Proceedings of the 10th Brazilian Congress of Thermal Sciences and Engineering -- ENCIT 2004
Braz. Soc. of Mechanical Sciences and Engineering -- ABCM, Rio de Janeiro, Brazil, Nov. 29 -- Dec. 03, 2004

Paper CIT04-0719

A SIMPLIFIED MODEL FOR THE ABSORPTION OF REFRIGERANTS BY LUBRICANT OIL

Lucas S. Sell
Departamento de Engenharia Mecânica, Universidade Federal de Santa Catarina, Florianópolis, SC, 88040-900, Brasil
lucas@nrva.ufsc.br

Jader R. Barbosa, Jr.
Departamento de Engenharia Mecânica, Universidade Federal de Santa Catarina, Florianópolis, SC, 88040-900, Brasil
jrb@nrva.ufsc.br

Abstract. *This paper addresses the problem of absorption of refrigerant vapour by a stagnant layer of lubricant. In the simple model proposed here, the bulk motion of the solute is described in terms of an apparent diffusion coefficient that encompasses both molecular diffusion and the macroscopic motion due to liquid density instability. Results are compared with experimental data available in the literature for several refrigerant-oil mixtures. The adequacy of the formulation will be assessed in the light of the basic assumptions and performance of the model.*

Keywords*. Oil-refrigerant mixtures, absorption, mass transfer*

1. Introduction

In refrigeration systems where capillary tubes are used as expansion devices, the problem of refrigerant (vapour) absorption by the lubricant oil in the compressor is of crucial importance to the determination of the system equalizing pressure. In reciprocating compressors, for example, high absorption rates of refrigerant are desirable since lower equalizing pressure means reduced torque and power required for compressor start-up.

Solubility and vapour-liquid equilibrium data for refrigerant-oil mixtures, as well as information on the transient behaviour during absorption, are important parameters in the selection of the most appropriate lubricants, especially those for HFC refrigerants and their mixtures, i.e., the polyol esters (POE) and poly-alkylene glycols (PAG).

Because of local density instability effects in the liquid phase (Silva, 2004), the complete description of refrigerant absorption by lubricant oil is an issue that still remains open. To overcome the difficulty of evaluating multi-dimensional effects within the flow field, a useful approach has been to define an apparent molecular diffusion coefficient for the refrigerant-oil mixture to describe both microscopic (molecular diffusion) and macroscopic (natural convection) effects in the liquid phase.

Fukuta *et al.* (1995) investigated both experimentally and analytically the absorption of R22 by three mineral oils of different viscosity grades (3GS, 4GS and 5GS) at constant temperature and pressure by stagnant oil layers of different depth to base diameter aspect ratios. They concluded that the absorption rates decreased for increasing oil viscosity (perhaps due to an inhibition of natural convection) and that the aspect ratio of the liquid layer influenced the transient to equilibrium. As far as the analysis was concerned, Fukuta *et al.* introduced an apparent diffusion coefficient, which was modelled in terms of the liquid layer aspect ratio and of an equivalent Grashof number.

Rates of absorption of refrigerants by a polyol ester (ISO 68) were measured by Goswami *et al.* (1998) over a wide range of constant pressure and temperature conditions. The following pure refrigerants and mixtures were analysed: R-134a, R-143a, R-125, R-32, R-404a (44% of R-125, 52% of R-143a and 4% of R-134a by mass), R-407c (23% of R-32, 25% of R-125 and 52% of R-134a by mass) and R-410a (50% of R-32 and 50% of R-125 by mass). Goswami *et al.* correlated the instantaneous volume averaged liquid mass fraction as follows

$$\langle x_R \rangle = w_R \left(1 - e^{Kt}\right) \tag{1}$$

where x_R is the refrigerant mass fraction, $\langle\ \rangle$ is a volume average operator, w_R is the refrigerant solubility, K is an absorption rate and t is time.

