Assessment of viscosity calculation for calcium-silicate based slags using computational thermodynamics

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Vinicius Cardoso da Rocha
Doutorando
Universidade Federal do Rio Grande do Sul - UFRGS
Programa de Pós-Graduação em Engenharia de Minas, Metalúrgica e de Materiais
Porto Alegre – Rio Grande do Sul – Brasil
vinicius.cardoso@ufrgs.br

Miguel Lahr da Silva
Mestrando
Universidade Federal do Rio Grande do Sul - UFRGS
Programa de Pós-Graduação em Engenharia de Minas, Metalúrgica e de Materiais
Porto Alegre – Rio Grande do Sul – Brasil
miguel.lahr@gmail.com

Wagner Viana Bielefeldt
Professor Adjunto
Universidade Federal do Rio Grande do Sul - UFRGS
Departamento de Metalurgia
Coordenador da Área de Aciaria do Laboratório de Siderurgia da UFRGS
Porto Alegre – Rio Grande do Sul – Brasil
wagner@ct.ufrgs.br

Antônio Cezar Faria Vilela
Professor-Titular
Universidade Federal do Rio Grande do Sul - UFRGS
Departamento de Metalurgia e de Pós-Graduação em Engenharia de Minas, Metalúrgica e Materiais - PPGE3M
Coordenador do Laboratório de Siderurgia
Porto Alegre – Rio Grande do Sul – Brasil
vilela@ufrgs.br

Abstract

This study focuses on the viscosity calculation of molten slags using computational thermodynamics. Different slag systems and their measured viscosities from different references were used and compared with those obtained through *FactSage* software. To calculate the viscosity of each slag the *Viscosity* module available in *FactSage* 6.4 was used. In order to perform the evaluation of computational thermodynamics in viscosity calculation, six different slag systems were presented, all of which were formed of calcium-silicate melts. In total, 162 slags, in temperatures ranges from 1423 K (1150 °C) to 2089 K (1816 °C) were presented for all slag systems. The software showed a tendency to produce viscosity values lower than those found in the literature measured by an experimental method. The relative deviation between the measured and calculated viscosity values is in the range of 13.31 to 37.53% for evaluated systems. Considering all references and systems, the average deviation between measured and calculated viscosities is 23.61%, which, according to literature, is an acceptable value. The $CaO\text{-}SiO_2\text{-}Al_2O_3$ and $CaO\text{-}SiO_2\text{-}FeO$ systems showed the best agreement between the experimental method and the method calculated through *FactSage* 6.4 with a very good fitting between viscosity values.

Keywords: Viscosity, slags, computational thermodynamics, *FactSage* 6.4.

1. Introduction

Viscosity is a physical property that is related to the structural properties of molten slags (Jung *et al*., 2014) and the viscous behavior of slags is very important during steelmaking operation processes. Slag viscosity can effect parameters such as the rate of desulphurization and heat transfer (Pengcheng and Xiaojun, 2016). Oxide based slags have very complex structures (including those with fluoride, sulfide or phosphide presence) and the viscosity of these slags can vary in a wide range of values (Costa e Silva, 2012).

More accurate data on slag viscosity is required to optimize the operation process, for example, of a blast furnace (Chen *et al*., 2014). Unfortunately, slag viscosity studies are highly problematic and time-consuming. Viscosity measurements are difficult, expensive and often carry considerable errors, according to Mills, Chapman, Fox and Sridhar (Mills *et al*., 2001). As cited in Jung (2010), these authors (Mills *et al*., 2001) promoted the "Round Robin Project" which showed that viscosity values for the same sample when measured by various groups in the world can differ by 20 to 50%. The reasons for this difference may be attributed to some error sources, which include incorrect equipment calibration, volatilization and interaction with atmosphere, as reported by Jung (2010). Vargas *et al*. (2001) suggested that the difficulties associated with viscosity measurement of molten oxides are related to:

i. Wide viscosity range;

ii. Low heat conducting properties of the liquid;

iii. Presence of bubbles in the liquid;

iv. High temperature during the experiments;

v. Deviation in temperature measurement and chemical composition of the melt.

Under the conditions listed, Jung (2010) mentioned the rotational technique as most suitable for viscosity measurement among other methods. However, besides the experimental techniques, computational thermodynamics can also be applied in predicting viscosity of multi-component systems within different chemical compositions and temperatures, due to the wide change in slag viscosities noticed by the dependence of these two parameters (Xu *et al*., 2016).

Accurate thermodynamic databases, which have been widely used in the last years, form the basis for developing the viscosity calculations (Jung, 2010). Thus, there is a continuous development of models for viscosity prediction, considering combinations of various oxides and temperature extrapolations that are difficult to achieve experimentally (Xu *et al*., 2014). Introduced by Pelton and Blander (1986), the modified quasi-chemical model (MQM), for example, describes phases of liquid slag in the *FactSage* thermodynamic software. In the software viscosity module, it is possible to calculate the viscosity of liquids from the MQM (FactSage Modules, 2016). It is reported that even multi-component slag systems have been successfully modeled through MQM (Suzuki and Jak, 2013).

Recently, Bale *el al*. (2016) published a summary of the developments in the *FactSage* software during the last six years with revised and updated databases that were added in the software. Academic and industrial collaboration are essential to the improvement of the *FactSage* software and its development is ongoing. Regarding this fact, the objective of this study was to evaluate the viscosity calculation accuracy through *FactSage* 6.4, by comparing the viscosity values with those obtained experimentally from literature for six calcium-silicate melt systems. A large amount of viscosity data is available in literature, obtained by applying experimental techniques with the use of a viscometer. In this perspective, the grouping of a number of slags of various different systems is the key feature of this article, including the main systems used in steel production over wide ranges of chemical compositions and temperatures. From comparison with the experimental results of viscosity, it is possible to identify the acceptable situation for application of the software, considering the possible experimental errors.

