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Experimental Study of the Viscosity of Lithium Vapor at High Temperatures[1]

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The viscosity of lithium vapor was measured at temperatures from 1600 to 2000 K and pressures from 0.02 to 0.1 MPa with an experimental setup consisting of a closed circuit with a short annular channel used as a measuring element. The accuracy of the data obtained was estimated to be 3–4%. The characteristic features of the designed apparatus are the following: a high stability of the pressure difference within the viscometer during experiment, the absence of condensate accumulation out of the flowmeter, and a sufficiently large flowmeter volume. Since the length of the measuring section is short, the hydrodynamics of the gas flow through an annular channel were studied carefully. This enabled us to introduce the necesary corrections in the working equation. The results obtained are compared with available experimental data and the results of theoretical calculations.

KEY WORDS: high temperature; lithium vapor; viscosity.

1. INTRODUCTION

In the experimental study of lithium vapor thermophysical properties there are difficulties in constructing a reliable high-temperature apparatus and in achieving a sufficiently long lifetime for the measuring unit under the condition of high chemical activity of the gaseous lithium. This has resulted in a lack of experimental data on the viscosity of lithium vapor until recently. For the first time, experimental results in the temperature range 1600–1850 K and at pressures of 33–75 kPa have been reported in Ref. 1. These were obtained with an apparatus consisting of a closed circuit in which a vapor flow through a short annular gap was monitored. This

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enabled the authors [1] to realize the advantages of applying well-developed methods of capillary and a falling cylinder while overcoming at the same time the difficulties of uniform temperature control over a long viscometer and stabilization of the cyclinder motion in a tube.

On the other hand, however, some disadvantages of the apparatus associated with the technique of control of the pressure drop across the measuring section and of condensate collection in the flowmeter created additional difficulties in both operation and data handling. As a result, average errors in the experimental viscosity were as much as 7%, and the data obtained did not enable final conclusions to be drawn about the temperature and pressure dependence of lithium vapor viscosity over a wide range of these variables.

For more experimental information and improved accuracy a new experimental setup has been designed which also utilizes the method of vapor flow through a short annular channel. However, based on previous experience [1], a new measuring unit design enables us to simplify substantially the experimental procedure and data processing as well as improve the accuracy twofold in comparison with that of the previous study [1].

2. WORKING EQUATION

Since a short annular channel is employed as a measuring element, the hydrodynamics of gas flow through the channel have been carefully studied. For this purpose the generalized Bernoulli equation has been used for isothermal flow of a real compressible fluid assuming that, for viscous loss within the section of fully developed flow, Poiseuille's law holds. It is also assumed that the lithium vapor viscosity change within the viscometer due to a change in the molecular composition of the vapor is negligible compared to the corrections encountered had the viscosity been constant.

As a result the following working equation has been derived for the vapor viscosity η:

$$\eta = \frac{\pi}{24} \frac{\mu}{RT} \frac{\tau}{M} (2P_2 + \Delta P)\, \Delta P^* f E_1 E_2 \tag{1}$$

where

$$\Delta P^* = \Delta P - \left(N \frac{\rho \bar{w}^2}{2} + \zeta \frac{\rho \bar{w}^2}{2} - \Delta P \frac{\Delta P}{2P_1} \right) \tag{2}$$

$$f = \delta^3 (r_1 + r_2)/l \tag{3}$$

$$E_1 = 1 + 6\lambda/\delta \tag{4}$$

Here μ and ρ represent the vapor molar weight and mass density corresponding to the molecular composition at average pressure $(P_1+P_2)/2$ and absolute temperature T; P_1 and P_2 are the pressures at the inlet and outlet of the channel, respectively. $\Delta P = P_1 - P_2$ is the measured pressure drop across the measuring section, M/τ is the mass flow rate of vapor through the viscometer, and E_2 is the correction for thermal expansion of the measuring element (empirical value). The quantity w is the vapor velocity variable over the channel cross section and $\bar{w}$ is the average value of the velocity, determined from the volumetric rate Q through channel cross section F: $w = Q/F$. $N = (I/F) \int_F (w/\bar{w})^3 \, dF$ is the Coriolis coefficient; ζ is the local resistance coefficient at the channel entrance. The quantities r_1, r_2, and l are the radii and length of the measuring element, respectively, and $\delta = r_2 - r_1$ is the gap between the inner and the outer channel surfaces. The quantity λ is the mean free path of the vapor molecules.

