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TRANSPORT PROPERTIES AND SURFACE TENSION OF R23/116 AZEOTROPIC MIXTURE

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ABSTRACT

Transport properties (viscosity and thermal conductivity) and surface tension have been measured for the R23/116 azeotropic mixture (46/54 mass %). Viscosity was measured by capillary tube method, thermal conductivity was measured using steady state hot wire method, and surface tension was measured by differential capillary rise method. Saturated transport properties and surface tension were determined over a temperature range from -100 to 10°C. Transport properties for the vapors at atmospheric pressure were measured over a temperature range from -80 to 100°C. Calculated uncertainties of the experimental viscosity, thermal conductivity, and surface tension data are less than $\pm 1.2\%$, $\pm 1.0\%$, and ± 0.05 mN/m, respectively. A set of equations for viscosity, thermal conductivity, and surface tension are presented.

INTRODUCTION

Transport properties (viscosity μ and thermal conductivity λ) and surface tension σ have various applications in the design of refrigeration systems, such as heat exchanger design, equipment retrofit etc., but the research of these properties for alternative refrigerants is very limited, especially for refrigerant mixtures.

The azeotropic mixture of the refrigerants R23/116 (46/54 mass %) has been introduced as an alternative to R503 for low-temperature applications. The R23/116 mixture has the proposed ASHRAE number R508B.

The successful application of this mixture as working fluid for refrigerating systems requires reliable thermophysical properties over a range of parameters including the saturated liquid and vapor and the single-phase vapor region. In this paper, we present new measurements of saturated-liquid and saturated-vapor viscosity and thermal conductivity, viscosity and thermal conductivity for the superheated vapors, and also a new original experimental apparatus and the obtained results for the surface tension of R23/116 mixture. A set of correlation for transport properties and surface tension are also presented.

EXPERIMENTAL PROCEDURE AND RESULTS

Viscosity

Viscosity of R508B was measured using the modified capillary tube method. A detailed description of the viscometer and the experimental procedure are given in our paper [1]. The experimental technique for the viscosity measurements involves creating a pressure difference within a glass mercury pump placed inside a high-pressure vessel. A special design feature of the pump provides for the return of mercury to its initial position after each experiment. Capillary tube with diameters of 0.076 and 0.92 mm

and a length of approximately 50 mm were used in these experiments. Parameters for the mercury pump (initial pressure difference, final pressure difference, volume of the fluid flowing in the capillary over the time of experiment, etc.) were found by calibrations. The viscosity values were calculated taking into account the corrections for the capillary end effects, thermal expansion of the capillary tube, and kinetic-energy factor. The sum of these corrections did not exceed 0.4% of the measured viscosity. Also, the following assumptions about the experiment were taken into account: the fluid expands in the capillary tube; the fluid is compressed inside the pump during the experiment due to a decrease in the pressure difference associated with the decrease in the height of the mercury; some energy dissipates to create the kinetic energy of the fluid flow. As a consequence, an average value for the pressure drop, a density change due to the pressure change, and a change in the mass flow due to the pressure change have been employed.

In these experiments, temperature was measured to within $\pm 0.01^\circ\text{C}$ using mercury thermometers, and pressure was measured to within ± 1 kPa with a digital pressure transducer. All measurements for vapor phase were done using a single capillary tube but different values of the pressure drop (from 0.6 to 3.1 kPa) corresponding to Reynolds number from 5 to 1000. For liquid phase, Re numbers were in the limits of 150-400. Error in the measurement of the pressure drop was $\pm 0.2\%$ and that in the flowrate was $\pm 0.4\%$. The estimated uncertainties in the experimental viscosity data did not exceed $\pm 1.2\%$ at the 95% confidence level. Each experiment was repeated at least ten times at each temperature. The deviation of the individual measurements from the average viscosity value at each temperature did not exceed $\pm 0.2\%$.

Experiments for viscosity of R508B were carried out over a temperature range from -100 to 10°C . The obtained results are given in Table. 1.

