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Viscosity of Liquid Lithium by an Oscillating-Cup Viscometer in the Temperature Range 464–923 K[1]

Y. Ito,[2] K. Minami,[2] and A . Nagashima[2]

The liquid lithium has been proposed as a blanket substance of a D-T fusion reactor. Among the previously published viscosity data of liquid lithium by different authors, a sizable discrepancy is observed. In the present study, the viscosity of liquid lithium was measured by an oscillating-cup viscometer in the temperature range from 464 to 923 K. It was concluded that the disagreement among the previous studies was owing to the difference of the theory used for calculating the viscosity and also to the influence of the corrosion of the container wall. It was shown that recalculation of values in previous studies with the aid of Kestin–Newell equation, the equation used in the present study, would show reasonable agreement with the present results. The accuracy of the present measurements was estimated as ±3%.

KEY WORDS: high temperature; liquid metal; lithium; oscillation viscometer; viscosity.

1. INTRODUCTION

Liquid lithium is an important substance in D-T fusion reactor research and therefore a number of studies on its thermophysical properties have been reported in recent years. On the viscosity of liquid lithium, the property important for heat transfer calculations and for simulation of flow characteristics, several studies reporting systematic measurements of the temperature dependence are available. However, the agreements between these experimental data are very poor and a new study is urgently needed. In addition to supplying a new set of reliable data, the new study should

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[2] Department of Mechanical Engineering, Keio University, Hiyoshi, Yokohama 223, Japan.

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explain the origin of disagreements among formerly available data sets since some of these previous measurements were performed by respectable researchers. In the present study, we report the measurement of the viscosity of liquid lithium using an oscillating-cup viscometer in the temperature range from 464 to 923 K along the saturation line. In the course of the study, we have found two important effects, which were probable causes of the discrepancy among previous data: the first was the difference among different theories used for an oscillation viscometer, and the second, the degradation of the sample.

2. EXPERIMENTAL

The principle and the fundamental design of the experimental setup were similar to those described in previous papers [1, 2]. Figure 1 shows a schematic diagram of the oscillating-cup viscometer, the viscometer employed in the present experiment. The viscometer consists essentially of an oscillating system with a thin suspension wire of 0.2-mm diameter and a hollow cylindrical cup which contains specimen fluid. The fluid is tightly enclosed in the cup, and the inside of the viscometer is evacuated to the

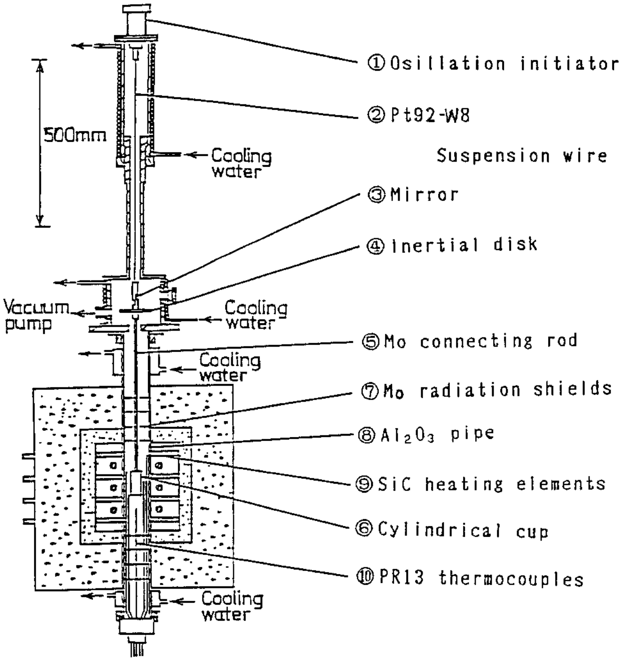

Fig. 1. Experimental apparatus.

order of 10^{-3} Pa so as to avoid the influence of the remaining gas on the suspension system. Once a torsional oscillation is given to the suspension system, the executed oscillation is gradually damped with a constant period and a constant logarithmic decrement and these parameters are subject to the viscosity and the density of the fluid, the moment of inertia of the system, and the geometrical dimensions of the cylindrical cup. The viscosity value of the fluid enclosed in the cup is thus evaluated from the characteristic dimensions of the suspension system and the characteristics of its torsional oscillation. For precise measurements of the period and the logarithmic decrement of oscillations, an optical measuring system is used.