Recently, Yokozeki (2002) proposed an absorption model in which the transient, one-dimensional diffusion equation was solved based on a definition of a constant apparent diffusion coefficient. The model framework was validated with the data of Lin (2000) (cf. Yokozeki, 2002) for absorption of water (from atmospheric air at 21°C) by polyol ester (POE22) polyvinyl ether (PVE32) and polyalkylene glycol (PAG488) oils, with the data of Fukuta *et al.* (1993) for absorption of R-22 vapour by 3GS oil (at 1.14 MPa and 30.8 °C) and with the data of Leung *et al.* (1998) for absorption of R-125, R-32 and R-134a by a polyol ester oil (POE68) at pressures ranging from 239 to 584 kPa and at a constant temperature of 24°C. Yokozeki concluded that, under constant temperature conditions, the apparent diffusion coefficient is directly proportional to pressure (and hence to the refrigerant-oil solubility). Finally, he presented a theoretical analysis, founded on the empirical proportionality relation between the diffusion coefficient and the solution viscosity, to support the utilization of the apparent diffusion theory to model refrigerant absorption by lubricant oils beyond the dilute solution limit.

The present paper is a first step towards a comprehensive description of absorption of pure refrigerant and mixtures by lubricant oil. Here, we revisit the analysis of Yokozeki (2002) for predicting refrigerant absorption through one-dimensional apparent mass diffusion models. In addition to some modifications in the original theory, namely the use of experimental values of refrigerant solubility as boundary conditions for the model, the range of experimental data against which the model was compared was substantially increased. As will be seen, this now covers the entire database of Goswami *et al.* (1998) for pure refrigerants and some preliminary estimates for the absorption of refrigerant mixtures. The adequacy of the formulation in predicting absorption of refrigerant mixtures will be assessed in the light of the basic assumptions and performance of the model.

2. Modelling

The geometry of the model, as illustrated in Fig. (1), reflects as closely as possible the conditions of the experiments of Goswami *et al.* (1998). Initially, the liquid layer is comprised by oil only and this initial amount of oil is always known. Pressure and temperature are kept constant for every experimental run. A one-dimensional model for the transport of the refrigerant in the liquid phase is given by

$$\frac{\partial}{\partial t}\rho_{RL} - v_{zL}\frac{\partial}{\partial z}\rho_{RL} = \frac{\partial}{\partial z}\left(D\frac{\partial}{\partial z}\rho_{RL}\right) \tag{2}$$

where ρ_{RL} is the mass concentration of refrigerant in the liquid phase, v_{zL} is the liquid phase velocity and D is the molecular diffusion coefficient of the refrigerant in the oil.

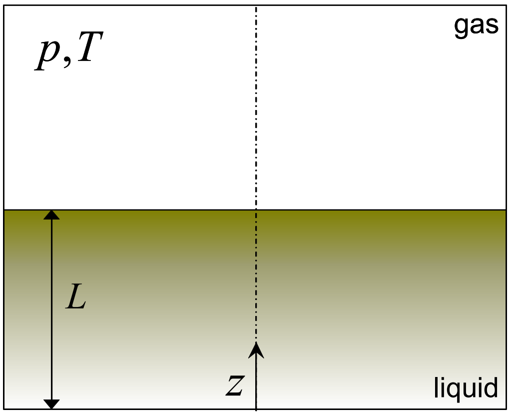

Figure 1. A schematic description of the problem geometry.

By defining an apparent diffusion coefficient, D_{ap}, one is able to combine the advective and diffusive terms into an apparent diffusive term as follows

$$\frac{\partial}{\partial t}\rho_{RL} = \frac{\partial}{\partial z}\left(D_{ap}\frac{\partial}{\partial z}\rho_{RL}\right) \tag{3}$$

where initial and boundary conditions for Eq. (3) are given by

$$\rho_{RL} = \rho_{RL,0}; \quad for \quad 0 \le z \le L(t) \quad and \quad t = 0 \tag{4.a}$$

$$\rho_{RL} = \rho_{RL,i}; \quad for \quad z = L(t) \tag{4.b}$$

$$\frac{\partial}{\partial z}\rho_{RL} = 0; \quad for \quad z = 0 \tag{4.c}$$

In Eq. (4.a), $\rho_{RL,0}$ is the initial mass concentration of refrigerant in the liquid (set to zero if the liquid layer is initially made up of oil only). Equation (4.b) reflects the assumption of phase equilibrium at the interface (subscript *i*). *A posteriori* scaling analyses revealed that the variation of the height of liquid layer, $L(t)$, as a result of refrigerant absorption was negligible in the experiments of Goswami *et al.* (1998). This is, therefore, assumed constant in the model. By definition, the local mass fraction is given by

$$x_R = \rho_{RL} / \rho_L \tag{5}$$

Therefore, Eqs. (3) and (4) can be written as

$$\frac{\partial}{\partial t} x_R = \frac{\partial}{\partial z}\left(D_{ap} \frac{\partial}{\partial z} x_R \right) \tag{6}$$

$$x_R = x_{R,0}; \quad for \quad 0 \le z \le L \quad and \quad t = 0 \tag{7.a}$$

$$x_R = w_R; \quad for \quad z = L \tag{7.b}$$

$$\frac{\partial}{\partial z} x_R = 0; \quad for \quad z = 0 \tag{7.c}$$

where ρ_L is the local liquid density and w_R is the refrigerant solubility obtained from the experimental results of Goswami *et al.* (1998) for each condition.

