

SOLUBILITY, DENSITY AND VISCOSITY OF A MIXTURE OF R-600a (ISOBUTANE) AND A LINEAR ALKYL BENZENE LUBRICANT OIL

Moisés A. Marcelino Neto, moises@polo.ufsc.br

Jader R. Barbosa, Jr., jrb@polo.ufsc.br

Polo-Research Laboratories for Emerging Technologies in Cooling and Thermophysics
Mechanical Engineering Department
Federal University of Santa Catarina, Florianópolis, 88040-900, SC, Brazil

Rosângela Maria Machado, rosangela_m_machado@embraco.com.br

Embraco
Rua Rui Barbosa 1020, Joinville, 89219-901, SC, Brazil

Abstract. Isobutane (R-600a) and carbon dioxide (R-744) are the most promising environmentally-friendly substitute refrigerants for hydrofluorocarbons (HFC) and chlorofluorocarbons (CFC): two major contributors to global warming and ozone depletion. In the vapor compression refrigeration system, the lubricant oil plays an important role and thus the behavior of the thermophysical properties of refrigerant-oil mixtures must be well understood. In the present work, thermophysical properties (solubility, density and viscosity) of R-600a and a new linear alkylbenzene lubricant oil (AB ISO 5) were determined experimentally at pressures and temperatures ranging from 1 to 20 bar and 23 to 80°C, respectively. The experimental solubility and density data were correlated using the Peng and Robinson (1976) and Soave-Redlich and Kwong (1972) equations of state. The correlation due to Focke et al. (2007), based on the molecular cluster theory of Scott (1956), was applied in order to correlate the mixture dynamic viscosity.

Keywords: lubricant oil, isobutane, solubility, density, viscosity.

1. INTRODUCTION

In the last decades, following the realization of the effect of refrigerants on the destruction of the ozone layer and their contribution to global warming, many researchers started to concentrate their efforts on the characterization of the thermophysical properties of substitute refrigerants and their mixtures with lubricant oils. In this context, isobutane (R-600a) is one of the most promising natural refrigerant substitutes for hydrofluorocarbons (HFC) and chlorofluorocarbons (CFC). Isobutane, together with carbon dioxide (R-744), has motivated the development of new compressor oils to optimize the performance and reliability of household refrigeration systems. The presence of lubricant oil in the refrigerant (and vice-versa) has a large influence on the thermodynamic properties of the working fluid. Therefore, the efficiency of refrigeration systems will depend on the optimal choice of the compressor oil.

In the past few years the number of publications on thermophysical properties of natural refrigerants with lubricant oils has increased considerably (Seeton and Hrňjak, 2006; Seeton et al., 2000; Hauk and Weidner, 2000; Youbi-Idrissi et al., 2005; Tsuji et al., 2004; Tsuji et al., 2005; Bobbo et al., 2005; Bobbo et al., 2006), but there is a lack of studies dealing specifically with isobutane and lubricant oil mixtures. Marcelino Neto and Barbosa (2008) measured the solubility and the liquid phase density and viscosity of a mixture of R-600a and a POE ISO 7 lubricant oil at temperatures ranging from 10 to 60°C. The VLE data were correlated with the Heil–Prausnitz and Flory–Huggins activity models and the Peng and Robinson (1976) equation of state (EoS). Liquid density was correlated with the Peng and Robinson EoS and with a first-order Redlich–Kister expansion for the excess molar volume. Liquid viscosity was correlated with an excess-property approach based on the classical Eyring liquid viscosity model. Kumagai et al. (2007) measured the viscosities of liquids mixtures of isobutane and squalane from 0 to 60°C. The experimental viscosities values were fitted with a Tait-like equation. Zhelezny et al. (2006) presented experimental data for solubility, density and capillary constants for solutions of isobutane with a commercial mineral compressor oil (Azmol) over wide ranges of temperature (30 to 90°C) and concentrations. The enthalpy of the liquid phase solution was calculated and an analysis of the behavior of the excess thermodynamic functions was carried out. The paper also examined the nature of the experimental uncertainties in the investigation of thermodynamic properties of the refrigerant/oil solutions.

