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

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-SiO$_2$-Al$_2$O$_3$ and CaO-SiO$_2$-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 et 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$_2$O$_3$-MgO (CSAM), CaO-SiO$_2$-Al$_2$O$_3$-K$_2$O (CSAK), CaO-SiO$_2$-Al$_2$O$_3$-MgO-CaF$_2$ (CSAMF), CaO-SiO$_2$-MgO-CaO (CSM), CaO-SiO$_2$-Al$_2$O$_3$ (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.

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

References

- Machin and Yee, 1948
- Urbain et al., 1982
- Chen and Zhao, 2015
- Jin et al., 2010
- Wu et al., 2011
- Ji et al., 1997
- Shankar et al., 2007
- Tang et al., 2011
- Pengchen and Xiaojun, 2016
- Machin et al., 1952
- Zhang and Chou, 2012
- Bale et al., 2016
- Pelton and Blander, 1986
- Suzuki and Jak, 2013
- Zhang and Chou, 2012
- Pelton and Blander, 1986
- FactSage Modules, 2016
- Xu et al., 2014
- Pelton and Blander, 1986
- FactSage Modules, 2016
- Xu et al., 2014
- Pelton and Blander, 1986
- FactSage Modules, 2016
- Xu et al., 2014
- Pelton and Blander, 1986
- FactSage Modules, 2016
- Xu et al., 2014
- Pelton and Blander, 1986
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 °C) to 1813 K (1540 °C) and in the Wu et al. (2011) study, the temperature range was 1697 K (1424 °C) to 1905 K (1632 °C). 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 °C) to 1973 K (1700 °C).

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).

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 $\text{Al}_2\text{O}_3$-$\text{B}_2\text{O}_3$-$\text{CaO}$-$\text{MgO}$-$\text{FeO}$-$\text{Fe}_2\text{O}_3$-$\text{MnO}$-$\text{NiO}$-$\text{PbO}$-$\text{ZnO}$-$\text{Na}_2\text{O}$-$\text{K}_2\text{O}$-$\text{TiO}_2$-$\text{SiO}_2$-$\text{F}$ (Jung et al., 2014). The viscosity database from FactSage applied in this study was Melts, valid for liquid and supercooled slags with moderate viscosity values (when $\ln$ (viscosity, Pa·s) < 15) (FactSage Modules, 2010). Table 2 shows the chemical composition range for each system adopted in the viscosity calculations considering all references listed in Table 2.

### Table 2

<table>
<thead>
<tr>
<th>Systems</th>
<th>Chemical composition range (% wt.)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO-SiO$_2$-Al$_2$O$_3$-MgO (70 slags)</td>
<td>(Pengchen and Xiaojun, 2016)</td>
<td>Shankar et al., 2007</td>
</tr>
<tr>
<td>CaO-SiO$_2$-Al$_2$O$_3$-K$_2$O (13 slags)</td>
<td>(Zhang and Chou, 2012)</td>
<td></td>
</tr>
<tr>
<td>CaO-SiO$_2$-Al$_2$O$_3$-MgO-CaF$_2$ (9 slags)</td>
<td>(Wu et al., 2011)</td>
<td></td>
</tr>
<tr>
<td>CaO-SiO$_2$-FeO (18 slags)</td>
<td>(Ji et al., 1997)</td>
<td>(Chen and Zhao, 2015)</td>
</tr>
<tr>
<td>CaO-SiO$_2$-MgO (4 slags)</td>
<td>(Schumacher et al., 2015)</td>
<td></td>
</tr>
<tr>
<td>CaO-SiO$_2$-Al$_2$O$_3$ (48 slags)</td>
<td>(Chopra and Taneja, 1964)</td>
<td>(Machin and Yee, 1948)</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Systems</th>
<th>Chemical composition range (% wt.)</th>
<th>Temp. range [K (°C)]</th>
<th>Exp. viscosity range (Pa·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>5 – 55</td>
<td>1723 (1450) – 1823 (1550)</td>
<td>0.17 – 3.87</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>30 – 65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>0 – 40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>0 – 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaF$_2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K$_2$O</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSAM</td>
<td>35.1 – 39</td>
<td>1713 (1440) – 1813 (1540)</td>
<td>1.09 – 4.53</td>
</tr>
<tr>
<td>CSAMF</td>
<td>43 – 60</td>
<td>1697 (1424) – 1905 (1632)</td>
<td>0.04 – 1.66</td>
</tr>
<tr>
<td>CSFeO</td>
<td>5.5 – 45.6</td>
<td>1423 (1150) – 1773 (1500)</td>
<td>0.02 – 0.54</td>
</tr>
<tr>
<td>CMS</td>
<td>51 – 55</td>
<td>1723 (1500) – 1973 (1700)</td>
<td>0.11 – 0.33</td>
</tr>
<tr>
<td>CSA</td>
<td>14 – 55</td>
<td>1611 (1338) – 2089 (1816)</td>
<td>0.12 – 5.39</td>
</tr>
<tr>
<td></td>
<td>15.1 – 65</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 – 40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 ($\eta$) 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).

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

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.
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$_2$O$_3$-MgO-CaF$_2$ system

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.

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.

![Graph showing viscosity comparison](graph1.png)

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$_2$O$_3$ 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.

![Graph showing viscosity comparison](graph2.png)

Figure 5
Calculated and measured viscosity comparison for the CaO-SiO$_2$-Al$_2$O$_3$ 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 FeO 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](image)

**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](image)

**Figure 7**
Relative deviation average for each system.
It can be seen from Figure 7 that the CaO-SiO$_2$-Al$_2$O$_3$ 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$_2$O. 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.

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$_2$O 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 ºC. 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$_2$O$_3$-MgO, CaO-SiO$_2$-Al$_2$O$_3$-K$_2$O, CaO-SiO$_2$-Al$_2$O$_3$-MgO-CaF$_2$, CaO-SiO$_2$-MgO, CaO-SiO$_2$-Al$_2$O$_3$ 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$_2$-Al$_2$O$_3$-MgO and CaO-SiO$_2$-Al$_2$O$_3$-K$_2$O 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$_2$O$_3$ 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.

**Acknowledgment**

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