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The viscosity of aluminium and its alloys—A review of data and models

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In this paper the available data for the measurement of viscosity of aluminium and its alloys are reviewed. Most measurements are performed with an oscillating vessel technique and the merits of this technique are discussed. The purity of the aluminium affects the measured viscosity values and we recommend a value of between 1.0–1.4 mPa·s for the pure element at the melting point. Although studies of the viscosity of aluminium alloys are limited, the effects of elemental additions to the alloy are similar to those for additions to the base metal. Thus an increase in concentration of Ti, Ni, Cr, Mn, Mg tends to increase the viscosity whereas the viscosity decreases with increasing Zn and Si concentrations. Also purification of an alloy decreases the viscosity. There is a wide variety of models ranging from those based on empiricism to thermodynamic methods. With the present quality of input data it is probably better to use a simple rather than a sophisticated model.

1. Introduction

Thermophysical properties are an important input for simulation models of liquid metal processing. These data are often very difficult and time consuming to measure and there is potentially great value in providing the engineer with an easy-to-use software package to predict the relevant properties, even if solely to establish which are the critical properties for direct measurement. We have previously developed such a software package to predict enthalpy, density, fraction solid and thermal conductivity for common industrial aluminium alloys [1] based on the calculation of phase equilibria from critically assessed thermodynamic properties using MTDATA [2] and simple physically based models. These predictions have been validated against experimental data.

Another important thermophysical property is viscosity and it is generally accepted that such transport properties are difficult to model. This paper describes the first steps in introducing such a model for the prediction of the viscosity for aluminium alloys. Throughout this paper, unless specified, we will discuss dynamic viscosity. The kinematic viscosity is related to the dynamic viscosity by dividing by the density.

The first stage is to establish a consistent set of viscosity values for the base elements and the definition of a suitable method to interpret experimental results over a range of temperature. The measured viscosity for a given element can vary widely. One of the worst examples is aluminium, for which there have been many measurement studies. Differences in viscosity values of the order of 400% have been reported. (see for example reference [3].) Some of the factors contributing to these differences will be reviewed and include:

- The choice of measurement method
- The interpretation, for a given method, of the experimental data in order to derive the viscosity values.
- The purity of the aluminium or its alloys, including inclusions or precipitates.

A further complication is the possibility that the atomic arrangement within liquid aluminium alloys changes during heating and cooling, and this may produce discontinuities in the viscosity values as a function of temperature. Establishing a database of viscosity values for the elements is not trivial.

The second stage is to establish a reliable set of experimental data for the viscosity of binary and multicomponent systems in order to model the effects of the introduction of additional elements. Here there are a wide variety of models available based on varying degrees of empiricism. These will be reviewed and some comments about their applicability discussed.

2. Measurement of viscosity of liquid metals

2.1. General

There are a large number of methods to measure the viscosity of materials. Methods suitable for liquid metals are limited by metal's low viscosities (of the order of 1 mPa·s), their chemical reactivity and generally high melting points. Proposed methods include: capillary, oscillating vessel, rotational bob or crucible, oscillating plate; levitation using the damping of surface oscillations and acoustic methods.

The *capillary rheometer* is generally thought to be best method for the measurement of the viscosity of liquids [3] and is based upon the time for a liquid to flow through a narrow bore tube. The disadvantage for the measurement of low viscosity fluids is that the requirement to ensure laminar flow defines a narrow ($r <$ 0.15–0.2 mm) and long ($l >$ 80 mm) capillary, which is easily blocked by particles such as oxides and bubbles. There is also a temperature limitation of about 1200°C for stable tubes. This method is unsuitable for the measurement of the viscosity of aluminium alloys because of the material's susceptibility to formation of oxide, which blocks the tube, but the viscosity of other metals such bismuth has been successfully measured [3].

For *the rotating bob technique* the torque on a cylinder rotated in a liquid is related to the viscosity of the fluid. Again because of the low viscosity of metals the clearance between the stationary and rotating parts is very small and it is difficult to maintain the system coaxially. In spite of the experimental difficulties the rotating bob technique has been used to measure the viscosity of aluminium and its alloys [4].