The present paper puts forward new data on solubility, density and viscosity of mixtures of isobutane and a linear alkylbenzene lubricant oil (LAB ISO 5) and uses the Peng and Robinson (1976) and Soave-Redlich and Kwong (1972) EoS to predict the phase equilibrium data and the density behavior. The viscosity data is correlated with a model based on the molecular cluster theory (Focke et al., 2007).

2. MATERIALS AND METHODS

2.1. Experimental apparatus and procedure

The experimental facility and procedure have been presented in previous papers (Marcelino Neto and Barbosa, 2007, 2008) and only its main features will be repeated here. A specified amount of lubricant oil is placed in the 4L

equilibrium cell (2). A vacuum of 0.04 mbar is generated in the apparatus to remove moisture and dissolved gases. An initial amount of refrigerant is fed into the cell. The system temperature is set by a thermostatic bath (1) that circulates service water through a tank (6) in which the equilibrium cell is fully immersed. In the present experiments, the pressure of the lubricant-refrigerant mixture is, therefore, the dependent variable. The equilibrium cell is instrumented for absolute pressure, P , and the temperature of the fluids in the cell is recorded by three type-T thermocouples ($T1$, $T2$, $T3$) located at three distinct heights to measure the temperatures of the liquid and vapor phases. A gear pump (5) moves the liquid lubricant-refrigerant mixture through the experimental facility. The speed of the electrical motor is set at its minimum value (12 Hz). The mixture first flows through a Coriolis-type mass flow transducer (4) that records flow rate, temperature and liquid density. Then, an oscillating piston viscometer (3) registers temperature and dynamic viscosity of the liquid mixture. The solubility of the mixture is measured gravimetrically using a liquid mixture sample collected in a 150 mL cylinder (7). The experimental apparatus is integrated with a signal conditioning module (8) and a computerized system for data acquisition and treatment (9). The tank (top, sides and bottom), connection tubing and instrumentation (Coriolis flow meter, pump and sampling cylinder) are thermally insulated to prevent heat losses. The temperature variation between the viscometer, the mass flow/density meter and test cell were within the uncertainty level set during the calibration of the thermocouples. The experimental procedure for obtaining the mixture solubility has been outlined in Marcelino Neto and Barbosa (2007).

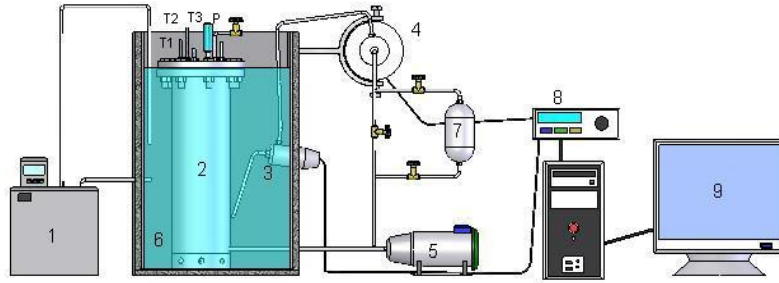


Figure 1. Schematic diagram of the Thermophysical Properties Facility.

2.2. Experimental conditions

Solubility, liquid density and liquid dynamic viscosity of the R-600a/LAB ISO 5 mixture were measured at temperatures between 23 and 80°C (nominal). R-600a was 99.5% according to its manufacturer/supplier. The molecular mass and the chemical structure of the lubricant oil are proprietary information.

3. MODELING

3.1. Solubility

For every component in the mixture, the phase equilibrium is characterized by an equality of the fugacities in both phases. In the case of vapor-liquid equilibrium, the condition of thermodynamic equilibrium is given by (Poling *et al.*, 2000),

$$\hat{f}_i^V = \hat{f}_i^L \quad (1)$$

Component fugacities in both phases are solved directly using the equations of state (EoS). Equations of state are widely used in the prediction of thermodynamic properties of pure fluid and fluid mixtures, in part because they provide a thermodynamically consistent route to properties of both gaseous and liquids. Consequently, equations of state may be used to determine phase equilibrium conditions as well as other properties. It is well known that a simple cubic type EoS can correlate pressure, temperature and composition data in VLE (vapor-liquid-equilibria) or VLLE (vapor-liquid-liquid-equilibria) with sufficient accuracy, although the volumetric correlation, particularly for the liquid phase, is poor (Yokozeki, 2001).

