

2012

Empirical relations for calculating selected physical properties of pure liquid metals and binary liquid alloys

فتحي الاقرع

جامعة الخليل, fathiaqra2009@hotmail.com

احمد عياد

جامعة الخليل, ahmadh@hebron.edu

فهد التكروري

جامعة الخليل, fahedt@hebron.edu

Follow this and additional works at: https://digitalcommons.aaru.edu.jo/hujr_a

 Part of the [Life Sciences Commons](#)

Recommended Citation

احمد عياد, فتحي الاقرع, and فهد التكروري (2012) "Empirical relations for calculating selected physical properties of pure liquid metals and binary liquid alloys," *Hebron University Research Journal-A (Natural Sciences) - (العلوم الطبيعية) - مجلة جامعة الخليل للبحوث- أ*: Vol. 6 : Iss. 1 , Article 1.

Available at: https://digitalcommons.aaru.edu.jo/hujr_a/vol6/iss1/1

This Article is brought to you for free and open access by Arab Journals Platform. It has been accepted for inclusion in Hebron University Research Journal-A (Natural Sciences) - (العلوم الطبيعية) - مجلة جامعة الخليل للبحوث- أ by an authorized editor. The journal is hosted on [Digital Commons](#), an Elsevier platform. For more information, please contact rakan@aarj.edu.jo, marah@aarj.edu.jo, dr_ahmad@aarj.edu.jo.



Empirical relations for calculating selected physical properties of pure liquid metals and binary liquid alloys

Fathi Aqra*. Ahmed Ayyad. Fahed Takrori

Department of Chemistry, Faculty of Science and Technology, Hebron University.

ABSTRACT:

In this paper, simple relations are reported for calculating viscosity (η), self-diffusion coefficient (D), friction coefficient (f_c), surface tension (γ), isothermal compressibility (k_{TM}) and thickness of liquid-vapor interface (L) of pure liquid metals at the melting point. The inter-relationships correlate these properties to each other and to density, atomic radius, atomic mass and temperature. The empirical relationships have been checked by compiling published data for liquid metals where better than 5% agreement was observed around the melting point. However, the formula relating viscosity to these properties has been applied for calculating the viscosity of binary liquid alloys (Ag-Cu) as a function of composition. It is found that the calculated viscosity of the alloy at 1373 K, as a specific temperature, decreases with increasing Ag concentration. This agrees well with the reported experimental data.

Key words: Physical properties, liquid metals, binary liquid alloys

*Corresponding author: fathiaqra2009@hotmail.com

المخلص:

تم في هذا البحث اشتقاق علاقات رياضية مبسطة يمكن من خلالها حساب قيم اللزوجة، معامل الانتشار الذاتي، معامل الاحتكاك، التوتر السطحي، قابلية الانضغاط وسماكة الطبقة البينية بين السائل والبخار للمعادن السائلة النقية عند درجات الانصهار الخاصة بكل واحدة منها، وقد وجد أن هذه المعادلات المشتقة ترتبط فيما بينها كما تعتمد على قيم مثل كثافة المعادن وأنصاف أقطار والكتل الذرية لهذه المعادن بالإضافة الى درجة الحرارة، وقد تم فحص قدرة المعادلات على حساب القيم المستهدفة من خلال مقارنتها بما تم إيجاده عمليا ونشره حيث وجد أن التوافق بين القيم المحسوبة وبين ما تم إيجاده عمليا يقع ضمن هامش يقترب من 5% عند درجات الانصهار لهذه المعادن، كما تم تطبيق المعادلة المشتقة الخاصة باللزوجة في حساب معاملات اللزوجة لمصهور سبيكة ثنائية تحوي على نسب مختلفة من الفضة والنحاس، وقد تبين إن هنالك تناقص في قيم معامل اللزوجة الذي تم حسابه نظريا حسب المعادلة المشتقة عند درجة حرارة محددة هي 1373 درجة مطلقة (كلفن) كلما ازدادت نسبة الفضة في السبيكة وهذا ما يتوافق مع النتائج التي وجدت عمليا.

الكلمات الرئيسية: خصائص فيزيائية، معادن سائلة (مصهورة)، سبيكة ثنائية سائلة.

INTRODUCTION:

Viscosity is a rheological property of materials which presents itself when the velocity gradient between different layers of material is observed, an important rheological parameter for understanding the hydrodynamics and kinetics of reactions in metal casting [1,2], and an indispensable quantity to predict other important transport coefficients (diffusivity, thermal conductivity and surface tension) of liquid metals. Viscosity and diffusion are transport properties of fluids where a transport process occurs in a liquid. The transport process of momentum, mass and energy involve viscosity, diffusion and thermal conduction, respectively, [1]. Mass, momentum, and energy transport processes in liquid metals will be well understood if thermophysical parameters such as density, surface tension, viscosity, diffusivity and thermal conductivity are measured precisely. Mathematical modeling and control of molten metal processing operations re-

quire a knowledge of the thermophysical properties of liquid metals at their melting points.

