THEORETICAL AND EXPERIMENTAL VISCOSITY DETERMINATION OF SLAGS[1]

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Abstract

Viscosity is an important parameter related to fluid flow at any temperature. The knowledge of the viscosity values of slags at elevated temperatures is of importance for the operation of metallurgical industrial reactors and for the modeling and simulation of their processes. Slag viscosity data, however, are still limited due to the difficulty and cost of viscosity measurements at elevated temperatures. Because of this, there are mathematical models proposed for its determination. This study presents a comparison of the experimentally measured viscosity data using a high temperature viscometer, with calculated results using the thermodynamic model and data reported in the literature.

Key words: Slag; Fluxes; Viscosity.

DETERMINAÇÃO TEÓRICA E EXPERIMENTAL DA VISCOSIDADE DE ESCÓRIAS

Resumo

A viscosidade é um parâmetro fundamental ligado ao escoamento de fluidos em qualquer temperatura. O conhecimento dos valores da viscosidade de escórias em temperaturas elevadas é importante para a operação de reatores metalúrgicos industriais e para o modelamento e a simulação dos processos que neles transcorrem. Os dados da viscosidade de escórias, contudo, ainda são limitados devido à dificuldade e aos custos de medições de viscosidade em temperaturas elevadas. Por causa disso, há modelos matemáticos propostos para a sua determinação. O presente estudo propõe uma comparação entre valores da viscosidade medidos experimentalmente por meio de um viscosímetro de alta temperatura, valores determinados por meio do modelo termodinâmico e valores apresentados na literatura.

Palavras-chave: Escórias; Fluxos; Viscosidade.

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1 INTRODUCTION

Slag melts are of chief importance in many pyrometallurgical processes such as extraction, refining and casting of metals. With the increasing use of mathematical models to explain, to study and simulate these processes, data describing the slag phase are essential, and there is a special need for reliable viscosity data.

There are several ways to measure viscosity; none of them is easy to perform, especially because of the high temperatures involved with this type of experiment.

Accordingly, the development of mathematical models to estimate the viscosity attains a great importance due to the possibility of circumventing the lack of certain data.

A new mathematical model for the viscosity of *single-phase* liquid slags and glasses has been developed recently and is available with the thermodynamic software FactSage (v. 6.2). Mills(1) stated that viscosity is expected to be a function of the slag *structure* (*i.e.* the degree of the *polimerization* of the melt). Accordingly, the model relates directly the melt viscosity to the melt structure. And the structure, in turn, is calculated from the thermodynamic equilibrium state.

The viscosity model – according to its authors – requires very few parameters (which were optimized to fit the experimental data for pure oxides and selected binary and ternary systems) and is able to predict the viscosities of multicomponent melts (and glasses) within experimental error limits.

In view of the above described facts, this paper aims to compare viscosity data of some slags, measured in the Institute of Iron and Steel Technology of the Freiberg University of Mining and Technology,(2) with viscosity values obtained with the help of the above mentioned computational thermodynamic model. Furthermore, it is within the scope of this work to determine with the mathematical model the viscosities of a number of slag systems given in the reference work 'Slag Atlas'(1) and compare the results with the data available in that publication.

2 METHODOLOGY

2.1Slags

Some simple to more complex slag types were chosen for this work (Table 1).

Table 1. Chemical composition of the chosen slags, [wt.%](2)

Slag	CaO	SiO_2	TiO_2	Na_2O	Al_2O_3	C*	*B***
CA	45.13				52.78	0.053	
CS	42.71	55.92				0.062	0.8
CST	36.76	46.31	17.92			0.036	0.8
CSTN_1	33.55	41.98	16.30	8.17		0.037	0.8
CSTN_2	30.88	36.99	16.16	15.64		0.07	0.8
CSTNA_1	34.77	38.88	14.10	9.54	2.97		0.9
CSTNA_2	31.44	39.41	15.40	7.03	6.80	0.22	0.8

** C is the carbon content; ** B, basicity, is the ratio wt.% CaO / wt.%* SiO_2

2.2 Viscometer

Viscosity measurements were carried out at the Freiberg University of Mining and Technology, Germany, using a rotational viscometer (Anton Paar MC 301).