In this study we have used two typical cubic EoS (Peng and Robinson (PR) and Soave-Redlich & Kwong (SRK)). They are written in the following general form for the compressibility factor, $Z = PV/RT$,

$$Z^3 - \lambda Z^2 + \delta Z - \Omega = 0 \quad (2)$$

where

$$\lambda = (1 - B), \delta = (A - 3B^2 - 2B), \Omega = (AB - B^2 - B^3) : \text{PR type EoS} \quad (3)$$

$$\lambda = (1 - B), \delta = (A - B^2 - B), \Omega = (AB) : \text{SRK type EoS} \quad (4)$$

$$A = \sum_{i=1}^n \sum_{j=1}^n x_i x_j (1 - k_{ij}) \sqrt{A_i A_j} \quad (5)$$

$$B = \sum_{i=1}^n x_i B_i \quad (6)$$

$$a\alpha = \sum_{i=1}^n \sum_{j=1}^n x_i x_j (1 - k_{ij}) \sqrt{(a_i \alpha_i)(a_j \alpha_j)} \quad (7)$$

$$b = \sum_{i=1}^n x_i b_i \quad (8)$$

$$A_i = \xi \alpha_i \frac{P_{r,i}}{T_{r,i}^2} \quad B_i = \tau \frac{P_{r,i}}{T_{r,i}} \quad (9)$$

$$a_i = \xi \frac{(RT_{c,i})^2}{P_{c,i}} \quad b_i = \tau \frac{RT_{c,i}}{P_{c,i}} \quad (10)$$

$$\alpha_i = \left[1 + n_i \left(1 - \sqrt{T_{r,i}} \right) \right]^2 \quad n_i = \varsigma + \vartheta \omega_i - \kappa \omega_i^2 \quad (11)$$

where

$$\xi = 0.45724, \tau = 0.07780, \varsigma = 0.37464, \vartheta = 1.54226, \kappa = 0.26992 : \text{PR type EoS} \quad (12)$$

$$\xi = 0.42747, \tau = 0.08664, \varsigma = 0.48508, \vartheta = 1.55171, \kappa = 0.15613 : \text{SRK type EoS} \quad (13)$$

and the interaction parameter k_{ij} is adjusted to best fit the experimental data.

The fugacity coefficient is calculated via the definition of the Gibbs energy departure function, and the expressions for such coefficients are obtained using the PR and SRK EoS, respectively (Assael *et al.*, 1996),

$$\ln \hat{\phi}_i = \frac{B_i}{B} (Z - 1) - \ln(Z - B) + \frac{A}{2.828B} \left[\frac{B_i}{B} - \frac{2}{a\alpha} \sum_{j=1}^N x_j (1 - k_{ij}) \sqrt{(a_i \alpha_i)(a_j \alpha_j)} \right] \ln \left(\frac{Z + 2.414B}{Z - 0.414B} \right) \quad (14)$$

$$\ln \hat{\phi}_i = \frac{B_i}{B} (Z - 1) - \ln(Z - B) + \frac{A}{B} \left[\frac{B_i}{B} - \frac{2}{a\alpha} \sum_{j=1}^N x_j (1 - k_{ij}) \sqrt{(a_i \alpha_i)(a_j \alpha_j)} \right] \ln \left(1 + \frac{B}{Z} \right) \quad (15)$$

where x_j is the component mole fraction in each phase. The vapor pressure of the lubricant oil is very low and it can be assumed with negligible loss of generality that the vapor mole fraction of refrigerant equals unity. Equations (14) and (15) can be used to calculate the fugacity coefficients in the liquid and vapor phases, the only differences being the values of the compressibility factors and mole fractions in each phase.