The viscosity of fluid materials is one of the fundamental properties directly related to the features of dynamics as well as the structure of molecules or atoms in these materials [3]. Values of the viscosities of liquid metals are important in the prediction of fluid flow in many metallurgical manufacturing processes. The viscosity of liquid metals and alloys is one of the important factors in the processing of crystals as well as in non-crystal formation [4], and plays an important role in liquid metal processing. The need for its study is due to the importance of viscosity in both the technology and theory of liquid metal behavior. Interest in this quantity stems both from practical considerations (their use as atomic reactor coolants) and philosophic considerations (their structural simplicity makes them good media to test current theories of the liquid state). The knowledge of viscosity is, therefore, of critical

importance in liquid metal processing operations or extractive metallurgy [5]. Also, some other dynamic properties of liquids such as diffusion involve viscosity as an essential quantity [1].

Reliable data on the viscosity of liquid metals and alloys is important for designing and optimizing of metallurgical processes (refining, casting, welding and solidification) and to understand the atomic level of structure and interactions in the melts [6]. Many experimental methods have been developed to measure the viscosity of liquid metals and alloys [1], but data is inadequate for the needs of today technology and there are significant discrepancies between the viscosity data obtained by different techniques. Critical contamination problems and chemical reactivity of liquid metals, at high temperatures, are the main reasons for a large scatter between different sets of experimental data or for the complete lack of the viscosity data, and therefore, the measured viscosity for a given element can vary widely [7]. However, many expressions concerning the modeling of viscosity of liquids have been reported [8-13], but none of them can be universally applied to predict the viscosity of a large class of systems [14] or can provide entirely satisfactory results when applied to liquid metals. Although several researchers have developed different models [1-5,13-26], expressions [5,13,27-29] and semi-empirical equations [11,18,24,30-35] for predicting viscosity of liquid metals and alloys, there is still a strong need for a theoretical formalism capable of describing the viscosity of liquid metals and alloys over a wide range of

concentrations. Such a model should be simple and capable of reproducing to a very reasonable degree the experimental viscosity data.

A study of self-diffusion in liquid metals is of critical importance. In liquid metals, there are problems associated with experimental measurement of self-diffusion and data are only available for a small number of liquid metals with insufficient accuracy. While a variety of expressions describing solute diffusivities has been proposed, most of them are unreliable in predicting solute-diffusivities in many liquid metal systems [14]. Diffusion is one of the key phenomena in producing materials. Therefore, knowledge of the value of diffusion coefficient is of high theoretical and practical importance. The study of diffusion in liquid metals is of great interest because of various scientific and technological reasons. The knowledge of diffusion coefficients plays important role in design of metallurgical and solidification process (casting industry). However, experimental data on the self-diffusion coefficients of liquid metals are available on few metals [36-38]. Self-diffusion coefficients have been calculated by different molecular dynamic modeling [39]. Hard sphere models have been used to estimate self-diffusion coefficient of liquid metals [40]. Further, analytical expressions are available for the diffusion coefficient of hard spheres [41]. Technique of molecular dynamics simulation has been used in describing various liquid properties [42-47]. The transport coefficients such as diffusion coefficients and viscosities of liquid metals have been reported

[45-53]. In the present study, viscosity, self-diffusion coefficient, friction coefficient, surface tension, isothermal compressibility and thickness in the liquid state of metals have been calculated and the results are compared with the available experimental data. The prediction capability of the empirical relations is excellent and fit to available experimental data. On the other hand, the purpose of this work is to investigate the applicability of a simple model for the evaluation of viscosity of binary liquid alloys which is checked against the Ag-Cu system to make a conclusion on the ability of the described model to reproduce the concentration dependence of the viscosity of binary alloys simpler than the published ones.

THEORY AND DISCUSSION

Viscosity

A liquid metal is a severe test for any liquid theory. Low vapor pressures at melting, small differences in volume between liquid and solid, and large temperature ranges of the liquid state lead to large differences between experimental and calculated values. An empirical formula is proposed for calculating the viscosity of pure liquid metals. This relation correlates viscosity to thermophysical properties and

$$\eta = [\gamma \cdot \rho \left(\frac{k \cdot r \cdot T_m}{M \cdot g} \right)^{1/2}]^{1/2} \cdot 10^{-3} \text{ (Pa s)} \quad (1)$$

where η is viscosity (Pa s), γ is the surface tension (J m^{-2}), ρ is density (kg m^{-3}), k is Boltzmann constant ($1.38 \times 10^{-23} \text{ J K}^{-1}$), r is atomic radius (m), T_m is the melting point (K), M is atomic mass

(kg) and g is acceleration due to gravity (9.8 m s^{-2}). Equation 1 has been examined for a large number of liquid metals and the viscosity values were found in the range 0.5 - 8 mPa s (Table 1). The calculated values are in good agreement with the reported data.

Viscosity of binary liquid alloys is an important parameter of materials processing. There are few existing measured data on concentration dependence of liquid alloys. Therefore, modeling the concentration of liquid alloys viscosity is always required, and is usually done through thermodynamic properties [20-25,54] or is based on different mixing rules [55-57]. On the other hand, in the application work, different models were applied [58-62]. The question, now, rises which equation [20-25,54] is best to reproduce the experimental values. The seven equations reported in the literature on the concentration dependence of the viscosity of binary liquid alloys have been discussed and checked against the measured viscosity data for the Ag-Cu system at 1373 K [63] and other binary liquid alloys [64]. It was found that some of the models are able to reproduce measured data with a reasonable accuracy, other models describe the character of the experimental data correctly but their magnitude differs significantly, few cannot be applied without a system-dependent semi-empirical parameter, while one of them predicts the excess viscosity of a wrong sign. However, eq. 1 can be used for calculating the viscosity of alloys at different composition, at a specific temperature, assuming that:

$$\gamma^{\text{alloy}} = \gamma^a \cdot x^a + \gamma^b \cdot x^b$$

$$\rho^{\text{alloy}} = \rho^a \cdot x^a + \rho^b \cdot x^b$$

$$M^{\text{alloy}} = M^a \cdot x^a + M^b \cdot x^b$$

$$\gamma^{\text{alloy}} = \left(\frac{r_a + r_b}{2} \right)$$

The extra insight given by this equation is that the calculation is easy which does not require unknown parameters. Calculation has been made for the viscosity isotherm of Ag-Cu alloys at different compositions at 1373 K as shown in Fig.

