The oscillating-cup viscometer placed in the magnetic field: the experiments under liquid gallium

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Metal melts have such conductivity, that magneto-hydrodynamic effects can be easily observed even in moderate magnetic fields (around 0.01T) under conditions achieved in conventional physicochemical experiments. This fact gives an opportunity to create new methods of analyzing metal melts properties. Current work represents the experiments with the oscillating cup viscometer placed in the uniform steady longitudinal magnetic field. The oscillation’ parameters dependencies on magnetic induction of the applied magnetic field have been measured. To record the motion of the viscometer the new optical scheme, which allows writing down quasi-continuously viscometer’s angle position, has been implemented. Estimation of oscillation’ parameters values (oscillation’ decrement and period) has been evaluated with the aid of wavelet analysis and optimization methods. Field dependences of oscillation’ parameters were being used for liquid gallium viscosity and electrical conductivity determination with the help of the viscosimetric theory, that was earlier suggested by us.

Introduction

Experiments, in which the oscillating cup viscometer has been placed in the external magnetic field have shown that the observed oscillations parameters significantly depend on the magnetic induction of the field [1,2]. The magnetic field often appears during the high temperature experiments due to high currents circulating in the setup’ heating system.

In the works [4-5], the theory of the oscillating cup viscometer has been generalized to take into account magnetohydrodynamic effects appearing during the metal melt motion in the magnetic field. The connection has been established between the melt properties (viscosity, electrical conductivity and density), setup parameters and the observed oscillations parameters (period and decrement). Therefore, there is a possibility to measure other properties (electrical conductivity and density) together with viscosity in the oscillating cup viscometer.

The purpose of the work is to define viscosity and electrical conductivity of the metal melt (gallium) by measuring the field dependence of the oscillating cup viscometer oscillations parameters.

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Experimental setup
The experimental setup scheme is presented in the figs. 1, 2. It differs from the other known ones by the existence of the solenoid for magnetic field producing, and the absence of the vacuum chamber (via solenoid’s size).

Oscillations’ registration. Viscometer oscillations have been registered by optical method in two different variants: 1) registration based on beam run time inside the slit of the photodetector and outside its boundaries, 2) registration based on continuous recording of the angular beam position with the aid of its intensity modulation after its passing through the screen with triangle slit. Instrument error in the definition of run time was $1.2 \times 10^{-6}$ s. The decrement and period of oscillations while using the first scheme have been defined by standard methods and while using the second scheme have been defined with the help of wavelet analysis and optimization methods. The second scheme has been involved mainly in the experiments with infinitesimal oscillations amplitudes.

![Figure 1. Fig.1 Scheme of the experimental setup](image)

Magnetic field. Magnetic field has been produced by cylindrical solenoid powered by stabilized constant-current source. Magnetic field induction in the center of the solenoid has been calculated by formula $B=CI$, where constant $C$ has been defined by computation and is equal to 211 Gs/A. Thus, when the current is maximum and equal to 3A, the maximum magnetic field induction in our experiments has been 600 Gs.

For the heating of the sample (to 40-50ºC) low-power cylindrical resistance furnace with bifilar winding has been used. This allowed us to minimize the magnetic field that the furnace produces.

The example of the record is shown in the fig. 3, the setup parameters are presented in the table 1.

| Table 1. Setup’s parameters. | The inner diameter of the cylinder, mm | Inertia momentum, g×sm² | Oscillations’ period of the empty cylinder, s | Oscillations’ decrement of the empty cylinder |
|-----------------------------|---------------------------------------|------------------------|---------------------------------------------|---------------------------------------------|
|                             | 26.01                                 | 77.03                  | 5.6073±0.0004                               | 0.0093±0.0006                               |

In the experiments two samples of the gallium have been performed with masses 39.686 g and 80.870 g. The experiments have been done in the air atmosphere, therefore the existence of the oxide film on the gallium surface could not be excluded.

Experiment results are presented in the fig. 4, where the field dependence of the oscillations’ decrement of the first sample (curve 1) is shown. Curve 2 is calculated in the frames of the theory.
[4,5] by using literature data on viscosity, density and electrical conductivity of the gallium. Let us notice, that theoretical and experimental data begin to diverge in the «high-field» region (B ~ 450 Gs). The field dependence of the oscillations period is weaker and so we do not reproduce it.

![Figure 2. Oscillations’ registration scheme.](image1)

![Figure 3. The example of the continuous record.](image2)

**Data evaluation**

In the fig. 5 the field dependence of the effective viscosity (that is calculated with the aid of the standard methods not taking into account the magnetohydrodynamic’ effects) is shown. Curves 1 (sample 1) and 2 (sample 2) have been calculated with the assumption that gallium has bordered on the rigid surface at the top, e.g. with the oxide film, and curves 3 (sample 1) and 4 (sample 2) have been calculated with the assumption that gallium has had the free surface. It can be seen that if B = 0, only curves 1 and 2 are in agreement.

![Figure 4. The field dependence of the decrement.](image3)

![Figure 5. The field dependence of the effective viscosity.](image4)

The divergence of these curves demonstrates the size effect with the field growth, i.e. when the magnetic field exists, the effective viscosity depends on the sample’s mass. In the fig. 6 and 7 the results of simultaneous viscosity and electrical conductivity definition with the help of the theory [4, 5] is shown. Theret defined viscosimetric equations have been solved by numerical optimization methods, i.e. the setup’s parameters were set and so the viscosity (ν) and electrical conductivity (σ), which are in the best agreement with the measured dependences δ(B) and τ(B) in the interval where B varies from zero to certain B_{max} have been found. It can be seen that the results for viscosity
weakly depends on the value of $B_{\text{max}}$ and their scattering is less than the scattering of the known experimental data. The dependence of the electrical conductivity on $B_{\text{max}}$ is more substantial. However, if we exclude the «high-field» region (see fig. 4) and «low-field» region, where magnetohydrodynamic’ effects are insignificant, we will get the results for the sample 1, those are in good agreement with the ones known from the literature. However, for the sample 2 they slightly exceed the upper bound of the literature data interval.

Due to the results of the numerical experiments uncovered size effect for electrical conductivity is probably caused by the insufficient definition’ precision of the setup’ parameters.

**Conclusion**

The data received for the liquid gallium do not yet aspire to exceptional precision because of the imperfection of our equipment. Nevertheless, they obviously demonstrate the possibility to expand the abilities of the oscillating-cup viscometer, to the simultaneous viscosity and electrical conductivity (and probably other properties of liquid metals) measurement.

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