The cylindrical cup used in the present study is shown in Fig. 2. The most severe trouble with the measurement of liquid metal is strong reactivity of the specimen liquid at high temperatures. In the case of lithium, it reacts even in the solid state with air. Considering strong corrosiveness of lithium, the cup was made of an alloy of titanium, zirconium, and molybdenum (TZM alloy). The cup was sealed by electron-beam welding in vacuum after filling it with the solid specimen in an argon dry box. Before welding, the cup was sealed with a tapered lid after evacuation.

Under the measuring conditions, the logarithmic decrement and the period of oscillations were measured and the viscosity of the specimen

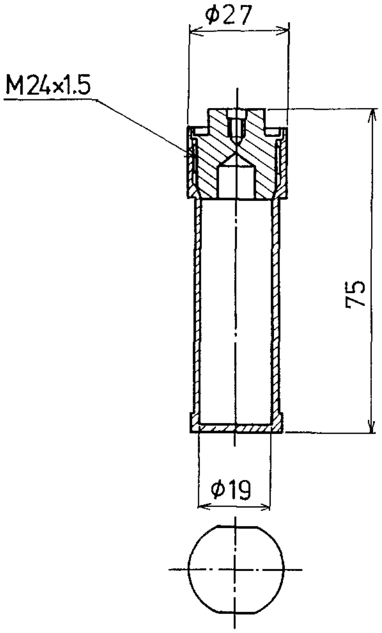

Fig. 2. Cylindrical cup.

liquid was calculated by the theory of Kestin and Newell [3]. The equation is

$$(S+\Delta_0)^2+1+D(S)=0 \tag{1}$$

where $D(S)$ is the characteristic function

$$D(S)=\frac{I'}{I}S^2\sum_{n=1}^{\infty}\frac{8}{\mu_n^2}\left\{1-\frac{S}{S_n^2}\left[1-\frac{\tanh(S_n\zeta_0)}{S_n\zeta_0}\right]\right\} \tag{2}$$

S is the complex frequency

$$S=\frac{T_0}{T}(-\Delta\pm i) \tag{3}$$

and Δ, Δ_0, S_n, ζ_0, and ξ_0 are defined as

$$\Delta=\frac{\delta}{2\pi},\qquad \Delta_0=\frac{\delta_0}{2\pi},\qquad S_n^2=\frac{\mu_n^2}{\xi_0^2}+S,$$
$$\zeta_0=h\sqrt{2\pi\rho/\eta T_0},\qquad \text{and}\qquad \xi_0=r\sqrt{2\pi\rho/\eta T_0}$$

In these equations, δ_0 denotes the logarithmic decrement of the suspension system alone, i.e., the intrinsic decrement, δ the logarithmic decrement observed with fluid, I' the moment of inertia for fluid in the cup, I the suspension system alone, r the inner radius of the cup, h the height of the fluid column, η the viscosity, the density, and μ_0 the roots of the first-order Bessel function $J(\mu_0)=0$, and T and T_0 are the periods of oscillation with and without fluid, respectively. It is worth noting that the term $\sqrt{(\eta T_0/2\pi\rho)}$ corresponds to an average boundary layer thickness. The errors in the decrement and the period were estimated as ± 1 and $\pm 0.01\,\%$, respectively. The error in temperature measurement was $\pm 1\,$K, which corresponded to $\pm 0.05\,\%$ error in the viscosity. The experimental error of the viscosity in the present measurement is $\pm 3\,\%$.