1. The results reveal that there is a decrease in the viscosity of the alloy as the concentration of Ag increases. The calculated values are comparable to the experimental data [1, 65]. It is important to compare the predicted data with the literature data in order to have a clear picture on mixing behavior in the Ag-Cu system. The applied empirical model links the viscosity and the surface tension of pure metals to the alloys using the mixing rules. Therefore, eq. 1 may be very useful for calculating the viscosity of pure liquid metals and binary alloys. It is easy, simple, straightforward and contains only constants or available data such as surface tension. However, to find a clear physical meaning of the empirical model, many alloys systems have to be analyzed.

DIFFUSION

Diffusion is the transport of mass from one region to another on an atomic scale. Diffusivities in the liquid state are much higher than that in solid state. In metals, diffusivities in the two states differ by a factor of 10^2 to 10^3 . The high atomic mobility of most metals above their melting temperatures (with diffusivities of the order of $10^{-9} \text{ m}^2 \text{ s}^{-1}$) is one of the most characteristic properties of liquids. The transport properties of liquids together with structural thermodynamic information can provide experimental basis for theories of the liquid state [67-69]. To understand such important material processing techniques as binary solidification and glass formation, a knowledge of the liquid state diffusion coefficient is required. Despite its fundamental importance, however, the diffusivity remains an elusive quantity. It is very difficult to measure experimentally and, unlike crystalline solids, it is not fully understood how the diffusion coefficient depends on the structure and thermodynamics of the liquid. Dzugutov [70] proposed a universal scaling relationship between the excess entropy of a liquid and the diffusion coefficient. Investigation of atomic transport of condensed matter has been attempted in the recent past [71-75]. The self-diffusion in the liquid state is different than that in the solid state in a sense that it does not require the presence of defects like vacancies and interstitials. Gorecki [76] has shown that for a number of metals there exists a simple proportionality between the

activation energies of self-diffusion coefficient in the solid and liquid phases. The mean value of the ratio of the self-diffusion coefficients in the solid phase to that for the liquid phase was found to be approximately 5.0.

The following formula is proposed for calculating D by rearranging eq. 1 as below:

$$D = \left[\left(\frac{\gamma}{\rho} \right) \left(\frac{k \cdot r \cdot T_m}{M \cdot g} \right)^{1/2} \right]^{1/2} \cdot 10^{-5} (\text{m}^2 \text{s}^{-1}) \quad (2)$$

As shown in Table 1, the self-diffusion coefficient (D) for liquid metals has the value of $10^{-9} \text{ m}^2 \text{ s}^{-1}$. These values are comparable to existing data.

FRICITION COEFFICIENT

Although the friction coefficient (fc) is known by Einstein-Sutherland relation (eq. 3), it can be correlated with surface tension by an empirical relation (eq. 4):

$$fc = \left(\frac{kT}{d} \right) (\text{kg s}^{-1}) \quad (3)$$

$$fc = \left(\frac{\gamma}{d} \right) r^2 (\text{kg s}^{-1}) \quad (4)$$

For liquid metals, the calculated value of friction coefficient by eq. 4 was found to be $10^{-12} \text{ kg s}^{-1}$ (Table 1) and agrees well with the literature.

SURFACE TENSION

The property of surface tension is very important and has been measured for most of the metallic elements. It is one of the fundamental and important quan-

ties in the realm of materials processing (welding, and sintering). Methods for measuring surface tension are established [77-79], but data suffer from scattering due to the effect of impurities. Computer simulations with Monte Carlo or molecular dynamics methods may be one of the reliable methods [80,81], but unfortunately suffer from high fluctuation and statistical uncertainty, and introduces additional complexity into the performance. Thus, the need of developing theoretical models and semi-empirical predictions has never declined. However, correlations between surface and bulk thermodynamic properties are always possible [82-87].

A simple relation is presented for calculating the surface tension γ of liquid metals as follows:

$$\gamma = \left(\frac{k \rho r}{M \alpha} \right) \quad (5)$$

Where α is the coefficient of thermal expansion (data taken from ref. 66). Eq. 6 has been examined for thirty-two liquid metals and the calculated values fit excellently with the experimental ones (Table 2).

