Experimental studies of the viscosities of multicomponent slags

F. Ji, Du Sichen and S. Seetharaman
Division of Theoretical Metallurgy,
Royal Institute of Technology,
S-10044 Stockholm, Sweden

ABSTRACT

The present paper describes the experimental determination of the viscosities of the ternary slag systems CaO-Fe_nO-SiO_2, MgO-Fe_nO-SiO_2, MnO-Fe_nO-SiO_2 and CaO--MnO-SiO_2 as well as the quaternary system CaO-Fe_nO-MnO-SiO_2, using the well-established rotating cylinder method. The experimental set up consists of a Brookfield digital viscometer mounted over a specially-designed furnace with graphite heating elements. Iron crucibles were used along with iron spindles. The measurements were carried out in the homogeneous liquid regions of these slags up to a maximum temperature of 1753 K. The measurements were made at varying rotating speeds of the spindle and the constancy of the viscosity values was confirmed. The experimental arrangement was periodically calibrated using the standard reference slag recommended by the European Union. The results were incorporated into a slag model developed at the Division of Theoretical Metallurgy, Royal Institute of Technology. The model is based on the classical Temkin-Lumsden description and enables the extrapolation of slag viscosities as functions of temperature as well as composition in the case of multicomponent systems. The viscosities of the four component system CaO-Fe_nO-MnO-SiO_2 were computed based on the experimental values.

1.INTRODUCTION

Viscosity is one of the most important thermophysical properties of metallurgical melts, in view of its direct effect on the kinetic conditions of the processes. In the development of metallurgical slags, viscosity is among the key properties to be taken into consideration. While the importance of slag viscosities has long been realized, the need for accurate viscosity data is even more strongly felt with the advancement of today's technology.

The oxides commonly used in steel slags are Al_2O_3, CaO, Cr_2O_3, MgO, MnO, SiO_2 as well as Fe_nO. Most of these oxides are also important components in the slags of non-ferrous metallurgy. Great efforts have been made to generate viscosity data for various slags since the early thirties of this century. However, the data available are still too few to meet the increasing demands of the advanced technology. Recently, a mathematical model for estimation of viscosities of multi-component melts has been developed at the present laboratory.[1] The model makes it possible to express viscosity as a function of temperature and composition for multi-component systems. Application of the model to various metallic and ionic melts has shown satisfactory results. In the light of this model, a long term project is currently being carried out at the Division of Theoretical Metallurgy to get a complete description of viscosities in the multi-component system, Al_2O_3-CaO-Cr_2O_3-FeO-Fe_2O_3-MgO-MnO-SiO_2. A reliable description for this multi-component system necessitates accurate experimental data for corresponding lower-order systems. In the present work, the viscosities in the CaO-Fe_nO-SiO_2, MgO-Fe_nO-

SiO_2, $MnO-Fe_nO-SiO_2$, $CaO--MnO-SiO_2$ and $CaO-Fe_nO-MnO-SiO_2$ systems are studied.

2. EXPERIMENTAL

2.1. Materials and preparation of the slags

The materials used in the present work are listed in Table I. While the SiO_2, MnO and Fe_2O_3 powders were dried at 393 K over night, the CaO and MgO powders were calcined at 1223K for 12 hours in a muffle furnace to decompose any carbonate or hydroxide before use. In order to keep the slags from both oxidation and reduction during the preparation of the slags as well as viscosity measurements in the case of Fe_nO containing slags, an oxygen partial pressure between $2.5 \cdot 10^{-10}$ and $1 \cdot 10^{-6}$ atm should be maintained in the gas phase at the experimental temperatures. The traces of moisture in the argon gas were removed by passing the gas through columns of silica gel as well as $Mg(ClO_4)_2$ and the CO_2 impurity was absorbed by ascarite kept in the gas stream. The gas was further passed through a column of copper turnings at 773 K to remove the traces of oxygen. The oxygen partial pressure of the gas was monitored constantly by a ZrO_2-CaO oxygen probe and found to be about 10^{-9} atm during both the preparation of the slags and the viscosity measurements.

In order to prepare a slag, the oxide powders of appropriate proportions were mixed well to achieve the desired slag composition. In the case of the Fe_nO containing slag, iron and Fe_2O_3 powders were first mixed. The $Fe-Fe_2O_3$ mixture had a total composition of 51 mole percent of oxygen, at which liquid oxide would be in equilibrium with δ-Fe at temperatures around 1673 K.[2] The $Fe-Fe_2O_3$ mixture was then mixed with the other oxides as mentioned earlier.

Table 1. Materials used in the present study

Material	Purity	Supplied by
Calcium Oxide (CaO)	Anhydrous, AR grade	Fisher Scientific, New Jersey, U.S.A.
Iron Oxide (Fe_2O_3)	Anhydrous, AR grade	E.Merck, Darmstadt, Germany
Magnesium Oxide (MgO)	Anhydrous, AR grade	E.Merck, Darmstadt, Germany
Manganese Oxide (MnO)	>99.5% pure	Johnson Matthey, Karlsruhe, Germany
Silicon Oxide, (SiO_2)	Merck - pro analysi	E. Merck, Darmstadt, Germany
Iron (Fe)	pro analyse grade	E. Merck, Darmstadt, Germany
Argon, (Ar)	Argon Plus	AGA Gas, Stockholm

The mixture was packed in a crucible made of pure iron. The dimensions of the iron crucible are given in Table II. The same crucible was later also employed for the viscosity measurement. After positioning the crucible in a resistance furnace, the reaction chamber was flushed by argon gas for 2 h. Thereafter, a constant low flow of argon (0.05 l/min) was maintained during the preparation of the slag. The sample was heated up to a desired temperature and hold there for more than 12 hours. After furnace cooling, the slag was

taken out and ocularly examined to ascertain that the sample had completely been melted. The iron crucible did not show any sign of oxidation. The slight blue colouration on the side of the crucible ensured that the oxygen partial pressure in the gas stream was neither oxidizing nor reducing. The slag along with the iron crucible was then stored in a desiccator before being used in the viscosity measurement.

2.2. Apparatus and procedure

The rotating cylinder method was employed for viscosity measurements. Figure 1 shows the experimental setup. A Brookfield digital viscometer (model RVDV-3) controlled by a PC through a DV-III controller, was used in the present work. The full scale torque associated with the viscometer was 7187 dyne·cm. The acquisition of the torque values and the calculations of the viscosities were carried out using the software supplied by Brookfield.