Analytical solutions of Eqs. (6) and (7) were provided by several authors, including Crank (1975), as follows

$$\frac{x_R - w_R}{x_{R,0} - w_R} = \sum_{n=1}^{\infty} C_n \exp\left(-\zeta_n^2 \frac{D_{ap} t}{L^2} \right) \cos\left(\zeta_n \frac{z}{L} \right) \tag{8}$$

where

$$C_n = \frac{4 \sin(\zeta_n)}{2\zeta_n + \sin(2\zeta_n)} \tag{9}$$

and

$$\zeta_n = \pi \frac{(2n-1)}{2} \tag{10}$$

In practice, the upper value of *n* is set sufficiently large in the calculations so that appropriate numerical convergence is obtained. The instantaneous volume averaged refrigerant mass fraction is obtained upon integration of Eq. (8) along *z* from *0* to *L*. Thus,

$$\langle x_R \rangle = w_R + (x_{R,0} - w_R) \sum_{n=1}^{\infty} C_n \exp\left(-\zeta_n^2 \frac{D_{ap} t}{L^2} \right) \frac{\sin(\zeta_n)}{\zeta_n} \tag{11}$$

Equation (11) is a key relationship in the present methodology; since it is through a comparison with instantaneous average refrigerant mass fractions obtained experimentally by Goswami *et al.* (1998) — see Eq. (1) — that the apparent diffusion coefficient will be determined for each refrigerant-oil pair as a function of pressure and temperature. This is performed through a minimization procedure of the objective function defined as follows (Martz and Jacobi, 1994)

$$Ob = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{\langle x_R \rangle_{cal,i} - \langle x_R \rangle_{\exp,i}}{\langle x_R \rangle_{\exp,i}} \right)^2 \tag{12}$$

where *N* is the number of experimental points obtained at different times along an absorption experiment and the subscripts *calc* and *exp* stand for calculated and experimental, respectively.

3. Results

Results are presented in terms of the volume averaged liquid mass fraction of refrigerant as a function of time. Figures (2), (3), (4) and (5) illustrate the absorption of R-32, R-125, R-134a and R-143a by lubricant oil POE68, respectively. The temperature is maintained constant at 24^{o}C for the four cases, whereas the variation of pressure is assessed at three different levels. As can be seen from Figs. (2)-(5), in conjunction with the results in Table (1), the trend suggested by Yokozeki (2002) that the apparent diffusion coefficients increase with pressure (and hence with solubility) at constant temperature has not been confirmed by the present study. In general, what can be observed from a comparison between the data exhibited in columns 3, 6 and 7 of Table (1) is that the behaviour of the apparent diffusion coefficient calculated from the present analysis is in line with that of the absorption rate, K, obtained by Goswami *et al.* (1998). This is exactly what one would expect just by examining the forms of Eqs. (1) and (8).

It is believed, therefore, that the contradiction in the conclusions of Yokozeki (2002) and the results in Table (1) may arise due to one or from a combination of the following:

(i) Experimental values of solubility were used in the interfacial boundary condition in the present study. This was not the case for Yokozeki (2002), whose value of w_R was determined as part of the solution methodology through a regression analysis;

(ii) A somewhat different (but not entirely so) database was used by Yokozeki (2002) to calibrate his model.

The values of solubility calculated as part of the solution procedure of Yokozeki (2002) practically eliminate option (i) above, since they are very close to the experimental values and also in very good agreement with solubility data from other sources (Martz and Jacobi, 1994). In addition, our apparent diffusion coefficients and those of Yokozeki — columns 3 and 7 of Table (1) — are in relatively good agreement also.

It is not the purpose of the present paper to undertake a point-by-point comparison between the databases published by Goswami *et al.* (1998) and by Leung *et al.* (1998) (the former is an internal report and the latter is a paper by the same authors, containing virtually the same database) and that used by Yokozeki (2002) in his paper. However, it is worthy of note that the experimental data for R-143a and the 239 kPa run for R-125 were not present in Yokozeki's analysis. Our apparent diffusion model exhibits a very particular behaviour for this run — see Fig. (3) — with diffusion coefficients in excess of 2 times higher than that for the 446 kPa case.

