TOWARD CALCULATION OF HEAT-ENGINEERING CHARACTERISTICS OF TWO-PHASE THERMOSIPHONS FILLED WITH ETHYLENE GLYCOL I. THERMOPHYSICAL PROPERTIES OF ETHYLENE GLYCOL

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We present the results of experimental investigation and engineering correlations for determining the thermophysical properties of ethylene glycol.

In designing and creating systems of cooling, thermal regulation, and thermal stabilization for various facilities operating under thermally stressed conditions, it is essential to calculate their heat-engineering characteristics to develop the most optimal designs of the above systems. In many cases, these problems can be solved successfully by using such effective heat-transfer devices as heat pipes (HP) and two-phase thermosiphons (TTS) operating on a closed evaporation-condensation cycle. Their calculation is based on the already available numerous and reliable data on the thermophysical, technological, and other properties both of the materials used for bodies and capillary-porous structures and of the heat carriers.

Nevertheless, for operating temperatures exceeding 180°C, the number of liquid heat carriers is considerably limited because of the closeness of their thermophysical characteristics to critical ones and their capacity for thermal decomposition (acetone, Freons, ammonia), as well as the large magnitudes of saturated vapor (water) pressure that require an increase in the thicknesses of the walls of heat-transfer devices.

At the same time, for some of the working fluids, for example, ethylene glycol, that show promise for elevated temperatures ($t \geq 180°C$) and have acceptable technological and operational characteristics, the data on the thermophysical properties are scanty and usually are determined in narrow temperature ranges, or sometimes are unknown. All of this considerably hinders the calculation of the heat-engineering characteristics of systems with ethylene glycol used as a heat carrier.

The aim of the present work is to study the thermophysical properties of ethylene glycol, to compare the experimental data with the known results and calculating procedures, and to generalize them for obtaining relations and recommendations necessary in the determination of the basic thermophysical characteristics of ethylene glycol.

We carried out investigations with pure ethylene glycol (State Standard GOST 10164-75) at atmospheric pressure in the temperature range 20–200°C. The density of ethylene glycol was determined by a quartz pycnometer. The coefficients of dynamic viscosity were studied by means of a comparison method in an Ostwald viscosimeter. Distilled water was used as a standard liquid. The surface tension was determined according to the Rebinder method.

Considering the sparse and fragmentary character of the data available for $\rho' = f(t)$, $\mu = f(t)$, and $\delta = f(t)$, before beginning the experiments we carried out an analysis of the methods that allow one to calculate these characteristics. As follows from [1], the properties of organic polar liquids (to which ethylene glycol belongs) are determined most precisely by:

  (a) the Gunn–Yamada method for determining density:
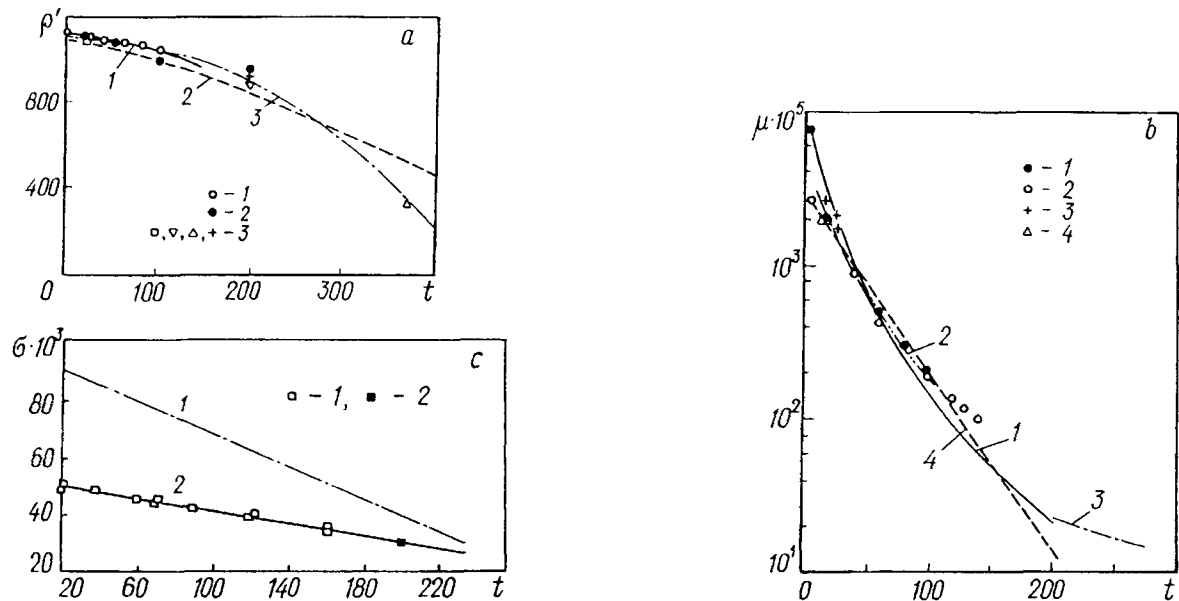