2. Methodology

In order to verify the accuracy of the *FactSage* software for the viscosity calculation, six different slag systems were presented: $CaO-SiO_2-Al_2O_3-MgO$ (CSAM), $CaO-SiO_2-Al_2O_3-K_2O$ (CSAK), $CaO-SiO_2-Al_2O_3-MgO-CaF_2$ (CSAMF), $CaO-SiO_2-MgO$ (CSM), $CaO-SiO_2-Al_2O_3$ (CSA) and $CaO-SiO_2-FeO$ (CSFeO). All presented systems featuring 162 slags in total, in temperatures ranging from 1423 K (1150 °C) to 2089 K (1816 °C). Table 1 shows more detailed information about the experiments in viscosity measurement from the literature adopted in this work.

Table 1
Some information about viscosity measurement from the references used in this work.

References	Viscometer	Calibration	Temperature measurement	Crucible/Spindle	Atmosphere
Pengchen and Xiaojun, 2016	Rotating cylinder method	Castor oil	Pt-6% Rh/Pt-30% Rh	Mo/Mo	Ar
Shankar *et al.*, 2007	Rotating cylinder method	Silicone oil standards with viscosities of 0.975 to 4.85 Pa·s at 298 ± 1 K	Optical pyrometry	Mo/Mo	Ar
Tang et al.,2011	Rotating cylinder method	Silicone oil standards at 298 ± 1 K	Pt-6% Rh/Pt-30% Rh	Mo/Mo	Ar
Machin *et al.*,1952; Machin and Yee, 1948	Oscillating cylinder-type	-	Leeds and Northrup type K potentiometer and Pt-Pt-10% Rh	Platinum/-	-
Zhang and Chou, 2012	Rotating cylinder method	-	Pt-6% Rh/Pt-30% Rh	Mo/Mo	Ar
Wu *et al.*, 2011	Rotating cylinder method	-	Pt-6% Rh/Pt-30% Rh	Mo/Mo	Ar
Ji *et al.*, 1997	Rotating cylinder method	Mineral oil standards and a reference slag	Pt-10% Rh/Pt	Iron/Iron (Armco iron)	Ar
Chen and Zhao, 2015	Rotating cylinder method	-	B-type	Mo/Mo	Ar
Schumacher *et al.*, 2015	Rotating cylinder method	Viscosity standards of 49.7, 97, and 488 mPa.s	B-type and R-type	Graphite/Mo	Ar
Urbain *et al.*, 1982	Rotating cup method and isothermal deformation method	-	Optical pyrometry	Mo/-	Vacuum or Ar

In the CSAM slag system, the apparatus for viscosity measurement adopted by Pengcheng and Xiaojung (2016), Shankar *et al.* (2007) and Tang *et al.* (2011) were made by the rotating cylinder method at 1723 K (1450 °C) to 1823 K (1550 °C). This measurement method was also applied in other studies (Ji *et al.*, 1997; Wu *et al.,* 2011; Zhang and Chou, 2012; Chen and Zhao, 2015) in the CSAK, CSAMF and CAFeO slag systems. In the Zhang and Chou (2012) study, the temperature range was 1713 K (1440 ºC) to 1813 K (1540 ºC) and in the Wu *et al.* (2011) study, the temperature range was 1697 K (1424 ºC) to 1905 K (1632 ºC). Lastly, in the CAFeO system (Ji *et al.,* 1997; Chen and Zhao, 2015) a range of 1423 K (1150 °C) to 1773 K (1500 °C) was used.

Using the same method in the viscosity measurement, Schumacher *et al.* (2015) studied the CSM slag system. The authors (Schumacher *et al.*, 2015) used a Deltech DT-31 Vertical Tube Laboratory Furnace equipped with a pneumatically actuated elevator. The experimental apparatus is also described in Park *et al.* (2002). According to Schumacher *et al.* (2015) there are few studies focused in the CSM systems. The experiments were conducted in a temperature range from 1723 K (1500 ºC) to 1973 K (1700 ºC).

In the CSA slag system, Santhy *et al.* (2005) studying the effect of oxygen and silicon ratio on slag viscosities, showed data on chemical composition and viscosities taken from literature (Chopra and Taneja, 1964) for a fixed temperature of 1773 K (1500 °C). Also, in the same temperature, Machin and Yee (1948) did some experimental measurements in viscosities for the CSA system. Moreover, Urbain *et al.* (1982) measured this system in an evaluated temperature range of 1611 K (1338 °C) to 2089 K (1816 °C).

Table 2
Systems adopted in viscosity calculations and their references.

Systems	References			
$CaO-SiO_2-Al_2O_3-MgO$ (70 slags)	(Pengchen and Xiaojun, 2016)	(Shankar *et al.*, 2007)	(Tang *et al.*,2011)	(Machin *et al.*,1952)
$CaO-SiO_2-Al_2O_3-K_2O$ (13 slags)	(Zhang and Chou, 2012)			
$CaO-SiO_2-Al_2O_3-MgO-CaF_2$ (9 slags)	(Wu *et al.*, 2011)			
$CaO-SiO_2-FeO$ (18 slags)	(Ji *et al.,* 1997)	(Chen and Zhao, 2015)		
$CaO-SiO_2-MgO$ (4 slags)	(Schumacher *et al.,* 2015)			
$CaO-SiO_2-Al_2O_3$ (48 slags)	(Chopra and Taneja, 1964)	(Machin and Yee, 1948)	(Urbain *et al.,* 1982)	

As seen, all systems are formed of calcium-silicate melts. The viscosity calculations were performed through the *Viscosity* module, available in version 6.4 of *FactSage*. The software provides a viscosity calculation module based on a structural viscosity model with an optimized database applicable for the slag containing $Al_2O_3-B_2O_3-CaO-MgO-FeO-Fe_2O_3-MnO-NiO-PbO-ZnO-Na_2O-K_2O-TiO_2-Ti_2O_3-SiO_2-F$ (Jung *et al.*, 2014). The viscosity database from *FactSage* applied in this study was *Melts*, valid for liquid and super-cooled slags with moderate viscosity values (when ln (viscosity, Pa·s) < 15) (FactSage Modules, 2010). Table 3 shows the chemical composition range for each system adopted in the viscosity calculations considering all references listed in Table 2.