3.2. Density

The density of the liquid phase was also calculated using an EoS approach. Having calculated the liquid phase compressibility factor, the mixture molar volume and the mixture density are given by,

$$V^L = \frac{Z^L RT}{P} \quad (16)$$

$$\rho^L = \frac{M}{V^L} \quad (17)$$

It is widely acknowledged that the major weakness of cubic equations is that they provide only rough predictions of liquid density. However, a simple empirical correction, known as volume translation, can be incorporated in order to improve the density prediction without affecting the pressure, temperature and composition calculations. In the liquid density calculations, the volume translation correction of Peneloux *et al.* (1982) was applied and the modified molar volume is given by,

$$V^{L*} = V^L + c(T, x_1, x_2) \quad (18)$$

where $c(T, x_1, x_2)$ is a correction modeled as,

$$c(T, x_1, x_2) = x_1 c_1 + x_2 c_2 \quad (19)$$

According to Assael *et al.* (1996), since the volume translation does not alter the shape of P - V isotherms, it has no effect on the predicted vapor pressure. In this way, $c(T, x_1, x_2)$ can be adjusted to obtain agreement with experimental molar volumes of the saturated liquid.

3.3. Viscosity

According to Scott's model (Scott, 1956) a multicomponent mixture may be viewed conceptually as a hypothetical collection of fluid clusters, as seen in Fig. 2. The cluster type is determined by the nature of the central molecule and its properties are governed by the interaction of this molecule with its nearest neighbors. The molecular interactions are characterized by binary coefficients a_{ij} with i indicating the nature of the central molecule of the cluster and j a neighboring molecule (Focke *et al.*, 2007).

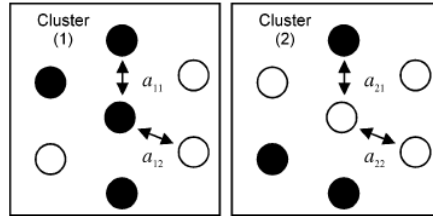


Figure 2. Schematic illustration of Scott's model for a fluid mixture: In cluster 1 a molecule of component 1 is located at the center whereas cluster 2 has a molecule of component 2 at the center (Scott, 1956).

In this context, Focke *et al.* (2007) defined a mixture model based on an estimation of the fluid cluster properties and on their combination to yield an overall mixture property. The authors obtained a particularly flexible form of the model by using a composition-weighted power law based on global mole fractions. The viscosity mixture model is given by,

$$\eta = \left[\sum_{i=1}^n x_i \left(\sum_{j=1}^n x_j \eta_{ij}^s \right)^{r/s} \right]^{1/r} \quad (20)$$

where r and s are adjustable parameters, η_{ii} is the pure component dynamic viscosity and η_{ij} is defined as,

$$\ln \eta_{ij} = \frac{|\ln \eta_i - \ln \eta_j|}{2} \quad (21)$$

3.4. Computational implementation and solution procedure

Standard iterative calculation procedures (Poling *et al.*, 2000; Assael *et al.*, 1996) were applied to solve Eq. (1) for phase equilibrium. The models were implemented in the Engineering Equation Solver (EES) program (Klein, 2004). Pure component constants for the refrigerant were obtained from the physical properties database embedded in EES. The acentric factor and critical properties of the oil were calculated using the group contribution method of Constantinou and Gani (1994), and Constantinou *et al.* (1995). The EoS interaction parameter k_{ij} , the volume translation corrections c_1 e c_2 and the viscosity adjustable parameters r and s were fitted using the genetic algorithms available in EES.

The following objective function was used,

$$Ob = \sum_{i=1}^n (\theta_{cal,i} - \theta_{exp,i})^2 \quad (22)$$

where θ can be pressure, liquid density or liquid dynamic viscosity. The search interval within each parameter was optimized and their optimum values are shown in Table 1.