A high temperature furnace, Laboratory Furnace Group 1000, supplied by Thermal Technology INC was used for the measurements. The furnace had a specially designed graphite heating element and was controlled by a regulator (Model 818) using an optical pyrometer sensor. The crucible containing the slag was placed in an alumina reaction tube mounted vertically inside the furnace. Special care was taken to ensure that the crucible was positioned in the even temperature zone of the furnace. Alumina radiation shields were placed both above and below the crucible. This arrangement ensured that the variation of the temperature in the even temperature zone was less than ±3 K in the whole experimental temperature range. A Pt-10%Rh/Pt thermal couple in an alumina sheath was placed in contact with the bottom of the crucible so that the slag temperature could be measured accurately during the experiment.

The viscometer was rigidly mounted on a movable platform above the furnace so that it could be properly aligned to the crucible. A metal flange-TEFLON bellows coupling was used to close the gap between the viscometer and the alumina reaction chamber.

As mentioned earlier, the iron crucible used for the premelting of the slag was later employed for the viscosity measurement as well. Pure iron spindles were used in the experiments. As shown in Figure 1, the spindles consisted of a bob and a shaft, with 45 degree tapers at the tip and near the shaft. The dimensions of spindles are also presented in Table II.

Table II The dimensions of the crucible and spindle

Fe Crucible	i.d (mm)	Height (mm)	wall thickness (mm)	base thickness (mm)	
	40	103	1	8	
Fe Spindle	i.d of bob (mm)	Length of bob (mm)	i.d of shaft (mm)	Length of shaft (mm)	Degree of Taper
	16	27	4	53	45

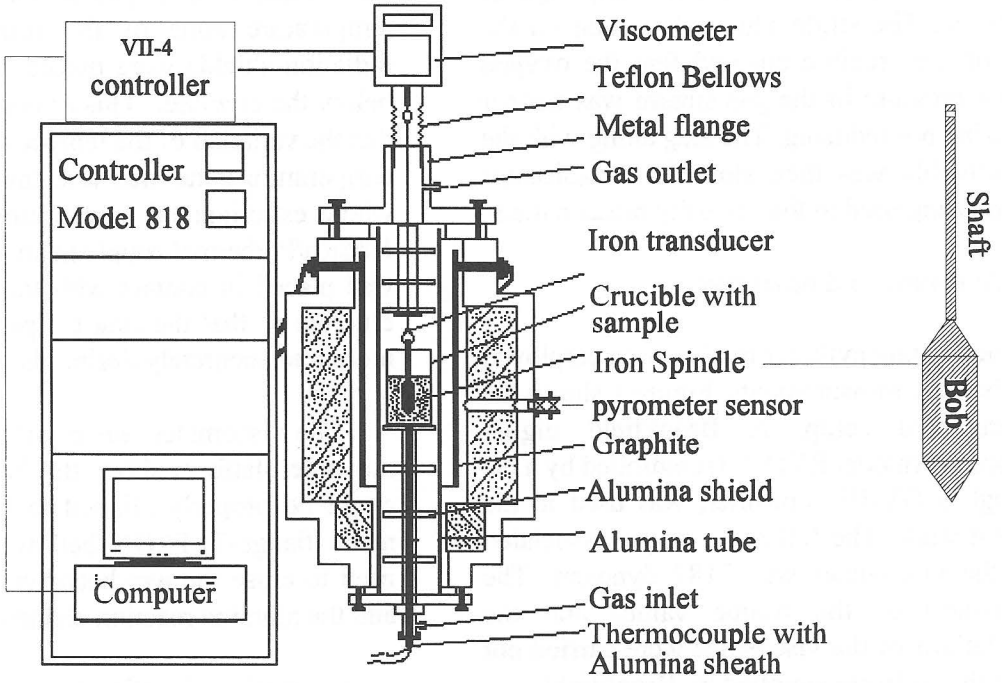


Figure 1 Experimental setup

In a general run, after the crucible with the premelted slag was placed in the even temperature zone of the furnace, the spindle mounted on the iron transducer was introduced into the alumina reaction tube. The reaction chamber was then sealed by coupling the TEFLON bellows and the metal flange. The length of the TEFLON bellows was adjusted to keep the iron spindle 1 cm above the slag. A stream of argon gas was introduced through the gas inlet near the bottom of the furnace. The gas was led out through the gas outlet connected to the metal flange on the top of the furnace. After flushing the reaction chamber for 1 hour, the flow rate of argon gas was reduced. Thereafter a constant flow of argon (about 0.2 $l \cdot min^{-1}$) was maintained during the whole course of the experiment. The slag was heated up to the desired temperature at a heating rate of 5 $K \cdot min^{-1}$. When the temperature was stabilized, the spindle, rotating at a speed of 40-60 r.p.m. was introduced into the molten slag by adjusting the length of the TEFLON bellows. The distance of the tip of the spindle from the crucible base was about 1.2cm and the length of the shaft immersed in the melt was 1.0 cm. The thermal equilibration time at each temperature set point was 30 min. When the thermal equilibrium was

obtained, viscosity measurements were carried out. Several rotating rates were employed and the equilibration time for viscosity measurement at each speed of rotation was chosen to be 2 min. The viscosity values obtained at different rotation rates were found to be in very good agreement. The viscosity measurements were usually carried out during cooling cycle. However, repetitions of some measurements during heating cycle showed very good reproducibility.

The viscometer was calibrated at 298 ± 0.1K with four mineral oil standard with viscosities 0.985, 0.960, 4.850, and 12.500 Pa·S respectively. The viscometer was also calibrated in the temperature range of 1463-1675 K using a reference slag, (consisting of Li_2O-Al_2O_3-SiO_2) developed for the BCR program of the European Union[3].

After the viscosity measurements, some of the slags were sent for chemical analysis using a sequential X-ray spectrometer SRS303 supplied by SIEMENS. The contents of CaO, FeO and SiO_2 obtained by analysis were in agreement with the weighed-in amounts within ±1 pct.