Table 3
Slag systems with their chemical composition range used during viscosity calculations.

Systems	Chemical composition range (% wt.)							Temp. range [K (°C)]	Exp. viscosity range (Pa·s)
	CaO	SiO_2	Al_2O_3	MgO	CaF_2	K_2O	FeO		
CSAM	5 – 55	30 – 65	0 – 40	0 – 30				1723 (1450) – 1823 (1550)	0.17 – 3.87
CSAK	35.1 – 39	54.9 – 61	0 – 10			0 – 5		1713 (1440) – 1813 (1540)	1.09 – 4.53
CSAMF	43 – 60	7.5 – 22	25	5 – 10	0 – 4.9			1697 (1424) –1905 (1632)	0.04 – 1.66
CSFeO	5.5 – 45.6	23.1 – 50.1					11 – 70	1423 (1150) –1773 (1500)	0.02 – 0.54
CSM	51 – 55	43 – 46.8		1.5 – 6				1723 (1500) –1973 (1700)	0.11 – 0.33
CSA	14 – 55	15.1 – 65	0 – 40					1611 (1338) –2089 (1816)	0.12 – 5.39

It can be seen that the systems cover a wide range in chemical composition. Thus, in order to compare the results of viscosities, the same slag composition was used during calculations in *FactSage*. A performance analysis of each slag system on viscosity (η) calculations through *FactSage* was evaluated by the mean deviation between measured and calculated viscosity (Equation 1) with n values (Davenport *et al.*, 2002; Zhang *et al.*, 2012; Pengcheng and Xiaojun, 2016).

$$\Delta = \frac{1}{n} \times \sum \frac{|\eta_{measured} - \eta_{calculated}|}{\eta_{measured}} \times 100 \quad (1)$$

In the Equation 1, *n* denotes the total number of slags for each system in particular, as quantified in Table 2.

3. Results and discussion

All systems and their viscosities will be presented in the following sections. The comparison between experimental and calculated viscosities is illustrated in Figures 1 to 6. In all the comparative analyses shown below, between viscosities of the slag systems, the possibility of errors and uncertainties in the experimental data will be taken into account in up to 30% as proposed in the Suzuki and Jak (2013) study and the Round Robin Project from Mills *et al.* (2001).

3.1 Viscosity of the CaO-SiO$_2$-Al$_2$O$_3$-MgO system

The quaternary slags in the CSAM system play a very important role in the steelmaking process, in view of the oxides commonly employed (Song *et al.*, 2011). Therefore, studies (Machin *et al.*, 1952; Shankar *et al.*, 2007; Tang *et al.*, 2011; Pengcheng and Xiaojun, 2016) have been conducted on the viscosity measurement of CSAM slag systems. Figure 1 shows the comparison between the viscosity values found in the references previously cited and those calculated by *FactSage* 6.4 for the CSAM system.

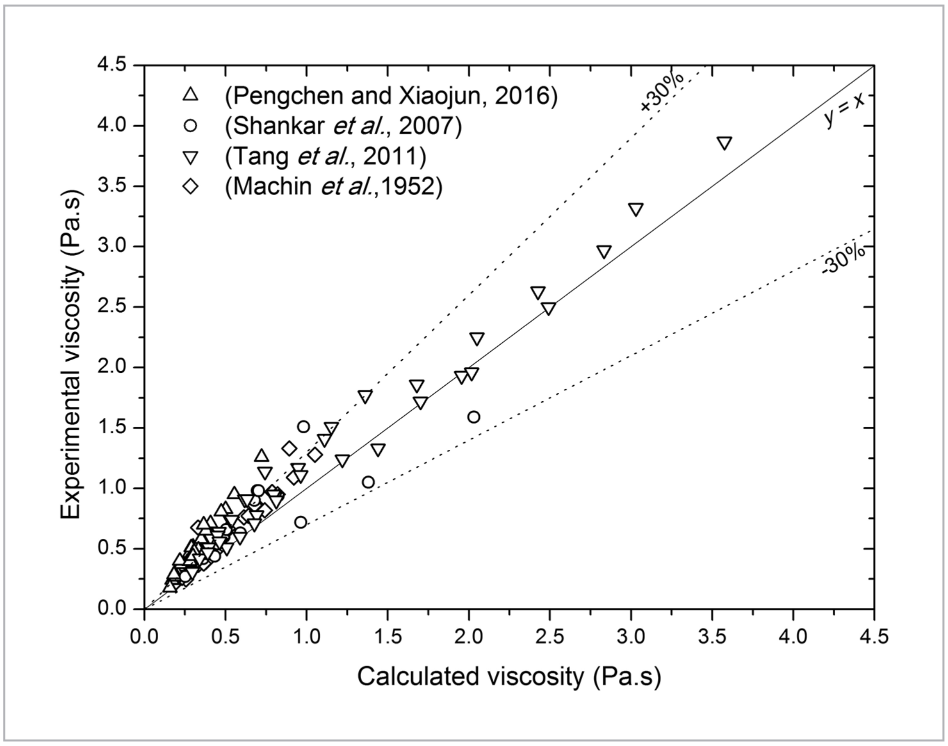

Figure 1
Calculated and measured viscosity comparison for CaO-SiO$_2$-Al$_2$O$_3$-MgO system.

The experimental viscosity values show a strong trend, higher than those calculated through *FactSage*, as illustrated in Figure 1. For the CSAM system, it is noted that above approximately 0.5 Pa.s the values between experimental and calculated viscosities are quite similar practically for all references. As viscosity increases, Figure 1 indicates a non-linear behavior in the ratio between the values. Muller and Erwee (2011) studying blast furnace slags in the CSAM system also reported that the overall correlation between the predicted and measured viscosity values is better at lower viscosities (higher temperatures), but deteriorates at higher viscosities. However, data from Tang *et al.* (2011) fit well with the estimated values through *FactSage* along the established viscosity range (0~4 Pa·s).