ISOTHERMAL COMPRESSIBILITY AND THICKNESS

It is known that the product γk_{TM} of the surface tension γ (J m^{-2}) and the isothermal compressibility k_{TM} ($\text{Pa}^{-1} = \text{m}^3/\text{J} = \text{s}^2 \text{ m/kg} = \text{m}^2/\text{N} = \text{cm}^2/\text{Dyne}$) of liquid metals (includes simple and polyvalent non-transition metals and noble metals) near the melting temperature varies by

a factor between 2 and 3 [88-92]. The separate values of γ and k_{TM} vary by a factor of 30 through the range of liquid metals. Isothermal compressibility of liquid metals (k_{TM}) is related to surface tension in its units as follows:

γ	k_{TM}
J/m^2	$m^3/J = Pa^{-1}$
Kg/s^2	$s^2 m/kg$
N/m	m^2/N
$Dyne/cm$	$cm^2/Dyne$

It has been reported that the thickness of the liquid vapor interface L (meter) is very sharp and ranges from 0.2 to 0.5×10^{-10} m [89, 91]. It is given by:

$$L = \gamma \cdot k_{TM} \tag{6}$$

The width L involves the bulk liquid structure factor which reflects the marked short-range ionic ordering in the liquid [93, 94]. In contrast to eq. 6, the isothermal compressibility can be calculated by:

$$k_{TM} = \left(\frac{r}{\gamma}\right) \cdot (1-3f) \tag{7}$$

where f is the fraction of broken bonds (0.287) [66]. Substituting eq. 7 in eq. 6, we get:

$$L = r \cdot (1 - 3f) \tag{8}$$

We found that the relatively sharp liquid-vapor interface (or the low value of L) appears to be a general property of liquid metals near the melting point. The calculated values of k_{TM} and L are consistent with the reported data [95,96]. The value of k_{TM} ranges from $0.07 - 7 \times 10^{-10} m^3/J$ for all liquid metals (Table 1).

CONCLUSION

Simple and straightforward formulas are proposed for calculating the viscosity (η), self-diffusion coefficient (D), friction coefficient (f_c), surface tension (γ), isothermal compressibility (k_{TM}) and thickness of liquid-vapor interface (L) of pure liquid metals at the melting point. Moreover, the viscosity of binary liquid alloys (Ag-Cu) as a function of composition has been calculated. The predicted values remarkably compare with the literature data.

REFERENCES

1. T. Iida and R.I.L. Guthrie, *The Physical Properties of Liquid Metals*, Oxford Press, Oxford, 1988).
2. J. Frenkel, *Kinetic Theory of Liquids*, Oxford University Press, London, 1946.
3. S. Morioka, B. Xiufang, and S. Minhua, *Z. Metallkd.*, 93, 4 (2002).
4. S. Morioka, **J. Non-Cryst. Solids**, 341, 46 (2004).
5. S.A. Rice and J.G. Kirkwood, **J. Chem. Phys.**, 31, 901 (1959).
6. R.N. Singh and F. Sommer, **Phys. Chem. Liquid**, 36, 17 (1998).
7. M. Born and H.S.A. Green, *General Kinetic Theory of Liquids*, University Press, Cambridge, 1949.
8. J.G. Kirkwood, **J. Chem. Phys.**, 14, 180 (1946).
9. J. Frenkel, *Kinetic Theory of Liquids*, Dover, New York, 1955.
10. H. Eyring, **J. Chem.Phys.**, 34, 2144 (1961).
11. E.N. Andrade, *Phil. Mag.*, S7(17), 497 (1934).
12. E. Helfand and S.A. Rice, **J. Chem. Phys.**, 32, 1642 (1960).
13. H.C. Longuet-Higgins and J.A. Pople, **J. Chem. Phys.**, 25, 884 (1956).
14. T. Iida and R.I.L. Guthrie, *The Physical Properties of Liquid Metals*, Clarendon Press, Oxford, 1993.
15. M. Born and H.S. Green, *Proc. Roy. Soc. A*, 188, 10 (1946).
16. S.A. Rice and A.R. Allnatt, **J. Chem. Phys.**, 34, 2144 (1961).
17. P. Macedo and T. Litovitz, **J. Chem. Phys.**, 42, 245 (1965).
18. M. Cohen and D. Turnbull, **J. Chem. Phys.**, 31, 1164 (1959).
19. E.A. Moelwyn-Hughes, *Physical Chemistry*, Pergamon Press, Oxford, 1961.
20. T. Iida, M. Ueda and Z. Morita, *Tetsu-to-Hagane*, 62, 1169 (1976).
21. Z. Morita, T. Iida and M. Ueda, *Ins. Phys.*, 30, 600 (1977).
22. L.Ya. Kozlov, L.M. Romanov and N.N. Petrov, *Izv. Vysch. Uch. Zav Chernaya Metallurgiya*, 3, 7 (1983).
23. M. Kucharski, *Z. Metallkd.*, 77, 393 (1986).
24. M. Hirai, *Iron Steel Inst. Jpn. Int.*, 33, 251 (1993).
25. S. Seetharaman and Du Sichen, **Mater. Mater. Trans. B**, 25B, 589 (1994).
26. S. Morioka, **Mater. Sci. Eng. A**, 362, 223 (2003).
27. M. Born and H.S. Green, **Proc. of R. Soc.**, A190, 455 (1947).
28. E. Helfand, **Phys. Rev.**, 119, 1 (1960).
29. S.A. Rice and P. Gray, *The Statistical Mechanics of Simple Liquids*, Interscience, New York, 1965.
30. S. Glasstone, K.J. Laidler and H. Eyring, *The Theory of Rate Processes*, McGraw-Hill, New York, 1941.
31. E. Eyring, D. Henderson, B.J. Stover and E.M. Eyring, *Statistical Mechanics and Dynamics*, John Wiley, New York, 1964.
32. P.P. Arsentyev and L.A. Koledov, *Metallurgical Melts and Their Properties*, Metallurgiya, Moscow, 1976.
33. V.F. Nozdrev, V.I. Stremousov, and V.V. Tekuchev, **Zh. Fiz. Khim.**, 53, 1199 (1979).
34. V.I. Stremousov, V.V. Tekuchev and V.M. Pivovarov, *Izv. ross. Akad.Nauk*

