

## DYNAMIC VISCOSITY CHARACTERISTICS OF LIQUID METALS

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**Abstract.** In the work it is considered the case when the potential inside the liquid metal is set by the Thomas-Fermi pseudopotential. Then the dynamic viscosity in liquid metals changes according to the law  $\eta = A \times T^{-2} - D$ . It was shown that the dynamic viscosity of a liquid metal is the sum of the ionic and temperature-independent electronic viscosity. Moreover, the ionic and electronic accumulations of viscosity were calculated and obtained results are presented for Hg, Pb and Sn. The calculated values of the viscosity of several liquid metals (for example, Pb, Sn, Zn) correspond to the experimental results with an error of  $\sim 4\%$ .

**Keywords:** liquid metals, dynamic viscosity, Thomas-Fermi pseudopotential.

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### 1. Introduction

Many new features have been discovered in the study of various physical processes occurring in liquids using modern research methods (Ahmadova, 2021; Safarov *et al.*, 2021; Lowe, 2020). One of the main problems in condensed matter physics is the phenomenon of viscosity in liquids in a velocity gradient field. Although there are many theoretical and experimental studies, there is currently no single model or theory of the viscosity mechanism (Bur, 1986; Eyvazov & Ibrahimli, 2020; Eyvazov, 2012). However, the state of a liquid aggregate is known to have a dynamic chaotic structure and statistically close order. Modern statistical theories have several disadvantages when applied to liquids. This is due to the fact that the statistical theory based on the existence of interactions between particles only allows to study of hypothetical simple liquids (Eyvazov & Ibrahimli, 2020). This theory cannot be applied to real fluids.

To test the applicability of these theoretical approaches to practice, liquids of inert elements or alkali metals are used. Despite the simplicity, the physical processes in these fluids are quite complex (Callaham *et al.*, 2021; DebRov & David, 1995.). For example, in liquids of alkali metals, interactions between ions are collective and occur in the presence of all ions and free electrons. Free electrons completely screen the interionic suspension shock at large distances, while providing effective interionic attraction at short distances. At short distances, the repulsive force is created by the effects of electron clouds. As you can see, the interaction between particles in liquid metals occurs in subsystems formed by ions and free electrons. Attraction arises at large distances between ions (Bur, 1986).

Note that at present there is no theory that accurately describes the interaction between molecules (ions) for a real liquid. There are different approaches depending on the range of variation of the state parameters. The theory of free electrons can sometimes

be applied to crystals and liquid metals (Ibrahimli, 2021; Zajman, 1972; Ubbelohde, 1965).

## 2. Phenomenological description of viscosity

Since the dynamic structure and close order change depending on physical conditions, it is impossible to describe the viscosity by one mechanism. For this reason, different models are often used. In this study, the dynamic viscosity of a number of liquid metals was studied under the assumption that the volume distribution in liquid metals is given by a pseudopotential of an oscillatory nature.

Assuming that the viscosity of liquids is due to intermolecular attraction, we will consider a phenomenological approach. Suppose the viscosity ( $\eta$ ) is determined by Newton's law. Then the internal friction force acting on the section  $dS$  of the liquid layers in the region of the stationary velocity gradient ( $\partial\vartheta/\partial r = \text{const}$ ) will be:

$$F_s = \eta \left( \frac{\partial\vartheta}{\partial r} \right) dS \quad (1)$$

Here  $\eta$  is the coefficient of dynamic viscosity:

$$\eta = F_s \left[ \left( \frac{\partial\vartheta}{\partial r} \right) \cdot dS \right]^{-1} \quad (2)$$

The dynamic viscosity is the friction force acting on a homogeneous surface ( $dS = 1$ ), taken perpendicular to the region of the unit velocity gradient ( $\partial\vartheta/\partial r = 1$ ). When  $\left( \frac{\partial\vartheta}{\partial r} \right) = \text{const}$ ,  $\left[ \left( \frac{\partial\vartheta}{\partial r} \right) \cdot dS \right]^{-1} = \text{const} = B$ , and we get

$$\eta = B \cdot F_s. \quad (3)$$

Consequently, the dynamic viscosity of a liquid in laminar flow is directly proportional to molecular attraction. As can be seen, the viscosity coefficient can be calculated if the analytical expression for the intermolecular gravitational force is known.