3. RESULTS

The experimentally determined viscosities in the Fe_nO-MnO-SiO_2, Fe_nO-CaO-SiO_2, Fe_nO-MgO-SiO_2, CaO-MnO-SiO_2 and CaO-Fe_nO-MnO-SiO_2 systems are presented in Tables III-VII, respectively. It should be pointed out that the viscosity at each temperature listed in these tables is the average value over the experimental data obtained using five different rotation rates. The maximum deviation of the experimental data from the mean values was found to be less than 1 percent.

The reproducibility of the measurements is demonstrated in Figure 2, where the measured viscosities of two runs for the CaO(45wt%)-MnO(15wt%)-SiO_2(40wt%) slag are plotted against temperature. It is seen that the agreement between two individual experiments is satisfactory. Figure 2 also shows the good agreement between the viscosity values obtained during cooling and heating cycles.

The effect of temperature on the viscosity in the quaternary system, CaO-Fe_nO-MnO-SiO_2 is shown in Figure.3. It is seen that while the viscosity generally increases with the decrease of temperature, the increase is more profound in the case of the slag having composition of $X_{CaO} = 0.265$, $X_{FeO} = 0.172$ and $X_{MnO} = 0.077$.

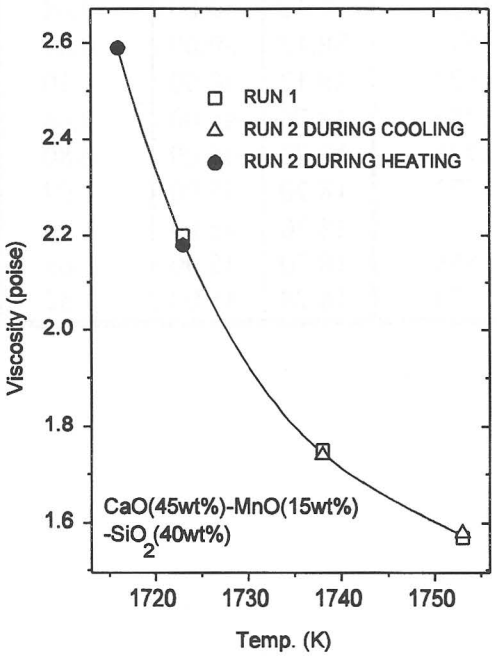


Figure 2 Measured viscosities of the CaO(45wt%)-MnO(15wt%)-SiO_2(40wt%) slag

Table III The measured viscosity values of some Fe_nO-MnO-SiO_2 slags

Temperature K	Fe_nO wt%	MnO wt%	Viscosities poise
1753	49.05	10.00	1.07
1723	49.05	10.00	1.24
1673	49.05	10.00	2.05
1653	49.05	10.00	2.35
1623	49.05	10.00	3.04
1603	49.05	10.00	3.54
1753	24.40	30.00	2.77
1753	10.00	44.20	2.88
1738	10.00	44.20	3.19
1723	10.00	44.20	3.64
1708	10.00	44.20	4.50
1753	38.12	30.00	0.47
1723	38.12	30.00	0.51
1673	38.12	30.00	0.58
1623	38.12	30.00	0.68
1573	38.12	30.00	0.84
1523	38.12	30.00	1.10
1753	18.70	45.00	0.68
1723	18.70	45.00	0.80
1673	18.70	45.00	1.07
1623	18.70	45.00	1.38
1588	18.70	45.00	1.65
1573	18.70	45.00	1.82

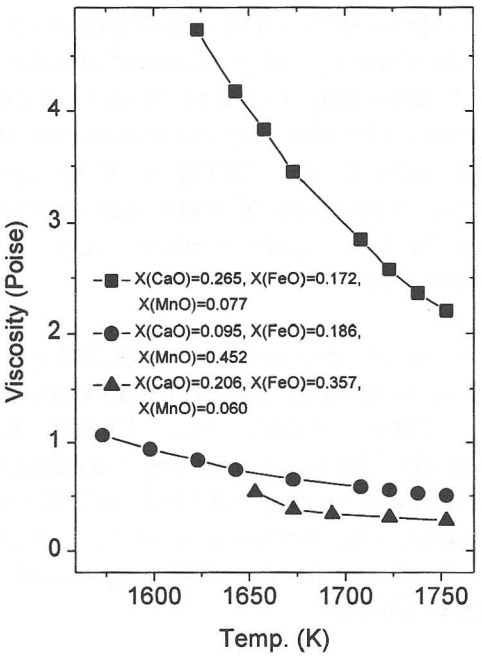


Figure 3 Viscosities as functions of temperature of some CaO-Fe_nO-MnO-SiO_2 quaternary slags

Table IV The measured viscosity values of some Fe_nO-CaO-SiO_2 slags

Temp. K	CaO wt %	Fe_nO wt %	Viscosity Poise	Temp. K	CaO wt%	Fe_nO wt%	viscosity Poise
1753	5.50	50.00	1.55	1623	24.38	35.00	1.09
1723	5.50	50.00	1.79	1573	24.38	35.00	1.39
1698	5.50	50.00	2.11	1523	24.38	35.00	1.84
1673	5.50	50.00	2.63	1493	24.38	35.00	2.32
1753	14.95	35.00	3.35	1473	24.38	35.00	2.68
1723	14.95	35.00	4.00	1753	36.90	18.00	1.89
1673	14.95	35.00	5.40	1738	36.90	18.00	2.06
1753	6.90	70.00	0.22	1723	36.90	18.00	2.27
1723	6.90	70.00	0.24	1698	36.90	18.00	2.70
1673	6.90	70.00	0.28	1673	36.90	18.00	3.26
1623	6.90	70.00	0.34	1753	45.57	11.00	1.88
1753	15.00	50.00	0.51	1738	45.57	11.00	2.05
1723	15.00	50.00	0.54	1723	45.57	11.00	2.45
1723	15.00	50.00	0.51	1753	33.28	35.00	0.48
1673	15.00	50.00	0.64	1723	33.28	35.00	0.54
1673	15.00	50.00	0.64	1673	33.18	35.00	0.62
1623	15.00	50.00	0.76	1623	33.28	35.00	0.94
1623	15.00	50.00	0.75	1573	33.28	35.00	1.33
1573	15.00	50.00	0.93	1553	33.28	35.00	1.52
1523	15.00	50.00	1.22	1753	25.60	50.00	0.33
1473	15.00	50.00	1.71	1723	25.60	50.00	0.38
1423	15.00	50.00	2.45	1673	25.60	50.00	0.47
1723	24.38	35.00	0.75	1623	25.60	50.00	0.59
1673	24.38	35.00	0.86	1573	25.60	50.00	0.92