The *oscillating plate method* is still under development [5]. The damping of linear oscillations of a plate immersed in a liquid is used to determine the viscosity. Although in theory a simple method, for low viscosity metals a thin oscillating plate of large area must be vibrated slowly within the liquid. As far as the authors are aware this method has not been used to measure the viscosity of liquid metals.

Most measurements of the viscosity of metals use some form of *oscillating vessel viscometer.* A liquid contained in a vessel, normally a cylinder, is set in motion about a vertical axis and the motion is damped by frictional energy absorption and dissipation within the liquid. The viscosity is determined from the decrement and time period of the motion. The main advantages of the method are that the time period and decrement are easily measured and the amount of liquid is relatively small which allows stable temperature profiles to be attained. One of the major difficulties is relating the measured parameters to the viscosity through the second order differential equation for the motion of an oscillating system—there are a number of mathematical treatments appearing to yield different results [6–10] with the same experimental data. Since this is the most commonly used method it will be discussed in more detail below.

A further method, the *damping of the surface oscillations on a levitated drop* of metal, is currently under development. In order to simplify the experiment trials were performed under microgravity [11] conditions although Paradis and Rhim [12] have claimed success terrestrially using this method. It is believed that experiments are under way in Germany to measure the viscosity of selected aluminium alloys using this technique.

The viscosity of a liquid can be measured by measuring the *damping of an acoustic wave*. There is one example for the measurement of aluminium [13] and some alloys using hole theory to interpret the results.

2.2. Oscillating vessel technique

Fig. 1 shows the experimental arrangement for an oscillating vessel viscometer and details of this particular design are given in reference [14]. The sample is contained within an alumina crucible (105 mm long by 14 mm internal diameter), which is screwed into a molybdenum lid and suspension rod and suspended on a torsion wire. A rotary solenoid is used to impart oscillatory motion to the crucible and an optical pointer with a diode array is used to measure the time constant and decrement of the system. The sample is heated by a two zone furnace. These authors claim an uncertainty of measurement of ±9% within a 95% confidence limit. A major contribution to the uncertainty is the extrapolation of the dimensions of the crucible and the height of liquid at high temperatures.

For a right circular cylinder that is infinitely long containing a fluid the equation of motion of the damped cylinder is:

$$I_o(\mathrm{d}^2\theta/\mathrm{d}T^2) + L(\mathrm{d}\theta/\mathrm{d}T) + f\theta = 0 \qquad (1)$$

where I_o is moment of inertia of an empty cup and suspension, T is the time, f the force constant of the torsion wire, θ is the angle of displacement of any small segment of the fluid from its equilibrium position and L is a function of the density and viscosity of the fluid, the internal radius of crucible and height of liquid. Expressions for L are determined by solving the Navier-Stokes equations for the motion of the liquid within the vessel (neglecting non-linear terms). The working formulae for the oscillating cup viscometer by Knappworst [6], Shvidkovskkii [7] and Roscoe [8] were reviewed recently by Iida and Guthrie [3] who recommended the Roscoe equation as providing the most accurate data with some provisos about the effects of wetting of the crucible and this seems to be the most widely adopted equation for molten metals. Ferriss *et al.* [15] have shown there is a missing numerator in one of the expansions as printed in the Roscoe paper. Chemical engineers have adopted a set of equations for oscillating cup viscometers by Kestin and Newell [9, 10] which have also been used recently for deriving the viscosity of liquid metals [15, 16].

Ferriss *et al.* [15] used data from the NPL oscillating cup viscometer to compare the use of the original Roscoe equation, the modified form and the Kestin and Newell equation. This demonstrated, for the two examples of data investigated, that the maximum error between the two implementations of the Roscoe equation was about 5% (but only ∼1% for the conditions used to measure aluminium and its alloys). Also the modified Roscoe and Kestin and Newell equations gave very similar results. It is generally recognised that to obtain accurate results the height of the liquid and radius of the crucible must exceed critical values.