- Metally**, 5, 51 (1993).
35. S. Seetharaman and D. Sichen, **Iron Stell Inst. Japan Int.**, 37, 109 (1997).
36. Y. Mishin, M. J. Mehl, D. A. Papaconstantopoulos, A. F. Voter and J. D. Kress, **Phys. Rev. B**, 63, 224106 (2001).
37. M. Doyama and Y. Kagure, **Comp. Mat. Sci.**, 14, 80 (1999).
38. Y. Rosenfeld, **J. Stat. Phys.**, 42, 437 (1986).
39. S. Dalgic, M. C. olakogullari and S. S. Dalgic, **J. Optoelectron. Adv. Mater.**, 7, 1993 (2005).
40. R. Castillo, A. Vellaverdo and J. Orozeo, **J. Mol. Phys.**, 74, 1315 (1991).
41. E. Rockenstein and H. Liu, **Ind. Eng. Chem. Res.**, 36, 3927 (1997).
42. S.M. Foiles, **Phys. Rev. B**, 32, 3409 (1985).
43. S.M. Foiles and J.B. Adams, **Phys. Rev. B**, 40, 5909 (1989).
44. L. Wang, H. Liu, K.Y. Chen and Z.Q. Hu, **Physica B**, 239, 267 (1997).
45. M.M.G. Alemany, L.J. Gallego, L.E. Gonzalez and D.J. Gonzalez, **J. Chem.Phys.**, 113, 10410 (2000).
46. F.J. Cherne and P.A. Deymier, **Scripta Mater.**, 45, 985 (2001).
47. X.J. Han, J.Z. Wang, M. Chen and Z.Y. Guo, **J. Phys.: Condens. Matter**, 16,2565 (2004).
48. J. Mei and J.W. Davenport, **Phys. Rev. B**, 42, 9682 (1990).
49. L. Yang, S. Kado and G. Derge, **Trans. Metal. Soc. AIME**, 212, 628 (1958).
50. J. Henderson and L. Yang, **Trans. Metal. Soc. AIME**, 221, 72 (1961).
51. J.I. Akhter and K. Yaldram, **Int. J. Mod. Phys. C**, 8, 1217 (1997).
52. E. Ahmed, J.I. Akhter and M. Ahmad, **Comp. Mater. Sci.**, 31, 309 (2004).
53. S.M. Foiles, M.I. Baskes and M.S. Daw, **Phys. Rev. B**, 33, 7983 (1986).
54. E.A. Moelwyn-Hughes, **Physical Chemistry**, Pergamon Press, Oxford, (1961).
55. R.P. Chabra and D.K. Sheth, **Chem. Eng. Process.**, 27, 53 (1990).
56. R.P. Chabra, **J. Alloys and Compounds**, 221, L1 (1995).
57. X.M. Zhong, Y.H. Liu, K-C. Chou, X.G. Lu, D. Zivkovic, Z. Zivkovic: **J. Phase Equilibria**, 24 (2003) 7.
58. I. Ohnuma, X.J. Liu, H. Ohtani and K. Ishida, **J. Electr. Mater.**, 28, 1164 (1999).
59. T. Tanaka, K. Hack and S. Hara, **MRS Bulletin**, 24, 45 (1999).
60. X-M. Zhong, K-C. Chou, Y. Gao, X. Guo and X. Lan, **Calphad**, 25, 455 (2001).
61. J.H. Lee and D.N. Lee, **J. Electr. Mater.**, 30, 1112 (2001).
62. X. Wang, H. Bao and W. Li, **Metall. Mater. Trans.**, 33A, 3201 (2002).
63. I. Budai, M. Z. Benkő and G. Kaptaý, **Materials Science Forum**, 473-474 309 (2005).
64. I. Budai, M. Z. Benkő and G. Kaptaý, **Materials Science Forum**, 537-538 489 (2007).
65. E. Gebhardt and G. Wörwag, **Z. Metallkd.**, 44, 358 (1951).
66. F. Aqra and A. Ayyad, **Applied Surface Science**, 257, 6372 (2011).
67. J. I. Akhter, E. Ahmed and M. Ahmad, **Mater. Chem. and Phys.**, 93, 504 (2005).
68. U. Domekeli, MSc Thesis, Department of Physics, Graduate School of Natural and Applied Sciences, Edirne,

