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# Modeling Viscosity of Converter Slag

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## Abstract

The paper is devoted to one of the most important factors influencing steel melting and operation of an oxygen converter, i.e. dynamic viscosity of slag. Knowing typical chemical composition of slag after melting, the viscosity was calculated with the use of Riboud and Urbain empirical models at temperatures 1400 °C to 1700 °C. The obtained mathematical results were compared with the results of simulations obtained with the FactSage program. The discrepancies between these results were caused by model assumptions and the fact that slag in lower temperatures consisted of liquid and solid phases.

**Key words:** viscosity, slag, modeling, FactSage

## 1. Introduction

One of the major problems of the steel converter process is wearing of the refractory lining during melting. Methods aimed at increasing resistance of the lining focus on its regeneration with the use of slag obtained from the melting processes [1-2]. As indicated in literature [3-9] the viscosity of slag is a key parameter which should be taken into consideration when using methods of refractory lining regeneration with the slag splashing technology. The viscosity of slag is a complex function which depends on the composition of slag, temperature and partial pressure of oxygen in the system. Slags are usually composed of 4 to 5 main components having different influence on viscosity, therefore determining this value in a multicomponent system, i.e. slag from industrial processing, is a difficult task.

The difficulty and high price of measurement of viscosity of slag, whose chemical composition varies due to the conditions of technological processes, leads to the development of methods which allow for determining this parameter without necessary experiments. A number of empirical and semi empirical models were created for defining viscosity of slag of a specific chemical composition. They are applicable mainly for liquid solutions of two or more components.

Mathematical models used in this paper can be used for predicting how slag viscosity changes in definite temperature conditions. Most of models for determining viscosity are designed for a limited slag composition and limited applicability temperature. Authors used Riboud and Urbain models and commercial software FactSage. The influence of FeO content on slag viscosity at temperatures corresponding to the real temperatures in an oxygen converter was analyzed in the paper.

## 2. Methodics

*a) Riboud model* [3]

Accordingly, the following cumulative molar fractions are defined:

$$X'SiO_2 = X_{SiO_2} + X_{P_2O_5} + X_{TiO_2} + X_{ZrO_2} \quad (1)$$

$$X'Al_2O_3 = X_{Al_2O_3} + \left\{ X_{P_2O_5} \right\} \quad (2)$$

$$X'CaO = X_{CaO} + X_{MgO} + X_{FeO} + X_{Fe_2O_2} + \{X_{MgO} + X_{NiO} + X_{CrO} + \\ + X_{ZnO} + X_{Cr_2O_3}\} \quad (3)$$

$$X'Na_2O = X_{Na_2O} + X_{K_2O} + \{X_{Li_2O}\} \quad (4)$$

Additionally, the molar fraction of $CaF_2$ - $X_{CaF2}$ must be taken into account. Thus, the following condition is fulfilled:

$$X'_{SiO_2} + X'_{Al_2O_3} + X'_{CaO} + X'_{Na_2O} + X'_{CaF_2} = 1 \quad (5)$$

Viscosity is expressed as the function of temperature [6]:

$$\eta = A \cdot T \cdot e^{B/T} \quad (6)$$

where A and B parameters are the functions of liquid slag composition expressed in cumulative molar fractions:

$$A = \exp(-19,81 + 1,73X'_{CaO} + 5,82X'_{CaF_2} + 7,02X'_{Na_2O} - \\ -35,76X'_{Al_2O_3}) \quad (7)$$

$$B = 31140 - 23896X'_{CaO} - 46356X'_{CaF_2} - 39159X'_{Na_2O} + \\ +68833X'_{Al_2O_3} \quad (8)$$

*b) Urbain model*

This model classified the various slag into the three categories:

– glass formers:

$$X_G = X_{SiO_2} \quad (9)$$

– network modifiers:

$$X_M = X_{CaO} + X_{MgO} + X_{CaF_2} + X_{FeO} + X_{MnO} + X_{CrO} + X_{NiO} + \\ + X_{K_2O} + 2X_{TiO2} + X_{ZrO_2} \quad (10)$$