3. RESULTS AND DISCUSSION

The experimental results for the viscosity of lithium are listed in Table I and shown also in Fig. 3. Values by other authors in previous measurements are included in Fig. 3. The reproducibility of the present measurements was $\pm 2.2\,\%$. Figure 4 shows the Arrhenius plot of the present measurement. It shows good linearity as expected from the theory.

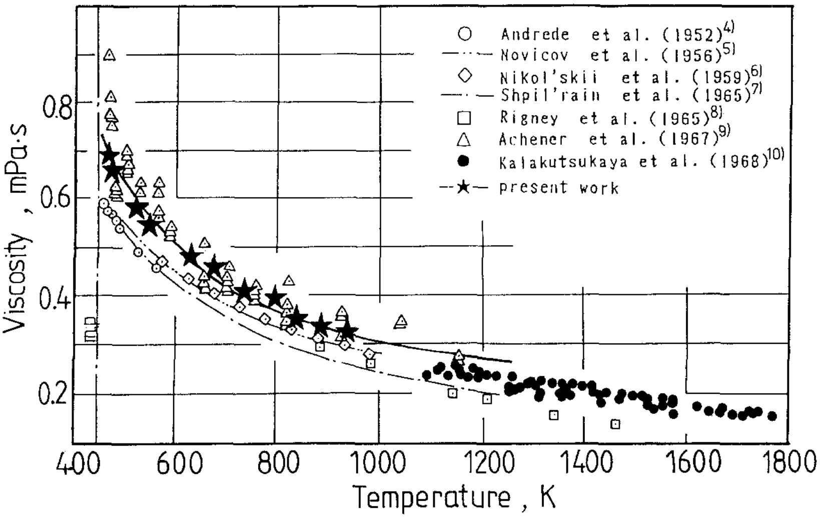

Fig. 3. Viscosity of lithium.

Through the least-squares fit procedure, the Arrhenius equation was determined as

$$\eta = 0.1522 \exp(703.66/T) \tag{4}$$

where η is the viscosity in 10^{-3} Pa·s and T is the absolute temperature in K. This equation represents the experimental results with a standard deviation of $\pm 1.2\%$ and a maximum deviation of $+3.7\%$. Deviations of

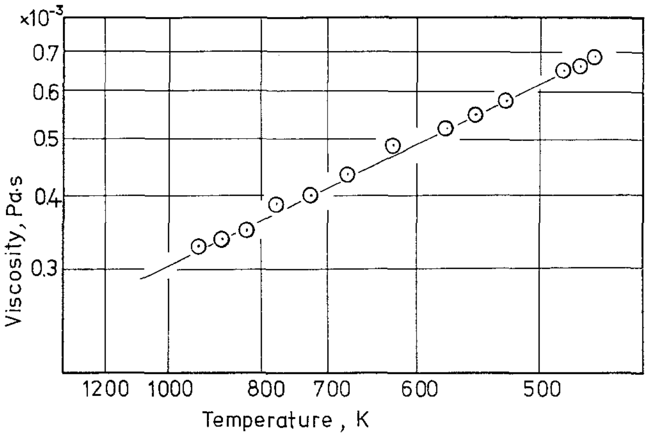

Fig. 4. Arrhenius plot of the measured viscosity.

Table I. Experimental Results for Lithium

T (K)	η (10^{-3} Pa · s)
464.1	0.695
465.5	0.692
466.9	0.683
467.9	0.679
468.0	0.681
467.7	0.685
474.5	0.662
474.6	0.657
474.6	0.665
485.0	0.652
485.0	0.651
485.0	0.653
523.8	0.579
523.9	0.580
547.8	0.552
547.8	0.546
547.8	0.547
572.7	0.510
572.9	0.523
573.0	0.522
573.8	0.529
573.6	0.527
573.3	0.511
573.1	0.513
622.8	0.492
622.7	0.488
622.5	0.483
675.4	0.435
675.2	0.429
675.0	0.432
674.2	0.441
674.2	0.439
674.2	0.438
723.8	0.407
723.8	0.396
723.5	0.399
774.4	0.385
775.6	0.391
775.5	0.389