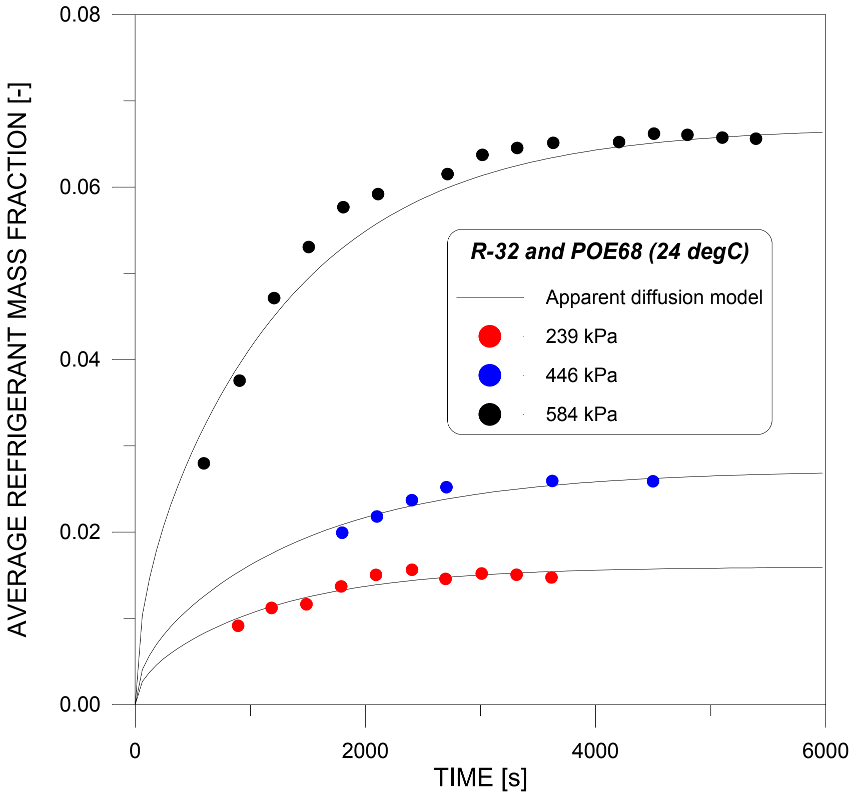

Figure 2. Absorption of R-32 by POE68 at 24^{o}C and different pressures.

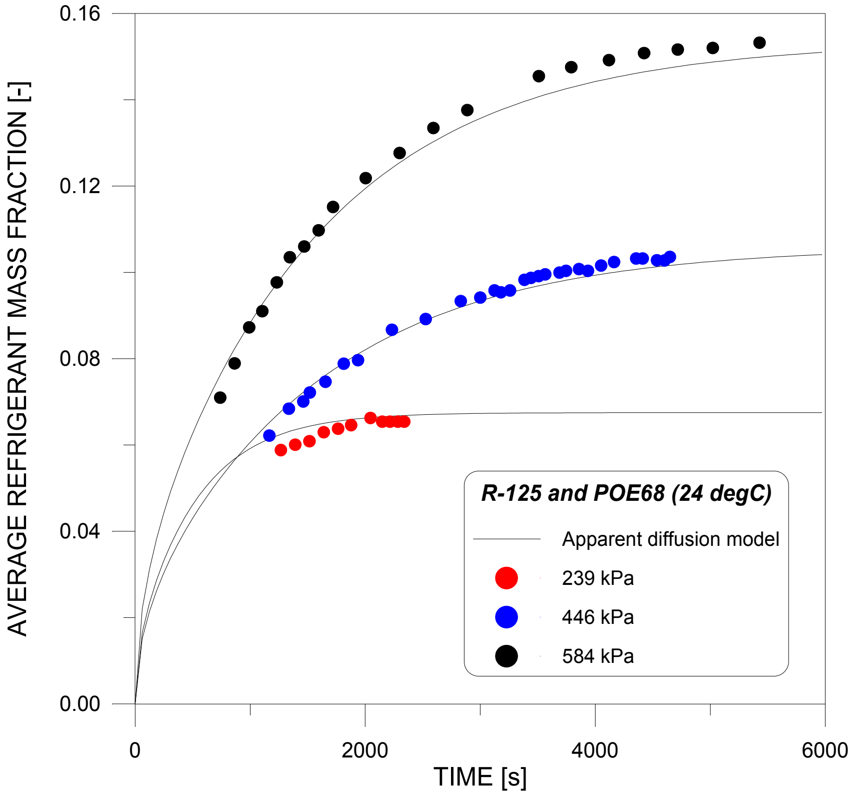

Figure 3. Absorption of R-125 by POE68 at 24°C and different pressures.

