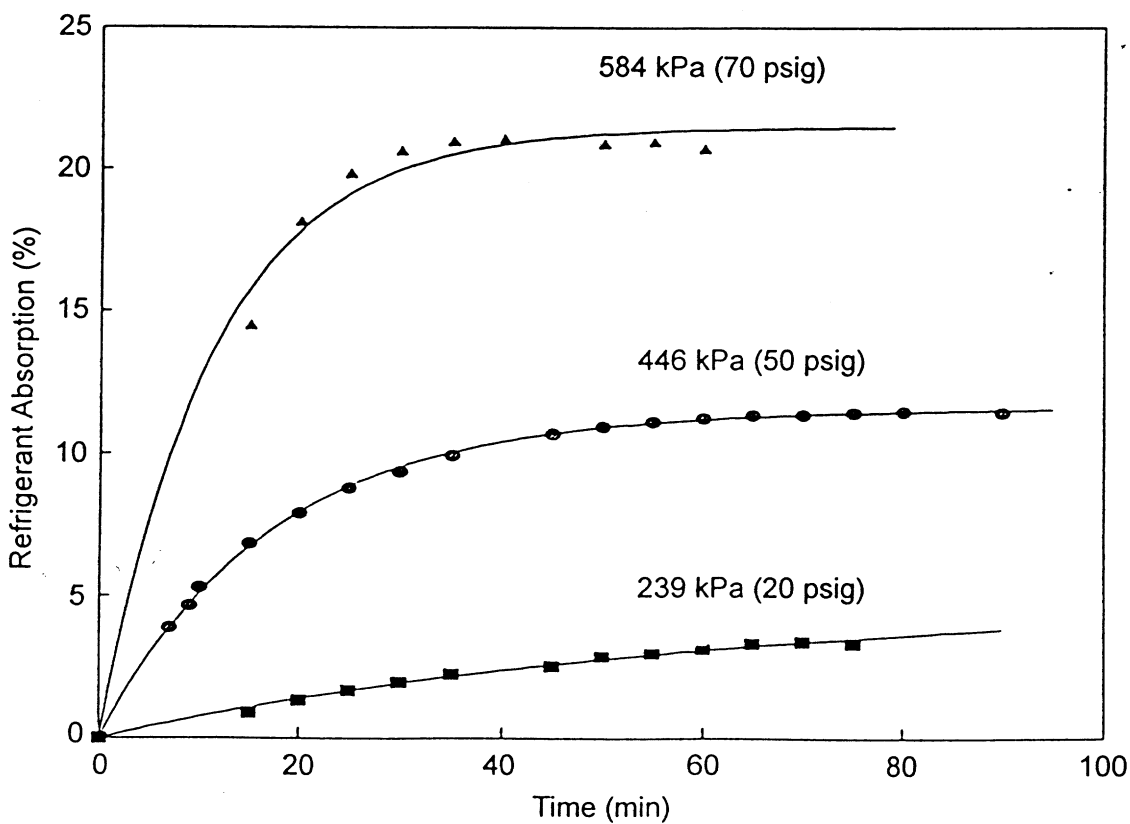**Figure 6. Absorption of R-404A in POE ISO 68 at room temperature**