3.2 Viscosity of CaO-SiO$_2$-Al$_2$O$_3$-K$_2$O system

Alkali oxide has importance in ironmaking and steelmaking processes. In a blast furnace, for example, the content of alkali oxide has significant influence on the viscosity of slag, which is very important in the ironmaking operation (Zhang and Chou, 2012). Figure 2 illustrates the measured and calculated viscosity for the CSAK system.

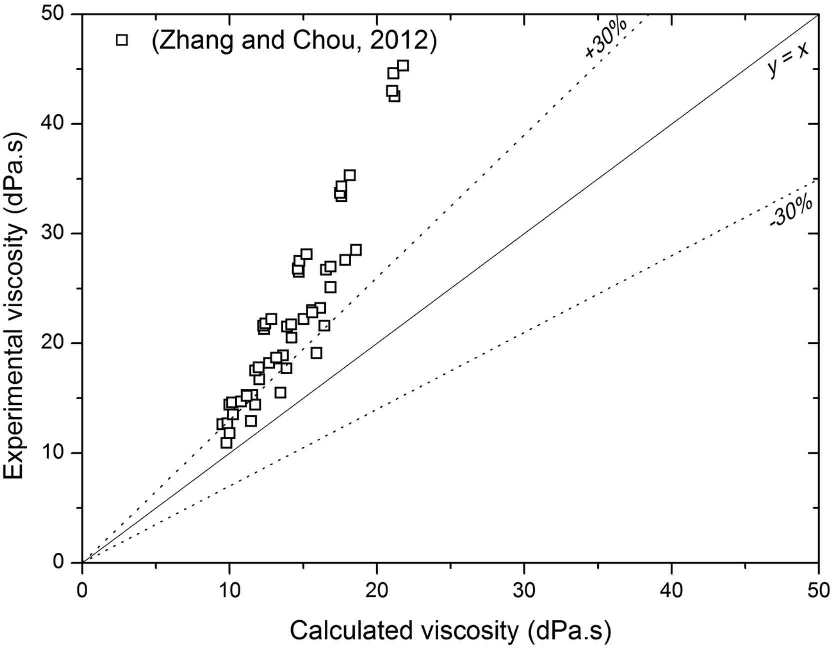

Figure 2
Calculated and measured viscosity comparison for CaO-SiO_2-Al_2O_3-K_2O system.

The values measured for viscosity are higher than those calculated through *FactSage*, as shown in Figure 2. Although there is a reasonable correlation for values lower than 10 dPa·s, a strong deviation as the viscosity increases is noted, which shows experimental viscosity values to be 30% higher than the *FactSage* values. Therefore, as experimental viscosity increases, the calculation method loses accuracy and the difference between viscosities becomes higher.

3.3 Viscosity of the CaO-SiO_2-Al_2O_3-MgO-CaF_2 system

The main application of the CSAMF system is in the steelmaking process, during secondary refining. Studying different slags, the authors (Wu *et al.*, 2011) evaluated the effect of CaF_2 in the slag viscosity. Figure 3 shows the experimental and calculated values for the viscosity of slags in the CSAMF system.

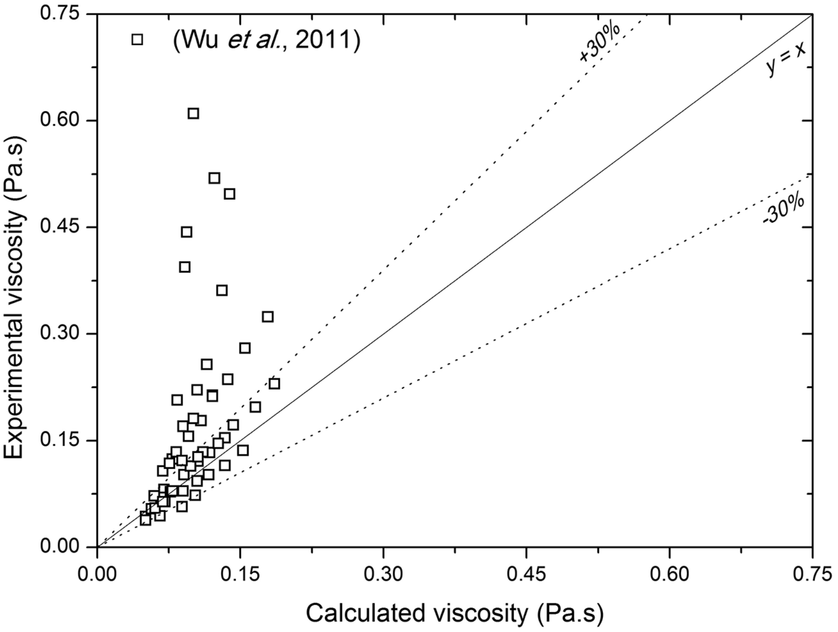

Figure 3
Calculated and measured viscosity comparison for the CaO-SiO_2-Al_2O_3-MgO-CaF_2 system.

Analyzing Figure 3, it is noted that a very good fitting between experimental and calculated viscosities up to 0.075 Pa·s exist. In this region, the majority of values of Figure 3 lay on the *y* = *x* line. As viscosity increases from 0.075 Pa·s, there is a dispersion of the viscosity values, especially around 0.10 Pa·s, where experimental viscosities are higher than calculated by a factor of up to

4 times higher than the calculated values. According to Jung *et al*. (2014) for oxide slags with an addition of CaF_2 there is a discrepancy between experimental data in the literature on CaF_2 viscosity and this fact can affect the comparison analysis.

3.4 Viscosity of the CaO-SiO_2-MgO system

Figure 4 shows the results for viscosities in the CSM system.