## 3. Viscosity of liquid metals

It is clear that expression (3) from the phenomenological approach is, in principle, applicable to all liquids. However, the exact expression for FS is not known for most types of liquids. Let us determine the viscosity of liquid metals. It is known that the motion of free electrons in an electrostatic field created by positively charged ions in metal crystals is characterized by the following pseudopotential (Burkov, 2016):

$$\varphi(r) = \frac{A_1}{r} \cdot e^{-B_1 r}. \quad (4)$$

Here  $A_1$  is a constant depending on the nature of the ion (mainly the electric charge),  $B_1 = \lambda^{-1}$  ( $\lambda$  is the screening radius). In the theory of free electrons in the Thomas-Fermi metal, the screening radius  $\lambda_{T-F}$  is practically independent of temperature and is determined by the concentration of free electrons and the Fermi energy corresponding to 0 K of the metal (Ubbelohde, 1965). Assuming  $e^{-B_1 r} \approx 1 - B_1 r + \frac{(B_1 r)^2}{2}$  when  $B_1 r < 1$  in (4):

$$\varphi(r) \approx \frac{A_1}{r} - A_1 B_1 + \frac{A_1 B_1^2}{2} r. \quad (5)$$

On the other hand, since  $F = -\text{grad}\varphi$ , the interlayer force can be written as follows:

$$F = -\frac{d\varphi(r)}{dr} = \frac{A_1}{r^2} - \frac{A_1 B_1^2}{2} = \frac{A_1}{r^2} - D_1 \quad (6)$$

Here  $D_1 = A_1 B_1^2 / 2$  is a constant independent of temperature. Taking into account (6) in (3), we obtain:

$$\eta = B \cdot F = \frac{BA_1}{r^2} - BD_1 = \frac{A_2}{r^2} - D_2. \quad (7)$$

In (7)  $A_2 = BA_1$  and  $D_2 = BD_1$ . As you can see, the viscosity of liquid metals can be taken as the sum of two limits:

$$\eta = \frac{A_2}{r^2} - D_2 = \eta_I + \eta_{II}. \quad (8)$$

It can be assumed that the first limit  $\eta_I = \frac{A_2}{r^2}$ , which is inversely proportional to the square of the distance from the positively charged ion, is the viscosity due to the gravitational force. The fact that the second limit  $\eta_{II} = -D_2 = -BD_1$  is negative and does not depend on the distance between the ions suggests that it is associated with a free electron gas. A phenomenological (8) approach is also expected in terms of general criteria. Thus, since a liquid and a metal consist of ionic and electronic subsystems that interact with each other, it is clear that both subsystems will, to one degree or another, participate in the formation of physical phenomena.

The first limit  $\eta_I$  is associated with the intersystem (ion-free) interaction, and the second limit  $\eta_{II}$  is associated with the electron-electron interaction. Since positively charged ions are screened by free electrons, ion-ion interactions practically do not play a role in the formation of viscosity. Since the coefficient of thermal expansion of liquids is the same as the coefficient of expansion of the solid phase, it can be assumed that the temperature dependence of the distance between atoms in liquids is given by the law:  $r \sim T$ . Then the temperature dependence of the viscosity of the liquid metal is obtained:

$$\eta(T) \approx \frac{A}{T^2} - D. \quad (9)$$

This is a general expression of the viscosity of liquid metals in our phenomenological approach. Viscosity is related to the ionic subsystem and consists of the sum of temperature independent limits. Since (9) does not depend on the type of liquid metal, it must be universal.

If the  $A$  and  $D$  values are known, the viscosity value can be calculated at any temperature. For this, we will use the semi phenomenological method. Let us assume that at two arbitrary temperatures  $T_i$  and  $T_j$  the viscosities are equal to  $\eta_i$  and  $\eta_j$ . Here from (9) it turns out:

$$\eta(T) = \left[ \frac{T_i^2 \cdot T_j^2}{T_j^2 - T_i^2} \Delta\eta_{ij} \right] \cdot \frac{1}{T^2} - \left[ \frac{T_j^2}{T_j^2 - T_i^2} \Delta\eta_{ij} - \eta_i \right]. \quad (10)$$

Here  $\Delta\eta_{ij} = (\eta_j - \eta_i)$ . Viscosity values for various liquid metals are shown in Table 1.

**Table 1.** Viscosity for various liquid metals.

Liquid metal	Viscosity (kg/m·s)	Temperature, K
Pb	$\eta = \frac{621}{T^2} - 6,38 \cdot 10^{-4}$	$720 \leq T \leq 1100$
Sn	$\eta = \frac{363}{T^2} - 5,60 \cdot 10^{-4}$	$510 \leq T \leq 1100$
Zn	$\eta = \frac{1500}{T^2} - 2,75 \cdot 10^{-4}$	$720 \leq T \leq 970$
Hg	$\eta = \frac{70}{T^2} - 7,42 \cdot 10^{-4}$	$253 \leq T \leq 573$

In fig. 1 shows the viscosity of the investigated liquids in the coordinates  $\eta = \eta \left( \frac{1}{T^2} \right)$ .