Fig. 1. Dependence of the density ρ', kg/m^3, dynamic viscosity μ, Pa·sec, and of the surface tension σ, N/m, of ethylene glycol on temperature, respectively: a) points: 1) [2], 2) [3], 3) [1]; curves: 1) experimental data of the present authors; 2) calculation by the Gunn−Yamada procedure [1]; 3) generalization by Eq. (5); b) points: 1) [2], 2) [3], 3) [4], 4) [5]; curves: 1) of the present authors; 2, 3) calculation by the Makhiya−Steirs and Letz−Steel procedures [1], 4) generalization by Eq. (6); c) points: 1) experimental data of the present authors; 2) [6]; curves: 1) calculation by the Brock−Byrd equation [1]; 2) generalization by Eq. (7).

$$\frac{V}{V^R} = \frac{V_r^{(0)} (T_r) \, [1 - \omega \Gamma (T_r)]}{V_r^{(0)} (T_r^R) \, [1 - \omega \Gamma (T_r^R)]}, \tag{1}$$

where $V_r^{(0)}(T_r)$, $V_r^{(0)}(T_r^R)$, $\Gamma(T_r)$, $\Gamma(T_r^R)$ are the functions of the reduced values for the current temperatures (0) and temperature at a certain reference point (R) [1];

(b) the Makhiya−Steirs method for determining the coefficients of dynamic viscosity:

$$\log \mu = A' + \frac{B'}{T - T'}, \quad 293 \le T \le 373 \ \text{K}, \tag{2}$$

where A', B', T' are the coefficients of Eq. (2); and the Letz−Steel correlation to obtain

$$\mu \xi = (\mu \xi)^{(0)} + \omega \, (\mu \xi)^{(1)}, \quad 0.76 \le T_r \le 0.98, \tag{3}$$

where $(\mu \xi)^{(0)}$, $(\mu \xi)^{(1)}$ are the functions of reduced temperatures [1], $\xi = T_c^{1/6} / M^{1/2} P_c^{2/3}$ is the parameter of Eq. (3);

(c) the method based on the application of a principle of corresponding states (the equation of Brock and Byrd) for determining the surface tension:

$$\sigma = P_c^{2/3} \, T_c^{1/3} Q \, (1 - T_r)^{11/9}, \tag{4}$$

where $Q = 0.1207 [1 + T_{b_r} \ln P_c / (1 - T_{b_r})] - 0.281$.