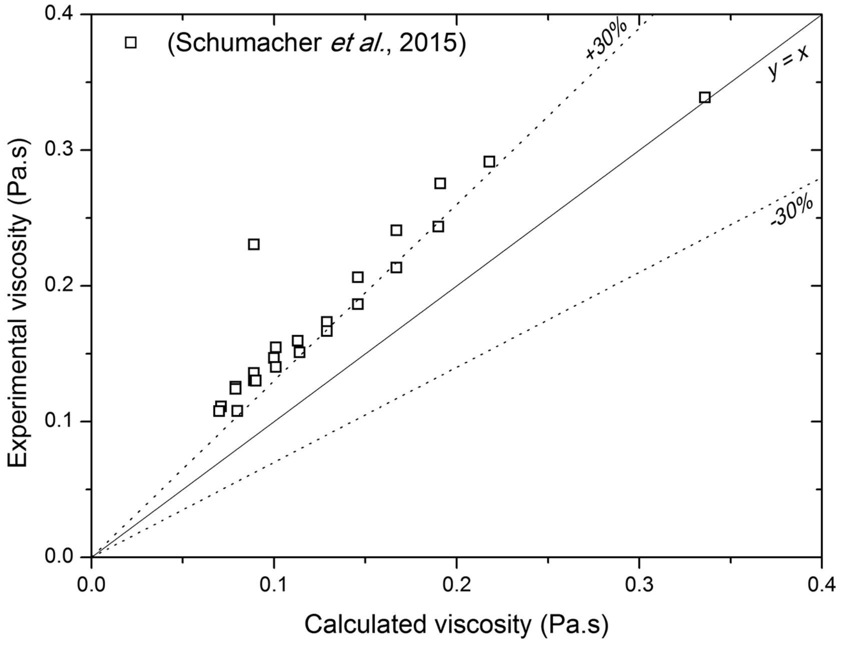

Figure 4
Calculated and measured viscosity comparison for the CaO-SiO_2-MgO system.

Figure 4 indicates that the difference between experimental and calculated viscosities is not high. It is possible to observe that as measured viscosity values increase, the calculated viscosities also increase, practically keeping a constant slope with experimental viscosity values around 30% higher than the calculated values. For viscosity values lower than 0.1 Pa·s, the data from viscosities seem to approach the line *y = x*.

3.5 Viscosity of the CaO-SiO_2-Al_2O_3 system

A basic system for secondary steelmaking operations is the CSA slag system (Jung *et al*., 2014). The change in the compositions of these systems has an impact on heat capacity, density and viscosity (Lis *et al*., 2012). Figure 5 shows the comparison between measured and calculated viscosities for this system.

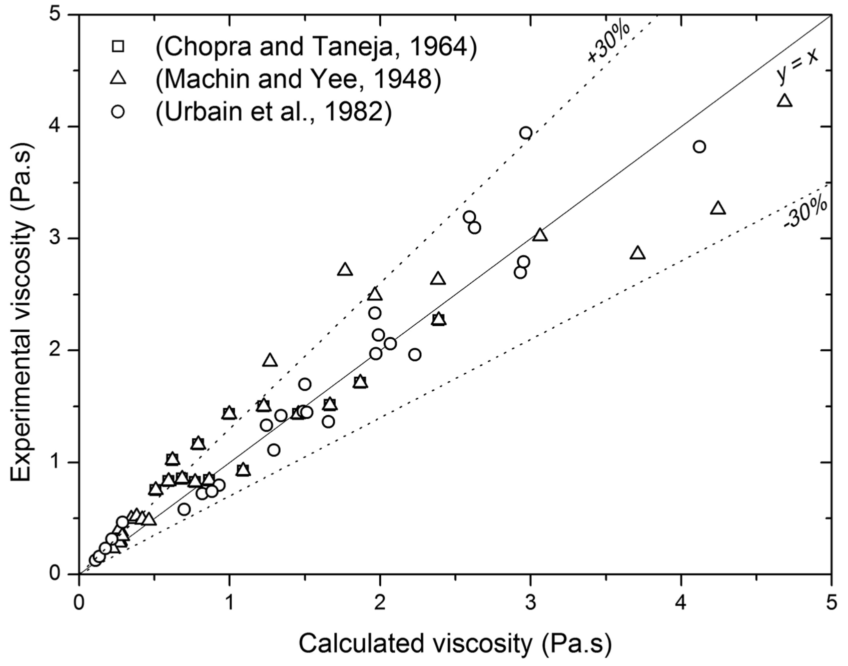

Figure 5
Calculated and measured viscosity comparison for the CaO-SiO_2-Al_2O_3 system.

It is possible to observe that data from literature (Chopra and Taneja, 1964; Urbain *et al.*, 1982) are near the $y = x$ line, especially for values below 2.5 Pa·s, as shown in Figure 5. The values shown in Figure 5 indicate a very well fitted relationship of the reference (Chopra and Taneja, 1964; Urbain *et al.*, 1982) data with the calculated viscosity values through *FactSage*. However, for Machin and Yee (1948), the viscosities seem to be similar only for values below 0.5 Pa·s.

3.6 Viscosity of the CaO-SiO$_2$-FeO system

According to Davenport *et al.* (2002), the system of SiO$_2$-FeO is presented in copper smelting slags as a main component. On the other hand, in secondary steelmaking processes, with CaO-based slags, there is employment of SiO$_2$ and even Fe$_n$O in the slag composition (Ji *et al.*, 1997). In view of the metallurgical applications, the viscosity study of CaO-SiO$_2$-FeO is very important. The comparison between experimental and calculated viscosities for the CaO-SiO$_2$-FeO system is shown in Figure 6.