- Turkey, 2003.
69. S.S. Dalgic, S. Dalgic and U. Domekeli, **J. Optoelectron. Adv. Mater.**, 5, 1263 (2003).
 70. M. Dzugutov, Nature (London), 381, 137 (1996).
 71. N.H. Nachtrieb, **Adv. Phys.**, XVI, 309 (1967).
 72. F. Zahid, G.M. Bhuiyan, S. Sultana, M.A. Khalaque, R.I.M.A. Rashid and S.M.M. Rahman, **Phys. Status Solidi** (b), 215, 987 (1999).
 73. Y. Rosenfeld, J. Phys.: Condens. Matter, 11, 5415 (1999).
 74. S. Sharma, R. Sing and D.K. Chaturvedi, Philos. Mag., A79, 2803 (1999).
 75. A.Z. Ziauddin Ahmad and G.M. Bhuiyan, Int. **J. Mod. Phys. B**, 16, 3837(2002).
 76. T. Gorecki, **J. Mater. Sci. Lett.**, 9, 167 (1990).
 77. S. Sauerland, G. Lohoefer and I.Egry, **J. Non-Cryst. Solids**, 156-158, 833 (1993).
 78. I. Egry, G. Lohoefera and S. Sauerland, Int. **J. Thermophys.**, 14, 573 (1993).
 79. K. C. Mills and R. F. Brooks, **Mater. Sci. Eng. A**, 178, 77 (1994).
 80. J. Miyazaki, J. A. Barker and G. M. Pound, **J. Chem. Phys.**, 64, 3364 (1976).
 - 81.E. Salomons and M. Mareschal, **Journal of Physics: Condensed Matter**, 3, 3645 (1991).
 82. J. Stephan, **J. Ann. Phys.**, 29, 655 (1886).
 83. A. S. Skapski, **J. Chem. Phys.**, 16, 386 (1948).
 84. A. S. Skapski, Acta Metalurgical, 4, 576 (1956).
 85. A. Tegetmeier, A. Croëll and K. W. Benz, **J. Cryst. Growth**, 141, 451 (1994).
 86. N. Eustathopoulos, B. Drevet and E. Ricci, **J. Cryst. Growth**, 191, 268 (1998).
 87. L. P. N. Rebelo, J. N. C. Lopes, J. M. S. S. Esperanca and E. J. Filipe, **Phys. Chem. B**, 109, 6040 (2005).
 - 88.J. Frenkel, Kinetic Theory of Liquids, Oxford Univ. Press, Oxford (1942).
 89. P. A. Egelstaff and B. Widom, **J. Chem. Phys.**, 53, 2667 (1970).
 90. Y. Waseda and K. T. Jacob, **Phys. Stat. Sol.** (1), 68, K117 (1981).
 91. J. A. Alonso and N. H. March, **Sur. J Sci.**, 160, 509 (1985).
 92. N. H. March, **Phys. Chem. Liquids**, 15, 1 (1985).
 93. R. C. Brown and N. H. March, **J. Phys. C.**, 5, L 363 (1973).
 94. M. Shimoji, Liquid Metals, Academic Press, London (1977).
 95. J. A. Alonso, **Phys. Chem. Liq.**, 17, 209 (1987).
 96. J. A. Alonso, **Phys. Chem. Liq.**, 21, 257 (1990).

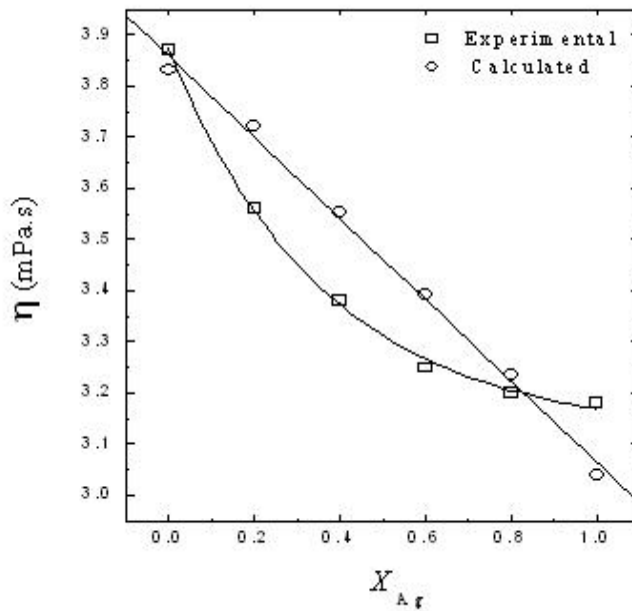


Figure 1: Viscosity of liquid Ag–Cu at 1373 K for various atomic concentrations of Ag.Squares represent experimental values,47 while circles represent calculated values.

TABLE 1: CALCULATED AND REPORTED VALUES OF TRANSPORT PROPERTIES FOR PURE LIQUID METALS WITH PARAMETERS NEEDED FOR CALCULATIONS. THE SURFACE TENSION DATA WERE TAKEN FROM REF 66.

