Short Note

Reflections on the Properties of the Molten PbBi Alloy

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Reflections on the Properties of the Molten PbBi Alloy

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Abstract: For the eutectic molten *PbBi* alloy, we tested the additive properties of density, sound velocity, compressibility and dynamic viscosity of this alloy in the temperature range 600 – 1200 *K*. All these values can be represented as a mass-weighted sum of the corresponding values of pure lead and bismuth in the temperature range 600 – 1000 *K* within the limit of experimental errors. In the temperature range 800 – 900 *K*, we found that interatomic forces in the eutectic increase with temperature, which is caused by a decrease in the size of accumulations of atoms, clusters, of melt. A decrease in the size of clusters is accompanied by an increase in bonds between atoms within the clusters, which make them more stable.

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1. Introduction and mathematical convention

The eutectic molten *PbBi* alloy (44.5 wt. % *Pb*, 55.5 wt. % *Bi*) is today considered as a promising primary coolant for small-sized fast neutron nuclear reactors [1], floating fast nuclear power plants of small and medium power [2]. To design those reactors, knowledge of the thermal-physical characteristics of lead-bismuth liquid is necessary. There is a lot of experimental data on the properties of *Pb*, *Bi* and *PbBi* melts, but due to the complexity of measurements at high temperatures, the high reactivity of the molten metal, and the complexity of equipment, there are differences in experimental measurements. There is still no analysis of the discrepancies between the experimental data. In this article we will try to check some properties of liquid *PbBi* alloy, taking into account experimental discrepancies, ignoring the recommended values.

Let us assume that at a certain temperature T we have a set of experimental measurements of the physical quantity L, different from each other: $\{L_1^{\exp}, L_2^{\exp}, ..., L_n^{\exp}\}$, where $L_i^{\exp} < L_{i+1}^{\exp}$. Let us denote: $L_1^{\exp} \equiv L_{lower}^{\exp}$ and $L_n^{\exp} \equiv L_{upper}^{\exp}$. For analysis, let us take the average value: $L^{\exp} \equiv \langle L \rangle = (L_{lower}^{\exp} + L_{upper}^{\exp})/2$, since we do not know the reason for the difference between the experimental L_i values, we therefore discard intermediate values. For the obtained average value, we introduce the experimental error: $\Delta L^{\exp} = (L_{lower}^{\exp} - L_{upper}^{\exp})/2$. For the obtained values $L^{\exp} + \Delta L^{\exp}$, we then test the idea that any physical quantity of a molten *PbBi* alloy can be expressed as a mass-weighted sum of the physical quantities of lead and bismuth:

$$L \pm \Delta L = w_{Pb} \cdot L_{Pb}^{\exp} + (1 - w_{Pb}) \cdot L_{Bi}^{\exp}, \tag{1.1}$$

where w_{Pb} is the mass fraction of lead, and the standard deviation is calculated as follows:

$$\Delta L = \sqrt{\left(\frac{\partial L}{\partial L_{Pb}^{\exp}}\right)^2 \cdot \left(\Delta L_{Pb}^{\exp}\right)^2 + \left(\frac{\partial L}{\partial L_{Bi}^{\exp}}\right)^2 \cdot \left(\Delta L_{Bi}^{\exp}\right)^2}, \tag{1.2}$$

or

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$$\Delta L = \sqrt{\left(w_{Pb}\cdot\Delta L_{Pb}^{\exp}\right)^2+\left((1-w_{Pb})\cdot\Delta L_{Bi}^{\exp}\right)^2}, \tag{1.2'}$$

where the experimental errors for lead and bismuth are determined as described above. Comparing $L^{\exp}+\Delta L^{\exp}$ and $L\pm\Delta L$ we accept idea (1.1) if both average values L and $L^{\exp}$ lie within one standard deviation.

2. Thermal-physical properties of molten PbBi eutectic

One of the most important characteristics of a molten *PbBi* alloy (melting temperature is 398 ± 1 *K* [3]) is density, which allows you to find the equation of state of the liquid if you know the dependence of density on temperature and pressure. Table 1 shows the experimental densities of *Pb*, *Bi* and *PbBi* liquids in the temperature range 600 ÷ 1200 *K*, taken from [3]. The [3] contains a set of experimental data that differ from each other. Table 1 shows the average experimental densities at certain T: $\rho^{\exp}=(\rho_{lower}^{\exp}+\rho_{upper}^{\exp})\cdot 0.5$, where $\rho_{upper}^{\exp}$ is the upper and $\rho_{lower}^{\exp}$ is the lower experimental value at a certain temperature T. Experimental errors, that is, standard deviations, were calculated as follows: $\Delta\rho^{\exp}=(\rho_{upper}^{\exp}-\rho_{lower}^{\exp})\cdot 0.5$. We use experimental data to verify the formula/idea (1.1):