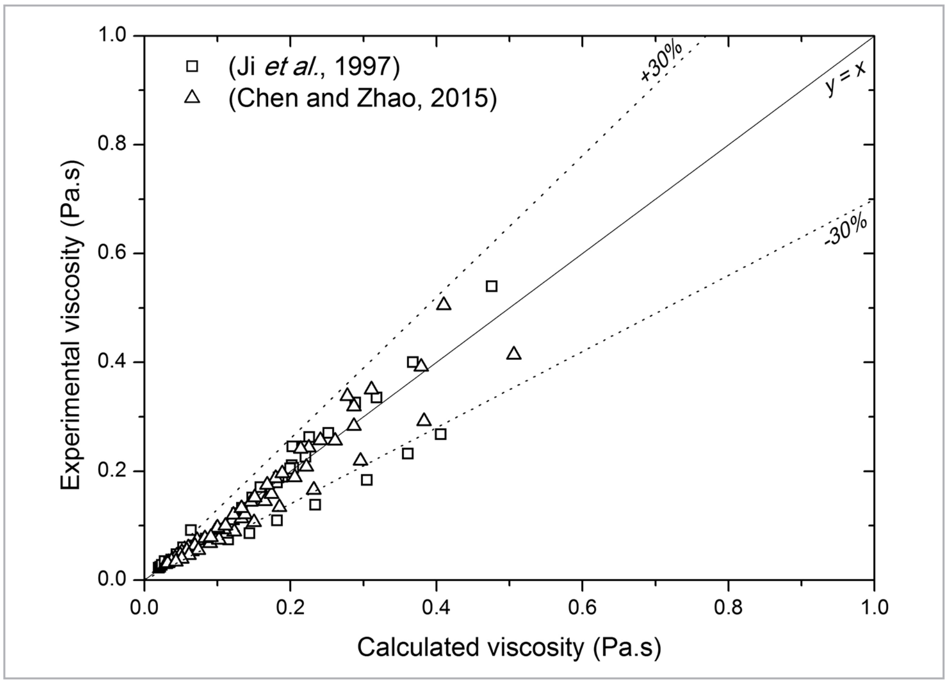

Figure 6
Calculated and measured viscosity comparison for the CaO-SiO$_2$-FeO system.

Figure 6 announces a good agreement between experimental and calculated viscosity values. The viscosity data from Chen and Zhao (2015) seem to show a better fit than the Ji *et al.* (1997) data along the viscosity range (0~0.6 Pa·s) in Figure 6. A few values of the measured viscosities presented by these studies (Chen and Zhao, 2015; Ji *et al.*,1997) presented distinct behavior with calculated viscosities higher than the measured values through the experimental method when viscosity increased (lower temperatures).

3.7 Accuracy of calculated viscosities

Accuracy of the calculated viscosities was evaluated by using Equation 1, which describes the relative deviation average for each system. The results are shown in Figure 7.

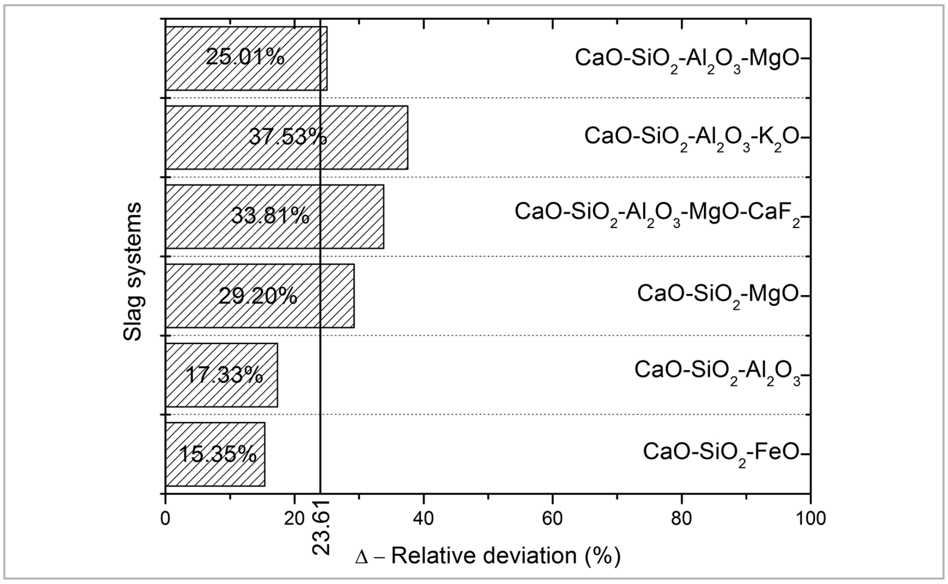

Figure 7
Relative deviation average for each system.

It can be seen from Figure 7 that the $CaO-SiO_2-Al_2O_3$ and $CaO-SiO_2-FeO$ systems showed better agreement between measured and calculated viscosities. On the other hand, other systems presented higher relative deviation average, from 25.01 to 37.53%. According to a study reported by Chen and Zhao (2016) the relative deviation of FactSage predictions is around 30%. The authors (Chen and Zhao, 2016) also evaluated the accuracy in viscosity calculation compared to the measured values with different models besides *FactSage* software, but only for the $CaO-SiO_2-K_2O$. A lower agreement in the high order systems may be attributed to the possible experimental data errors from literature (Suzuki and Jak, 2014) or still result from complicated interactions between the cations and anions that make the predictions and modeling of slag viscosity quite difficult (Rosypalová *et al.*, 2014). Thus, both methods of obtaining slag viscosity can carry some degree of uncertainty in the results.

Table 4 shows the relative deviation considering each reference where the measured viscosity data was taken, in order to compare with the calculated values through *FactSage*.

References	Relative deviation (%)
Pengchen and Xiaojun, 2016	34.65
Shankar *et al.*, 2007	30.37
Tang *et al.*, 2011	15.87
Machin et al.,1952	19.17
Zhang and Chou, 2012	37.53
Wu *et al.*, 2011	33.81
Ji *et al.*, 1997	13.31
Chen and Zhao, 2015	17.39
Schumacher *et al.*, 2015	29.20
Chopra and Taneja, 1964	18.18
Machin and Yee, 1948	19.15
Urbain *et al.*, 1982	14.67
Average	**23.61**

Table 4
Relative deviation between measured and calculated viscosities for each reference.