Table V The measured viscosity values of some Fe_nO-MgO-SiO_2 slags

Temperature K	Fe_nO wt%	MgO wt%	Viscosities Poise
1753	50.0	8.0	1.02
1738	50.0	8.0	1.09
1723	50.0	8.0	1.17
1703	50.0	8.0	1.30
1673	50.0	8.0	1.47
1648	50.0	8.0	1.71
1623	50.0	8.0	1.98
1608	50.0	8.0	2.13
1753	44.0	13.0	1.12
1738	44.0	13.0	1.21
1723	44.0	13.0	1.30
1713	44.0	13.0	1.37
1693	44.0	13.0	1.50
1673	44.0	13.0	1.70
1753	68.0	9.0	0.66
1738	68.0	9.0	0.69
1723	68.0	9.0	0.96
1708	68.0	9.0	1.20

Table VI The measured viscosity values of some $CaO-MnO-SiO_2$ slags

Temperature K	CaO wt%	MnO wt%	Viscosities Poise	Temperature K	CaO wt%	MnO wt%	Viscosities Poise
1753	31.85	18.00	3.67	1573	8.31	45.00	8.72
1738	31.85	18.00	4.09	1753	23.00	42.00	0.82
1723	31.85	18.00	4.46	1723	23.00	42.00	0.92
1708	31.85	18.00	4.94	1673	23.00	42.00	1.17
1708	31.85	18.00	4.95	1638	23.00	42.00	1.40
1688	31.85	18.00	5.63	1623	23.00	42.00	1.53
1673	31.85	18.00	6.31	1598	23.00	42.00	1.81
1753	21.58	30.00	3.08	1573	23.00	42.00	2.14
1723	21.58	30.00	3.66	1753	11.00	56.00	0.68
1673	21.58	30.00	4.89	1723	11.00	56.00	0.73
1643	21.58	30.00	6.04	1673	11.00	56.00	0.84
1623	21.58	30.00	6.98	1623	11.00	56.00	1.05
1601	21.58	30.00	8.33	1598	11.00	56.00	1.22
1573	21.58	30.00	10.55	1753	45.00	15.00	1.57
1753	8.31	45.00	2.69	1753	45.00	15.00	1.58
1723	8.31	45.00	3.20	1738	45.00	15.00	1.75
1696	8.31	45.00	3.72	1738	45.00	15.00	1.74
1673	8.31	45.00	4.27	1723	45.00	15.00	2.20
1653	8.31	45.00	4.86	1723	45.00	15.00	2.18
1623	8.31	45.00	5.94	1716	45.00	15.00	2.59
1598	8.31	45.00	7.21				

Table VII The measured viscosity values of some $CaO-Fe_nO-MnO-SiO_2$ slags

Temperature K	CaO wt%	Fe_nO wt%	MnO wt%	Viscosities Poise
1753	8.00	20.00	48.00	0.28
1723	8.00	20.00	48.00	0.31
1693	8.00	20.00	48.00	0.34
1673	8.00	20.00	48.00	0.38
1653	8.00	20.00	48.00	0.54
1753	24.00	20.00	8.80	2.20
1738	24.00	20.00	8.80	2.36
1723	24.00	20.00	8.80	2.58
1708	24.00	20.00	8.80	2.85
1673	24.00	20.00	8.80	3.45
1658	24.00	20.00	8.80	3.83
1643	24.00	20.00	8.80	4.18
1623	24.00	20.00	8.80	4.74
1753	18.00	40.00	6.60	0.51
1738	18.00	40.00	6.60	0.53
1723	18.00	40.00	6.60	0.56
1708	18.00	40.00	6.60	0.59
1673	18.00	40.00	6.60	0.66
1643	18.00	40.00	6.60	0.75
1623	18.00	40.00	6.60	0.84
1598	18.00	40.00	6.60	0.94
1573	18.00	40.00	6.60	1.07

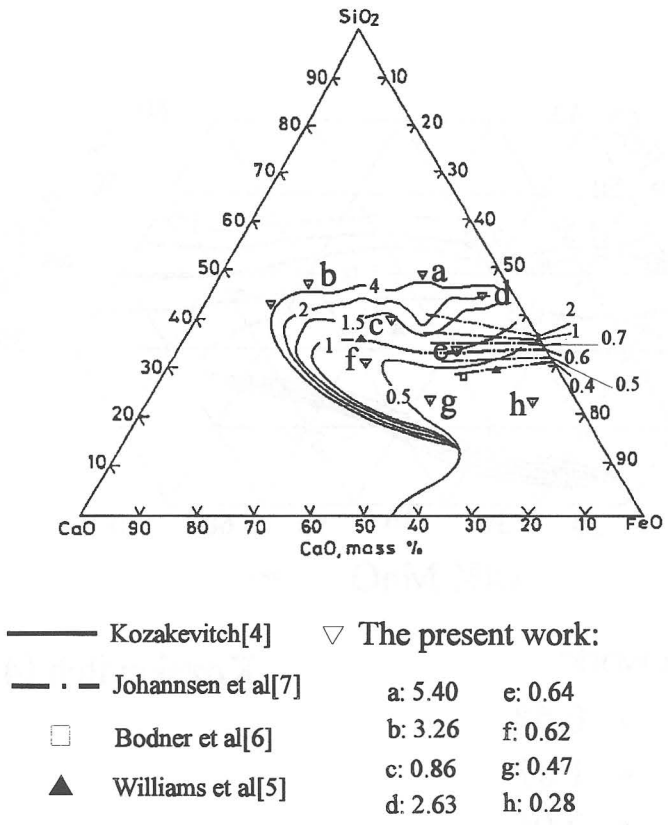
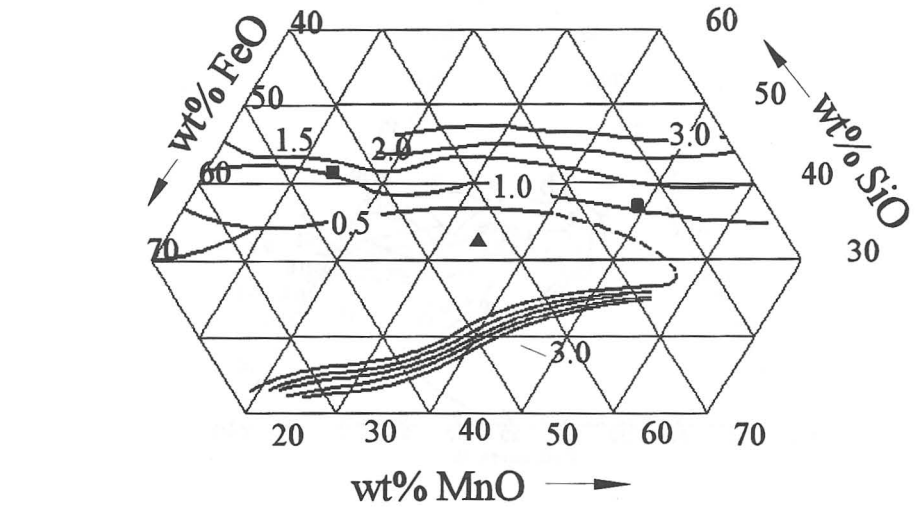


