Viscosities of Lead-Copper Converter Slags

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ABSTRACT

The viscosity of an industrial lead-copper converter slags was experimentally determined as a function of temperature using a Brookfield viscometer. The experiments were carried out in argon atmosphere in the temperature range of 1200 to 1573 K. The experimental viscosity data was fitted to a non-linear function involving both composition of the slag and temperature. Parameters of the model equation were evaluated by regression analysis using the experimental data. The calculated viscosity values were in good agreement with experimental data of the slags.

1. INTRODUCTION

Viscosity is a very important property of slag which determines not only the flow characteristics of the slag, but also affects the mass transfer across the slag/metal interface, heat transfer in the slag, refractory attack in the blast furnace and entrainment of metal in the slag. Slag-metal reactions are important in the extraction and refining of metals by pyrometallurgical processes. Typical copper converter slag consists of iron oxide, silica, alumina, and calcium oxide and some metallic and non-metallic impurities in the form of entrainments in the slag. Viscosity affects the settling of matte or metal droplets in slag and distribution of various elements in the slag in copper smelting and converting processes.

There have been several studies on the viscosities of borate and silicate slags /1-7/. One of the authors studied the viscosities of commercial lead smelting slags and applied the Arrhenius type of relation to describe the viscosity as functions of composition and temperature /1/. Reddy *et al.* /2, 3/ have modeled the viscosities of several silicate slag systems by considering the ionic structure of the slags. They extended the structure based model to predict the viscosities of binary and ternary borate melts /4-6/. Altman *et al.* /8/ measured the viscosities of industrial lead blast furnace slags in the temperature range of 1400–1573 K.

In a previous research, the authors studied the viscosity of lead blast furnace slags as function of composition and temperature /9/. In this research, viscosity data for lead-copper converter slags were experimentally determined using a Brookfield Digital Viscometer RVT DV-II. A viscosity model equation was developed to describe the variation of viscosity as function of both temperature and composition of slag. The constants involved in the equation were evaluated by means of regression analysis of the experimental data. The calculated viscosities were compared with those of the experimental values. Activation energy of viscosity for the slags was determined.

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2. EXPERIMENTAL

A. Experimental Setup

Viscosity measurements were carried out using a Brookfield Digital Viscometer (RVT DV-II) by the rotating cylindrical spindle method. The details of the experimental setup and procedure are described in an earlier publication /4/.

B. Sample Preparation

Industrial lead-copper converter slags studied in this research were obtained from various copper primary processing industries. The compositions of the slags result from a mixture of lead blast furnace slags and copper converter slags. Table 1 lists the compositions of seven slags, labeled as S1-S7, studied in this research. The viscosity of each slag was measured at different temperatures in the temperature range of 1200–1573 K. Alumina stirrer rods and alumina crucibles were used in the experiments. The mixture was melted in a resistance furnace to obtain the homogenized sample composition. Following the melting, the solidified composites were crushed to a particle size of 2-3 mm.

C. Experimental Procedure

Major oxides present in the present slags are CaO, FeO, and SiO_2, although other oxides such as PbO, Cu_2O, MgO, ZnO, BaO, Al_2O_3, along with some metal values such as Co, Sb, Sn, Ni, are present in minute quantities. The silicon carbide furnace was heated to the desired temperature, which is high enough to melt a given slag. After the furnace attains the desired temperature, an alumina crucible filled with the slag is lowered into the furnace. The furnace is maintained at this temperature for several minutes to allow the thermal equilibrium to occur. Once the melting of the slag begins, the alumina spindle is lowered and centered from the bottom of the crucible. Viscosity measurements were carried out in the temperature range of 1200–1573 K. Temperature was measured with the help of two Pt/Pt-10% Ph thermocouples with an accuracy of ±0.5 K. All the experiments were carried out in argon atmosphere. Measurements were also repeated during cooling in order to check the reproducibility of the data.

Table 1

Compositions of seven industrial copper converter slags along with their basicity index (BI) values

Component	SI	S2	S3	S4	S5	S6	S7
Pb	0.81	0.83	1.64	1.5	1.23	1.68	2.51
Cu	0.53	0.41	0.55	0.53	0.35	0.41	0.39
Ni	0.029	0.026	0.06	0.045	0.015	0.022	0.036
Co	0.048	0.043	0.074	0.074	0.05	0.073	0.111
As	0.021	0.018	0.026	0.054	0.053	0.077	0.081
Sb	0.039	0.038	0.05	0.057	0.072	0.088	0.105
Sn	0.26	0.25	0.46	0.46	0.32	0.48	0.7
ZnO	7.57	7.77	7.63	7.51	7.83	7.84	7.11
MgO	1.86	1.87	1.89	1.73	1.76	1.44	1.57
CaO	18.39	18.05	17.22	16.39	20.1	19.54	18.71
SiO_2	27.52	28.23	28.06	27.52	29.34	26.69	27.75
FeO	31.18	31.22	31.33	32.10	29.91	30.99	32.52
BaO	0.72	0.69	0.73	0.74	0.4	0.4	0.39
Al_2O_3	5.08	5.31	3611	5.69	3.36	3.13	3.34
Cr_2O_3	0.50	0.45	0.63	0.41	0.1	0.1	0.1
BI	**1.80**	**1.75**	**1.69**	**1.74**	**1.83**	**2.01**	**1.93**