Table 1. Experimental Viscosity Data of R508B

T ($^\circ\text{C}$)	Viscosity ($\mu\text{Pa}\cdot\text{s}$)		
	Vapor at Atmospheric Pressure	Saturated Vapor	Saturated Liquid
-90			373.2
-80	9.70	9.81	
-70	10.21	10.32	285.2
-50	11.20	11.41	222.3
-48.44			217.7
-40.00		11.73	196.5
-30.00		12.45	173.0
-20.00	12.74	13.40	150.0
-10.00		14.48	130.5
0.00	13.73	16.21	111.4
4.00			101.1
5.00		17.85	
6.09			95.61
8.02		19.34	
20.00	14.71		
40.00	15.70		
60.00	16.67		
80.00	17.65		
100.00	18.59		

Thermal Conductivity

The thermal conductivity of R508B was measured using a modified steady-state hot-wire method. A detailed description of the apparatus and the experimental technique are given elsewhere [2]. A special feature of the thermal conductivity apparatus is the application of a thin-walled platinum capillary tube (outside diameter = 1.0 mm, inside diameter = 0.9 mm) as the outer resistance thermometer. A platinum wire (diameter = 0.1 mm and length = 80 mm) located inside this capillary tube is used as an electric heater and at the same time as the inner resistance thermometer. In order to center this wire inside the capillary tube, the latter was placed within a glass tube that can be adjusted in two orthogonal directions by set screws. The wire was centered by visual observation using a microscope. The frame for this apparatus was designed to have minimal clearance with the glass tube, thus eliminating convective heat transfer on the outside of the tube.

Thermal conductivity was calculated from the measured temperature difference, current, and geometric constant. The geometric constant was determined by direct measurements, and was then verified using standard reference data for toluene. Thermal conductivity was calculated taking into account the corrections for end effects, eccentricity of the wire, and radiation heat transfer. The sum of these corrections does not exceed 1% of the measured thermal conductivity for liquid and 2% for vapor.

The apparatus was installed in a high-pressure vessel, placed in a special constant temperature bath to provide temperature control to within $\pm 0.002^\circ\text{C}$. The temperatures of both resistance thermometers were determined by measuring the potential difference across each thermometer relative to the potential across standard resistances. The accuracy of these measurements using a digital voltmeter is to within ± 1 nV. The pressure was measured with a digital pressure transducer to within ± 1 kPa.

During the thermal conductivity measurements the temperature difference in the fluid sample between the wire and the capillary tube is 1 - 4°C for liquid phase and 4 - 10°C for vapors. For these conditions, $Gr \cdot Pr$ numbers (Gr is Grashof number and Pr is Prandtl number) were less than 1500 in all experiments, indicating negligible effects due to natural convection. Calculated uncertainties in the experimental thermal conductivities are less than or equal to $\pm 1\%$.

The obtained thermal conductivity data are given in Table 2.

Table 2. Experimental Thermal Conductivity Data of R508B

Vapor at Atmospheric Pressure		Saturated Vapor		Saturated Liquid	
T ($^\circ\text{C}$)	λ (mW/m, $^\circ\text{C}$)	T ($^\circ\text{C}$)	λ (mW/m, $^\circ\text{C}$)	T ($^\circ\text{C}$)	λ (mW/m, $^\circ\text{C}$)
-73.19	7.27	-78.49	7.54	-96.54	109.8
-70.18	7.48	-74.93	7.77	-94.74	109.0
-37.94	9.31	-61.22	8.75	-78.30	100.4
-34.20	9.53	-58.48	8.98	-76.90	99.7
-16.59	10.59	-46.23	10.13	-61.11	91.2
-11.80	10.79	-44.18	10.34	-59.68	90.5
10.08	12.12	-34.96	11.28	-48.00	84.6
13.28	12.34	-33.12	11.54	-46.71	83.9
38.90	13.78	-23.50	12.86	-37.38	78.8
67.18	15.41	-21.63	13.05	-35.94	77.8
70.38	15.70	-9.23	15.38	-22.71	70.6
94.93	17.07	-8.01	15.81	-21.30	70.1
98.15	17.26	1.64	19.20	-6.50	61.9
		2.90	19.96	-4.74	61.2
		6.88	22.60	1.45	57.6
		7.73	23.29	2.55	57.7
				7.19	54.0
				8.05	53.7

Surface Tension

A new original experimental apparatus was designed for measuring the surface tension of alternative pure and mixed refrigerants as well as refrigerant/lubricant oil mixtures over a range of parameters. This apparatus use the differential capillary rise method that allowed us to avoid the influence of the location of the bulk meniscus. In order to increase the reliability of the obtained results, the measurements were made using a set of 5 calibrated capillary tubes with different diameters.