Figure 4 A comparison of the present experimental data with the literature values for the $CaO\text{-}Fe_nO\text{-}SiO_2$ system.

4 DISCUSSION

The viscosities in the $CaO\text{-}Fe_nO\text{-}SiO_2$ and $MnO\text{-}Fe_nO\text{-}SiO_2$ systems were earlier studied by Kozakevitch[4] at 1673 K. The viscosities of the $CaO\text{-}Fe_nO\text{-}SiO_2$ slags at 1673 K were also measured by other research groups.[5-7] The viscosities suggested by different authors at this temperature are compared with the present experimental data in Figure 4 for the $CaO\text{-}Fe_nO\text{-}SiO_2$ system. While in general, the agreement between the results of the present work and the literature data is reasonable, the present viscosity values between 0.5 and 1 poise are somewhat lower than Kozakevitch's results[4] but agree well with the iso-viscosity lines reported by Johannsen et al.[7] In Figure 5, the present experiment data of the $MnO\text{-}Fe_nO\text{-}SiO_2$ slags are compared with the iso-viscosity lines recommended by Kozakevitch.[4] It is seen that the present viscosity values are much higher than Kozakevitch's results. The differences



The present work:

- ▲ 0.58
- ● 1.07
- ■ 2.05

—— Kozakevitch [4]

Figure 5 A comparison of the present experimental data with the literature values for the MnO-Fe_nO-SiO_2 system.

between the results may be attributed to the refinement in the measuring technique in later years.

In order to express viscosities in multi-component systems as functions of temperature and composition, a mathematical model has earlier been developed at the Division of Theoretical Metallurgy.[1] To give an orientation to the reader, some of the salient features of the model when applied to oxide systems are presented in this section.

The viscosity, η can be expressed by the equation

$$\eta = \frac{hN\rho}{M} \cdot \exp\left(\frac{\Delta G^*}{RT}\right) \qquad (1)$$

where h is the Planck's constant, N is the Avogadro's number, R is the gas constant, T is the temperature, ρ and M stand for density and molecular weight of the melt, respectively. ΔG^* in equation (1) is the Gibbs energy of activation for viscosity, which is considered to be a function of both temperature and composition of the melt.

For unary systems, the Gibbs energy of

activation can be described as a function of temperature.[1] In the case of multi-component systems, the use of equation (1) requires the molecular weight and the density of the melt. The molecular weight can be calculated by

$$M = \sum X_i \cdot M_i \qquad (2)$$

where, X_i and M_i represent the mole fraction and the molecular weight of the component i in the solution, respectively. As a first approximation, the average density of a solution is represented by a similar equation:

$$\rho = \sum X_i \cdot \rho_i \qquad (3)$$

where ρ_i is the density of the pure component i in liquid state.

The Gibbs activation energy in the case of multi-component systems can be represented as

$$\Delta G^* = \sum X_i \Delta G_i^* + \Delta G^*_{Mix} \qquad (4)$$

where ΔG_i^* is the Gibbs energy of activation of the pure component i in liquid state. The second term in equation (4) is due to the mutual interactions between different species and is expected to be a function of composition. In the case of ionic solutions, the Temkin description is adopted. An oxide ionic solution can be represented by the formula:

$$(C1,C2,...Ci,...Cn)_P(O)_Q \qquad (5)$$

where P and Q are the stoichiometric coefficients and C1, C2, Ci,..., Cn represent different cations. The ionic fraction of cation Ci within the cation grouping is defined as

$$y_{Ci} = \frac{N_{Ci}}{\sum N_C} \qquad (6)$$

In equation (6), N represents the number of the ions and the summation covers all the cations in the system.

ΔG^* may be considered to consist of two parts:

$$\Delta G^*_{Mix} = -\Gamma \cdot T + \Delta^E G^*_{Mix} \qquad (7)$$

For an ionic solution in which only oxygen ions are present in the anionic grouping, the term $\Gamma \cdot T$ is expressed by:

$$\Gamma = -R \cdot P \sum y_{Ci} \cdot \ln y_{Ci} \qquad (8)$$

The $\Delta^E G^*_{Mix}$ term in equation (7) is meant to take into account all non-linear, non-symmetrical interactions between the various ionic species. This term is expressed by suitable polynomials.[1]

Model calculations were carried out using the present experimental data and the experimental information from the literature. Table VIII lists the sources of the experimental information adopted in the present work. The optimized parameters are presented in Tables IX. Even the density data for the five oxides are given in the same table. It is noted that the model parameters listed in Table IX should be considered to be preliminary, as further experimental information that is currently being acquired is to be incorporated in a very near future. In Figure.4, the calculated viscosities are plotted against the experimental values. It is seen that the experimental data are well reproduced by the model calculations.

The calculated iso-viscosity lines at 1673 K in the three ternary systems, Fe_nO-MnO-SiO_2, Fe_nO-CaO-SiO_2 and CaO-MnO-SiO_2 are presented in Figures 7-9, respectively. The present experimental data are also included in these figures. The agreement between the results of the model calculations and the experiments are again brought out in the case of all the three ternary systems. A common trend is observed in these ternaries, viz. the viscosity increases with SiO_2 content.