$$\rho_{PbBi}\pm\Delta\rho_{PbBi}=w_{Pb}\cdot\rho_{Pb}^{\exp}+(1-w_{Pb})\cdot\rho_{Bi}^{\exp}, \tag{2.1}$$

where w_{Pb} = 0.445, and errors are calculated as follows:

$$\Delta\rho_{PbBi}=\sqrt{\left(\frac{\partial\rho_{PbBi}}{\partial\rho_{Pb}^{\exp}}\right)^2\cdot\left(\Delta\rho_{Pb}^{\exp}\right)^2+\left(\frac{\partial\rho_{PbBi}}{\partial\rho_{Bi}^{\exp}}\right)^2\cdot\left(\Delta\rho_{Bi}^{\exp}\right)^2}. \tag{2.2}$$

We compare $\rho_{PbBi}\pm\Delta\rho_{PbBi}$ (5th column) with the experimental density $\rho_{PbBi}^{\exp}\pm\Delta\rho_{PbBi}^{\exp}$ (2nd column). In the temperature range 600 ÷ 1100 *K*, the theoretical ρ_{PbBi} and experimental $\rho_{PbBi}^{\exp}$ average values coincide within one standard deviation, as can be seen from Table 1. At 1200 *K* the difference between experiment and theory exceeds two standard deviations, but the relative error between them is only 1%. Thus, it can be concluded that the density of a molten eutectic *PbBi* alloy can be expressed as the mass-weighted sum of the densities of its components:

$$\rho_{PbBi}^{\exp}=w_{Pb}\cdot\rho_{Pb}^{\exp}+(1-w_{Pb})\cdot\rho_{Bi}^{\exp}. \tag{2.3}$$

This result has not been taken into account anywhere before, and the recommended (semi-empirical) values of densities of liquid metals *Pb*, *Bi* and *PbBi* do not satisfy formula (2.3) [3].

It is known from experimental data that the recommended velocity of sound in a liquid *PbBi* alloy is expressed as the mass-weighted sum of the recommended velocity of sound in pure *Pb* and *Bi* [3]:

$$u_{PbBi}^{recom}=w_{Pb}\cdot u_{Pb}^{recom}+(1-w_{Pb})\cdot u_{Bi}^{recom}. \tag{2.4}$$

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Table 1. Experimental data on the densities of liquid Pb, Bi and PbBi eutectic at various temperatures were taken from [3]. The additive density ρ_{PbBi} of the PbBi alloy is calculated according to (2.1). The relative difference between the calculated ρ_{PbBi} and experimental density $\rho_{PbBi}^{\exp}$ was calculated using the formula: $\delta = 100\% \cdot \left| \frac{\rho_{PbBi}^{\exp} - \rho_{PbBi}}{\rho_{PbBi}^{\exp}} \right|$..

T, K	$\rho_{PbBi}^{\exp}$, kg/m^3	$\rho_{Pb}^{\exp}$, kg/m^3	$\rho_{Bi}^{\exp}$, kg/m^3	ρ_{PbBi}, kg/m^3	δ,%
600	10293±54	10619±64	10023±90	10288±57	0.05
700	10166±54	10516±59	9801±102	10119±62	0.50
800	10045±60	10403±57	9760±102	10046±62	0.01
823	10018±67	10372±57	9756±88	10030±55	0.10
900	9931±70	10280±57	9639±96	9924±59	0.07
1000	9783±70	10161±54	9526±92	9809±56	0.30
1100	9616±40	10043±49	9387±111	9679±65	0.70
1200	9488±37	9925±51	9308±62	9583±41	1.00

Without paying attention to the recommended values, we took experimental data for sound velocities in the same way as for densities, and they are presented in Table 2 in the temperature range 600 ÷ 1000 *K*. Experimental errors were taken into account in the same way as for densities. Sound speeds with additive character (5th column) are calculated as follows:

$$u_{PbBi} \pm \Delta u_{PbBi} = w_{Pb} \cdot u_{Pb}^{\exp} + (1 - w_{Pb}) \cdot u_{Bi}^{\exp}, \tag{2.5}$$

and the errors of u_{PbBi} were calculated by (1.2′): $\Delta u_{PbBi} = \sqrt{(w_{Pb} \cdot \Delta u_{Pb}^{\exp})^2 + ((1 - w_{Pb}) \cdot \Delta u_{Bi}^{\exp})^2}$ are also shown in Table 2. From Table 2 it can be seen that the experimental velocity of sound (2nd column) for the PbBi alloy coincides with that calculated by (2.5) (5th column) within one standard deviation.