3. Viscosity data

3.1. Aluminium including effects of purity

Wide ranges of values of viscosity of molten aluminium have been reported in the literature and the results have been collated by Iida and Guthrie [3] (Fig. 2) for seven investigations, which demonstrate a spread of about 400% in values. The earliest works report the higher values with one study by the rotating bob method and

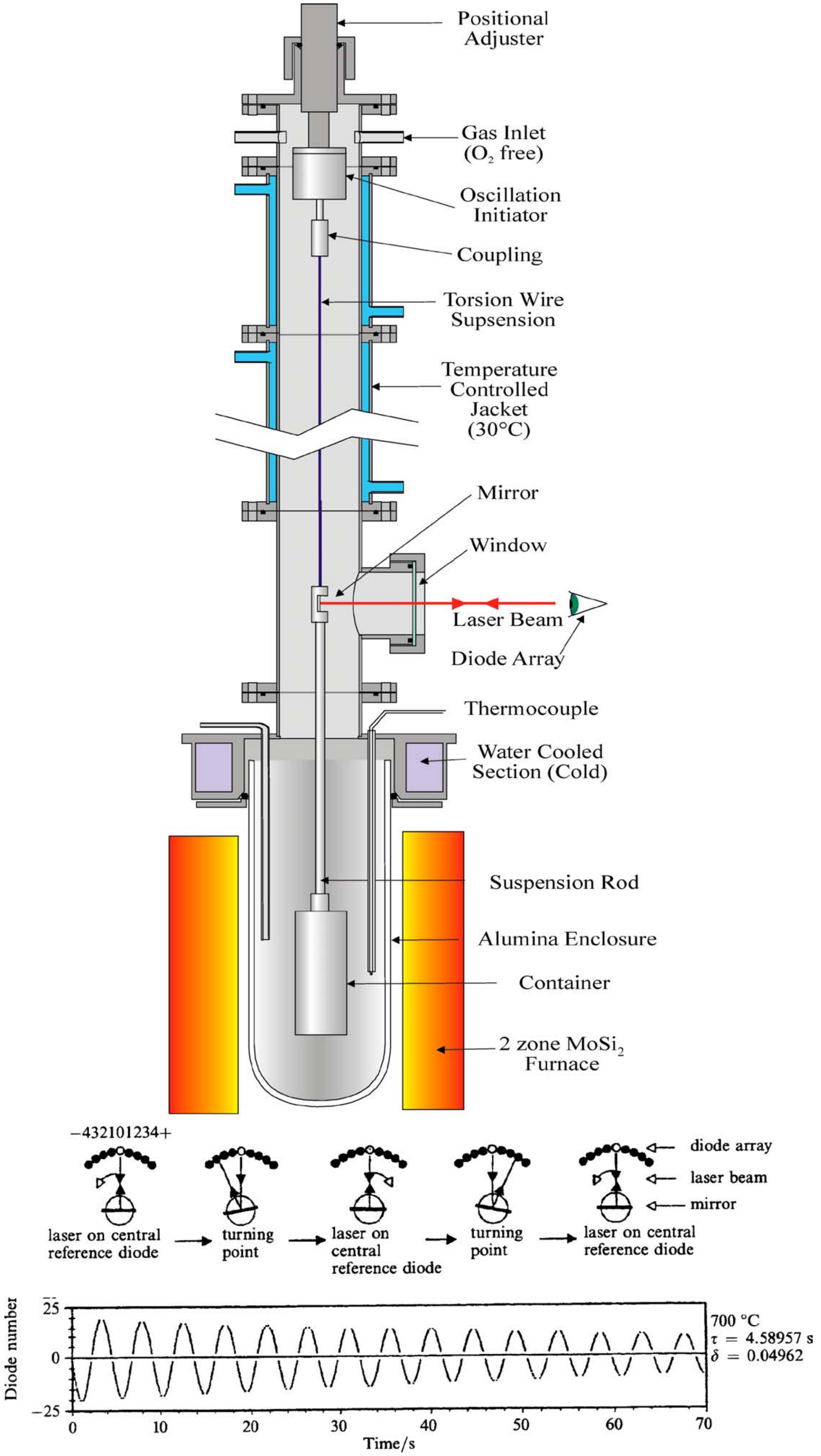

Figure 1 The experimental arrangement for an oscillating cup viscometer.