– amphoterics compounds:

$$X_M = X_{Al_2O_3} + X_{B_2O_3} + X_{Fe_2O_3} + X_{Cr_2O_3} \quad (11)$$

Urbain model makes use of the Weymann equation:

$$\eta = A \cdot T \cdot e^{1000B/T} \quad (12)$$

where:

$$\ln A = -(0,29B + 11,57) \quad (13)$$

B is calculated from equations:

$$a = \frac{x_M}{x_M + x_A} \quad (14)$$

$$B_i = a_i + b_i + c_i a^2 \quad (15)$$

where a, b, c are constant

$$B = B_0 + B_1 X_{SiO_2} + B_2 X^2_{SiO_2} + B_3 X^3_{SiO_2} \quad (16)$$

$B_0$, $B_1$, $B_2$, $B_3$ can be calculated from equations 17-20. These parameters are introduced into 16.

$$B_0 = 13,8 + 39,9355\alpha - 44,049\alpha^2 \quad (17)$$

$$B_1 = 30,481 - 117,1505\alpha + 139,9978\alpha^2 \quad (18)$$

$$B_2 = -40,9429 + 234,0486\alpha - 300,04\alpha^2 \quad (19)$$

$$B_3 = 60,7619 - 153,9276\alpha + 211,1616\alpha^2 \quad (20)$$

*c) Kondratiev model*

Kondratiev and Jak modified the Urbain viscosity model for calculated viscosities of multi-component slags. The equation for the viscosity of the solution oxide (Pa·s) takes the following form in this model [6]:

$$\eta = A \cdot T \cdot \exp\left(\frac{B \cdot 10^3}{T}\right) \quad (21)$$

where A and B are related to the relationship:

$$-\ln A = m \cdot B + n \quad (22)$$

B is a function of the composition of the slag, expressed in mole fraction, m and n are empirical parameters.

$$B = \sum_{i=0}^{3} b_i^0 \cdot \left(X_{SiO_2}\right)^i + \sum_{i=0}^{3}\sum_{j=1}^{2} b_i^{'j} \cdot \frac{x_{CaO}}{x_{CaO} + x_{FeO}} + b_i^{''j} \cdot \frac{x_{CaO}}{x_{CaO} + x_{FeO}} \cdot \\ \cdot a^j \cdot \left(X_{SiO_2}\right)^j \quad (23)$$

A is a function of the chemical composition of the slag

$$a = \frac{x_{CaO} + x_{FeO}}{x_{CaO} + x_{FeO} + x_{Al_2O_3}} \quad (24)$$

Parameter m is expressed as:

$$m = m_{SiO_2} \cdot X_{SiO_2} + m_{CaO} \cdot X_{SiO} + m_{Al_2O_3} \cdot X_{Al_2O_3} + \\ + m_{FeO} \cdot X_{FeO} \tag{25}$$

The parameters m and n are as follows:

$$m_{SiO_2} = 0{,}12;\ m_{CaO} = 0{,}587;\ m_{Al_2O_3} = 0{,}370;\ m_{FeO} = 0{,}665;$$

*d) Iida model*

The structure of molten slags has a high influence on viscosity therefore should be considered in modeling. Iida viscosity model tries to establish a relation between the structure and basicity of slag. There are three groups of slags which can be found in slags [10].

a) Acid oxide ($SiO_2$, $B_2O_3$, $P_2O_5$)
b) Basic oxide ($CaO$, $MgO$, $K_2O$, $CaF_2$, …)
c) Amphoteric ($Al_2O_3$, $Fe_2O_3$, $TiO_2$)

The Arrhenius Equation is the base of this model which divides oxides into two group (a) and (b), but it has been modified by considering group (c) as the third group [11].
The viscosity of slags can be estimated by Eq. (26-28):

$$\mu = A\mu_0 \exp\left(\frac{E}{B_{i^*}}\right) \tag{26}$$

$$A = 1{,}745 - 1{,}962 \times 10^{-3} T + 7 \times 10^{-7} T^2 \tag{27}$$

$$E = 11{,}11 - 3{,}65 \times 10^{-3} T \tag{28}$$

where A and E are parameters that have best fit to the experiment, T = absolute temperature, μ = viscosity, Bi*= basicity index.