Table 2. Experimental data on the sound velocities of liquid Pb, Bi and PbBi at various T were taken from [3]. The additive velocity of sound u_{PbBi} for the PbBi alloy is calculated using (2.5). The relative difference between the calculated and experimental data was calculated using the formula: $\delta = 100\% \cdot \left| \frac{u_{PbBi}^{\exp} - u_{PbBi}}{u_{PbBi}^{\exp}} \right|$.

T, K	$u_{PbBi}^{\exp}$, m/s	$u_{Pb}^{\exp}$, m/s	$u_{Bi}^{\exp}$, m/s	u_{PbBi}, m/s	δ,%
600	1726±11	1803±33	1639±32	1712±23	0.8
700	1714±4	1778±32	1608±55	1684±34	1.7
800	1691±4	1756±29	1629±16	1685±16	0.4
823	1685±3	1748±29	1622±15	1678±15	0.4
900	1666±3	1733±25	1611±16	1665±14	0.06
1000	1640±3	1701±38	1586±19	1637±20	0.2
1100	–	1668±45	1549±10	1602±21	–

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1200	–	1667±18	1519±4	1585±8	–

The compressibility of condensed matter is a quantity measured indirectly through measurements of the velocity of sound and density using the formula:

$$\beta^{\exp} = \left(\rho^{\exp} \cdot (u^{\exp})^2\right)^{-1}, \tag{2.6}$$

Taking the experimental values of density and sound velocity from the tables above, we calculate the compressibility of molten lead, bismuth and *PbBi* alloy according to (2.6) and present them in Table 3. Errors were calculated using the following formula:

$$\Delta\beta^{\exp} = \sqrt{(\partial_\rho \beta^{\exp} \cdot \Delta\rho^{\exp})^2 + (\partial_u \beta^{\exp} \cdot \Delta u^{\exp})^2} = (\rho^{\exp} \cdot (u^{\exp})^2)^{-2} \cdot \sqrt{(u^{\exp})^4 \cdot (\Delta\rho^{\exp})^2 + 4(\rho^{\exp} \cdot u^{\exp})^2 (\Delta u^{\exp})^2}, \tag{2.7}$$

Table 3. Experimental compressibility data calculated according to (2.6) for liquid Pb, Bi and PbBi at various T, where the densities and sound velocities were copied from Tables 1 and 2.

T, K	$\rho^{\exp}_{PbBi}$, *kg/m³*	$u^{\exp}_{PbBi}$, *m/s*	$\beta^{\exp}_{PbBi}\cdot 10^{-11}$ *Pa⁻¹*	$\rho^{\exp}_{Pb}$, *kg/m³*	$u^{\exp}_{Pb}$, *m/s*	$\beta^{\exp}_{Pb}\cdot 10^{-11}$ *Pa⁻¹*	$\rho^{\exp}_{Bi}$, *kg/m³*	$u^{\exp}_{Bi}$, *m/s*	$\beta^{\exp}_{Bi}\cdot 10^{-11}$ *Pa⁻¹*
600	10293±54	1726±11	3.26±0.05	10619±64	1803±33	2.90±0.10	10023±90	1639±32	3.71±0.15
700	10166±54	1714±4	3.35±0.02	10516±59	1778±32	3.01±0.11	9801±102	1608±55	3.95±0.27
800	10045±60	1691±4	3.48±0.03	10403±57	1756±29	3.12±0.10	9760±102	1629±16	3.86±0.09
823	10018±67	1685±3	3.52±0.03	10372±57	1748±29	3.15±0.11	9756±88	1622±15	3.90±0.08
900	9931±70	1666±3	3.63±0.03	10280±57	1733±25	3.24±0.09	9639±96	1611±16	4.00±0.09
1000	9783±70	1640±3	3.80±0.03	10161±54	1701±38	3.40±0.15	9526±92	1586±19	4.17±0.11
1100	9616±40	1608±23	4.02±0.12	10043±49	1668±45	3.58±0.20	9387±111	1549±10	4.44±0.08
1200	9488±37	1593±9	4.15±0.05	9925±51	1667±18	3.63±0.08	9308±62	1519±4	4.66±0.04