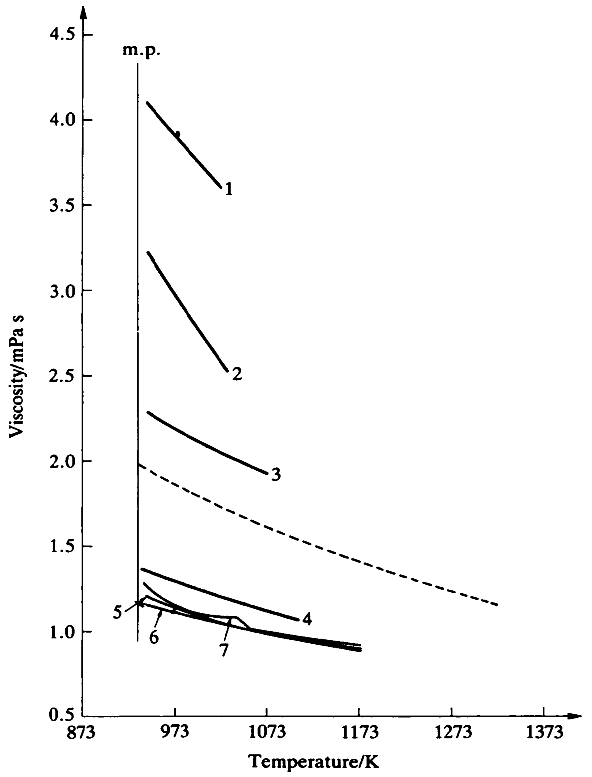

Figure 2 Measured viscosity of molten aluminium from the compilation of Iida and Guthrie [3].

the two others predating the equations now used for analysing oscillating vessel results. Four later investigations show values in the range 1.2–1.4 mPa·s at the melting point with one set showing some break from a smooth curve about 750°C. The temperature dependence of viscosity appears greater for the higher measured viscosities but it should be emphasised that this is a selection of available results.

Arsent'ev *et al.* [17] reviewed other measurements and deduced that atmosphere control (reducing the oxygen potential to a minimum) and the choice of crucible material (e.g., graphite would appear to influence the measurements) are also important experimental factors affecting the results. The choice of equations to analyse the results will also have some effect. For this reason it is probable that comparing results amongst different workers requires careful evaluation whereas comparing results within the same laboratory will yield more reliable trends.

Independent studies [17, 18] show that the viscosity of aluminium decreases as the purity of the metal increases. A range of viscosity values from 1.22 to 0.7 mPa·s at the melting point [18] (this is the lowest value reported) and 1.65 to 1.22 mPa·s [17] were quoted. It was concluded that the superficial film of oxide affects the measured viscosity of aluminium. The viscosity of nitrogen containing melts increases (∼1.39 to 1.7 mPa·s) with an increase in nitrogen levels (undetected to 0.01%N). It is suggested that the increase is due to the formation of AlN in the melt [19]. None of these studies revealed discontinuities in the values as a function of temperature but other workers have associated changes of this type with polymorphic transformations. Arsent'ev *et al.* [20] reviewed the evidence and dismissed the claims: "experimental checks on the polymorphism in liquid aluminium have yielded negative results." However this is still a hotly debated phenomenon.

There are few measurements by techniques other than the oscillating cup. Jones *et al.* [4] used the rotating bob technique and derived higher values than those generally reported with the oscillating cup. Although the data are scattered for acoustic technique, the values obtained favour lower values for the viscosity of aluminium [13]. Recent studies using the oscillating vessel technique have given 1.38 mPa·s at the melting point [16] (a modified Beckwith analysis) and 1.1 mPa·s using both the Roscoe and Beckwith analysis [21].