3. RESULTS AND DISCUSSION

Viscosities of industrial copper converter slags were measured in the temperature range of 1200–1573 K. Unlike synthetic slags, industrial slags usually contain more than 8 elements. The components are PbO, Cu_2O, MgO, ZnO, FeO, CaO, BaO, SiO_2, Al_2O_3, and other impurities such as As, Sb, Sn, Ni, Co.

Experimental viscosities determined for the slags at various temperatures are shown in Fig. 1. The viscosity data, in mPa.s, are plotted as function of temperature for different slags whose identity is given by the basicity index (BI). Basicity Index (BI) of a slag is defined as the ratio of sum of amounts of basic oxides to that of acidic oxides and is given by:

$$BI = \frac{\%CaO + \%FeO + \%MgO + \%ZnO + \%BaO}{\%SiO_2 + \%Al_2O_3 + \%Cr_2O_3}$$

where the symbol '%' refers to 'mass percent' of the oxide. Table 1 also lists the basicity index values for the seven slags studied in the present investigation. The solid line in the plot refers to trend line indicating the variation of viscosities of the slags with temperature. Basicity index values of the slags are in the range of 1.66–1.99 and the viscosity data falls within a narrow band of 40 mPa.s about the trend line. The variation in

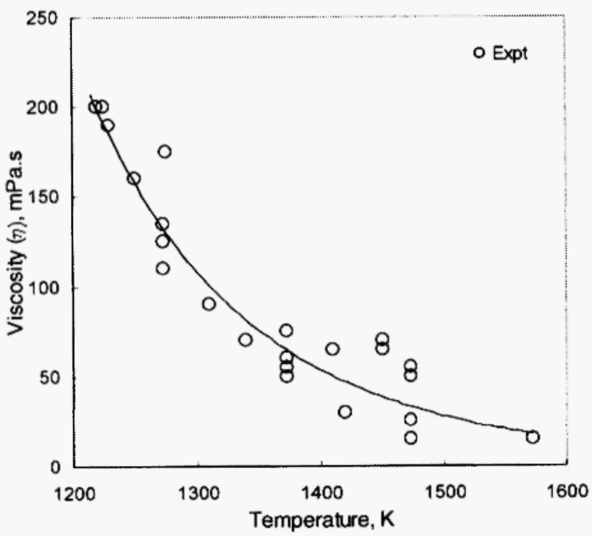

Fig. 1: Experimental viscosities of the seven copper converter slags (S1-S7) as function of temperature. Solid line indicates the trend.

measured viscosities is usually < 5% of the reported value which is less than the experimental uncertainty range of 6 to 10%. The slags displayed Newtonian behavior, i.e., the viscosity is independent of the shear rate at constant temperature and composition of the slag. Reddy et al. /1-6/ proposed a structure based model and also reviewed several models that are available to predict viscosities of molten alloys and slags.

In this study, the following viscosity-temperature-composition relation was used to model the experimentally determined viscosities of the slags.

$$\log(\eta) = C_1 \log(BI) + \frac{C_2}{RT} + C_3 \qquad (1)$$

where C_1, C_2, C_3 are constants to be evaluated by regression analysis of the experimental viscosity data as function of composition and temperature, 'BI' is the basicity index, R is the gas constant and T is the absolute temperature. The regression constants C_1, C_2, and C_3 estimated for the slags using the experimental data are 1.637, 49859.112 and −2.990 respectively. The value of C_2 multiplied by 2.303 yields the activation energy of viscosity for the converter slags.

Table 2 shows the comparison of experimental and calculated viscosity data for the slags (S1-S7) along with their temperatures and BI values. The calculated viscosity values are plotted along with the experimental data in Fig. 2. The solid line shows the trend line for the calculated viscosity data for the slags. The standard deviation of viscosity data for all the slag samples was 18 mPa.s. An excellent agreement between the predicted viscosity data and the experimental data was observed for both the slag samples. A simple expression given by equation (1) was sufficient to describe the viscosity behavior of the present slag samples as function of both composition and temperature.

From equation (1), a plot of log (η) *vs.* 1/T should yield a straight line whose slope refers to the activation energy of viscosity of the slags. Figure 3 shows the plot of calculated viscosity values versus temperature as log (η) *vs.* 10000/T for the slags along with activation energy of 114.8 kJ which was determined from the slope of the graph. The activation energy obtained in this study is comparable to 157 kJ/mol and 110 kJ/mol obtained in our previous results /9/.