Having the results of Table 3 for the compressibility of liquid *Pb*, *Bi* and *PbBi*, let us now check the idea (1.1):

$$\beta_{PbBi} + \Delta\beta_{PbBi} = w_{Pb} \cdot \beta^{\exp}_{Pb} + (1 - w_{Pb}) \cdot \beta^{\exp}_{Bi},\ \Delta\beta_{PbBi} = \sqrt{(w_{Pb} \cdot \beta^{\exp}_{Pb})^2 + ((1 - w_{Pb}) \cdot \beta^{\exp}_{Bi})^2}, \tag{2.8}$$

and the results are shown in Table 4 (5th column). Comparing the results obtained by (2.8) in 5th column with those obtained by (2.6) in 2nd column, we see that they agree within the limit of one standard deviation. This result is confusing because it is impossible to derive (2.8) from (2.6):

Table 4. Experimental data on the compressibility of liquid Pb, Bi and PbBi at various T, taken from table 3. The additive compressibility of the PbBi alloy calculated according to (2.8) - in the 5th column. The relative difference between the calculated β_{PbBi} and experimental compressibility $\beta^{\exp}_{PbBi}$ was calculated using the formula: $\delta = 100\% \cdot \left|\frac{\beta^{\exp}_{PbBi} - \beta_{PbBi}}{\beta^{\exp}_{PbBi}}\right|$.

T, K	$\beta^{\exp}_{PbBi}\cdot 10^{-11}$ *Pa⁻¹*	$\beta^{\exp}_{Pb}\cdot 10^{-11}$ *Pa⁻¹*	$\beta^{\exp}_{Bi}\cdot 10^{-11}$ *Pa⁻¹*	$\beta_{PbBi}\cdot 10^{-11}$ *Pa⁻¹*	δ,%
600	3.26±0.05	2.90±0.10	3.71±0.15	3.35±0.09	2.8
700	3.35±0.02	3.01±0.11	3.95±0.27	3.53±0.16	5.4
800	3.48±0.03	3.12±0.10	3.86±0.09	3.53±0.07	1.4
823	3.52±0.03	3.15±0.11	3.90±0.08	3.57±0.07	1.4

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900	3.63±0.03	3.24±0.09	4.00±0.09	3.66±0.06	0.8
1000	3.80±0.03	3.40±0.15	4.17±0.11	3.83±0.09	0.8
1100	4.02±0.12	3.58±0.20	4.44±0.08	4.06±0.10	1.0
1200	4.15±0.05	3.63±0.08	4.66±0.04	4.20±0.04	1.2

$$\beta_{PbBi}^{\exp}=\left(\rho_{PbBi}^{\exp}\cdot(u_{PbBi}^{\exp})^2\right)^{-1}=\frac{1}{(w_{Pb}\cdot\rho_{Pb}^{\exp}+(1-w_{Pb})\cdot\rho_{Bi}^{\exp})\cdot(w_{Pb}\cdot u_{Pb}^{\exp}+(1-w_{Pb})\cdot u_{Bi}^{\exp})^2}= \\ =\textit{should be equal to}=w_{Pb}\cdot\frac{1}{\rho_{Pb}^{\exp}\cdot(u_{Pb}^{\exp})^2}+(1-w_{Pb})\cdot\frac{1}{\rho_{Bi}^{\exp}\cdot(u_{Bi}^{\exp})^2}, \quad (2.9)$$

and we cannot yet explain this mystery.

The next important physical parameter of liquids is dynamic viscosity. Let us present the experimental data taken in [3] for the viscosity of molten *Pb*, *Bi* and *PbBi* in Table 5, and then check the idea of the additivity of this parameter:

$$\eta_{PbBi}\pm\Delta\eta_{PbBi}=w_{Pb}\cdot\eta_{Pb}^{\exp}+(1-w_{Pb})\cdot\eta_{Bi}^{\exp}, \quad (2.10)$$

where we calculated the error using formula (1.2′). Comparing the results (2.10) in the 5th column and the experimental data in the 4th column, we see that in the temperature range 600 ÷ 1000 *K*, formula (2.10) is satisfied within one standard deviation, but the relative difference between these data approaches 19%.

Let us assume that (2.10) does not work. Instead of this formula we will wright the following:

$$\eta_{PbBi}=(w_{Pb}\cdot\eta_{Pb}^{\exp}+(1-w_{Pb})\cdot\eta_{Bi}^{\exp})\cdot q, \quad (2.11)$$

where q is a variable within which a set of the melt's parameters is hidden. Table 5 shows the values of q, which give a viscosity (8th column) equal to the experimental one (4th column).