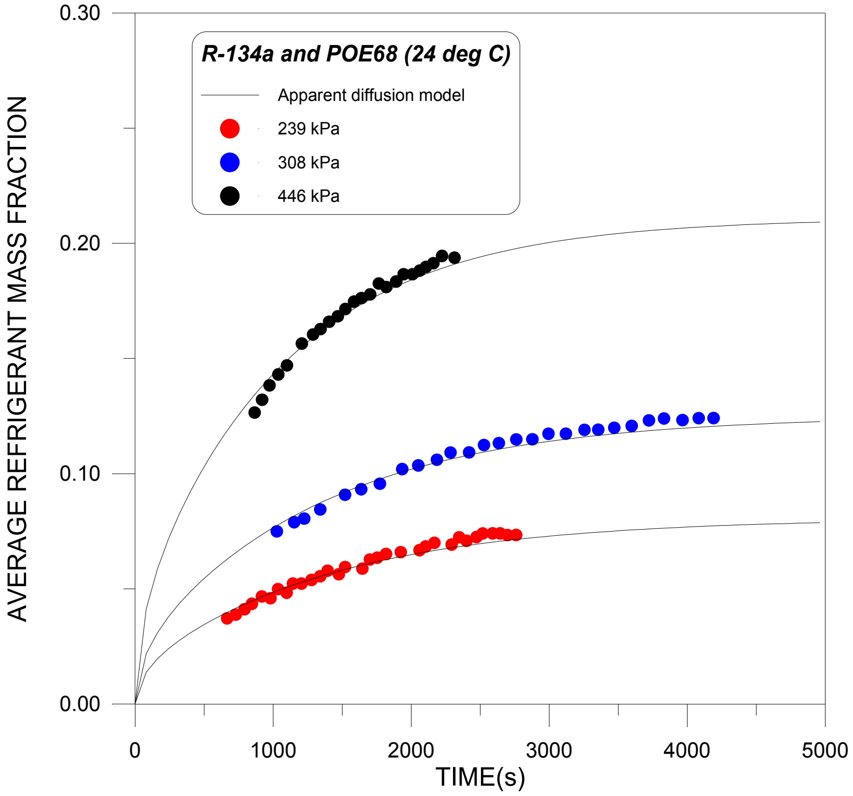

Figure 4. Absorption of R-134a by POE68 at 24°C and different pressures.