Table 1. Model Parameters

Model	Property	Parameter	Search Interval	RMS(%)	AAD(%)	Bias(%)
PR EoS	x_l	$k_{12}=-0.02668$	-1 to 1	1.75	8.01	-4.57
SRK EoS	x_l	$k_{12}=-0.03839$	-1 to 1	1.92	8.73	-4.94
PR EoS	ρ	$c1=0.002647$ $c2=0.05364$	-1000 to 1000	0.18	1.08	-0.01
SRK EoS	ρ	$c1=-0.03861$ $c2=-0.01688$	-1000 to 1000	1.97	8.50	1.73
Focke <i>et al.</i> (2007)	η	$r=-0.8578$ $s=0.5310$	-2 to 2	1.28	7.34	-1.06

4. RESULTS

In order to compare the ability of present different models to predict the VLE, density and viscosity behavior, the following statistical quantities are defined,

$$RMS = \frac{100}{n} \sqrt{\sum_{i=1}^n \frac{(\theta_{cal} - \theta_{exp})^2}{\theta_{exp}^2}} \quad (23)$$

$$AAD = \frac{100}{n} \sum_{i=1}^n \left| \frac{(\theta_{cal} - \theta_{exp})}{\theta_{exp}} \right| \quad (24)$$

$$Bias = \frac{100}{n} \sum_{i=1}^n \frac{(\theta_{cal} - \theta_{exp})}{\theta_{exp}} \quad (25)$$

where n is the total number of experimental points, θ_{exp} the measured solubility, density or viscosity, and θ_{cal} the value calculated using a given model.

4.1. Solubility

Figure 3 shows the experimental data of vapor pressure as a function of solubility and temperature. The predictions of each EoS are also presented. The Peng and Robinson (1976) and Soave-Redlich and Kwong (1972) EoS have shown a similar performance, with a typical average absolute deviation (AAD) of the order of 8% (nevertheless, the agreement was notably worse at 80°C). The root mean square (RMS) deviation, the average absolute deviation (AAD) and the Bias of the vapor pressure (Eqs. (23)–(25)) associated with PR EoS are 1.75%, 8.01% and -4.57%, respectively. The RMS deviation, the AAD and the Bias of the SRK EoS are 1.92%, 8.73% and -4.94%, respectively. Despite the structural similarities between the Peng and Robinson (1976) and Soave-Redlich and Kwong (1972) EoS and the fact that both

require only the pure components critical constants and the pure components acentric factors for mixture predictions, the performance of the PR EoS was superior, especially at higher temperatures. Daubert *et al.* (1978) reported in a comprehensive study of the predictive capabilities of various thermodynamics models that the Soave-Redlich and Kwong (1972) and Peng and Robinson (1976) EoS were of roughly equal reliability for VLE calculations in the vicinity of the critical point, although the PR representation of the PVT data was better. It should be noted that in both EoS predictions only one adjustable parameter (k_{12}) was used for all the experimental data, reflecting the good performance of the model to predict the phase equilibrium in the liquid mixture.

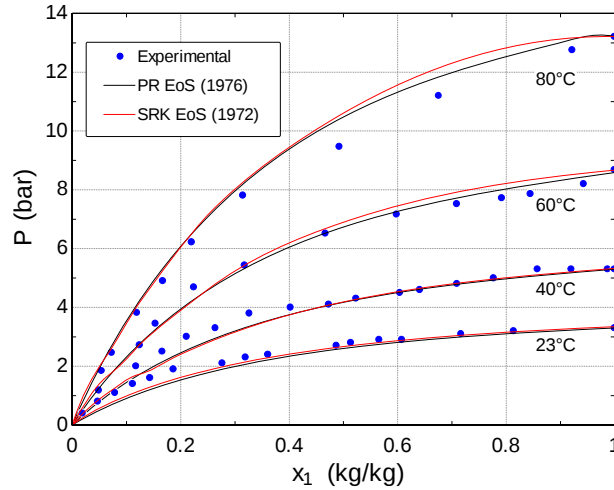


Figure 3. Experimental data and modeling predictions of the vapor pressure versus solubility for the R-600a/LAB ISO 5 liquid mixture.