The slags were melted under Ar atmosphere in a molybdenum crucible using an induction furnace.

The mass of each slag sample was 30 grams.

After melting, the slag was cooled directly from the liquid state (at a cooling rate of 10°C/min) while measuring the viscosity at a rotation speed of 15 rpm. The measurements stopped when the torque exceeded 2,000 μNm.

2.3 Thermodynamic Viscosity Model

Theoretical viscosity was determined using a new ‘module’ of FactSage v.6.2 software, developed specially for the viscosity determination of (single-phase) liquid slags and glasses. It is distinct from other viscosity models in that it directly relates the viscosity to the structure of the melt, and the structure in turn is calculated from the thermodynamic description of the melt using the Modified Quasichemical Model.

The thermodynamic viscosity model has been checked against the experimental data (by the producer of the software) available for melts and glasses. For melts, the systems are: Al_2O_3 - B_2O_3 - CaO - FeO - Fe_2O_3 - K_2O - MgO - MnO - Na_2O - NiO - PbO - SiO_2 - TiO_2 - Ti_2O_3 - ZnO - F. This database is valid for liquid and supercooled slags with viscosities which are not too high, that is when log(viscosity) < 7.5, with viscosity given in [P], or, ln(viscosity) < 15, with viscosity given in [Pa·s].

2.4 Viscosity Uncertainties

Most viscosity measurements are subject to experimental uncertainties(1) of ± 25%; in some cases they could be greater than ± 50%. Experimental uncertainties of ± 10% could be achieved by careful calibration of viscometers with high and low reference materials.

Prime source of experimental uncertainties are changes in the composition of the melt due to reactions between the melt and graphite and, to a lesser extent, errors in the temperature measurements of the melt.

3 RESULTS AND DISCUSSION

3.1 CaO-Al_2O_3 Binary Slag Viscosity

The viscosity of the binary slag CaO-Al_2O_3 (named CA in this text) was determined with the thermodynamic model using both the temperature and the composition as variables.

In order to make a comparison possible with some data presented in the reference publication Slag Atlas,(1) the composition CaO = 0.62 wt.% was used for the first of these comparisons, using the temperature as variable. The results are shown in Figure 1.

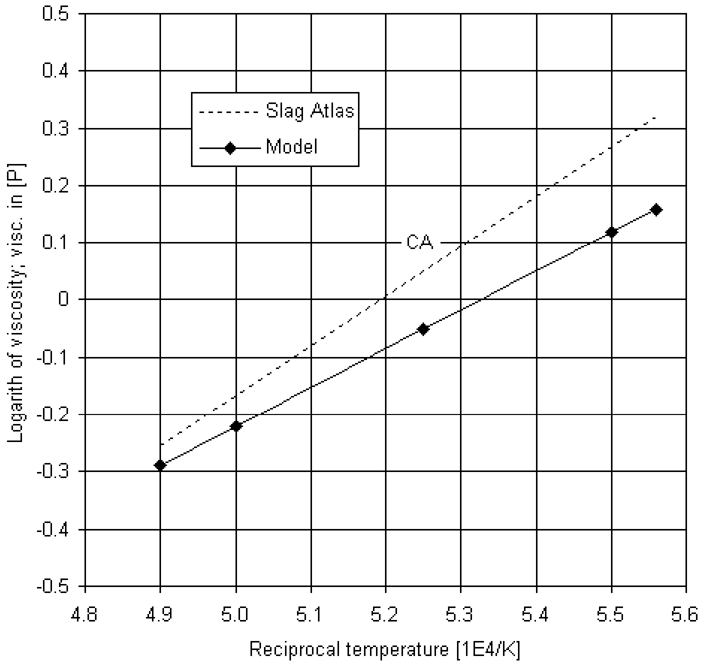

Figure 1. Logarithm of $CaO-Al_2O_3$ slag viscosity, for CaO = 0.62 at.%, as a function of the temperature.

Another viscosity determination for this slag system was also performed using the composition as variable. In this case, the temperature was set at 1,700°C. Results can be seen in Figure 2.