$$\mu_0 = \sum_{i=1}^{n} \mu_{0i} X_i \tag{29}$$

The value of $\mu_{0i}$ can be calculated from Equation (30):

$$\mu_{0i} = 1{,}8 \times 10^{-7} \frac{\left[M_i (T_m)_i\right]^{0,5} \exp\left(\frac{H_i}{RT}\right)}{(V_m)_i^{2/3} \exp\left[\frac{H_i}{R(T_m)_i}\right]} \tag{30}$$

$$H_i = 5{,}1 (T_m)_i^{0.5} \tag{31}$$

where $T_i$ – mole fraction, $T_m$ – melting temperature, $\mu_0$ – hypothetical viscosity of pure oxide, R – universal gas constant, $V_m$ – molar volume at melting point, M -– the formula weight, i – component, Bi* – modified basicity which can be calculated from Equation (32):

$$B_i^* = \frac{\sum(\alpha_i W_i)_B + \alpha^*_{Fe_2O_3} W_{Fe_2O_3}}{\sum(\alpha_i W_i)_A + \alpha^*_{Al_2O_3} W_{Al_2O_3} + \alpha^*_{TiO_2} W_{TiO_2}} \tag{32}$$

where α – specific coefficient, A – acidic oxide, B – basic or fluoride oxide, $W_i$ – mass percentage. $\alpha_1$ and $\mu_{0i}$ – parameters in table.

Interaction between amphoteric oxide and other component is indicated by $\alpha_i$* (modified specific coefficient) that itself is dependent on $B_i$* and $W_i$.

The value for $\alpha^*_{Al_2O_3}$ can be calculated from Equation (33) which gives the best fit to experimental results.

$$\alpha^*_{Al_2O_3} = aB_i + bW_{Al_2O_3} + c \tag{33}$$

$$a = 1{,}26 \times 10^{-5} T^2 - 4{,}3552 \times 10^{-2} T + 41{,}16 \tag{34}$$

$$b = 1{,}4 \times 10^{-7} T^2 - 3{,}4449 \times 10^{-4} T + 0{,}2062 \tag{35}$$

$$c = -8 \times 10^{-6} T^2 + 2{,}5568 \times 10^{-2} T - 22{,}16 \tag{36}$$

If we consider $\alpha_i^* = \alpha_i$ which means that $\alpha_i^*$ is independent of composition then the modify basicity index (Bi*) will be the same as the basicity index (Bi) [10].

*e) Model FactSage*

The program allows for determining the slag viscosity with the viscosity module on the basis of thermodynamic Ftoxid base, being part of the FactSage package.

# 3. Description of obtained results

The data from table 1 were used for calculating converter slag viscosity with the Riboud model, Urbain model and FactSage software.

Table 1. Chemical composition of converter slag

| *CaO* | *FeO* | *MgO* | *$SiO_2$* | *MnO* | *$Al_2O_3$* |
|---|---|---|---|---|---|
| 44.6% | 26.8% | 9.3% | 11.5% | 4.2% | 2.0% |

The discrepancies between results were considerable, figs. 1 to 3.