Table 5. Experimental data on the dynamic viscosity of liquid Pb, Bi and PbBi at various temperatures are taken from [3]. Dynamic viscosity of the PbBi alloy, calculated according to (2.10) - in the 5th column. The relative difference between the calculated and experimental dynamic viscosity was calculated using the formula: $\delta=100\%\cdot\left|\frac{\beta_{PbBi}^{\exp}-\beta_{PbBi}}{\beta_{PbBi}^{\exp}}\right|$. q is a variable from (2.11) giving viscosity equal to $\eta_{PbBi}^{\exp}$. h is calculated by (2.13). Force interaction F between pairs of atoms calculated by (2.15).

T, *K*	$\eta_{Pb}^{\exp}\cdot10^{-3}$ *Pa·sec*	$\eta_{Bi}^{\exp}\cdot10^{-3}$ *Pa·sec*	$\eta_{PbBi}^{\exp}\cdot10^{-3}$ *Pa·sec*	$\eta_{PbBi}\cdot10^{-3}$ *Pa·sec*, by (2.10)	δ,%	*q*	$\eta_{PbBi}\cdot10^{-3}$ *Pa·sec*, by (2.11)	*h*	$F\cdot10^{-10}$ *N*
600	2.68±0.21	1.52±0.11	1.79±0.14	2.04±0.11	14.0	0.877	1.79	40.816	–
700	2.11±0.06	1.28±0.07	1.48±0.13	1.65±0.05	11.5	0.897	1.48	39.888	–
800	1.72±0.03	1.13±0.05	1.30±0.10	1.39±0.03	6.9	0.936	1.30	38.193	7.73
823	1.67±0.05	1.41±0.34	1.29±0.10	1.53±0.19	18.6	0.843	1.29	42.494	8.60
900	1.48±0.05	1.26±0.28	1.16±0.10	1.36±0.16	17.2	0.853	1.16	41.986	8.50
1000	1.34±0.03	1.18±0.22	1.09±0.11	1.25±0.12	14.7	0.872	1.09	41.054	–
1100	1.25±0.10	0.90±0.02	0.94±0.03	1.06±0.05	12.8	0.887	0.94	40.346	–
1200	1.24±0.15	0.85±0.02	0.89±0.03	1.02±0.07	14.6	0.873	0.89	41.006	–

We assume that q should contain the atomic numbers (nuclear charges) of the metals of the liquid alloy, since they determine the electronic and atomic structure of the melt: $q = q(Bi, Pb)$, where $Bi = 83$, $Pb = 82$. It must also contain characteristics of the atomic structure of the melt, that is, the most

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probable distance between atoms in the liquid. Currently, there is only one experimental data for the distances between pairs of atoms in the eutectic liquid *PbBi* alloy at $T = 823$ *K* [4]: for *Pb-Pb* pairs $a_{PbPb} = 2.73239$ Å, for *Pb-Bi* pairs $a_{PbBi} = 2.40845$ Å, for *Bi-Bi* pairs $a_{BiBi} = 2.17606$ Å. As an approximation, let us take the average value: $a = 2.439$ Å. Then suppose that the variable q depends on this average distance: $q = q(Bi, Pb, a)$. The next parameter within q is the nature of the change in the distance between atoms with a change in temperature, which characterizes the type of interatomic bonds. This parameter is the first derivative of a with respect to T: $q = q(Bi, Pb, a, \partial_T a)$. Considering that q is a dimensionless quantity, we assume that a and $\partial_T a$ are contained within some dimensionless parameter h: $q = q(Bi, Pb, h(a, \partial_T a))$. After going through various combinations, we came to the conclusion that the following version of the variable best matches the experimental data:

$$q = \left(\frac{1}{(1 - w_{Pb}) \cdot Bi} + \frac{h}{w_{Pb} \cdot Pb} \right)^{-1}, \tag{2.12}$$

where we related h to the atomic number of lead as being the most electronegative compared to *Bi*. The latter is done in order to give a rule of use (2.12) in relation to other substances.

Suppose $h = g(a) \cdot \partial_T a$, where $g(a)$ is a quantity (function of a) with unit measure $[K/m]$ compared to $\partial_T a$ with $[m/K]$, which makes h dimensionless. If we multiply and divide $\partial_T a$ by Boltzmann's constant k: $k \cdot \partial_T a / k$, then in the denominator we have $k \cdot \Delta T$, which has a measure of energy. Then $h = F(a) \cdot \partial_T a / k$, where $F(a)$ has a measure $[J/m]$, which we relate to the force of interatomic interaction. Thus: $g(a) = F(a)/k$.