The relative deviation between the measured and calculated viscosities is in the range 13.31 to 37.53%. The lower relative deviation corresponds to Ji *et al.* (1997) in the $CaO-SiO_2-FeO$ system study. The higher was obtained from Zhang and Chou (2012) for the $CaO-SiO_2-K_2O$ system. Considering all references and systems, the average deviation between measured and calculated viscosities is 23.61%. Even with the higher relative deviation (37.53%) observed, the calculated viscosities are within the range of uncertainties reported by Mills (1995). According to author (Mills, 1995), the viscosity measurements were subject to experimental uncertainties from the possible arise of problems, such as temperature difference from thermocouple measurement, actual temperature of the melt, and also possible fluorine losses (for CaF_2 based slags), which may occur if held in the system for a long time at temperatures > 800 °C. In view of this, the viscosity measurements differ from recommended values by an average of ± 30%, and in some cases more than 50%. In this context, it can be said that the obtained results in terms of relative deviation have shown reasonable values, with almost all calculated data within the experimental uncertainty ranges.

Slag viscosity modeling is a challenging activity. As commented before, this physical property of viscosity may exhibit great variability depending on temperature and chemical composition. The experimental methodology and its results are fundamental and can be used as key indicators for the optimization of models for the prediction of slag viscosities. In general, for all the systems described in this study, it was verified that for the lower viscosity values, the coherence between the measured and calculated viscosities were higher. However, it is extremely important to search for a further understanding regarding the discrepancy between the data, which is verified when the viscosity becomes higher. In this context, an important first step was taken in this study, where information about the agreement of the viscosity values is presented. Another step is needed to accurately assess the major factors apart from the experimental errors, which may affect the discrepancies observed for higher viscosity indices.

4. Conclusions

Within the realm of experimental uncertainties, the *FactSage* viscosity model has accurately reproduced the viscosity calculation for a wide range of composition and temperatures including different calcium-silicate based slags. The relative deviations between measured and calculated viscosities were consistent with the literature. For the systems $CaO-SiO_2-Al_2O_3-MgO$, $CaO-SiO_2-Al_2O_3-K_2O$, $CaO-SiO_2-Al_2O_3-MgO-CaF_2$, $CaO-SiO_2-MgO$, $CaO-SiO_2-Al_2O_3$ and $CaO-SiO_2-FeO$ the average relative deviations between measured and the calculated viscosity values were 25.01, 37.53, 33.81, 29.20, 17.33 and 15.35%, respectively.

For the $CaO-SiO-Al_2O_3-MgO$ and $CaO-SiO_2-Al_2O3-K_2O$ systems, as viscosity increases the deviation between measured and calculated viscosities becomes higher, when a non-linearity ratio between the values is observed. However, for lower viscosity values (< 0.50 Pa·s for the CSAM system and 10 dPa·s for the CSAK system), there is a good agreement between measured and calculated viscosities. The system with CaF_2 shows a good fitting of the values up to 0.075 Pa·s, however around 0.10 Pa·s a dispersion occurs and the measured viscosities are fourfold higher than the calculated values. In the CaO-SiO_2-MgO system, the measured and calculated viscosities tend to become equal (approaching the $y = x$ line) for viscosity values lower than 0.10 Pa·s.

The two systems, CaO-SiO_2-Al_2O_3 and CaO-SiO_2-FeO, showed the best agreement between the experimental method and the method calculated through *FactSage* 6.4 with a very good fit between the viscosity values.

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References

BALE, C. W. et al. FactSage thermochemical software and databases. ***Calphad,*** New York, v. 54, p. 35-53, 2016.

CHEN, M. et al. Viscosities of Iron Blast Furnace Slags. ***ISIJ International,*** Tokyo, v. 54, p. 2025-2030, 2014.

CHEN, M., ZHAO, B. Viscosity measurements of SiO_2-“FeO”-CaO system in equilibrium with metallic Fe. ***Metallurgical and Materials Transactions B,*** Warrendale, v. 46, n. 1, p. 577-584, 2015

CHEN, M., ZHAO, B. Viscosity measurements of the SiO_2–K_2O–CaO system relevant to biomass slags. ***Fuel,*** London, v.180, p. 638-644, 2016.

CHOPRA, S. K., TANEJA, C. A. Utilization of the Indian Blast Furnace Slags. In: SYMPOSIUM ON UTILIZATION OF METALLURGICAL WASTES, 1964, Jamshedpur. ***Proceedings of Utilization of Metallurgical Wastes.*** Jamshedpur: National Metallurgical Laboratory, 1964. p. 224-225.

COSTA E SILVA, A. Estimating Viscosities in iron and steelmaking slags in the CaO--Al_2O_3-MgO-SiO_2-(TiO_2) system with basis on a thermodynamic model. ***Journal of Materials Research and Technology,*** Rio de Janeiro, v. 1, n. 3, p. 154-160, 2012.

DAVENPORT, W. G. et al. ***Extractive Metallurgy of Copper*** (4th ed.). Oxford: Pergamon Press, 2002. 432p.

CENTER FOR RESEARCH IN COMPUTATIONAL THERMOCHEMISTRY (CRCT). FactSage modules: viscosity. Canada: 2010. Disponível em: <http://www.crct.polymtl.ca/factsage/fs_viscosity.php>. Acesso em: 07 Jul. 2016.

JI, F. Z. et al. Experimental studies of the viscosities in the CaO-FenO-SiO_2 slags. ***Metallurgical and Materials Transactions B,*** Warrendale, v. 28, n. 5, p. 827-834, 1997.

JUNG, I. H. et al. Viscosity of slags. In: SEETHARAMAN, S., MCLEAN, A., GUTHRIE, R., SRIDHAR, S. (Orgs.). ***Treatise on process metallurgy.*** United Kingdom: Elsevier, 2014. v.2, p. 653-674. (Process Phenomena).