We conclude that the measured viscosity of aluminium is strongly dependent on its purity and this review favours the lower values.

3.2. Viscosity of relevant elements

One method to model viscosity is to apply unary data and build it into binary and ternary interactions. Several compendia of viscosity data for the elements exist and we have chosen to illustrate the data with two of these [22, 23] listing the viscosity at the melting point and the temperature dependence in the Arrhenius form:

$$\eta(T) = \eta_o \exp(E/RT) \qquad (2)$$

where E is the activation energy for viscous flow, η_o is the pre-exponential viscosity, which are both constants for the particular element, T is the temperature in K and R is the gas constant (taken to be 8.3144 J mol^{-1}K^{-1} in the compilations).

Table I lists the values for the two compendia for some relevant elements. Clearly there are discrepancies

TABLE I Data for the viscosity of relevant elements drawn from two compendia [22, 23]

Element	M.Pt [3] T_m(°C)	$\eta(T_m)$ (mPa·s)	η_o (mPa·s)	E (kJ mol^{-1})	$\rho(T_m)$ [3] (kg·m^{-3})
Al	660	1.38	0.257	13.08	2380
		1.30	0.149	16.5	
Cu	1083	4.38	0.529	23.85	8000
		4.0	0.301	30.5	
Fe	1535	6.93	0.315	46.5	7030
		5.5	0.370	41.4	
Mg	650	–	–	–	1590
		1.25	0.025	30.5	
Mn	1244	–	–	–	5760
		5	0.12–1.02	20–46.5	
Si	1414	–	–	–	2530
		0.8	0.06–0.12	27–36	
Zn	419	3.50	0.527	10.91	6580
		3.85	0.413	12.7	
Ag	960	4.27	0.589	20.34	9300
		3.88	0.453	22.2	
Cr	1905	–	–	–	6290
		5.7	1.7×10^{-4}	∼185	
Ni	1455	–	–	–	7900
		4.9	0.166	50.2	
Sn	231	1.87	0.467	5.83	6980
		1.85	0.538	5.4	
		2.2			
Ti	1725	2.2	–	–	4130
		5.2	∼0.034	∼68	

between the values and this again reflects difficulty of obtaining accurate data. The first line relates to the Iida and Shiraishi [22] compendium in which some elements are not covered. The data from Battezzati and Greer [23], in the second line, makes clear that the values for some refractory elements (e.g., Cr) are uncertain and in other cases large discrepancies in the values exist in the literature (e.g., Mn).

3.3. Binary and ternary alloys of aluminium

In this paper we present a brief review of relevant binary viscosity data. Ganean *et al.* [24] have reviewed the available data for the Cu-Al system: they discounted data measured by the rotating bob [4] method and one set of data [25] which does not show the same general trend as the other studies. The final analysis is based upon two sets of data [26, 27]. Using similar criteria we conclude that:

For additions of Ti, Ni, Cu, Cr; and Mn the viscosity rises as the concentration of the solute increases. Some of these effects are summarised by Polyakova and Arsent'ev [28] for the dynamic viscosity at 800°C and for a larger temperature range by Kinun'ko *et al.* [29]

- For Si the viscosity decreases as the concentration increases [18, 29–31]. The work by Persion [31] reports complex behaviour especially near the eutectic composition, which they associate with changes in the structure of the liquid.
- The reported behaviour of additions of Mg and Zn are more complicated [29, 33]. Again data generated with the rotating bob method are in disagreement with the bulk of results [4] and the limited acoustic wave studies show the same general trend as the oscillating vessel measurements [13].

There are few ternary studies but they include Al-Fe-Cr at relatively high temperatures [32] and a study at 750°C of an Al-7%Si with Zn content varying between 0–2.5wt% [33].