Figure 7. Absorption of R-407C in POE ISO 68 at room temperature
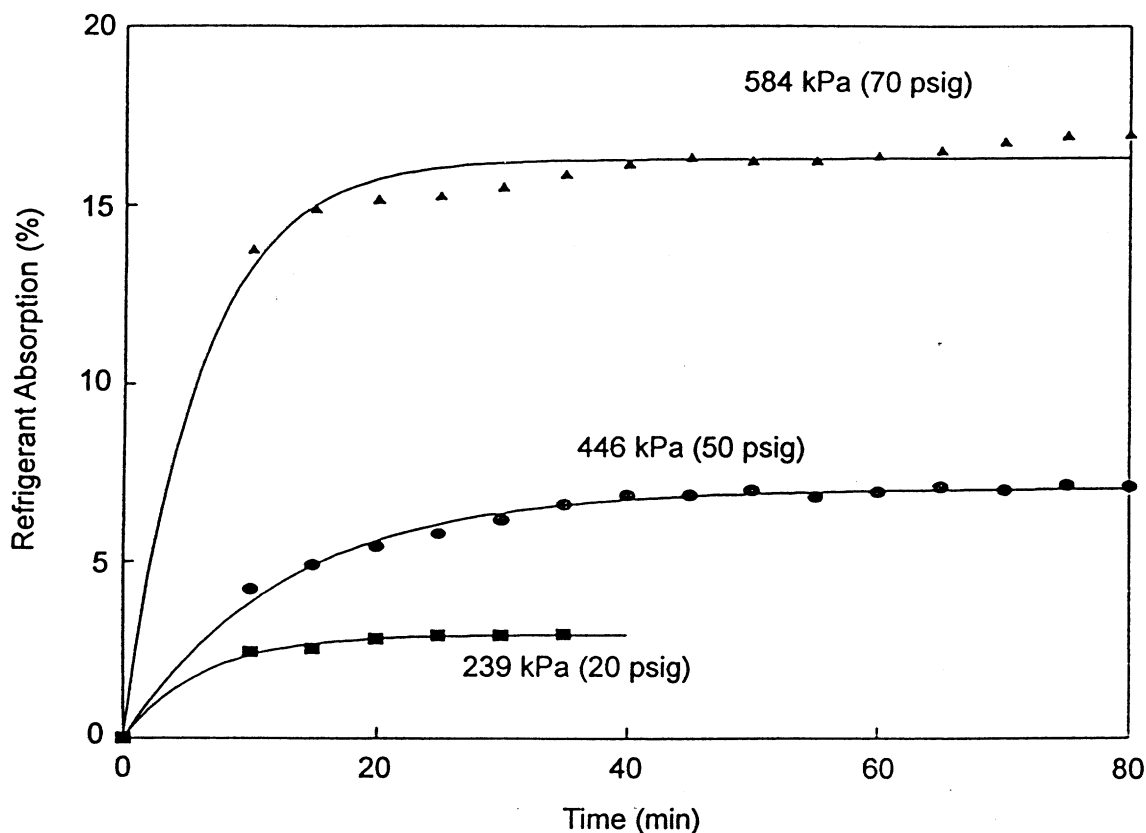
Figure 8. Absorption of R-410A in POE ISO 68 at room temperature

When the refrigerant was initially charged to pressurize the vessel, the temperature increased by 1.3 to 6.9°C (2 to 11°F) depending on the pressure. The refrigerant charging process took 15 seconds to 1 minute, depending on the final pressure realized. Thus, the charging was accomplished with a non steady-state adiabatic process, resulting in an increase in the temperature and internal energy of the charge in the chamber. However, after charging, the temperature returned to room temperature in a short time. In addition, the flow of the refrigerant charge caused instability in the initial mass measurements. These erroneous initial data points were discarded.

The measured solubility versus pressure curves for the refrigerants are shown in Figure 9. In Figure 10, selected solubility curves are plotted again for comparison with the data from the literature (Martz et al.1996, Sibley 1993). This figure gives credibility to the measurements obtained by the new online mass gain method, as the measurements agree with the data in the literature within the 2% limits of experimental error mentioned before.

CONCLUSIONS

The absorption rates and solubility of selected HFC single and blended refrigerants in POE ISO 68 lubricant were measured by a new online measurement method at room temperature and under various pressures. The absorption and desorption rates at the interface affect the foaming characteristics that are important for sound absorption in the compressor and heat transfer in the evaporator. The reported data, coupled with the HFC/POE mixture properties, such as viscosity, density, and foamability, will help to improve current air-conditioning system designs to use HFC refrigerants with POE lubricants effectively.