The results of the present investigation, as well as the correlations $\rho' = f(t)$, $\mu = f(t)$, and $\delta = f(t)$ obtained according to the procedures of [1] and the data of [1-6], are given in Fig. 1. The experimental values obtained for
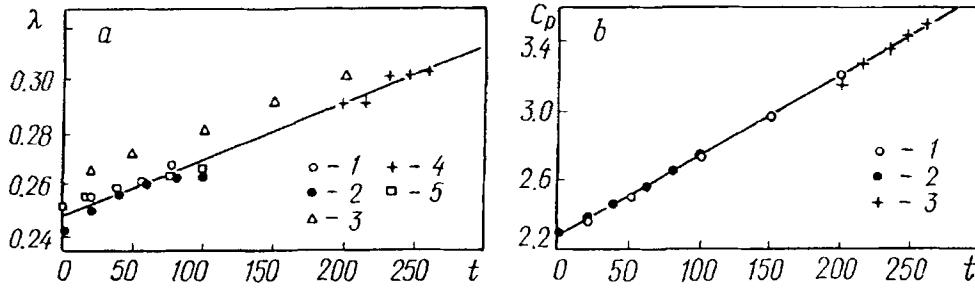
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Fig. 2. Dependence of the change in the coefficients of thermal conductivity λ, W/(m·K), and specific heat c_p, kJ/(kg·K), of ethylene glycol on temperature: a) points: 1) [1], 2) [2], 3) [3], 4) [6], 5) [7]; curve: generalization by Eq. (8); b) points: 1) [3], 2) [2], 3) [6]; curve: calculation by formula (9).

ρ' and μ agree satisfactorily with the known results of other authors and have small scatter (within the accuracy of the experiment and of the methods used for determining the thermophysical properties). At the same time, the comparison of these correlations with computational methods (1)-(4) shows that they satisfactorily describe experimental data for the density and coefficients of dynamic viscosity of ethylene glycol only at low temperatures ($t \leq 100^{\circ}C$) in a narrow range, whereas at higher temperatures they have a large error or a discontinuity (for example, Fig. 1a and b). The experimental data on surface tension agree well with the results of [6], although this is the only experimental point. The methods for calculating σ given in [1, 3] are unsuitable in view of their high error and uncertainty of the parameters involved.

Taking into account the fact that there are no reliable procedures for engineering calculation of ρ', μ, and σ, we generalized all the available data and obtained the following empirical formulas:

$$\rho' = 1108.2017 + 0.1325t - 0.0058t^2 \quad (\delta = \pm\ 6\ \%),$$ (5)

$$\mu = 3.245 \cdot 10^{-2} \exp\left(-\ 0.02703t\right) \quad (\delta = \pm\ 15\ \%),$$ (6)

$$\sigma = (53.4723 - 0.1196t) \cdot 10^{-3} \quad (\delta = \pm\ 3\ \%).$$ (7)

The subsequent selection of procedures for calculating the thermophysical properties of ethylene glycol and their comparison with the experimental data of [1-3, 6, 7] (Fig. 2) showed that the thermal conductivity and specific heat could be calculated by using the equation suggested by the present authors and the recommendations of [3], respectively:

$$\lambda = 0.2491 + 0.0002t \quad (\delta = \pm\ 4.5\ \%),$$ (8)

$$c_p = 2.256 + 4.96 \cdot 10^{-3}t \quad (\delta = \pm\ 2\ \%).$$ (9)

It should be noted the literature virtually lacks experimental data on the latent heat of evaporation and density of the vapors of ethylene glycol. However, as the analysis carried out shows, these magnitudes can be determined by using the following methods [1]:

(a) the correlations of Fish and Lilmesch for the latent heat of evaporation:

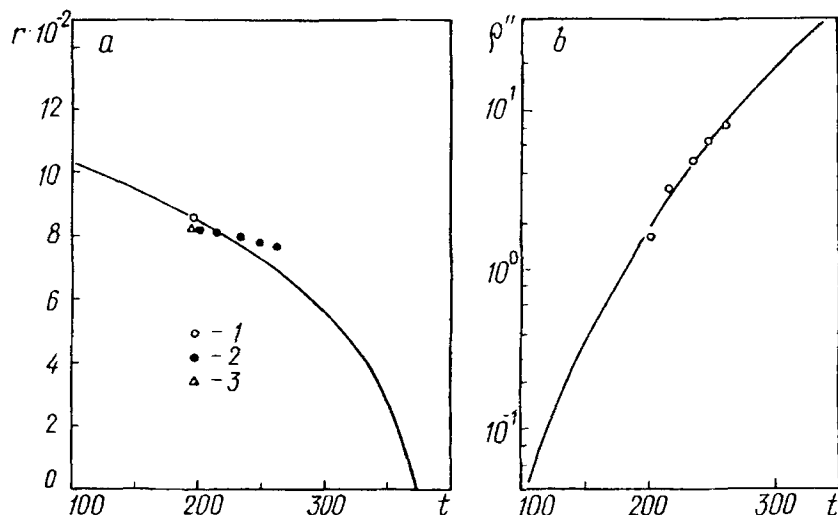$$r = r_b \frac{T_r}{T_{b_r}} \frac{X + (X)^{0.35298}}{1 + (X)^{0.13856}},$$ (10)