3.4. Commercial aluminium alloys

Taran *et al.* [34] investigated the viscosity of the Russian alloy, AK12M2MgN (see Table II for composition of the alloy). The kinematic viscosity was measured after various purification routes likely to remove oxides and the viscosity was lowered by these treatments. A hysteresis was observed at about 700°C between measuring in heating and cooling. The effect became less as the purity increased.

Wang and Overfelt [16] have recently published data for the alloys designated, A201, A319 and A356 and shows a drop in the viscosity compared to his results for the Si containing alloys A319 and A356 whereas the data for A201 are very similar to the Al data. The data for Al and LM25 (very similar composition to A356) published by NPL [21] are at variance with this. The measured viscosity of the Al is lower and the LM25 a little higher than the Wang data. The LM25 had a higher impurity level than that for the A356 used by Wang and it is possible that this is responsible for the higher measured viscosity of the LM25.

3.5. Additions to aluminium alloys

Kusun'ko [35] made various single additions of Si; Mg; Mn and Cu and additions of combinations of these elements to four Russian alloys designated AK9; AK7; AK5M2; AK5M7. The viscosity dropped with increasing Si level and rose for the additions of Mn, Cu, and Mg. Additions of combinations of the elements lowered the viscosity, showing the dominant effect of Si at the levels used in these experiments.

Efimenko *et al.* [36] added Zn from 0 to 14 wt%. to the alloy AK5M2. They observed a drop in the kinematic viscosity with increasing Zn content but the effect was not linear. They attempted to explain the results in terms of a quasi-polycrystalline model of the melt structure.

4. Models for viscosity of metals

The following section presents some of the models, which are used to describe the viscosity of the elements and multicomponent systems. Our aim is to attempt to recommend a model which describes the viscosity of aluminium alloys adequately for a first estimate suitable for modelling solidification. The list is not comprehensive and we have not included molecular models or relationships between liquid diffusion coefficients and viscosity such as the Stokes Einstein equation.

TABLE II Compositions of aluminium alloys for viscosity measurements

	Ag	Cu	Si	Fe	Mg	Mn	Ti	Others
A201 [16]	0.59	4.7	<0.05	0.05	0.28	0.31	0.21	–
A319 [16]	–	3.01	6.1	0.68	0.3	0.71	–	–
A356 [16]	–	–	6.9	0.08	0.34	–	0.013	–
LM25 [21]		0.07	7.3	0.37	0.46	0.16	0.1	–
AK12M2MgN [34]	–	1.52	11.6	0.7	0.86	0.46	0.1	0.96 Ni; 0.28 Zn 0.22 Cr
AK9 [35]	–	1.0	8.05	0.63	0.33	0.28	–	0.36 Zn 0.08 Ni
AK7 [35]	–	1.2	6.8	0.6	0.4	–	–	0.31 Zn 0.05 Ni
AK5M2 [35, 36]	–	2.11	4.5	0.69	0.28	0.25	–	0.36 Zn
AK5M7 [35]	–	6.84	4.9	0.87	0.33	–	–	0.6 Zn

4.1. Elements

4.1.1. Andrade equation for viscosity at melting point [40]

This is based upon the supposition that the characteristic vibration frequency in the liquid (ν_L) and solid (ν_S) near the melting point are equal using the fact that the specific heats of liquid and solid metals at their melting point are similar.

$$\eta(T_m) = C_A * \{T_m \cdot A\}^{1/2} / V^{2/3} \tag{3}$$

Andrade showed that C_A is approximately a constant for pure metal melts and estimated a value of 1.65×10^{-7} (J/K·mol$^{1/3}$)$^{1/2}$ where A is the atomic weight and V is the molar volume of the liquid at T_m.

Battezzati and Greer [23] have drawn together information for the viscosity of liquid elements at their melting points and tested Andrade's equation. They note several exceptions to the predicted value of C_A.

They question whether the experimental values for the viscosities of some elements such as chromium, manganese and the refractory metals are accurate enough to test the model.

Selenium, which is known to form associates, has a very high measured viscosity ($\sim$25 mPa · s at its melting point) compared to other metals yielding a C_A value of 29×10^{-7} (J/K·mol$^{1/3}$)$^{1/2}$.