4.1. Density

Figure 4 presents the behavior of the experimental density and its predictions with the Peng and Robinson (1976) as a function of refrigerant solubility and temperature. In all cases, the EoS overpredicts the experimental data (demonstrating the weak capability of this EoS in predicting the volume behavior). The liquid density predictions improve considerably when the volume translation of Eq. (18) is used (Peneloux *et al.*, 1982). The model predicts the data with associated RMS deviation, AAD and Bias of 0.18%, 1.08% and -0.01%, respectively. The Soave-Redlich and Kwong EoS (1972) predictions of the liquid density mixture were very much worse than the PR EoS and the empirical volume translation technique has shown little effect at improving the predictions, so graphical results will not be shown here. The RMS, AAD and Bias for this model can be confirmed in Table 1. The EoS volume translation is the focus of some works in the literature (Frey *et al.*, 2007; de Sant'Ana *et al.*, 1998) and, according to these authors, there are some specific volume translation models that work better than others depending on the EoS.

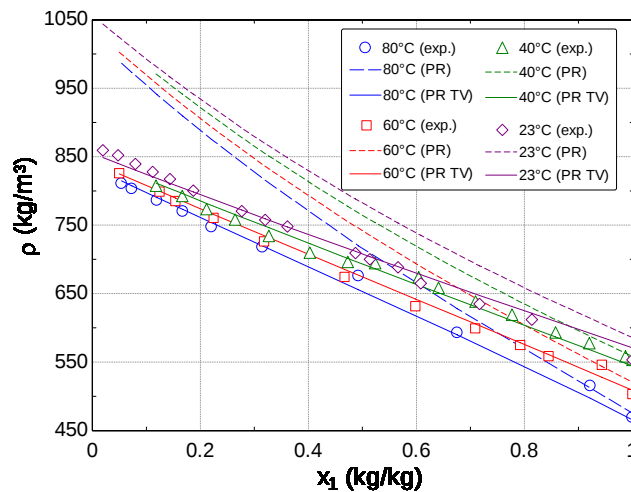


Figure 4. Experimental data and PR EoS predictions of the density versus solubility for the R-600a/LAB ISO 5 liquid mixture.

4.1. Viscosity

In Fig. 5, the experimental data for the liquid mixture viscosity versus the mole fraction are presented together with the predictions of the Focke *et al.* (2007) model. Good agreement between the model and the experimental data is observed, suggesting that the model is also applicable in the prediction of the liquid viscosity of refrigerant-lubricant mixtures, since the authors primarily evaluated this model with water and some hydrocarbons mixtures. Only two parameters were optimized to fit all the experimental data. The obtained RMS, AAD and Bias were 1.28%, 7.34% and -1.36%, respectively. It should be pointed out that this model reduces to known mixing rules with $r=s=0$ (Grunberg and Nissan, 1949) and $r=s=1$ (the Scheffé K-polynomial suggested by Hind *et al.* (1960) as a mixing rule).

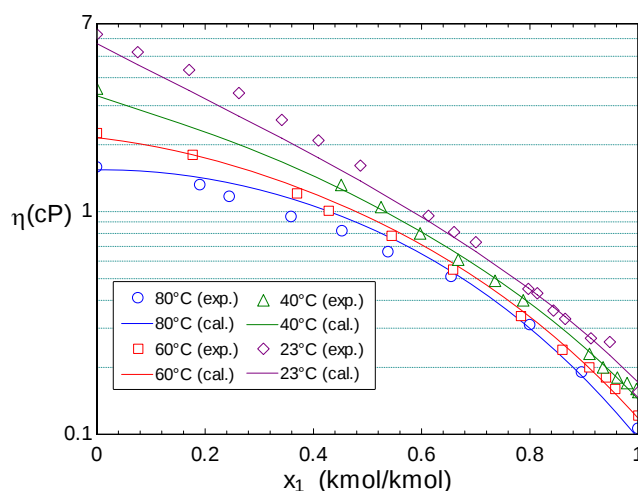


Figure 5. Experimental data and PR EoS predictions of the density versus solubility for the R-600a/LAB ISO 5 liquid mixture.