A schematic diagram of the experimental apparatus is shown in Fig. 1. A set of capillary tubes is installed inside the optical cell made from stainless steel and provided with the highly processed sapphire optical windows. The optical cell is immersed into a special constant temperature bath to provide temperature control to within $\pm 0.002^\circ\text{C}$. The temperature was measured with a resistance thermometer to within $\pm 0.02^\circ\text{C}$, and the pressure was measured with a digital pressure transducer to within ± 1 kPa. A cathetometer was used for measuring the differential capillary rising.

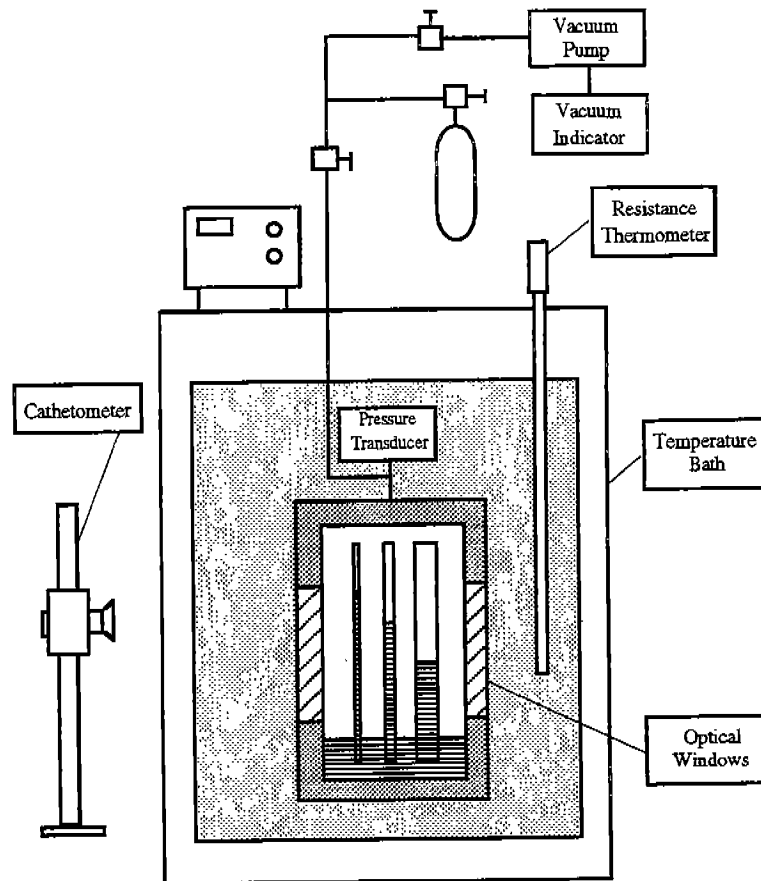


Fig. 1. Surface Tension Apparatus

The surface tension was calculated from the well known Rayleigh equation

$$\sigma = \frac{g(d_{sl} - d_{sv})\Delta h}{2\left(\frac{1}{R_1} - \frac{1}{R_2}\right)} \quad (1)$$

where g is the local gravitational acceleration in m/s^2 ; d_{sl} and d_{sv} are the saturated-liquid and the saturated-vapor densities, respectively, in kg/m^3 ; Δh is the differential capillary rising in mm; R_1 and R_2 are inner radius of the two capillaries under consideration in mm.

Surface tension of R23/116 mixture (46/54 mass %) was measured over a temperature range from -100 to 10°C. The experimental data are given in Table 3. Calculated uncertainties of the experimental data are to be within ± 0.05 mN/m. The reliability of the obtained results is confirmed by measuring the surface tension of R134a and comparisons of the obtained results with the most accurate data available from the literature.