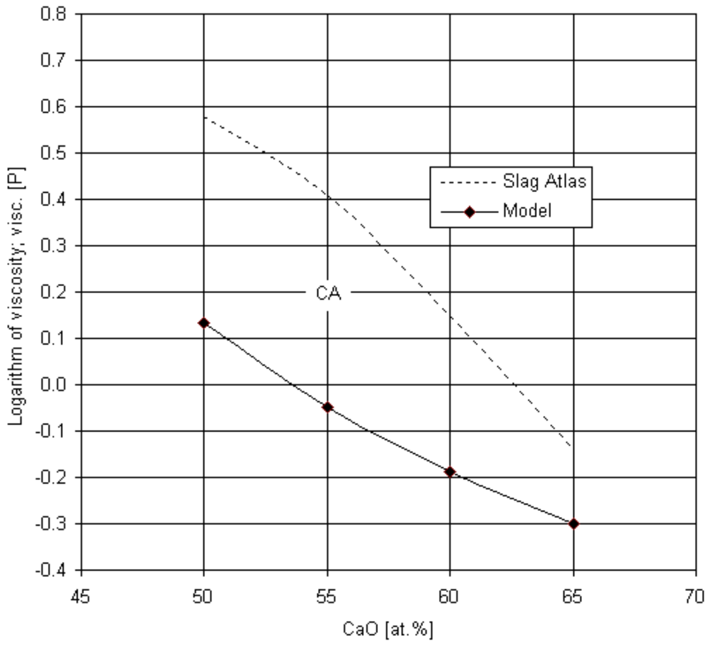

Figure 2. Logarithm of $CaO-Al_2O_3$ slag viscosity, at 1,700ºC, as a function of the composition.

Observing these two figures, the difference between results from the literature and from the model is clearly visible. Results deriving from the mathematical model are always lower than those presented in the reference work.

The viscosity of a CA slag, having the composition CaO = 45.13 wt.% (48.28 at.%), was measured experimentally as a function of the temperature. This experiment was simulated using the thermodynamic model. As shown in Figure 3, experimental results show viscosity values higher than those of the model – the same trend was observed in the comparison between the 'Slag Atlas' results and those determined with the aid of the model.

Although the general conditions are different, once both the literature (Figure 2) and the experimental values (Figure 3) are larger than those obtained with the model, one could expect experiment and literature viscosity results to be close to each other.

Conversely, one could conclude that for this slag the mathematical model gives viscosities which are lower than those from experiment or literature. Nevertheless, results show some tendency to approach the referred values, for higher temperatures or CaO content.

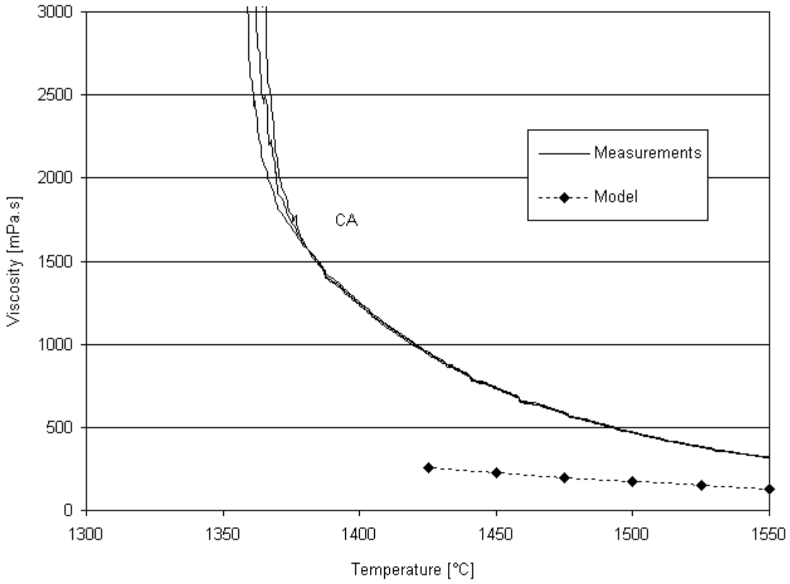

Figure 3. $CaO-Al_2O_3$ (CA) slag viscosity as a function of the temperature.