Table 2
Experimental and Calculated Viscosity Data for Slags (S1-S7)

S. No.	Slag BI	Temperature, K	Viscosity (η), mPa.s Experiment	Viscosity (η), mPa.s Calculated
1	1.80	1220	200	220.96
2	1.80	1230	190	201.53
3	1.80	1250	160	168.40
4	1.80	1273	135	137.93
5	1.80	1373	60	62.60
6	1.75	1273	110	131.64
7	1.75	1310	90	96.90
8	1.75	1340	70	76.53
9	1.75	1373	55	59.74
10	1.75	1473	15	30.18
11	1.69	1225	200	189.51
12	1.69	1275	175	121.8
13	1.69	1273	125	123.89
14	1.69	1373	75	56.23
15	1.74	1273	125	129.88
16	1.74	1373	50	58.94
17	1.74	1473	25	29.78
18	1.83	1450	70	37.53
19	1.83	1473	55	32.35
20	1.83	1573	15	17.83
21	2.01	1410	65	57.49
22	2.01	1420	30	53.66
23	1.93	1450	65	41.09
24	1.93	1473	50	35.41
25	1.93	1573	15	19.51

4. CONCLUSIONS

Viscosities of industrial lead-copper converter slags were measured in an argon atmosphere in the temperature range of 1200–1573 K. A Brookfield viscometer (RVT DV-II) and alumina stirrer and crucibles were used in this study. From the experimental data the following can be deduced:

1. The viscosities of the slags decreased with increase in temperature of the melt following an Arrhenius behavior.
2. A viscosity model for the slag samples has been developed to describe viscosity as a function of both temperature and composition of the slags. An excellent agreement between the experimental data and calculated viscosity values is observed.
3. Activation energies of 114.8 kJ were determined for the lead-copper converter slags from the Arrhenius plot of viscosity versus temperature.

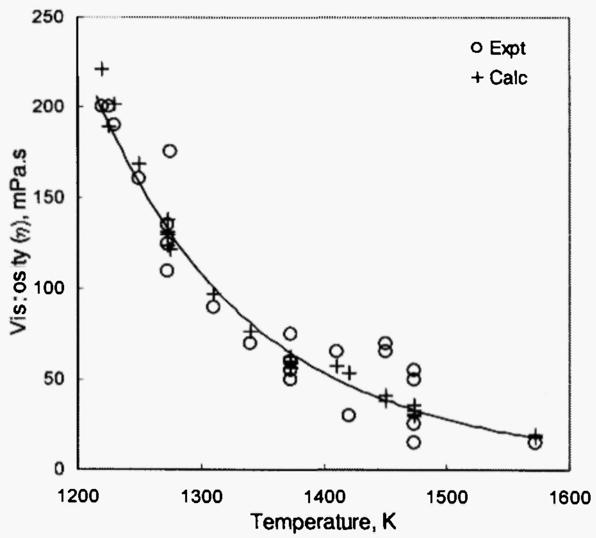

Fig. 2: Comparison between the calculated and experimental viscosities of the seven copper converter slags (S1-S7). Solid line refers to the trend line of the calculated viscosities.

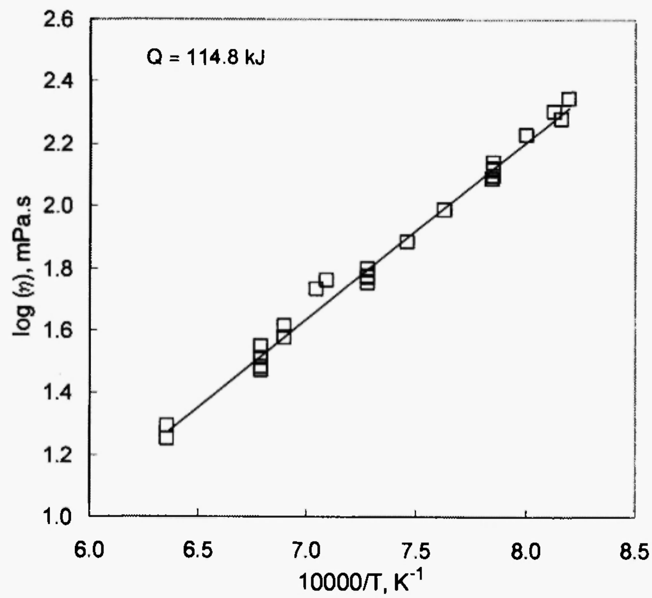

Fig. 3: Plot of log (η) *vs.* 10000/T for the seven copper converter slags along with the activation energy (Q) for viscosity.

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