The semiconductors, silicon and germanium, show low values of C_A and they propose that, as other physical properties indicate, these materials are non metallic in the solid and metal in the liquid. Hence the assumption made in Andrade's formula about the equality of the characteristic vibration frequencies in the solid and liquid at the melting point is negated. They apply a correction based on the anomalous high entropy of fusion of these elements to correct the characteristic vibration frequency and for example the C_A for silicon is adjusted from 0.6 to 1.3×10^{-7} (J/K·mol$^{1/3}$)$^{1/2}$.

4.1.2. Temperature dependence of viscosity of the elements

There are a wide number of equations, which have been derived to describe the viscosity as function of temperature for pure liquids. (see Chhabra and Seth [38] and Beyer and Ring [39]) These frequently involve two or three adjustable parameters. Chhabra investigated three common models: Arrhenius; Andrade and the Hildebrand Fluidity equation and compared them against experimental data.

4.1.2.1. Arrhenius equation. The Arrhenius equation is the one most frequently used to represent data on viscosity:

$$\eta = A\exp(E/RT) \tag{4}$$

where T is temperature in K, A is the pre-exponential factor, R is the gas constant and E is the activation energy for viscous flow.

Chhabra *et al.* derived values for A and E from various experimental data for Ag, Al, Au, Bi, Ca, Cd, Co, Ca, Cu, Fe, Ga, Ge, Hg, In, K, Li, Mg, Na, Ni, Pb, Pu, Rb, Sb, Sn, Tl and Zn. It should be noted that the value that they chose for the viscosity of aluminium is at the high end of the range. They concluded that, for the data available, it provides a satisfactory fit. Battezzati and Greer [23] also show an adequate fit for the temperature dependence of viscosity with the pre exponential viscosity taking an approximately constant value of 0.4 mPa·s.

4.1.2.2. Andrade treatment [40]. The equation by Andrade described above underestimates the temperature dependence of viscosity. Recognising this limitation, Andrade suggested that the viscosity was lowered by the loss of local molecular orientational order but there is discussion whether this is a tenable argument [23].

Andrade gave an equation in the form:

$$\eta(T) = C_1/\upsilon^{1/3} * \exp(C_2/\upsilon T) \tag{5}$$

where C_1 and C_2 are constants and υ is the specific volume. This is similar to Arrhenius equation and Chhabra [38] shows that the two equations yield similar quality fits for his experimental database. Battezzati and Greer [23] concentrate their analysis using the Arrhenius form of the equations after pointing out the similarity.

Hirai [41] modified the Andrade equation based upon characteristic frequency of vibration to give:

$$\eta(T_m) = 1.7 \times 10^{-7} \rho^{2/3} T_m^{1/2} M^{-1/6} \quad \text{in Pa·s} \tag{6}$$

where ρ is the density and M is the atomic weight. Using the compendium of data [22] he derives the following relationships for the viscosity of the elements:

$$\eta = A\exp(E/RT) \tag{7}$$

$$A = \left\{1.7 \times 10^{-7} \rho^{2/3} T_m^{1/2} M^{-1/6}\right\} / \exp(E/RT_m) \tag{8}$$

$$E = 2.65 T_m^{1.27} \tag{9}$$

Although the expressions describe the viscosity of the elements well and have formed the basis of the unary data for at least one model [50] the extension of these equations to alloys has not met with success.

4.1.2.3. Hildebrand's free volume theory [42]. The fluid flow is governed by the extent of the free space available:

$$1/\eta = \Phi = B\{(V - V_0)/V_0\} \tag{10}$$

where V is the atomic volume, V_0 is the intrinsic volume where flow is stopped and B is a characteristic constant. Both B and V_0 are considered constants independent of temperature. Chhabra [38] shows that this model is only marginally worse than the Arrhenius model in describing the viscosity values in his database.