3.2 $CaO-SiO_2$ Binary Slag Viscosity

The viscosity of the binary slag $CaO-SiO_2$ (CS) was determined with the thermodynamic model using composition and temperature as variables.

As before, in order to provide a comparison with some data presented in 'Slag Atlas', T = 1,600°C was used in the determination having the composition as the only variable. The results are shown in Figure 4. The similarity between results from the literature and from the model results is clearly visible.

The viscosity of a CS slag with the composition SiO_2 = 55.92 wt.% (51.72 at.%) was measured experimentally. The same experiment was simulated using the thermodynamic model. As can be seen in Figure 5, the experimental results show viscosity values slightly lower than that of model. Toward higher temperatures, however, the experimental data and model values tend to get closer.

The thermodynamic model performance is much better with the CS slag than with the CA slag system.

3.3 Higher Order Slag Viscosity

The viscosity of some slags of interest, of higher order like ternary, quaternary and quinary was also determined both with the thermodynamic model and experimentally.

The viscosity of a single slag from the system CaO-SiO_2-TiO_2 was determined as a function of temperature. The experimental results and those obtained with the application of the model can be seen in Figure 6. There is a good approximation between the experiment and model results.

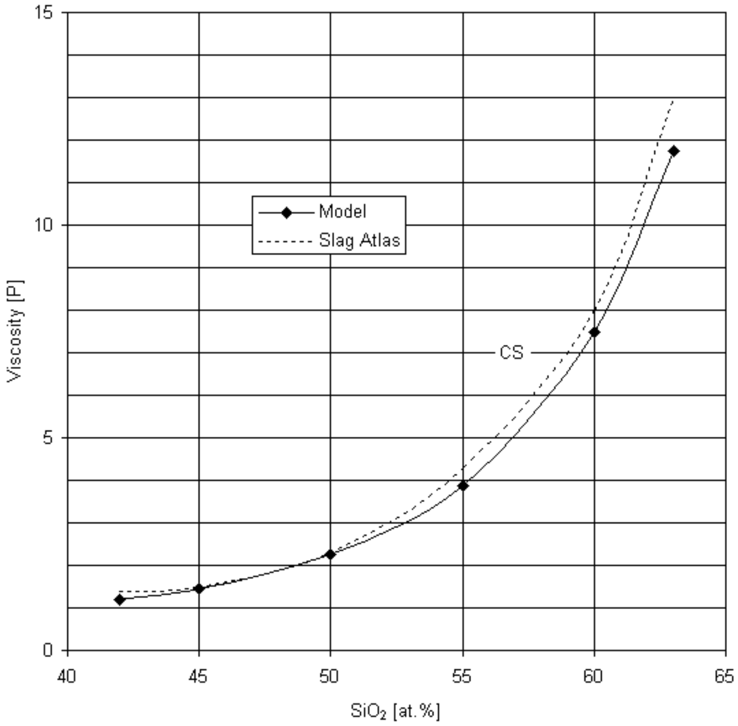

Figure 4. CaO-SiO_2 (CS) slag viscosity (T = 1,600ºC) as a function of the composition.