Table 5 shows h derived from (2.12), where we already know q (7th column):

$$h = w_{Pb} \cdot Pb \cdot \left(\frac{1}{q} - \frac{1}{(1 - w_{Pb}) \cdot Bi} \right). \tag{2.13}$$

Knowing F at a specific T, we can find $\partial_T a$ using the formula:

$$h = \frac{F}{k} \cdot \frac{\partial a}{\partial T}. \tag{2.14}$$

The problem of finding F in a metal was solved in [5]. Applying the same approach to the melt, we got:

$$F = \sqrt{\frac{3\pi a k T}{\beta}}, \tag{2.15}$$

where β is a compressibility of the melt at temperature T. We know the average distance between atoms at 823 *K*, as already mentioned: $a = 2.439$ Å. At this temperature T we know the compressibility from the Table 4: $\beta_{PbBi}^{\exp} = 3.52 \cdot 10^{-11}$ Pa^{-1}. And from (2.15) we obtain the force: $F = 8.6 \cdot 10^{-10}$ *N*. And from (2.14) we obtain the derivative:

$$\frac{\partial a}{\partial T} = h \cdot k / F = 0.068188 \text{ Å}/K. \tag{2.16}$$

This means that the angle of inclination of the function $a(T)$ to the T axis is zero in the vicinity of $T = 823$ *K*. Let us assume that in the temperature range 800 – 900 *K* this angle changes slightly, that is, the interatomic distance remains constant. Then from (2.14) we can find F:

$$F = h \cdot k \cdot \left(\frac{\partial a}{\partial T} \right)^{-1}. \tag{2.17}$$

From Table 5 we know h at 800 and 900 *K*. Having calculated F at these temperatures, we see (Table 5, last column) that the interaction force between the atoms of the lead-bismuth melt tends to increase as T changes from 800 to 900 *K*. This cannot confuse us, since we know from [6] that liquid metals

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consist of accumulations of atoms - clusters, with diameters up to 20 *nm*. The size of these clusters decreases with increasing T, but the forces between atoms within the clusters increase, which makes the clusters stable [6].

Thus, we found that the dynamic viscosity of the eutectic *PbBi* melt can be represented as the mass-weighted sum of the viscosities of pure *Pb* and *Bi*, multiplied by a variable that depends on the atomic numbers of *Pb* and *Bi*, on interatomic distances, derivatives of interatomic distances with temperature, compressibility of pure *Pb* and *Bi*:

$$\eta_{PbBi} = (w_{Pb} \cdot \eta_{Pb}^{\exp} + (1 - w_{Pb}) \cdot \eta_{Bi}^{\exp}) \cdot \left(\frac{1}{(1 - w_{Pb}) \cdot Bi} + \frac{\sqrt{3\pi akT} \cdot \frac{\partial a}{\partial T}}{w_{Pb} \cdot Pb \cdot k \cdot \sqrt{w_{Pb} \cdot \beta_{Pb}^{\exp} + (1 - w_{Pb}) \cdot \beta_{Bi}^{\exp}}} \right)^{-1}, \quad (2.18)$$

where we combined (2.11), (2.12) and (2.13) – (2.17). As a result, we expressed the dynamic viscosity of the *PbBi* melt in terms of the viscosity and compressibility of pure elements.

3. Conclusion

It was found that, within the experimental errors for the eutectic *PbBi* melt, the density obeys the additive law in the temperature range 600 ÷ 1100 *K*, the sound velocity – in the temperature range 600 ÷ 1000 *K*, compressibility – in the temperature range 600 ÷ 1000 *K*, dynamic viscosity – in the temperature range 600 ÷ 1000 *K*. In the latter case, the experimental errors reach 10%, and the relative difference between the experiment and the results obtained using the additive law lies in the range of 10 ÷ 19%. To improve the latter result, we multiplied the mass-weighted sum of the viscosities of pure *Pb* and *Bi* by a variable depending on the atomic numbers of the pure elements of the alloy, their partial masses, weighted compressibilities of the pure elements, interatomic distances and their derivatives relative to the temperature. An assessment of interatomic forces shows that in the temperature range of 800 ÷ 900 *K* they increase due to a decrease in the size of the clusters with strengthening of bonds between the atoms of the clusters.

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