At the present stage, no model calculation has been made for the MgO-Fe_nO-SiO_2 system, as the experimental data are so far mainly in the low MgO region. It is felt that more experiments need to be carried out for the slags having higher MgO contents, before reliable model calculations could be made.

Table VIII The sources of the experimental data employed for the model calculations

System		References
Unary	CaO	8
	FeO	9
	SiO_2	10-17
Binary	CaO-SiO_2	18-22
	Fe_nO-SiO_2	23-25
	MnO-SiO_2	26-29
Ternary	Fe_nO-CaO-SiO_2	Present work
	Fe_nO-MnO-SiO_2	Present work
	CaO-MnO-SiO_2	30, Present work
Quater-nary	CaOFe_nO-MnO-SiO_2	Present work

The iso-viscosity lines in the quaternary system, CaO-MnO-Fe_nO-SiO_2 at 1773 K and X_{SiO2} =0.5 are plotted in Figure 10. It shows that the slags having composition around X_{CaO} =0.1, X_{FeO} =0.2 and X_{MnO} = 0.2 have highest viscosities. The viscosity does not show dramatic change in this section.

SUMMARY

In the present work, the viscosities in the Fe_nO-CaO-SiO_2, Fe_nO-MnO-SiO_2, Fe_nO-MgO-SiO_2, CaO-MnO-SiO_2 and CaO-Fe_nO-MnO-SiO_2 systems have been determined using rotating cylinder technique. Iron crucibles and spindles have been employed. The present experimental results have been compared with the available literature data at 1673 K. While the comparison has shown agreement in the case of Fe_nO-CaO-SiO_2 system, the present viscosity values have been found to be considerably higher than the literature data in the Fe_nO-MnO-SiO_2 system. Calculations have been carried out using the viscosity model earlier developed at the Division of Theoretical Metallurgy. The model calculations have been based on the present experimental data and the information assessed for the viscosities in the relevant lower order systems. The experimental data have been well fitted by the model calculations in the case of both the CaO-Fe_nO-MnO-SiO_2 system

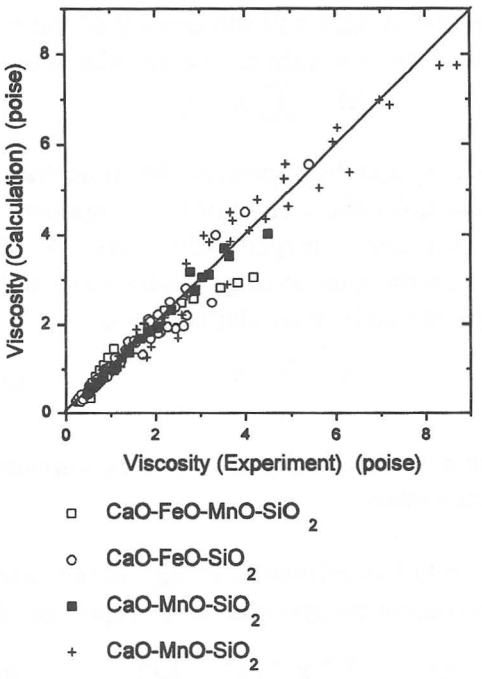


Figure 6 A comparison of the calculated viscosities with the experimental data

Table IX The optimized model parameters

Component i	Density($g.cm^{-3}$)	ΔG_i^* ($J.mole^{-1}$)
CaO	3.3	$1.86211759 \cdot 10^5$
Fe_nO	4.7	$1.33749 \cdot 10^5 - 18.032553 \cdot T$
MnO	5.4	$2.44844371 \cdot 10^4$
SiO_2	2.3	$427554.041 - 8.54698812 \cdot T$

		$\square^E G^*_{Mix}$
Binary	$CaO-Fe_nO$	$\Delta^E G^*_{Mix}(CaO-Fe_nO) = y_{Ca}y_{Fe}(1.16701247 \cdot 10^6 - 467.039849 \cdot T)$
	CaO-MnO	$\Delta^E G^*_{Mix}(CaO-MnO) = y_{Ca}y_{Mn}(2.13418485.10^6 - 420.322098 \cdot T)$
	$CaO-SiO_2$	$\Delta^E G^*_{Mix}(CaO-SiO2) = y_{Ca}y_{Si}\,((-8.48791647 \cdot 10^5 + 120.369642 \cdot T) + 2.56430864 \cdot 10^5 (y_{Ca} - y_{Si}))$
	Fe_nO-MnO	$\Delta^E G^*_{Mix}(Fe_nO-MnO) = y_{Fe}y_{Mn}(-1.11655212 \cdot 10^7 + 6191.44176 \cdot T)$
	Fe_nO-SiO_2	$\Delta^E G^*_{Mix}(Fe_nO-SiO_2) = y_{Fe}y_{Si}\,((-1.00534363 \cdot 10^6 + 282.697236 \cdot T) + 2.01709998 \cdot 10^5 (y_{Fe} - y_{Si}))$
	$MnO-SiO_2$	$\Delta^E G^*_{Mix}(MnO-SiO_2) = y_{Mn}y_{Si}\,((-4.69335571 \cdot 10^5 + 102.136386 \cdot T) + 2.92864789 \cdot 10^5 (y_{Mn} - y_{Si}))$
Ternary	$CaO-Fe_nO-SiO_2$	$\Delta^E G^*_{Mix}(CaO-Fe_nO) + \Delta^E G^*_{Mix}(CaO-SiO_2) + \Delta^E G^*_{Mix}(Fe_nO-SiO_2) + F_{CFS}$ $F_{CFS} = y_{Ca}y_{Fe}y_{Si}\,((3.12041186 \cdot 10^6 + 405.389958 \cdot T) - 1.27469520 \cdot 10^7 . y_{Ca} - 4.95984073 \cdot 10^6 . y_{Fe} + 1.38608984 \cdot 10^7 \cdot y_{Ca}^2))$
	$CaO-MnO-SiO_2$	$\Delta^E G^*_{Mix}(CaO-MnO) + \Delta^E G^*_{Mix}(CaO-SiO_2) + \Delta^E G^*_{Mix}(MnO-SiO_2) + F_{CMS}$ $F_{CMS} = y_{Ca}y_{Mn}y_{Si}\,((8.61061762 \cdot 10^5 + 1.12340732 \cdot 10^3 \cdot T) - 9.97865389 \cdot 10^6 \cdot y_{Ca} - 9.05475078 \cdot 10^6 \cdot y_{Mn} + 2.92390372 \cdot 10^6 \cdot y_{Ca}^2))$
	$Fe_nO-MnO-SiO_2$	$\Delta^E G^*_{Mix}(Fe_nO-MnO) + \Delta^E G^*_{Mix}(Fe_nO-SiO_2) + \Delta^E G^*_{Mix}(MnO-SiO_2) + F_{FMS}$ $F_{FMS} = y_{Fe}y_{Mn}y_{Si}\,((2.77075874 \cdot 10^7 - 1.49874069 \cdot 10^4 \cdot T) + (1.39405992 \cdot 10^7 - 7.43995272 \cdot 10^3 \cdot T) \cdot y_{Ca})$
Quaternary	$CaO-Fe_nO-MnO-SiO_2$	$\Delta^E G^*_{Mix}(CaO-Fe_nO) + \Delta^E G^*_{Mix}(CaO-MnO) + \Delta^E G^*_{Mix}(CaO-SiO_2) + \Delta^E G^*_{Mix}(Fe_nO-MnO) + \Delta^E G^*_{Mix}(Fe_nO-SiO_2) + \Delta^E G^*_{Mix}(MnO-SiO_2) + F_{CFS} + F_{CMS} + F_{FMS} + y_{Ca}y_{Fe}y_{Mn}y_{Si} \cdot (1.67951738 \cdot 10^8 - 1.01492515 \cdot 10^5 \cdot T + y_{Ca}(-8.74469716 \cdot 10^8 + 4.90583622 \cdot 10^5 \cdot T))$