4.1.2.4. Chhabra model [43]. Mehrota [44] developed a model based on the viscosity values of organic liquids following modifications of equations by Walther [45]:

$$\mathrm{Log}(\eta + 0.8) = 10^{\mathrm{b1}} T^{\mathrm{b2}} \tag{11}$$

A strong correlation was shown between b1 and b2 for light and medium organic liquids. Chhabra and Tripathi extended the model to liquid metals and derived an equation:

$$\mathrm{Log}(\eta + 1) = 10^{\mathrm{b1}} T^{\mathrm{b2}} \tag{12}$$

They were unable to demonstrate a strong correlation between b1 and b2 but claim the equation gives improved description of viscosity values over the Arrhenius equation.

4.2. Multicomponent systems

4.2.1. Moelwyn-Hughes model [46]

The viscosity of a binary system is given by:

$$\eta = (x_{\mathrm{A}}\eta_{\mathrm{A}} + x_{\mathrm{B}}\eta_{\mathrm{B}})(1 - 2x_{\mathrm{A}}x_{\mathrm{B}}\Omega/RT) \tag{13}$$

where η_{A} and η_{b} are viscosities of elements, x_{A} and x_{B} are their mole fractions and Ω is the regular solution interaction parameter.

Equation 13 predicts a negative deviation of the viscosity for systems having a positive heat of mixing, ΔH_{mix}, in the liquid. This appears to be successful for some metal systems but does not always predict the lower viscosities expected in eutectic systems. Iida and Guthrie [3] modified the model to include the effect of the size of the atoms.

4.2.2. Chhabra model [47]

Chhabra modified his model to extend it from elements to mixtures and modified the b1 and b2 coefficients:

$$b_{1,\mathrm{alloy}} = \Sigma x_{\mathrm{i}} b_{1,\mathrm{i}} \quad b_{2,\mathrm{alloy}} = \Sigma x_{\mathrm{i}} b_{2,\mathrm{i}} \tag{14}$$

$$\mathrm{Log}(\eta + 1) = 10^{\mathrm{b1,alloy}} T^{\mathrm{b2,alloy}} \tag{15}$$

He applied the model to 29 binary systems and one ternary system. For most binaries it predicted the viscosity within 10% although there were some exceptions. The worst case was Sn-Mg with a 90% difference. For the Pb-Sn-Sb ternary at two temperatures there was a maximum difference of 8% between the predicted and measured values.

4.2.3. Thermodynamic models [48–50]

There have been attempts to model viscosity using thermodynamic concepts. Kucharski [48, 49] developed two models: one based upon rate theory to describe multicomponent mixtures, where all the parameters have physical meaning, and another model predicting multicomponent mixtures from the knowledge of thermodynamic properties, densities and viscosities data of the limiting binaries. She tested this for a Ag-Cu-Au system. Du Sichen *et al.* [50] used an absolute reaction rate theory and were able to reproduce the viscosity of some binary compositions well.

5. Conclusions

- The measured viscosity of aluminium is dependent on its purity.
- Most data are measured using an oscillating vessel technique, which is still capable of improvement especially in the derivation of the viscosity from the time period and decrement. Better alternative methods of measuring the viscosity are required to corroborate the measurements by an oscillating vessel technique.
- Reviewing the literature suggests that the viscosity of aluminium lies between about 1.0–1.4 mPa·s at the melting point.

  The values of viscosity of the component elements are not known with great accuracy.

  For binary mixtures of Al-X we conclude that the viscosity rises with increasing concentration of Ti; Ni; Cu; Cr; Mn; and drops for increasing Si. The behaviour of Zn and Mg is more complicated.

  Although the data are sparse, the viscosity of multicomponent alloys follows a similar pattern for the addition of elements as the binary mixtures.
- One work shows a decrease of viscosity of an alloy as the purity increases.
- Several models have been located to describe the viscosity of the elements and multicomponent systems. These models range from empirical to thermodynamically based.
- With the present quality of input data it is probably better to describe the viscosity of aluminium alloys with fairly simple rather than with a sophisticated model.
- The effect of inclusions needs to be reviewed.

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