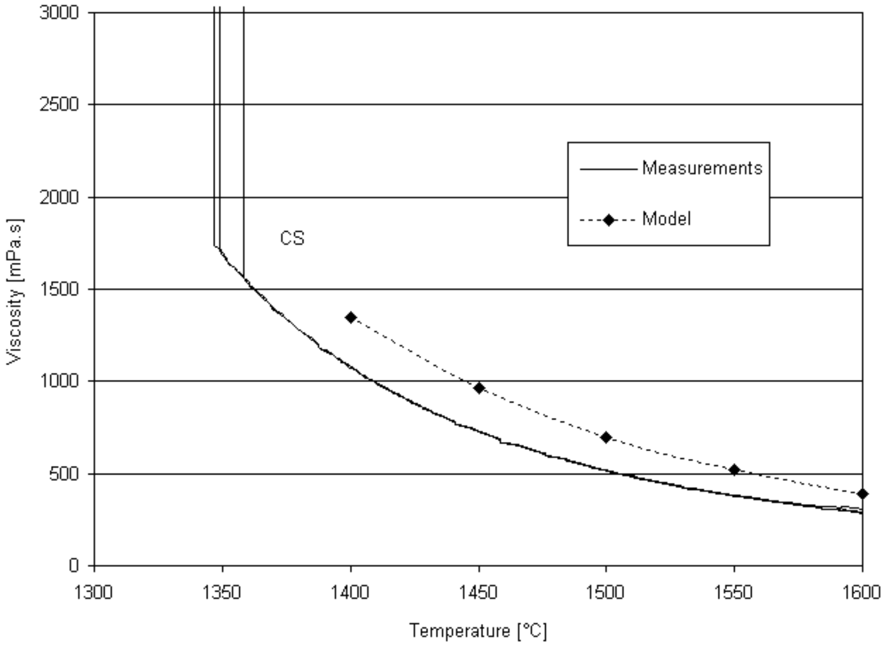

Figure 5. CaO-SiO_2 (CS slag) viscosity (SiO_2 = 51.72 at.%) as a function of the temperature.

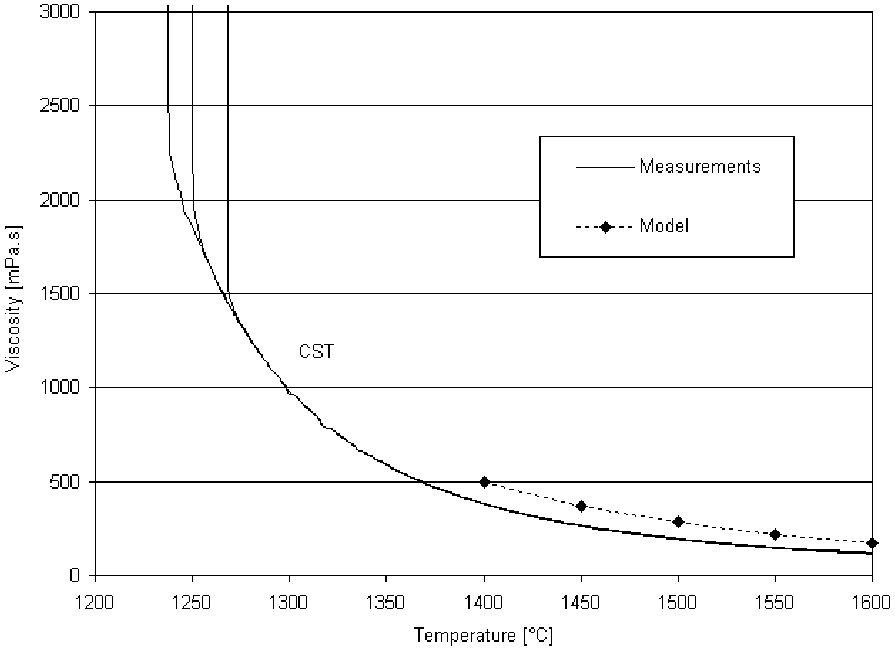

Figure 6. CaO-SiO_2-TiO_2 (CST) slag viscosity as a function of the temperature.

The viscosity of slags from the quaternary and quinary systems, CSTN and CSTNA, was determined experimentally and the results can be seen in Figures 7 and 8. Comparing these values and the viscosity values determined by the thermodynamic model one can say that there is a reasonable approximation between them.