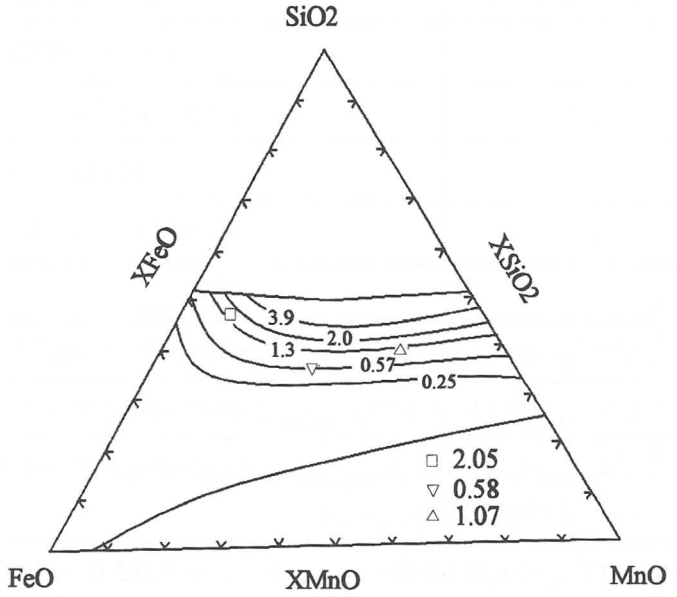


Figure 7 Iso-viscosities in the MnO-Fe O-SiO $_2$ System at 1673 K
n

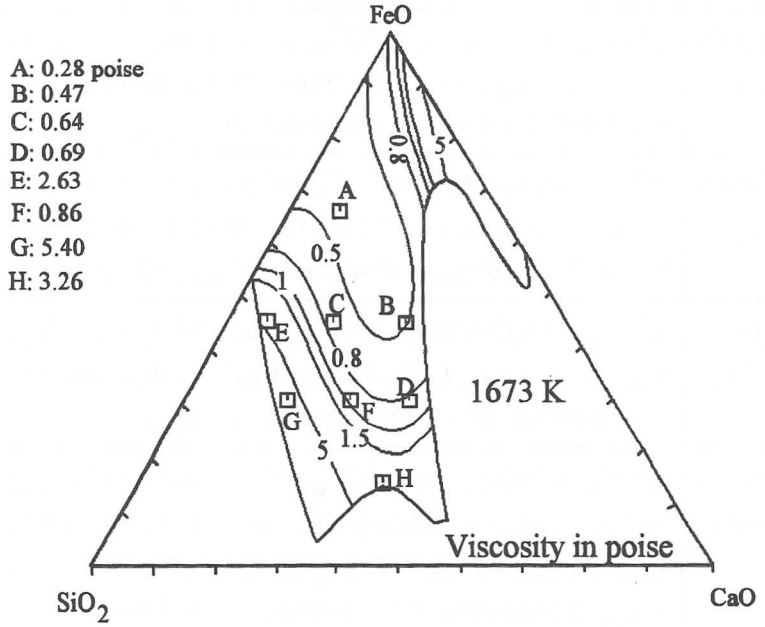


Figure 8 Iso-viscosities in the Fe O-CaO-SiO $_2$ system at 1673 K
n

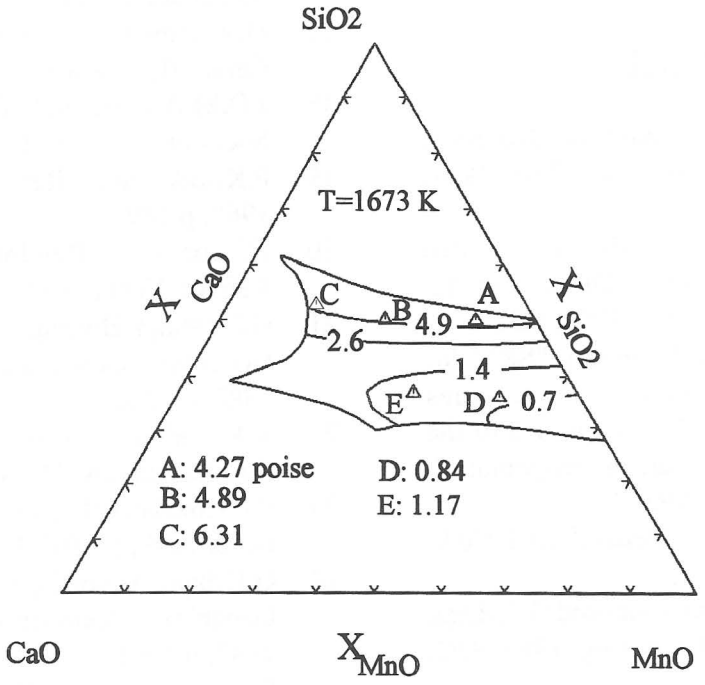


Figure 9 Iso-viscosities in the CaO-MnO-SiO_2 system at 1673 K

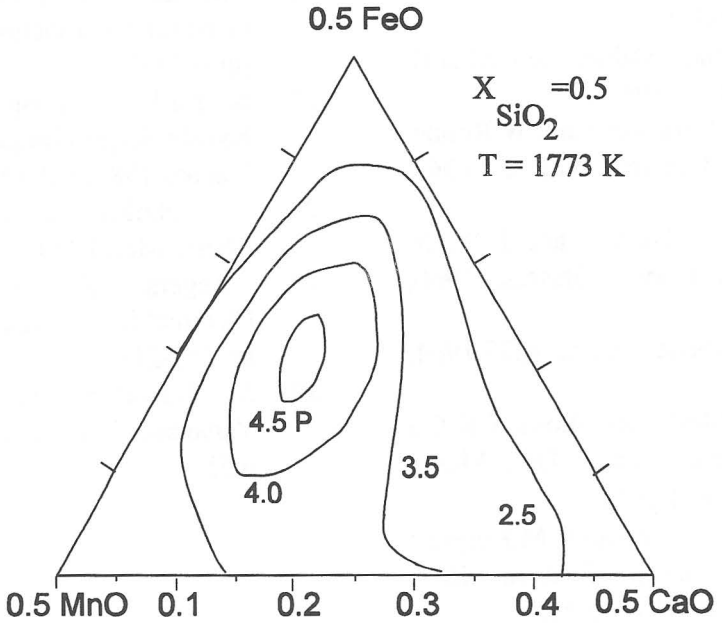


Figure 10 Iso-viscosities in the CaO-Fe_nO-MnO-SiO_2 system at 1673 K and X_{SiO2} =0.5

and the corresponding lower order systems. Iso-viscosity lines have been evaluated for different systems.

REFERENCE

1. Du Sichen,J.Bygden, and S.Seetharaman: Metall. Mater. Trans.B, Vol.25B, 1994, pp.1-7.
2. E.M.Levin,C.R.Robbins and H.F.McMurbie: Phase Diag. Ceram., Vol.1, Amer. Cera. Soc., 1964, p.38.
3. K. C. Mills and A. A. Shirali, "SRM for high Temperature Viscosities Measurements-Results for Phase 3 of the Interlaboratory Comparison Programme", NPL Report, Aug. 1993.
4. P.P.Kozakevitch:Rev.Metall.,XLVI, No.9, 1949, pp.572-82.
5. P. Williams, M. Sunderland and G. Briggs, Trans. Inst. Min. Metall. Eng. 1983, 92C, p.105
6. L. Bodnar, K. Cempa, K. Tomasek and L. Bobok, Chem. Zvesti 1987, vol. 32, p.798.
7. F. Johannsen and W. Sishkov, Erzmetall 1988, vol.11, pp.1-15
8. Slag atlas, Verlag Stahleieisen M.B.H. Dusseldotf, 1981, p.194.
9. H.Schenck, M.G.Frohberg and W.Rohde: Archiv Eisenhuttenwes, Vol.32, 1961, pp.521-523.
10. J. F. Bacon, A. A. Hasapis and J. W. Jr. Wholley, Phys. Chem. Glasses, 1960, vol.1, pp.90-98.
11. R.Bruckner, Glastech.Ber.,Vol37,1964, p.413.