fc (10 ⁻¹² kg s ⁻¹) Cal. Rep	L (10 ⁻¹⁰ m) Cal. Rep	kMT (10 ⁻¹⁰ Pa ⁻¹) Cal. Rep.	D (10 ⁻⁹ m ² /s) Cal. Rep.	η (mPa s) Cal. Rep.	M (10 ⁻²⁵ kg)	γ _m (J/m ²)	r (10 ⁻¹⁰ m)	ρ (kg/ m ³)	T _m (K)	Metal
0.646	0.21 0.45	0.48 1.1	15.77 6.5	0.80 0.8	0.116	0.441	1.52	512	453	Li
1.15	0.26 0.37	1.36 1.86	5.72 4.5	0.53 0.7	0.382	0.19	1.86	927	371	Na
1.31	0.31 0.42	3.12 3.82	3.96 3.76	0.32 0.51	0.647	0.101	2.27	828	336	K
2.34	0.34 0.42	3.96 4.74	2.29 2.22	0.33 0.68	1.41	0.087	2.48	1460	312	Rb
2.94	0.37 0.48	5.4 6.30	1.62 2.16	0.29 0.63	2.21	0.068	2.65	1843	301	Cs
0.915	0.14 0.26	0.09 0.19	19.29	3.26	0.149	1.601	1.05	1690	1560	Be
1.27	0.22 0.29	0.62 0.50	7.17 5.63	1.13	0.398	0.356	1.60	1584	923	Mg
1.65	0.27 0.38	0.96 1.1	6.67	0.91	0.664	0.284	1.97	1378	1115	Ca
2.77	0.3 0.39	1.34 1.31	3.72	0.88	1.46	0.223	2.15	2375	1050	Sr
3.94	0.3 0.45	1.37 1.78	2.81	0.93	2.27	0.225	2.22	3338	1000	Ba
2.19	0.2 0.21	0.2 0.26	9.21 4.87	2.18 1.4	0.448	0.985	1.43	2375	933	Al
4.53	0.19 0.16	0.26 0.20	2.87 2.0	1.74 0.67	1.16	0.713	1.35	6095	303	Ga
6.53	0.23 0.17	0.4 0.3	2.43 1.77	1.70 1.8	1.91	0.569	1.67	7020	430	In
7.62	0.23 0.18	0.59 0.48	1.5 1.5	1.68	3.39	0.396	1.70	11220	577	Tl

5.11	0.19 0.15	0.28 0.27	2.65 2.31	1.84 1.81	1.98	0.689	1.40	6990	505	Sn
7.69	0.24 0.16	0.62 0.35	1.55 1.67	1.64 2.1	3.44	0.388	1.75	10660	600	Pb
6.23	0.21	0.56 0.43	1.5 0.9	1.50 1.61	3.47	0.383	1.56	10050	545	Bi
2.71	0.22 0.32	0.25 0.36	8.67	2.42	0.747	0.895	1.62	2800	1814	Sc
4.60	0.25	0.3	5.89	2.49	1.48	0.837	1.80	4240	1799	Y
3.43	0.2 0.21	0.15 0.14	8.68	3.56 4.42	0.797	1.38	1.47	4110	1941	Ti
5.58	0.22	0.15	6.7	3.88 3.5	1.51	1.461	1.60	5800	2128	Zr
9.27	0.22	0.14	4.21	5.05 5.0	2.95	1.543	1.59	12000	2506	Hf
3.76	0.18 0.25	0.1 0.13	8.39	4.61	0.847	1.756	1.34	5500	2183	V
6.22	0.2	0.09	7.61	6.52 4.5	1.54	2.22	1.46	8570	3750	Nb
10.10	0.2	0.09	4.74	7.10 8.6	3.00	2.242	1.46	15000	3290	Ta
3.41	0.17 0.19	0.12 0.11	7.04	4.43	0.863	1.465	1.28	6300	2180	Cr
6.23	0.19	0.09	6.51	6.07	1.59	2.099	1.39	9330	2896	Mo
10.70	0.19	0.07	4.84	8.52 6.9	3.05	2.684	1.39	17600	3695	W
2.95	0.17 0.19	0.18 0.17	5.3	3.15	0.913	0.969	1.27	5950	1519	Mn
7.26	0.19	0.08	6.01	6.61	1.64	2.359	1.36	11000	2430	Tc
10.70	0.19	0.07	4.45	8.40 7.9	3.09	2.541	1.37	18900	3459	Re
3.84	0.17 0.19	0.11 0.14	6.45 4.16	4.49 4.9	0.930	1.56	1.26	6980	1811	Fe
6.63	0.18	0.08	5.94	6.32 6.1	1.68	2.193	1.34	10650	2607	Ru
11.20	0.18	0.07	4.32	8.64	3.15	2.648	1.35	20000	3306	Os
6.92 6.19	0.26 0.30	0.33 0.43	3.89 2.65	2.30 2.45	2.31	0.769	1.87	5940	1193	La

7.43 6.73	0.25 0.33	0.3 0.04	3.72 2.45	2.43 2.90	2.32	0.834	1.82	6550	1068	Ce
6.54 6.47	0.25 0.30	0.36 0.04	3.49 2.79	2.27 2.80	2.34	0.69	1.82	6500	1208	Pr
6.40 6.77	0.25 0.23	0.38 0.03	3.34 2.64	2.29 3.23	2.39	0.652	1.81	6890	1297	Nd
6.83 7.00	0.25	0.36	3.43 2.67	2.40 3.37	2.44	0.7	1.83	7000	1315	Pm
5.13 5.08	0.25	0.61	2.59 2.62	1.85 2.01	2.49	0.409	1.80	7160	1345	Sm
3.76 3.55	0.25 0.17	0.9 0.06	2.38 2.72	1.22 1.34	2.52	0.276	1.80	5130	1099	Eu
6.46	0.25 0.25	0.37 0.03	3.34	2.47	2.61	0.667	1.80	7400	1585	Gd
7.10	0.24 0.24	0.29 0.03	3.73	2.85 5.3	2.56	0.845	1.77	7650	1629	Tb
6.37	0.24 0.19	0.41 0.03	3.01	2.51	2.69	0.605	1.78	8370	1680	Dy
6.28	0.24 0.12	0.39 0.02	3.04	2.53	2.74	0.617	1.76	8340	1734	Ho
6.71	0.24 0.15	0.36 0.02	3.11	2.75	2.77	0.673	1.76	8860	1802	Er
5.57	0.24	0.51	2.66	2.27	2.81	0.479	1.76	8560	1818	Tm
3.91	0.24 0.14	0.98 0.04	1.98	1.22	2.87	0.249	1.76	6210	1097	Yb
7.81	0.24 0.18	0.26 0.02	3.53	3.28	2.91	0.911	1.74	9300	1925	Lu
11.20	0.25	0.2	3.52	4.12	3.85	1.234	1.79	11700	2115	Th
12.80	0.21	0.15	2.68	4.63	3.95	1.404	1.56	17300	1405	U
11.60	0.22	0.24	1.97	3.27	4.02	0.906	1.59	16630	912	Pu
4.21	0.17 0.18	0.1 0.14	6.19 4.0	4.80 4.7	0.979	1.668	1.25	7750	1768	Co
6.38	0.18	0.1	5.22	5.58 5.0	1.71	1.854	1.34	10700	2237	Rh
10.50	0.19	0.09	3.82	7.25 7.0	3.19	2.159	1.36	19000	2739	Ir
4.36	0.17 0.18	0.09 0.14	6.38 5.3	4.98 4.1	0.979	1.81	1.24	7810	1728	Ni