Fig. 3. Dependence of the change in the latent heat of evaporation r, kJ/kg, and density of vapors ρ'', kg/m^3, of ethylene glycol on temperature: a) 1) [1], 2) [3], 3) [6]; curve: calculation by the Fish–Lilmesch correlation [1]; b) points, [6]; curve: calculation by the procedure of [1].

where $X = (T_{b_r}/T_r)(1 - T_r)/(1 - T_{b_r})$;

b) the diagrams $Z - T_r - P_r$ [1] for the density of vapors. In this case the data on the pressure of the saturated vapors P_{vp} of ethylene glycol are determined by using the Antoine correlation:

$$\ln P_{vp} = A - \frac{B}{T + C},$$

where A, B, and C are the parameters of this correlation.

Figure 3 presents the results of calculation by the proposed procedures and the data of [1, 3, 6]. From these graphs it follows that there is a satisfactory agreement between the calculated and experimental data.

The analysis of the results obtained for the thermophysical properties of ethylene glycol showed that the character of all the correlations that describe the experimental data was in good agreement with the theory and physical concepts on the nature of variation of the thermophysical properties of substances with temperature. Considering this fact, it is possible to extend the temperature ranges of the equations and procedures indicated by the authors for determining the thermophysical properties of ethylene glycol. At the same time, comparison of the experimental results with the methods suggested in [1] for determining the thermophysical properties confirms that in many cases these methods are not always applicable to ethylene glycol, since they were obtained for different classes of compounds (for example, ethers, phenols, organic acids, etc.) and satisfactorily generalize the data on the thermophysical properties of only a narrow range of substances. It must also be taken into account that the values of the critical parameters and ω of ethylene glycol can be determined only by computational methods because of its thermal decomposition at $t \geq 250°C$.

NOTATION

T, t, temperature; T_c, P_c, critical temperature and pressure; T_b, normal temperature of boiling; ρ', ρ'', densities of liquid and vapor; μ, σ, λ, coefficients of dynamic viscosity, surface tension, and thermal conductivity, respectively; c_p, r, specific heat and latent heat of evaporation; ω, factor of Pitzer's acentricity; $V = 1/\rho$, specific volume; M, molecular mass; $T_r = T/T_c$, $T_{b_r} = T_b/T_c$, $P_r = P/P_c$, reduced temperatures and pressure; r_b, latent heat of evaporation at boiling temperature; Z, compressibility factor; δ, relative error. Subscripts: c, critical; b, boiling; r, reduced; vp, vapor.

REFERENCES

1. R. Reid, J. Prausnits, and T. K. Sherwood, Properties of Gases and Liquids [Russian translation], Leningrad (1982).
2. W. H. McAdams, Heat Transmission [Russian translation], Moscow (1961).
3. A. V. Chechetkin, High-Temperature Heat-Carriers [in Russian], Moscow (1971).
4. V. A. Rabinovich and Z. Ya. Khavin, Brief Chemical Handbook [in Russian], Leningrad (1977).
5. A. M. Sukhotin (ed.), Corrosion and Protection of Chemical Apparatuses. Reference Textbook, Vol. 3 [in Russian], Leningrad (1970).
6. I. L. Pioro, V. A. Antonenko, and L. S. Pioro, Effective Heat Exchangers with Two-Phase Thermosiphons [in Russian], Kiev (1991).
7. N. B. Vargaftik, Handbook of Thermophysical Properties of Gases and Liquids [in Russian], Moscow (1972).