Table 2. Experimental Surface Tension Data of R508B

Temperature, °C	Surface Tension, mN/m
-100.0	15.62
-78.2	12.14
-70.0	10.79
-55.0	8.462
-40.0	6.221
-29.8	4.809
-20.0	3.475
-10.0	2.262
0.0	1.143
10.0	0.223

MODEL AND CORRELATIONS

The following equations have been obtained for representing the measured R508B transport properties within the temperature range from -100 to 10°C:

$$\mu_0 = 13.7 + 4.96 \cdot 10^{-2} T - 9.48 \cdot 10^{-6} T^2 \quad (2)$$

$$\mu_{sl} = 110 - 2.11 T - 4.92 \cdot 10^{-3} T^2 - 1.52 \cdot 10^{-4} T^3 \quad (3)$$

$$\mu_{sv} = 16.2 + 1.92 \cdot 10^{-1} T + 3.96 \cdot 10^{-3} T^2 + 5.26 \cdot 10^{-5} T^3 + 2.58 \cdot 10^{-7} T^4 \quad (4)$$

$$\lambda_0 = 11.5 + 5.84 \cdot 10^{-2} T + 1.15 \cdot 10^{-7} T^2 \quad (5)$$

$$\lambda_{sl} = 58.4 - 0.546 T - 1.38 \cdot 10^{-4} T^2 \quad (6)$$

$$\lambda_{sv} = 18.9 + 3.65 \cdot 10^{-1} T + 6.06 \cdot 10^{-3} T^2 + 6.06 \cdot 10^{-5} T^3 + 2.45 \cdot 10^{-7} T^4 \quad (7)$$

where μ_0 and λ_0 are viscosity and thermal conductivity of the vapor at atmospheric pressure, μ_{sl} and λ_{sl} are viscosity and thermal conductivity of the saturated liquid, μ_{sv} and λ_{sv} are viscosity and thermal conductivity of the saturated vapor, and T is the temperature (μ in $\mu\text{Pa}\cdot\text{s}$; λ in mW/m , °C; T in °C).

Calculated transport properties can be based on modified [3] or "extended" [4, 5] corresponding states models, or on the empirical or semi-empirical correlations. It should be noted that the methods based on the corresponding states models require some additional information: the order parameters for the modified corresponding states method and the shape factors for the "extended" corresponding states

models. In the application of corresponding states to mixtures, the mixing rules for these parameters require further study.

In our previous paper [2], we considered the method for calculating liquid thermal conductivities and viscosities of binary refrigerant mixtures on the basis of pure-component data alone, and the following equations for the thermal conductivity and the viscosity, respectively, were proposed

$$\lambda_{mix} = \lambda_{id} - \alpha \Delta\lambda X_1 X_2 \quad (8)$$

$$\mu_{mix} = \mu_{id} (1 - \beta X_1 X_2) \quad (9)$$

where $\lambda_{id} = \lambda_1 X_1 + \lambda_2 X_2$; $\Delta\lambda = \lambda_1 - \lambda_2$; $\mu_{id} = \mu_1 X_1 + \mu_2 X_2$; X_i is the mass fraction of component i , α and β are coefficients that are functions of density (d) and vary from 0 when $d = 0$ to a constant value when $d \geq 2d_c$. For mixed liquid refrigerants the coefficients are found to be $\alpha = 0.72$ and $\beta = 0.25$.

The accuracy of this approach for the saturated liquid transport properties of R508B is quite good. The deviations are less than 2% for the thermal conductivity and do not exceed 2.5% for the viscosity.

The following equation for the surface tension has been obtained on the basis of our experimental results

$$\sigma = \sigma_0 T_r^{k \cdot \varphi(T_r)} \quad (10)$$

where σ is surface tension in mN/m; $\sigma_0 = 52.90$ mN/m; $k = 1.271$; $T_r = 1 - T/T_c$; $\varphi(T_r)$ is found to be an universal function

$$\varphi(T_r) = 1 - 0.0353 \left(\frac{T_r^{1.5}}{\ln T_r} \right) - 0.3165 \left(\frac{T_r^2}{\ln T_r} \right) + 0.3425 \left(\frac{T_r^3}{\ln T_r} \right) \quad (11)$$

The deviations between the calculated results from the above correlation with the experimental surface tension data are within 1.5%.

CONCLUSIONS

New transport properties (viscosity and thermal conductivity) and surface tension measurements of R23/116 mixture (R508B) over a range of parameters are presented. The experimental apparatus for measuring the surface tension is described. A set of equations for calculating saturated-liquid viscosity, saturated-liquid thermal conductivity, and surface tension of R508B is also presented.

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