In addition, this research demonstrates the feasibility of the new online mass gain method in measuring absorption rates of refrigerants in lubricants. Compared to the conventional sample withdrawal method, the new technique is simple to use, however, the experimental error is relatively high. This drawback could be improved if better force transducers were available, and
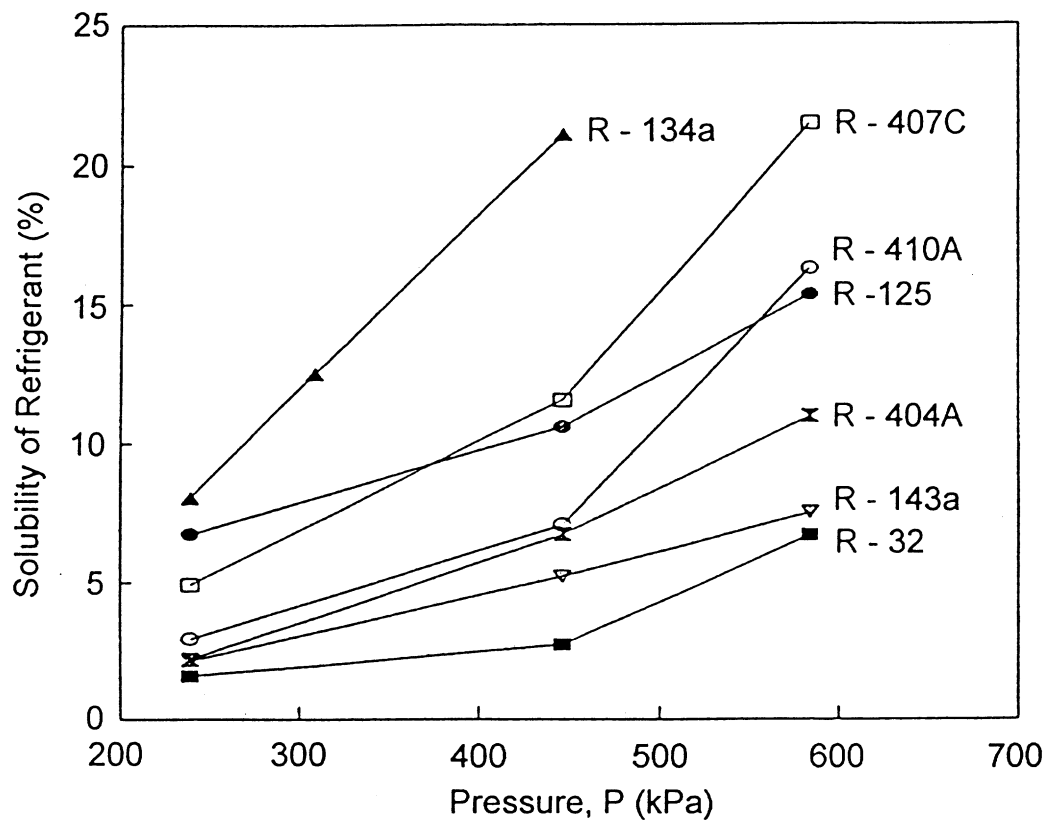
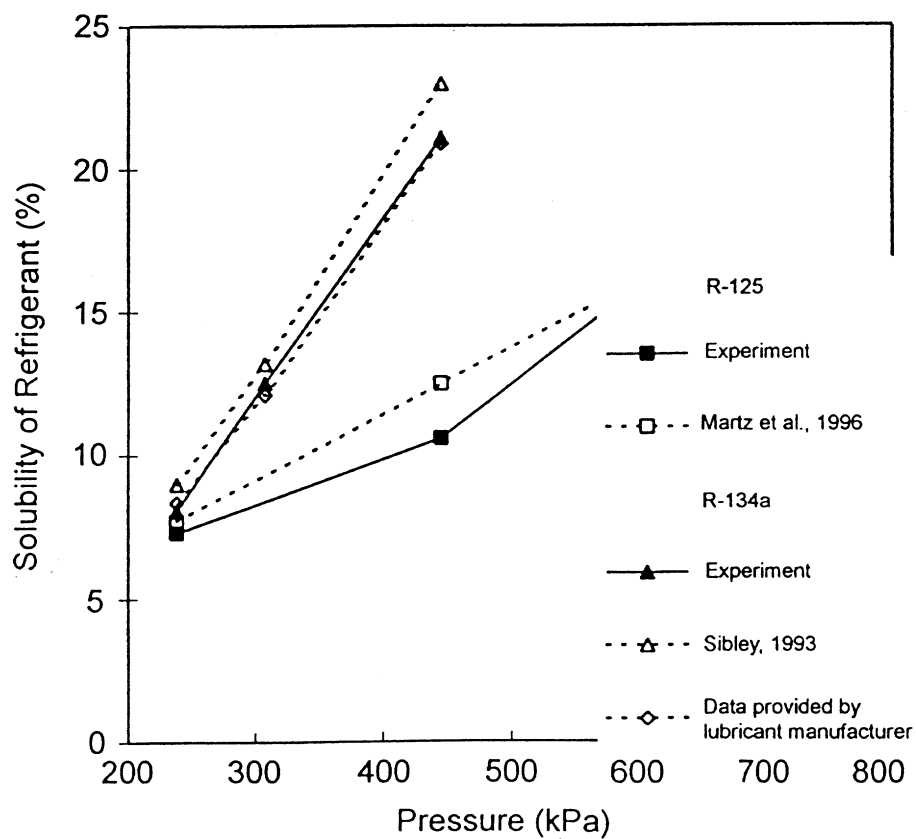**Figure 9. Solubility of HFC refrigerants in POE ISO 68**

Figure 10. Comparison between measured solubility and published data

better temperature control could be obtained. The new online mass gain method is especially useful in studying the surface phenomena of absorption and desorption rates. The methods available in the literature can only be used to study bulk mixing and diffusion.

Tests at room temperature have been completed. The next phase is to extend the work to measure the absorption of refrigerants in lubricants at other temperatures simulating actual operating conditions. Measuring the absorption of HFC refrigerants in other compatible synthetic lubricants, such as glycols, would also be beneficial to the industry.

NOMENCLATURE

k	= absorption rate constant	w	= uncertainty
m_l	= mass of pure lubricant sample	x	= mass composition of refrigerant
m_r	= mass gain due to absorption of refrigerant	$\dot{x}$	= absorption rate
		$\dot{x}_o$	= initial absorption rate
t	= time	X	= solubility of refrigerant in lubricant

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