5.58	0.19 0.2	0.16 0.13	4.05	4.20	1.76	1.205	1.37	10380	1828	Pd
11.10	0.19	0.1	3.23	6.38	3.24	1.855	1.39	19770	2041	Pt
4.11	0.18 0.19	0.15 0.13	4.78 4.1	3.83 3.97	1.05	1.2	1.28	8020	1357	Cu
5.34	0.2 0.17	0.24 0.18	3.27 2.77	3.04 3.4	1.79	0.841	1.44	9320	1235	Ag
9.48	0.2	0.18 0.12	2.41 3.37	4.16 4.5	3.27	1.1	1.44	17310	1337	Au
4.06	0.18 0.19	0.22 0.23	3.78 2.55	2.48 1.8	1.08	0.854	1.34	6570	692	Zn
5.43	0.21 0.19	0.36 0.32	2.45 2.0	1.96 2.0	1.86	0.584	1.51	7996	594	Cd

TABLE IIA: CALCULATED AND REPORTED SURFACE TENSION OF SOME LIQUID METALS (S BLOCK), AND PARAMETERS NEEDED FOR CALCULATIONS.

Metal	T _m (k)	Atomic weight (amu)	α_m ($\times 10^{-4}$) (K ⁻¹)	Density at m. p (kg m ⁻³)	Atomic radius ($\times 10^{-12}$) (m)	Y _m (mJ/m ²) Cal.	Y _m (mJ/m ²) Rep
Na	371	23	3.7	927	186	168	197
K	336	39	4.1	828	227	97	110
Rb	312	85	4.4	1460	248	80	85
Cs	301	133	4.6	1843	265	66	70
Mg	923	24	1.5	1584	160	585	557

TABLE IIB: CALCULATED AND REPORTED SURFACE TENSION OF LIQUID METALS (D BLOCK), AND PARAMETERS NEEDED FOR CALCULATIONS.

Metal	Tm (K)	Atomic weight (amu)	α_m ($\times 10^{-5}$) (k^{-1})	Density .at m. p ($kg\ m^{-3}$)	Atomic radius ($\times 10^{-12}$) (m)	Ym (mJ/m ²) .Cal	Ym (mJ/m ²) .Rep
Y	1799	89	7.72	4240	180	923	872
Ti	1941	48	7.16	4110	147	1461	1500
Zr	2128	91	6.53	5800	160	1298	1400
Hf	2506	178	5.54	12000	159	1608	1614
V	2183	51	6.36	5500	134	1889	1770
Ta	3290	181	4.22	15000	146	2383	2360
Mn	1519	55	9.15	5950	127	1115	1100
Tc	2430	99	5.72	11000	136	2196	2350
Fe	1811	56	7.67	6980	126	1702	1830
Ru	2607	101	5.33	10650	134	2204	2180
Co	1768	59	7.86	7750	125	1736	1830
Rh	2237	103	6.21	10700	134	1863	1915
Ir	2739	192	5.07	19000	136	2206	2225
Ni	1728	59	8.04	7810	124	1697	1838
Pd	1828	106	7.60	10380	137	1467	1475
Pt	2041	195	6.81	19770	139	1720	1860
Cu	1357	63	10.24	8020	128	1322	1310
Ag	1235	108	11.25	9320	144	918	910
Au	1337	197	10.39	17310	144	1012	1149

TABLE IIC: CALCULATED AND REPORTED SURFACE TENSION OF LIQUID METALS (F BLOCK), AND PARAMETERS NEEDED FOR CALCULATIONS.

Metal	T _m (K)	Atomic weight (amu)	α_m ($\times 10^{-4}$) (k^{-1})	Density .at m. p ($kg\ m^{-3}$)	Atomic radius ($\times 10^{-12}$) (m)	Y _m (mJ/m ²) .Cal	Y _m (mJ/m ²) .Rep
Pr	1208	141	1.15	6500	182	606	716
Nd	1297	144	1.07	6890	181	673	687
Pm	1315	147	1.05	7000	183	690	660
Tb	1629	154	0.85	7650	177	860	893
Yb	1097	173	1.28	6210	176	410	320
Lu	1925	175	0.72	9300	174	1067	940
Th	2115	232	0.65	11700	179	1154	1006
Pu	912	242	1.5	16630	159	605	550