JUNG, I. H. Overview of the applications of thermodynamic databases to steelmaking processes. Calphad, New York, v. 34, n. 3, p. 332-362, 2010.

LIS, T. et al. The impact of the chemical composition of continuous casting moulds on their physical properties. ***Journal of Achievements in Materials and Manufacturing Engineering,*** Gliwice, v. 55, n. 2, p. 345-348, 2012.

MACHIN, J. S. et al. Viscosity studies of system CaO-MgO-Al_2O_3-SiO_2: III, 35, 45 and 50% SiO_2. ***Journal of the American Ceramic Society,*** Malden, v. 35, p. 322-25, 1952.

MACHIN, J. S., YEE, T. B. Viscosity studies of system CaO-MgO-Al_2O_3-SiO_2: II, CaO-Al_2O_3-SiO_2. ***Journal of the American Ceramic Society,*** Malden, v. 31, p. 200-204, 1948.

MILLS, K. C. et al. ‘Round Robin’ project on the estimation of slag viscosities. ***Scandinavian Journal of Metallurgy,*** Copenhagen, v. 30, n. 6, p. 396-404, 2001.

MILLS, K. C. ***Viscosities of molten slags – slag atlas*** (2nd ed.) Düsseldorf: Verlag Stahleisen GmbH, 1995. 349p.

MULLER, J., ERWEE, M. Blast furnace control using slag viscosities and liquidus temperatures with phase equilibria calculations. In: SOUTHERN AFRICAN PYROMETALLURGY CONFERENCE. 2011. Johannesburg. ***Proceedings of Southern African Pyrometallurgy.*** Johannesburg: Southern African Institute of Mining and Metallurgy, 2011. p. 309-326.

PARK, J. H. et al. The effect of CaF_2 on the viscosities and structures of

$CaO-SiO_2(-MgO)-CaF_2$ slags. ***Metallurgical and Materials Transactions B,*** Warrendale, v. 33, n. 5, p. 723-729, 2002.

PELTON, Arthur D., BLANDER, Milton. Thermodynamic analysis of ordered liquid solutions by a modified quasichemical approach – application to silicate slags. ***Metallurgical and Materials Transactions B,*** Warrendale, v. 17, n. 4, p. 805-815, 1986.

PENGCHENG, L., XIAOJUN, N. Effects of MgO/Al_2O_3 ratio and basicity on the viscosities of $CaO-MgO-SiO_2-Al_2O_3$ slags: experiments and modeling. ***Metallurgical and Materials Transactions B,*** Warrendale, v. 47, n. 1, p. 446-457, 2016.

ROSYPALOVÁ, L. et al. Verification of mathematical models for calculation of viscosity of molten oxide systems. ***Metalurgija,*** Sofia, v. 53, n. 3, p. 379-382, 2014.

SANTHY, K. et al. Effect of oxygen to silicon ration on the viscosity of metallurgical slags. ***ISIJ International,*** Tokyo, v. 45, n. 7, p. 1014-1018, 2005.

SCHUMACHER, K. J. et al. Viscosities in the calcium-silicate slag system in the range of 1798 K to 1973 K (1525 °C to 1700 °C). ***Metallurgical and Materials Transactions B,*** Warrendale, v. 46, n. 1, p. 119-124, 2015.

SHANKAR, A. et al. Experimental investigation of the viscosities in $CaO-SiO_2$--$MgO-Al_2O_3$ and $CaO-SiO_2-MgO-Al_2O_3-TiO_2$ slags. ***Metallurgical and Materials Transactions B,*** Warrendale, v. 38, n. 6, p. 911-915, 2007.

SONG, M. et al. Viscosities of the quaternary $Al_2O_3-CaO-MgO-SiO_2$ Slags. ***Steel Research International,*** Düsseldorf, v. 82, n. 3, p. 260-268, 2011.

SUZUKI, M., JAK, E. Development of a quasi-chemical viscosity model for fully liquid slags in the Al_2O_3–CaO–'FeO'–MgO–SiO_2 system: the revised model to incorporate ferric oxide. ***ISIJ International,*** Tokyo, v. 54, n. 10, p. 2134-2143, 2014.

TANG, X. et al. Viscosities Behavior of $CaO-SiO_2-MgO-A1_2O_3$ Slag With Low Mass Ratio of CaO to SiO_2, and Wide Range of $A1_2O_3$ Content. ***Journal of Iron and Steel Research International,*** Beijing, v. 18, n. 2, p. 1-6, 2011.

URBAIN, G. et al. Viscosity of liquid silica, silicates and alumino-silicates. ***Geochimica et Cosmochimica Acta,*** Oxford, v. 46, n. 6, p. 1061-1072, 1982.

VARGAS, S. et al. Rheological properties of high-temperature melts of coal ashes and other silicates. ***Progress in Energy Combustion Science,*** Oxford, v. 27, n. 3, p. 237–429, 2001.

WU, L. et al. The effect of calcium fluoride on slag viscosity. ***Metallurgical and Materials Transactions B,*** Warrendale, v. 42, p. 928-931, 2011.

XU, J. et al. Experimental investigation on viscosity of $CaO-MgO-(-Al_2O_3)-SiO_2$ slags and solid-liquid mixtures. ***Journal of Iron and Steel Research International,*** Beijing, v. 22, n. 12, p. 1091-1097, 2016.

ZHANG, G., CHOU, K. Measuring and Modeling Viscosity of $CaO-Al_2O_3$--$SiO_2(-K_2O)$ Melt. ***Metallurgical and Materials Transactions B,*** Warrendale, v. 43, n. 4, p. 841-48, 2012.

ZHANG, G., et al. Modelling viscosities of $CaO-MgO-FeO-MnO-SiO_2$ molten slags. ***Metallurgical and Materials Transactions B,*** Warrendale, v. 43, n. 1, p. 64-72, 2012.

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