Table I. *(Continued)*

T (K)	η (10^{-3} Pa · s)
823.4	0.352
823.2	0.353
823.5	0.353
825.9	0.350
826.5	0.352
825.5	0.349
872.4	0.333
872.7	0.333
872.5	0.335
875.7	0.338
875.0	0.340
872.7	0.339
873.2	0.336
873.1	0.344
873.7	0.340
873.6	0.339
923.3	0.331
923.3	0.326
923.1	0.330
923.7	0.331

values by other authors from Eq. (4) are plotted as a function of temperature in Fig. 5.

As seen in Fig. 5, the agreement between the available data are very poor. We can observe two typical facts: first, the values of Achener show a larger scatter but lower systematic deviations from the present results; and second, the values of Rigney have large systematic deviations, although their scatter is less. The temperature dependences of all the previous studies are surprisingly close to that of the present results. For this kind of discrepancy, reasons to be suspected are the difference in theories for the oscillation viscometer and deterioration of the specimen liquid. In the present study, the viscosity was calculated using the Kestin–Newell theory which had been derived from the rigorous solution of the characteristic equation for the oscillating system. Since the dimensional details of the oscillating system in other studies were not known from the literature, we performed calculations of the viscosity using other equations written in the references with our data and constants from our own viscometer. In Fig. 6, viscosity values calculated with the aid of equations used by Rigney et al.

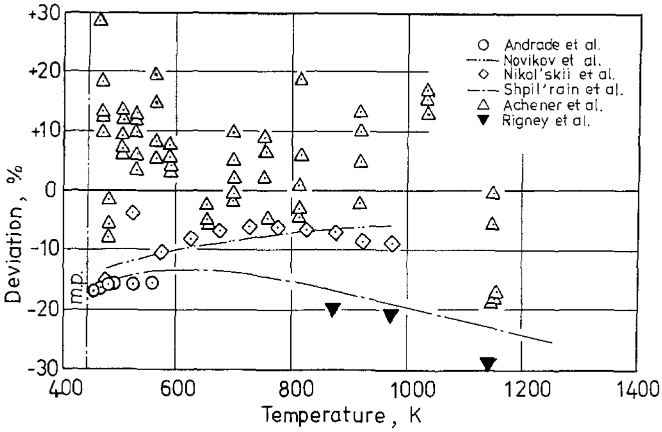

Fig. 5. Deviations from the results of the present work.

[8] and by Achener [9] are shown in deviation plots from the values with the Kestin–Newell theory. The value given by the equation used by Achener is very close to that by the Kestin–Newell equation, and on the other hand, that by Rigney's equation is lower by about 25%. This can explain the systematic discrepancy of Rigney's from the present data. Recalculation of Rigney's data would lead to values much closer to the

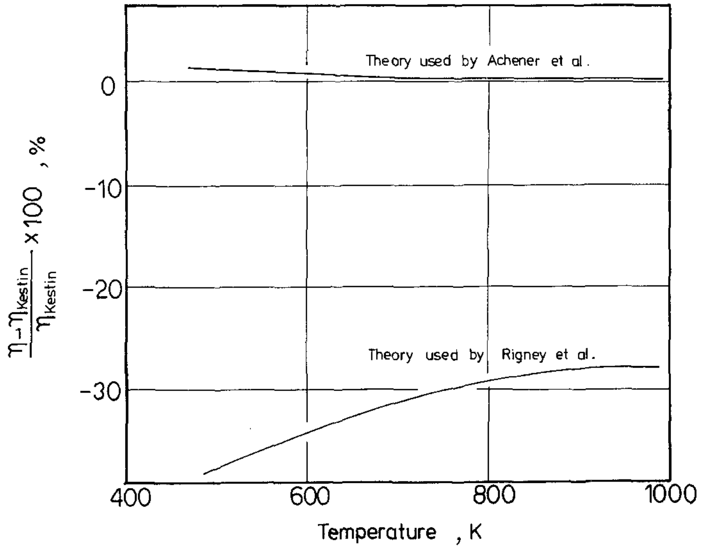

Fig. 6. Deviations of values calculated by other studies' theory from values calculated by Kestin–Newell's theory.