4. CONCLUSIONS

In the present work, experimental data on solubility, density and viscosity of refrigerant fluid (R-600a) and a linear alkylbenzene lubricant oil (LAB ISO 5) were presented at pressures and temperatures ranging from 1 to 20 bar and 20 to 80°C, respectively. The solubility and density data were correlated using two cubic equations of state and the viscosity data were correlated with a model based on the cluster molecular theory. The main conclusions from this study are as follows:

1. Despite the similarities between the Peng and Robinson (1976) and Soave-Redlich and Kwong (1972) EoS, the former has proven to be more effective in the prediction of the VLE for the present mixture. However, in general, both equations showed an acceptable performance in correlating the relationship between solubility and vapor pressure.
2. Both EoS demonstrated a weak capability with respect to the volume predictions (liquid density). Furthermore, the volume translation technique by Peneloux *et al.* (1982) was successfully incorporated into the Peng and Robinson EoS. Probably this volume technique is not the most adequate for the Soave-Redlich and Kwong EoS.
3. The weighted-power-mean mixing rule for liquid viscosity advanced by Focke *et al.* (2007) has presented a very good agreement with the experimental viscosity data obtained for this refrigerant-lubricant mixture.

5. ACKNOWLEDGEMENTS

This work was financially supported by CAPES, CNPq, FINEP and Embraco. The authors thank Mr. Fabiano Vambommel (UFSC) for technical support.

6. REFERENCES

- Assael, M.J., Trusler, J.P.M., Tsolakis, T.F., 1998, Thermophysical Properties of Fluids: An Introduction to their Prediction. Imperial College Press, London, 353p.
- Bobbo, S., Scattolini, M., Camporese, R., Fedele, L., Stryjek, R., 2005, Solubility of carbon dioxide in pentaerythritol esters. IIR 2005 Vicenza Conference – Thermophysical Properties and Transfer Processes of Refrigerants, Vicenza, Italy, 193-200.
- Bobbo, S., Scattolini, M., Camporese, R., Fedele, L., Stryjek, R., 2006, Solubility of Carbon Dioxide in Some Commercial POE Oils. 7th IIR Gustav Lorentz Conference on Natural Working Fluids, Norway, May, 409-411.