Equations (3) and (4) for the geometrical factor f and correction for molecular slippage E_1 correspond to a very narrow annular gap $(r_1/r_2 \sim 1)$. Under the same conditions it is possible to calculate $N \approx 1.54$. Terms in parentheses on the rightside of Eq. (2) represent corrections peculiar to the method used, i.e., for gas acceleration through the inlet section of the channel, for local losses at the channel entrance, and for gas expansion within the channel, respectively.

It should be pointed out here that direct calculation of the value for local losses is not possible because the coefficient ζ in the real viscometer can be determined empirically only. However, under the condition of the present experiment with lithium vapor, these losses are negligible (as well as the correction for gas acceleration). This assumption has been employed in Ref. 1, where these quantities have not been taken into account and Poiseuille's law has been directly used as the working formula with a correction for the channel geometry. This, however, cannot be considered satisfactory because the value of the geometrical factor f of the real viscometer can deviate markedly from that calculated with Eq. (3). It is thus necessary to determine the factor f empirically on the basis of Eqs. (1) and (2) using gases with a well-established viscosity. For practical convenience, such a calibration of the measuring apparatus is carried out at atmospheric pressure. In this case, the local losses at the channel entrance are no longer negligible. In addition, the Reynolds number (Re) dependence of the coefficient ζ and the existence of a channel inlet section with undeveloped flow both affect the calibration data. The results of a detailed study of the role of local losses at the short channel entrance is gas viscosity measurements were published in Ref. 2.

Thus given the correction for local losses and effects at the inlet section are considered negligible, the factor f obtained in the calibration run turns out to be dependent on the Reynolds number (Re) so that the value of factor f can differ considerably from the apparent one. Taking all this into account in the calibration runs, we determined the geometrical factor as a function of Re, the dependence $f(\mathrm{Re})$ having then been extrapolated to the lower Reynolds numbers typical for runs with lithium vapor to obtain an effective value of the factor f. In this case, when calculating f from calibration data, the local losses term in Eq. (2) must be neglected since the effect of the losses is taken into account by empirical values of factor f.

3. EXPERIMENTAL SETUP AND PROCEDURE

The method used has been applied in an apparatus similar to that described previously [3]. Taking into account, however, the temperature range of interest, the high-temperature measuring unit was fabricated from Nb(base)–Zr–C–alloy and contained in a vacuum chamber. The pressure control system with argon as an intermediate gas has been employed to create a pressure difference across the measuring section. Analogous systems have been used extensively in previous works [3, 4].

Having passed through the annular channel of the measuring section formed by the inner surface of a tube ($r_2 = 2.50$ mm) and the side surface of a cylinder ($r_1 = 2.34$ mm, $l = 26$ mm), the lithium vapor is condensed and collected in the flow meter. The latter is a stainless-steel tube of 28-mm ID with a calibrated diameter. To establish is level of condensate within the flowmeter, a movable contact is employed, with the displacement of the contact being read directly with a cathetometer. When touching the surface of condensate, the contact completes an electrical circuit.

The rise of the condensate level within the flowmeter is measured 10–12 times during each measurement cycle at a given P and T (the cycle period has been 40–60 min at a pressure difference across the measuring section of about 1.5 kPa). After that, the time dependence of the condensate level height is fitted by a least-squares straight line, and the mass flow rate of lithium vapor is calculated.

To improve wetting of the condensate at the line walls (see Ref. 5) and so to ensure the absence of condensate accumulation out of the flowmeter, the temperature of the line and flowmeter is kept high (up to 900 K).

Before the measuring unit is assembled, the chanel of the viscometer is calibrated at room temperature. For this purpose a simple arrangement is used to determine the flow rate of pure argon and dry air through the channel at a given pressure difference. The unique dependence $f(\mathrm{Re})$

obtained for both gases is found to be linear within a Reynolds number range of 70–300, the mean square deviation from the fitting line being about 1.5%. This dependence is extrapolated to Re ~ 10, typical for runs with lithium vapor.