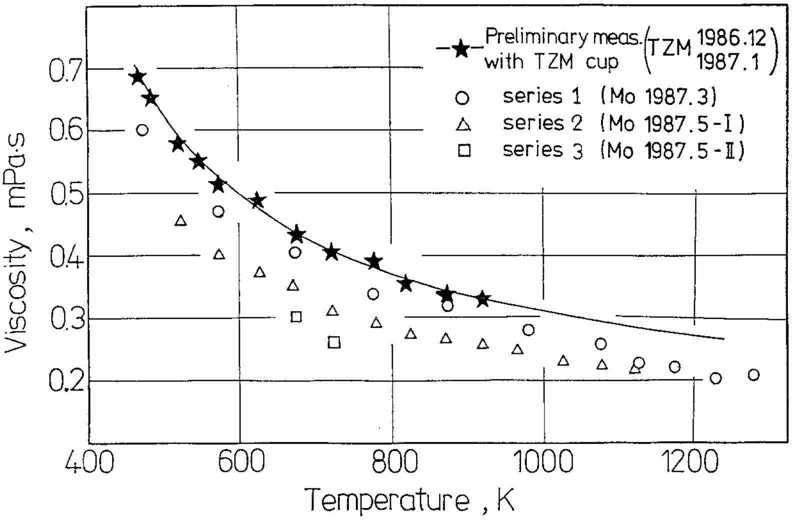

Fig. 7. Preliminary measurements with the TZM cup and with the molybdenium cup.

present authors. Although our final measurements were performed with the cup made of TZM alloy, we have performed a series of preliminary measurements with cups made of molybdenum. In the case of molybdenum cups, the measured viscosity values decreased with the time period after melting. Figure 7 clearly shows this tendency. Measured values with the molybdenum cup decreased with the time after melting, while values with the TZM cup showed no systematic change with time. This result leads us to conclude that previous data with molybdenum cups, such as in Ref. 10, are subject to serious error.

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REFERENCES

1. S. Ishito, N. Kojima, and A. Nagashima, *Proc. 3rd Jap. Symp. Thermophys. Prop.* **61** (1982).
2. Y. Abe, O. Kosugiyama, H. Miyajima, and A. Nagashima, *J. Chem. Soc. Faraday I* **76**:2531 (1980).
3. J. Kestin and G. F. Newell, *Z. Angew. Math. Phys.* **8**:433 (1957).

4. E. N. Andrede and E. R. Dobb, *Proc. Roy. Soc.* **211A**:12 (1952).
5. I. I. Novicov, A. N. Soloriev, E. M. Khabakhnasheva, V. A. Gruzdef, A. I. Pridantzev, and M. Ya. Vasenina, *J. Nuclear Eng.* **4**(3):387 (1957).
6. N. A. Nikol'skii, N. A. Kalakutskaya, I. M. Plelkin, T. B. Klassen, and V. A. Bel'mishchva, *Tepoenerg.* **2**:92 (1959).
7. E. E. Shpil'rain, Yu. A. Sldatenco, K. A. Yakimovich, V. A. Formin, V. A. Savachenko, A. M. Belova, D. N. Kagen, and I. F. Krainova, *Teplofiz. Vys. Temp.* **3**(6):930 (1965).
8. D. V. Rigney, D. M. Kapelner, and R. E. Cleary, *The Viscosity of Lithium*, Report TIM-849 (1965).
9. P. Y. Achener, *Viscosity of Liquid Sodium and Lithium*, Report AGN-8191 (1965), p. 5.
10. N. A. Kalakutsukaya, *Teplofiz. Vys. Tem.* **6**(3):455 (1968).