- Constantinou, L., Gani, R., 1994, New group contribution method for estimating properties of pure compounds, *AIChE Journal*, Vol. 40 (10), pp. 1697–1710.
- Constantinou, L., Gani, R., O’Connell, J.P., 1995, Estimation of the eccentric factor and the liquid molar volume at 298 K using a new group contribution method, *Fluid Phase Equilibria*, Vol. 103(1), pp. 11–22.
- Daubert, T.E., Graboski, M.S., Danner, R.P., 1978, Documentation of the basis for selection of the contents of chapter 8 – Vapor-liquid equilibrium K-values in technical data book – Petroleum Refining (API, No 8-78, 1978).
- De Sant’Ana, H.B., Ungerer, P., De Hemptinne, J.C., 1999, Evaluation of a improved volume translation for the prediction of hydrocarbon volumetric properties, *Fluid Phase Equilibria*, Vol. 154, pp. 193-204.
- Focke, W.W., Sandroock, C., Kok, S., 2007, Weighted-power-mean mixture model: Application to multicomponent liquid viscosity, *Ind. Eng. Chem. Res.*, Vol. 46, pp. 4660-4666.
- Frey, K., Augustine, C., Ciccolini, R.P., Paap, S., Modell, M., Tester, J., 2007, Volume translation in equations of state as a mean of accurate property estimation, *Fluid Phase Equilibria*, Vol. 260, pp. 316-325.
- Grunberg, L., Nissan, A.H., 1949, Mixture Law for Viscosity, *Nature*, Vol. 164, pp. 799-800.
- Hauk, A., Weidner, E., 2000, Thermodynamics and fluid-dynamic properties of carbon dioxide with different lubricants in cooling circuits for automobile application. *Ind. Eng. Chem. Res.*, 39, 4646-4651.
- Hind, R.K., McLaughlin, E., Ubbelohde, A.R., Structure and viscosity of liquids. Camphor + Pyrene Mixtures, *Trans. Faraday Soc.*, Vol. 56, 328.
- Klein, S.A., 2004, Engineering Equation Solver, Professional version.
- Kumagai, A., Tomida, D., Yokoyama, C., 2007, Measurements of the liquid viscosities of mixtures of isobutene with squalane to 30 MPa. *Int. J. Thermophys.*, Vol. 28, pp. 1111-1119.
- Marcelino Neto, M.A., Barbosa Jr., J.R., 2007, Experimental characterization of phase equilibrium, liquid density and viscosity of a mixture of R-744 (CO₂) and polyol ester oil. In: 19th International Congress of Mechanical Engineering (COBEM 2007), Brasília.
- Marcelino Neto, M.A., Barbosa, Jr., J. R., 2008, Solubility, density and viscosity of a mixture of R-600a and polyol ester oil. *International Journal of Refrigeration*, Vol. 31, pp. 34-44.
- Poling, B.E., Prausnitz, J.M., O’Connell, J.P., 2000, *The Properties of Gases and Liquids*. McGraw-Hill, New York, Fifth Edition.
- Peneloux, A., Rauzy, E., Freze, R., 1982, A consistent correction for Redlich–Kwong–Soave volumes. *Fluid Phase Equilibria*, Vol. 8, pp. 7–23.
- Peng D.Y., Robinson D.B., 1976, A new two-constant equation of state. *Ind. Eng. Chem.* 15(1), 59-64.
- Scott, R.L., 1956, Corresponding states treatment of nonelectrolyte solutions, *J. Chem. Phys.*, Vol. 25, 193.
- Seeton CJ, Fahl J, Henderson D. 2000, Solubility, viscosity, boundary lubrication and miscibility of CO₂ in synthetic lubricants. *Proc. 4th IIR-Gustav Lorentzen Conference of Natural Working Fluids at Purdue*, pp. 417-24.
- Seeton CJ, Hrnjak P. 2006, Thermophysical properties of CO₂-lubricant mixtures and their affect on 2-phase flow in small channels (less than 1 mm). *Proc. Int. Refrigeration and Air Conditioning Conference at Purdue*, Paper R170, July 17-20.
- Soave, G., 1972, Equilibrium constants from a modified Redlich-Kwong equation of state. *Chem. Eng. Sci*, Vol. 27, pp. 1197-1203.
- Tsuji T., Tanaka S, Hiaki T, Saito R. 2004, Measurements of bubble point pressure for CO₂ + decane and CO₂ + lubricating oil, *Fluid Phase Equilibria* 219 pp. 87–92.
- Tsuji, T., D. Namikawa, T. Hiaki, R. Saito, M. Ito, 2005, Simultaneous Measurement of Solubility, Density and Viscosity of Lubricants with CO₂ (R-744) at High Temperature and Pressures for Refrigerating Systems, *IIR 2005 Vincenza Conference – Thermophysical Properties and Transfer Processes of Refrigerants*.
- Yokozeki A., 2001, Solubility of refrigerants in Various Lubricants. *International Journal of Thermophysics*, Vol. 22, n° 4, 1057-1071.
- Youbi-Idrissi M, Bonjour J, Terrier MF, Meunier F, Marvillet C. 2005, Solubility of CO₂ in a synthetic oil. *Proc. International Congress of Refrigeration 2003*, Washington, D.C., Paper R0300.
- Zhelezny, P.V., Zhelezny, V.P., Prochenko, D.A., Ancherbak, S.N., 2007. An experimental investigation and modeling of the thermodynamic properties of isobutene–compressor oil solutions: some aspects of experimental methodology. *International Journal of Refrigeration* 30, 433–445.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.