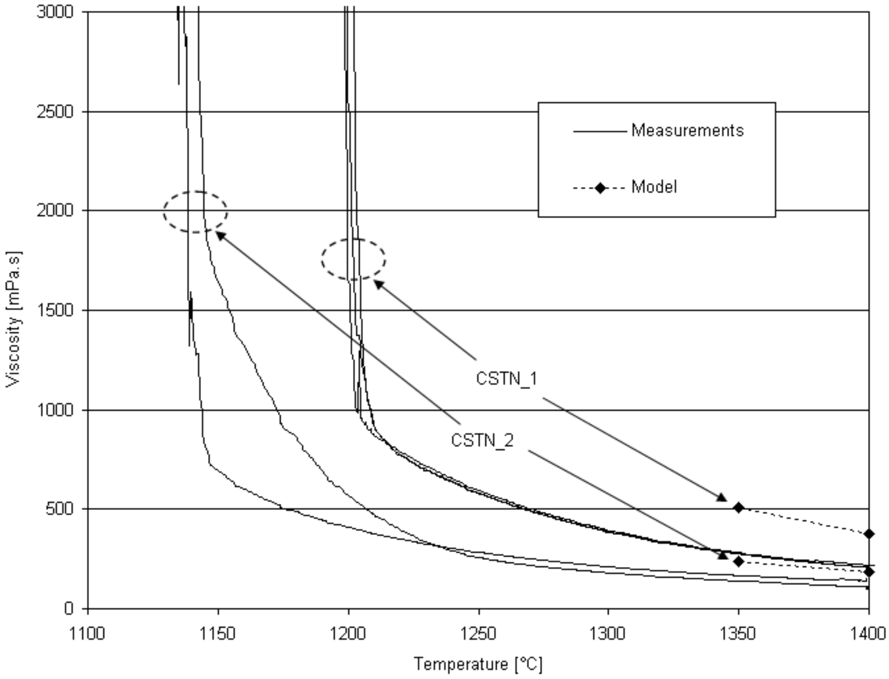

Figure 7. CaO-SiO_2-TiO_2-Na_2O (CSTN) slag viscosity as a function of the temperature.

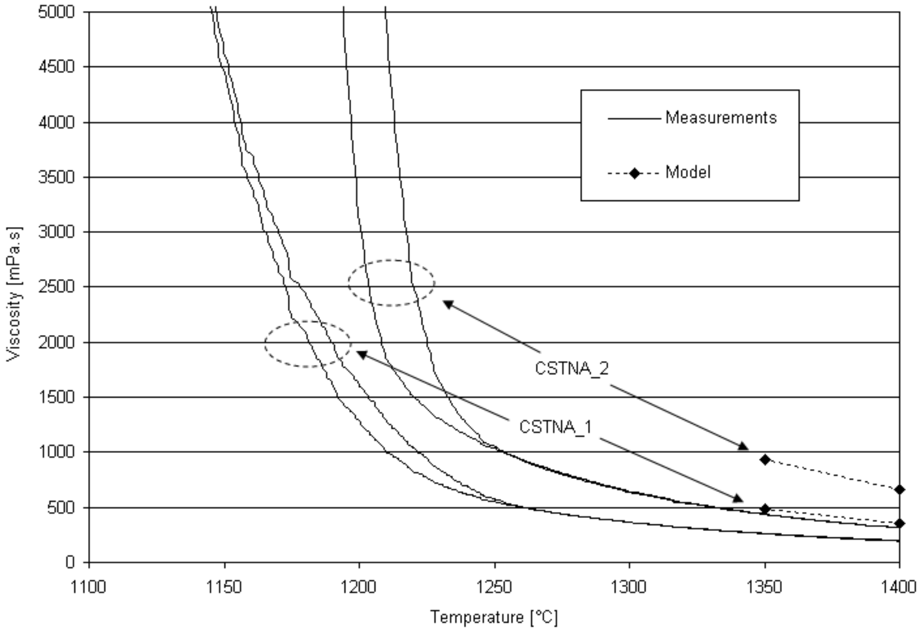

Figure 8. $CaO-SiO_2-TiO_2-Na_2O-Al_2O_3$ (CSTNA) slag viscosity as a function of the temperature.

4 CONCLUSIONS

Based on a number of experimental measurements and data published in the reference work ‘Slag Atlas’, it can be said that, for the compositions and temperatures tested, the thermodynamic model of viscosities which is available with the software FactSage v.6.2 presents results that are, more often than not, realistic. However, as shown, results obtained with the $CaO-Al_2O_3$ slag system are somewhat lower in comparison with those from the literature and experimental determinations.
In general, for all slag systems tested, the higher the temperature, the closer the results are to literature and experimental data.

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