4. RESULTS

The viscosity of lithium vapor has been measured at temperatures from 1600 to 2000 K in the pressure range 0.02–0.1 MPa. In operation, the

Table 1. Experimental Data on Lithium Vapor Viscosity

No.	T (K)	P (kPa)	$\eta \cdot 10^7$ (Pa·s)
1	1595	21.7	163
2[a]	1596	33.0	178
3	1607	73.8	143
4[a]	1615	52.6	173
5[a]	1615	53.6	149
6[a]	1620	53.6	160
7[a]	1636	33.1	175
8[a]	1665	55.8	170
9	1668	23.9	187
10[a]	1670	33.1	180
11	1692	41.2	174
12	1700	22.6	183
13[a]	1710	53.0	182
14[a]	1711	63.0	182
15[a]	1713	63.1	179
16[a]	1715	53.0	180
17	1715	71.3	165
18[a]	1717	74.7	173
19	1722	98.3	160
20[a]	1723	55.1	185
21[a]	1728	55.1	181
22	1747	26.0	195
23[a]	1793	58.5	190
24	1812	84.9	184
25	1815	21.5	193
26	1823	47.3	193
27	1830	65.0	192
28[a]	1839	61.2	197
29	1852	89.9	186
30	1970	54.9	210
31	1983	106.8	208

[a] Data from Ref. 1.

high stability of the experimental parameters has been achieved; the pressure difference across the measuring section has been found to be practically constant, and the temperature of the section has been kept within 10 K during any run. There was no observable deviation of the time dependence of the condensate level height in the flowmeter from a straight line.

Based on the analysis of the experimental errors, the accuracy of the data obtained has been estimated to be 3–4%. The data together with previous results [1] are summarized in Table I. In order to compare all these results, we have used the fitting equation established in Ref. 1, which represents the dynamic viscosity η as a function of temperature T and the mole fraction of molecular component X_2 of lithium vapor:

$$\eta(X_2, T)\,10^7 = 178 - 530(X_2 - 0.05) + 0.071(T - 1700) \qquad (5)$$

where η is in Pa · s and T is in K. Deviations of our data from Eq. (5) do not exceed 3%.

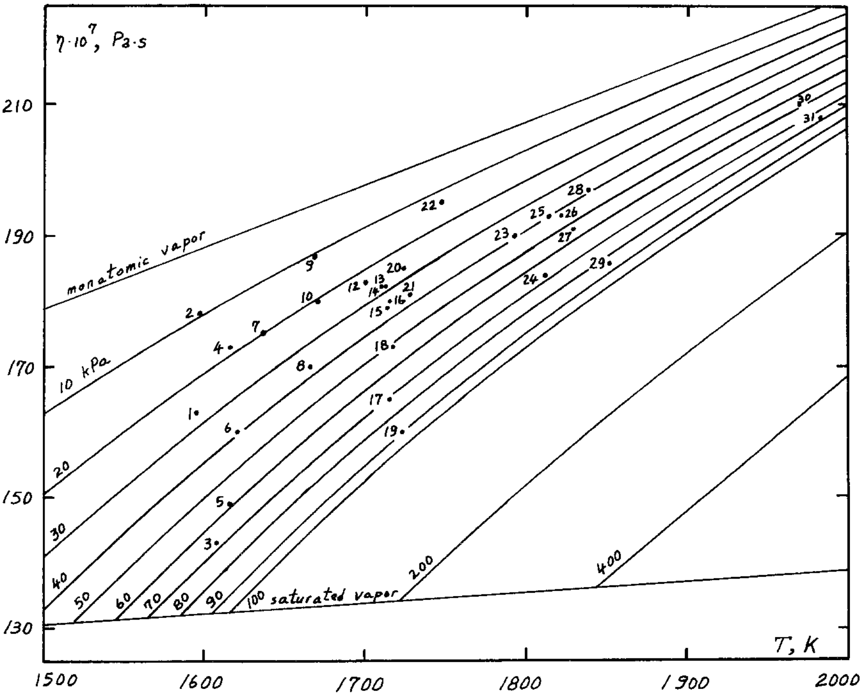

Fig. 1. Comparison between experimental data (all obtained) and results of theoretical calculation [6]. Point numbers correspond to those in Table I.

In Fig. 1 the available experimental data are shown together with theoretical isobars [6]. It is seen that there is a rather good agreement between the experimental data and the theoretical calculations within the experimental accuracy.

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