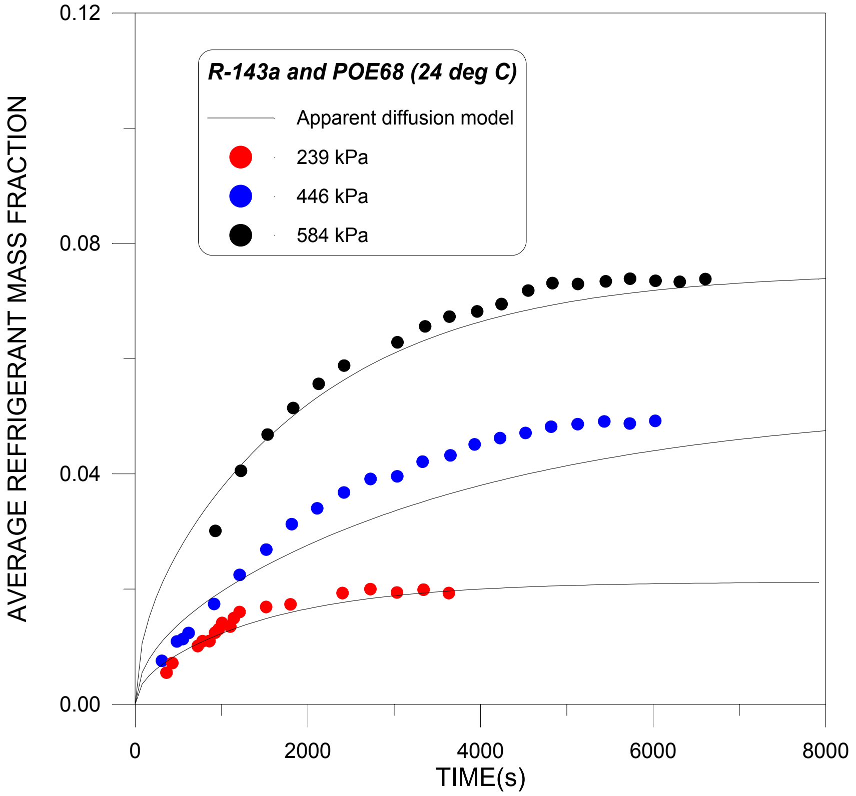

Figure 5. Absorption of R-143a by POE68 at 24°C and different pressures.

Table 1. Summary of calculated and experimental results absorption of pure refrigerants by lubricant oil.

		R-125				
p [kPa]	**T [^{o}C]**	**D_{ap} [10^{-9} m^2/s]**	**Ob [10^{-3} -]**	**w_R [-]^a**	**K [min^{-1}]^b**	**D_{ap} [10^{-9} m^2/s]^c**
239	24	4.7753	0.4002	0.0675	0.0975	-
446	24	1.6185	0.4038	0.1060	0.0506	1.422
584	24	1.6371	0.7923	0.1536	0.0520	1.498
239	34	5.8486	2.5545	0.0292	0.1849	-
		R-32				
p [kPa]	**T [^{o}C]**	**D_{ap} [10^{-9} m^2/s]**	**Ob [10^{-3} -]**	**w_R [-]^a**	**K [min^{-1}]^b**	**D_{ap} [10^{-9} m^2/s]^c**
239	24	2.2093	3.0333	0.0160	0.0630	1.789
446	24	1.7618	1.1246	0.0272	0.0491	1.796
584	24	1.9032	3.0499	0.0670	0.0605	1.847
239	34	3.4846	5.1156	0.0092	0.1084	-
		R-134a				
p [kPa]	**T [^{o}C]**	**D_{ap} [10^{-9} m^2/s]**	**Ob [10^{-3} -]**	**w_R [-]^a**	**K [min^{-1}]^b**	**D_{ap} [10^{-9} m^2/s]^c**
239	24	1.7987	1.4148	0.0806	0.0557	1.494
308	24	1.8625	0.6825	0.1252	0.0510	1.729
446	24	2.3490	0.4705	0.2109	0.0662	2.016
239	34	7.5746	3.1342	0.0828	0.2049	-
		R-143a				
p [kPa]	**T [^{o}C]**	**D_{ap} [10^{-9} m^2/s]**	**Ob [10^{-3} -]**	**w_R [-]^a**	**K [min^{-1}]^b**	**D_{ap} [10^{-9} m^2/s]^c**
239	24	1.6577	14.1156	0.0213	0.0509	-
446	24	0.6869	34.8658	0.0523	0.0290	-
584	24	1.2291	3.2185	0.0751	0.0379	-
239	34	9.3867	77.6663	0.0340	0.5941	-

a: Experimental values by Goswami *et al.* (1998)
b: Absorption constant obtained by Goswami *et al.* (1998)
c: Apparent diffusion coefficient obtained by Yokozeki (2002)

The effect of temperature on the apparent diffusion coefficient is observed in Figs. (6) and (7) for R-32 and R-125 with POE68 for 24 and 34^{o}C at 239 kPa. As can be seen, the model conforms to the data reasonably well and, according to Table (1), apparent diffusion coefficient values are higher for higher temperatures. This observation supports the fact that higher solubility alone is not the sole responsible for higher apparent diffusion coefficients.