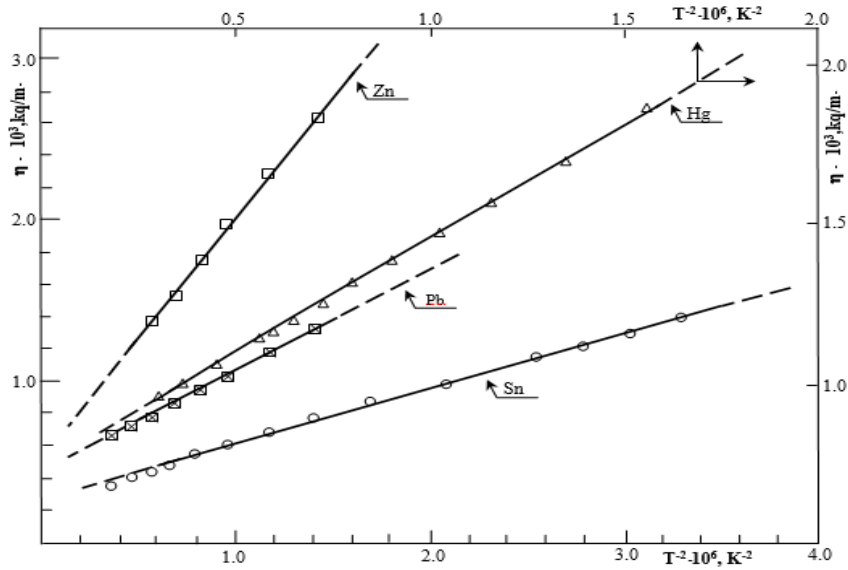


Fig 1. Temperature dependence of dynamic viscosity

For all three liquids, this dependence is linear, according to (9). The dynamic viscosity of all liquid metals, regardless of their electronic structure (alkaline, non-alkaline, etc.) in the solid phase is determined similarly to (9). For liquid metals, this pattern is associated with the fact that the volume potential in all liquid metals is similar to the Thomas-Fermi potential. In metals, the electron gas has a quantum nature, in contrast to the classical gas - electrons interact relatively strongly with each other. For this reason, the electron gas in a metal is called a "Fermi liquid".

The viscosity is equal to the sum of ions ( $\eta_i$ ) and electrons ( $\eta_{II}$ ). Using expressions (8) and (9), it is possible to calculate the ionic and electronic accumulations of viscosity. The corresponding results for Hg, Pb and Sn fluids are shown in Fig 2.

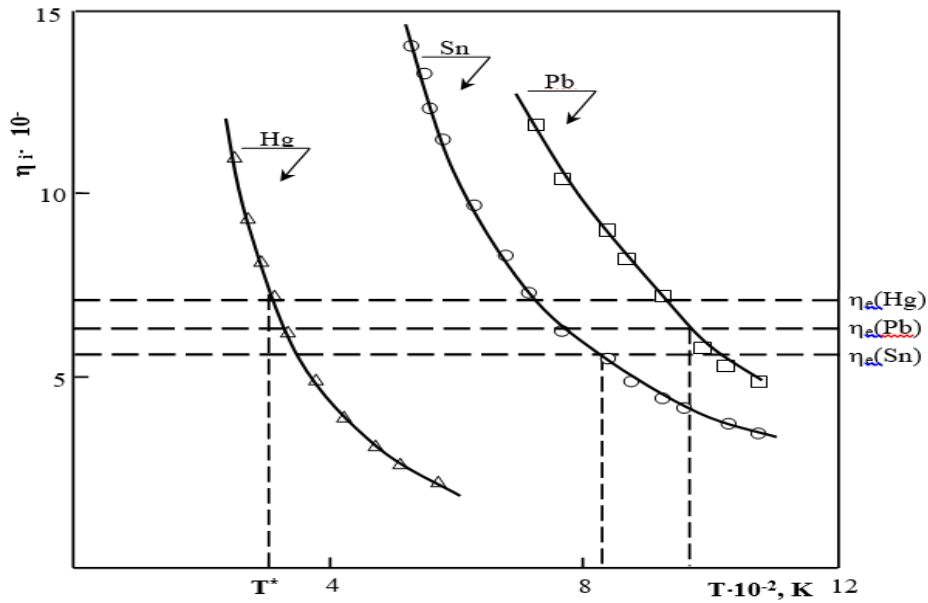


Fig. 2. Temperature dependence of the viscosity of the ionic ( $\eta_i$ ) and electronic ( $\eta_e$ ) parts.

#### 4. Conclusion

Thus, in this study, a semi-empirical analytical expression was found suitable for the viscosity of all liquid metals. It was found that the dynamic viscosity of a liquid metal is the sum of the ionic and temperature-independent electronic viscosity, which decreases with increasing temperature according to the law  $\eta_i \sim T^{-2}$ . In this study, the viscosities of Pb, Sn, Hg and Zn liquids were isolated and compared. Unlike other types of liquids, the viscosity of liquid metals is transferred in two significantly different ranges. This is due to the fact that each metallic fluid can be considered as a unique liquid solution, consisting of ionic and electronic subsystems.

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