12. V.K.Leko,E.V.Meshcheryakova,N.K.Gusakova and R.B.Lebedeva: Opt. Mekh. Prom., Vol.12, 1974, p.42
13. S.G.Loryan,K.A.Kostanyan,V.M.Kafyrov and E.Kh.Bogdasaryan: Elektron. tekh., Ser.6, Mater., Vol2.1976, p.53.
14. G.Hofmaier and G.Urbain: Sci. Ceram.,Vol.4, 1968, p. 25.
15. M.P.Volarovich and A.A.Leontieva: J.Soc.Glass Techn., Vol.20, 1936, p.141.
16. G.Urbain and M.Boiret: Ironmaking Steelmaking,Vol.17, 1990, pp.255-260.
17. D.W.Bowen and R.W.Taylor, Ceram.Bull.,Vol.57, 1978, pp.818-819.
18. J.O,M.Bockris and D.C.Lowe: Proc. R. Soc. London, Ser., 1954, p.423.
19. P.Kozakevitch: Rev.Metall.,Paris,Vol57, 1960, p.149.
20. G.Urbain: Rev.Int.Hautes Temp. Refract.,Vol11, 1974, p.3.
21. G.Urbain,Y.Bottinga and P.Richet: Geochim. Cosmochim. Acta, Vol.46, 1982, p.1061.
22. V.K.Endell and Gunther.:Archiv fur.Eisehuttenw, Vol.10, 1936, pp.85-90.
23. P.P.Kozakevitch: Rev. Metallurgie XLVI, No.8, 1949, pp.505-16.
24. G.Urbain.,Y.Bottinga and P.Richet: Geochim. Cosmochim. Acta, Vol.46, 1982, p.1061.
25. P. Röntgen, H.winterhager and R.Kammel: Erzmetall, Vol.9, 1956, pp.207-14.
26. G.Urbain, Y.Bottinga and P.Richet, Geochim.Cosmochim.Acta, 1982, vol.46, pp.1061-72.
27. S. Yagi, K. Mizoguchi, Y. Suginohara, Kyushu Kogyo Daigaku Kenkyu, Hokoku, kogaku 1980, vol.40, pp.33-38.
28. V.I. Sokolov, S.I. Popel, O.A. Esin, VUZ Chern. Met. 1970, vol. 4, pp.40-45.
29. L.Segers, A. Fontana,R. Winard, Electrochim. Acta, 1979, vol.24, pp.213-218.
30. M. Kawahara, K. Morinage and T. Yanagase: J. Jpn. Inst. Met., 1979, vol.43, p.55