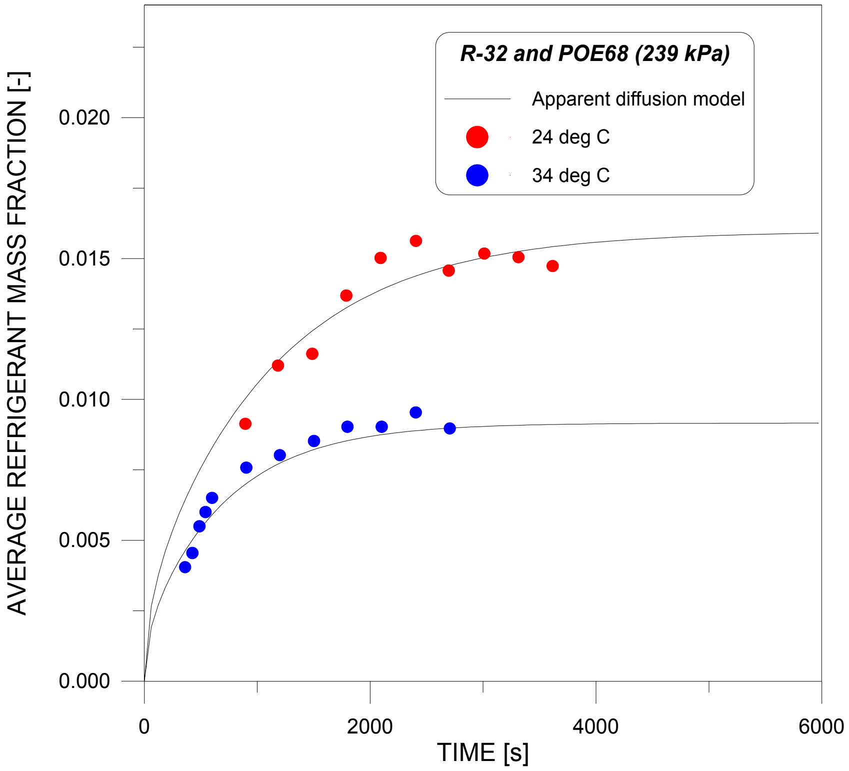

Figure 6. Absorption of R-32 by POE68 at 289 kPa and different temperatures.

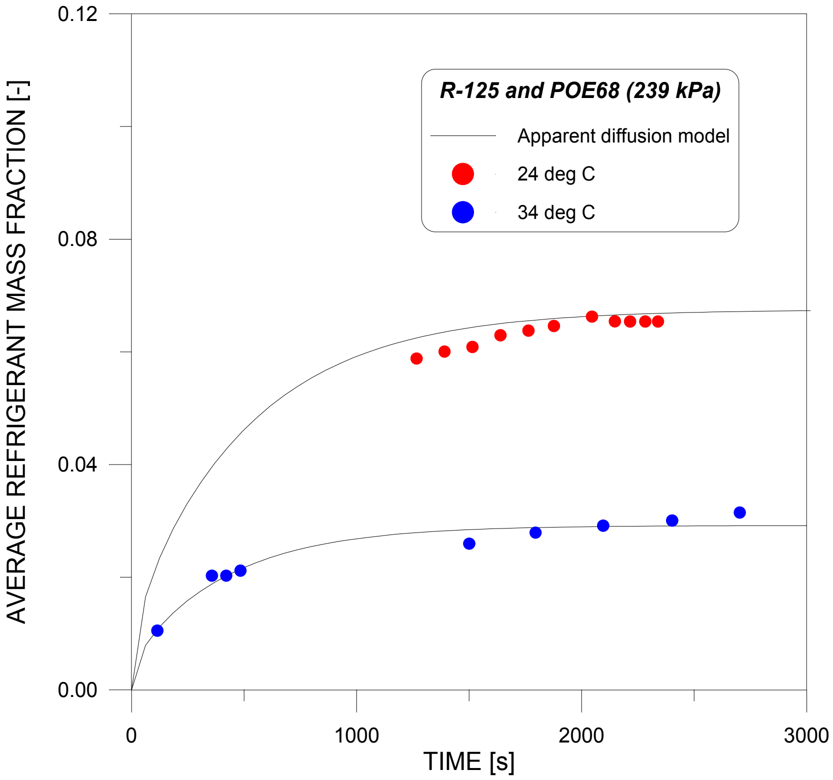

Figure 7. Absorption of R-125 by POE68 at 289 kPa and different temperatures.

Preliminary results for the absorption of refrigerant mixtures are presented in Table (2). As can be seen from the values of *Ob*, the methodology still can be applied with relative success in these cases. However, it is felt that the model is as limited as the adsorption constant model of Goswami *et al.* (1998) because it does not provide physical insight into the nature of the absorption phenomena since it is impossible to evaluate the interaction between individual refrigerant-oil pairs and between pairs of refrigerants.

Table 2. Summary of calculated and experimental results for absorption of refrigerant mixtures by lubricant oil.

		R-410a			
p **[kPa]**	***T*** **[°C]**	D_{ap} **[10^{-9} m^2/s]**	***Ob*** **[10^{-3} -]**	w_R **[-]**^{a}	***K*** **[min^{-1}]**^{b}
239	24	5.5015	1.3377	0.0294	0.1614
446	24	2.7371	0.4349	0.0707	0.0781
584	24	6.3136	0.6858	0.1630	0.1690
239	34	5.3288	1.3375	0.0172	0.1402
		R-407c			
p **[kPa]**	***T*** **[°C]**	D_{ap} **[10^{-9} m^2/s]**	***Ob*** **[10^{-3} -]**	w_R **[-]**^{a}	***K*** **[min^{-1}]**^{b}
239	24	0.3581	38.8984	0.0493	0.0166
446	24	1.7330	3.2197	0.1158	0.0581
584	24	3.0389	2.0741	0.2149	0.0887
239	34	2.4009	1.5215	0.0605	0.0739
		R-404a			
p **[kPa]**	***T*** **[°C]**	D_{ap} **[10^{-9} m^2/s]**	***Ob*** **[10^{-3} -]**	w_R **[-]**^{a}	***K*** **[min^{-1}]**^{b}
239	24	0.3628	110.6713	0.0220	0.0211
308	24	0.9787	3.6823	0.0674	0.0281
446	24	1.0034	9.0818	0.1099	0.0329
239	34	8.6078	0.3508	0.0465	0.2162

a: Experimental values by Goswami *et al.* (1998)

b: Absorption constant obtained by Goswami *et al.* (1998)

4. Conclusions

This paper utilized the concept of the apparent molecular diffusion coefficient (Fukuta *et al.*, 1995) to describe the absorption of refrigerant vapour by stagnant oil. The one-dimensional absorption model combined with a least-square minimization procedure were conformed to the experimental data of Goswami *et al.* (1998) in order to provide apparent diffusion coefficients for a given oil-refrigerant pair under different pressure-temperature conditions.

For absorption of pure refrigerants by polyol ester oil, the results differ somewhat from those obtained by Yokozeki (2002), who employed a similar model but calibrated it with only part of the database of Goswami *et al.* (1998). When using the whole database as in the present study, the straightforward conclusion that the apparent diffusion coefficient increases with increasing pressure (and therefore solubility) at a constant temperature no longer holds.

As for absorption of refrigerant mixtures, the model still can be used with relative success to predict refrigerant absorption. However, it provides little physical insight into the nature of the absorption of the pure components individually. A next step is to combine the apparent diffusion model for the liquid phase with a one-dimensional diffusion model for the vapour phase and with a vapour-liquid equilibrium model for the interface. Such an analysis is under implementation by the present authors and will be presented at a later stage.

5. Acknowledgements

The authors are grateful to CNPq and to Embraco S.A. for financial support.

6. References

Crank, J., 1975, “The Mathematics of Diffusion”, 2nd Ed., Oxford Science Publications.

Fukuta, M., Yanagizawa, T., Shimizu, T. and Saijo, H., 1993, “Characteristics of Refrigerant Solution for Lubricating Oil, Proceedings of the Japanese Association of Refrigeration Meeting, pp. 21-24.

Fukuta, M., Yanagizawa, T., Shimizu, T. and Nishijima, H., 1995, “Transient Mixing Characteristics of Refrigerant with Refrigeration Oil, Proceedings of the 19th International Congress of Refrigeration IVa, pp. 215-222.

Goswami, D.Y., Shah, D.O., Jotshi, C.K., Bhagwat, S.S., Leung, M., Gregory, A.S. and Lu S., 1998, “Foaming Characteristics of of Refrigerant/Lubricant Mixtures”, ARTI-MCLR Report 665-53200.

Leung, M., Jotshi, C.K., Goswami, D.Y., Shah, D.O. and Gregory, A., 1998, “Measurements of Absorption Rates of HFC Single and Blended Refrigerants in POE Oils”, International Journal of HVAC&R Research, Vol. 4(2), pp. 141-151.

Martz, W.L. and Jacobi, A.M., 1994, "Refrigerant-Oil Mixtures and Local Composition Modeling", ACRC Report TR-68, University of Illinois at Urbana-Champaign.

Silva, A., 2004, "Cinemática e Dinâmica do Processo de Absorção de Gás Refrigerante em Óleo Lubrificante", D.Eng. Thesis, Universidade Federal de Santa Catarina.

Yokozeki, A., 2002, "Time-Dependent Behavior of Gas Absorption in Lubricant Oil", International Journal of Refrigeration, Vol.25, pp. 695-704.