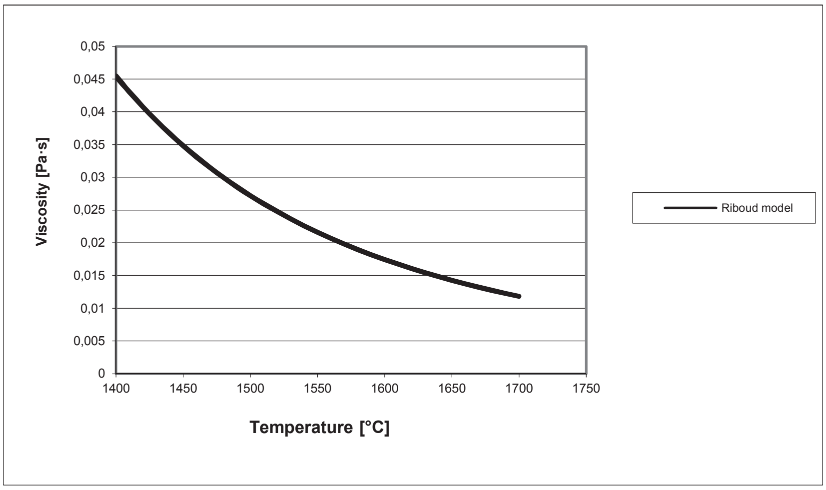


Fig. 1. Influence of temperature on slag viscosity calculated with Riboud model

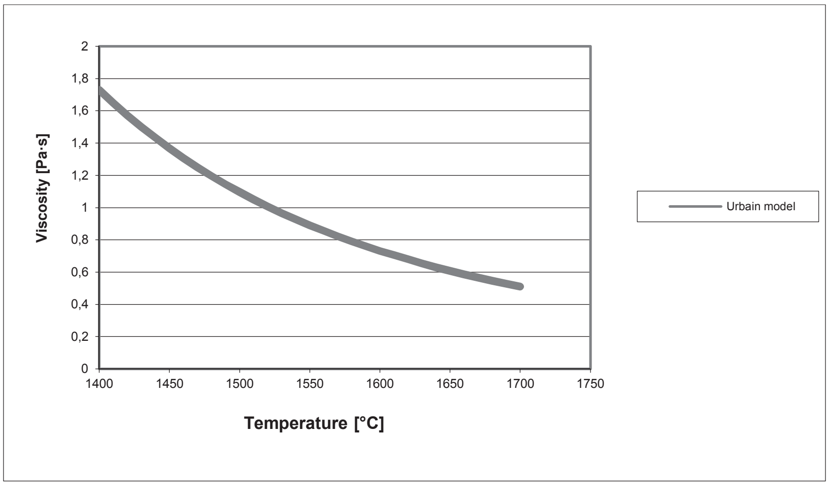


Fig. 2. Influence of temperature on slag viscosity calculated with Urbain model

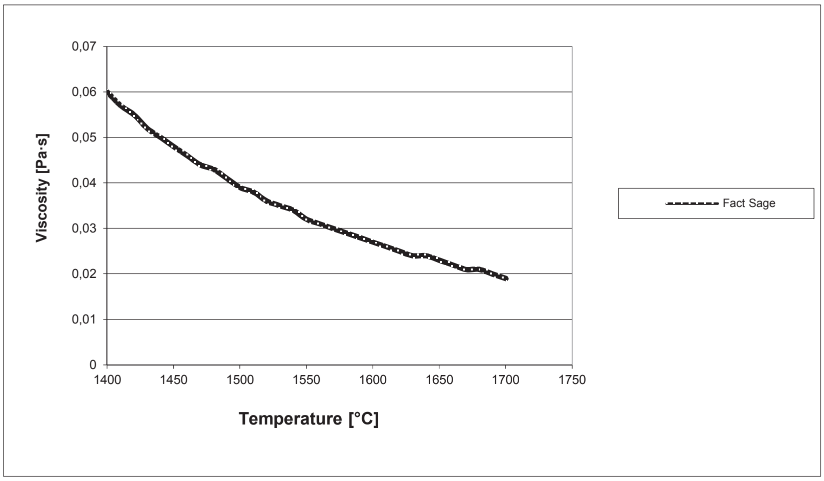


Fig. 3. Influence of temperature on slag viscosity calculated with FactSage program

Parameters A and B in the Riboud and Urbain models are functions of liquid slag expressed in mole fractions. The analysis of fig. 1 reveals that viscosity at temperature 1400 °C equals to 0.045 *Pa·s*, whereas overheating to 1700 °C brings about viscosity of 0.011 [*Pa·s*]. The results obtained from calculations with the Urbain model are one order higher than the previous ones; at a temperature of 1400 °C the viscosity equals to 1.73 [*Pa·s*], and at 1700 °C it is 0.5 *Pa·s*. The results obtained from FactSage program (fig. 3) reveal that at the same temperatures viscosity changes from 0.06 *Pa·s* to 0.019 *Pa·s* and is comparable with the results from the Riboud model.

Then the influence of FeO on slag viscosity was analyzed. FeO content was changed from 10% to 30%. The calculations for slags having composition as in table 2 were performed with the use of Riboud and Urbain models.

Table 2. Chemical composition of slags

| № | *CaO* | *FeO* | *MgO* | $SiO_2$ | *MnO* | $Al_2O_3$ |
|---|---|---|---|---|---|---|
| 1 | 44.6% | 10% | 9.3% | 28.3% | 4.2% | 2.0% |
| 2 | 44.6% | 20% | 9.3% | 18.3% | 4.2% | 2.0% |
| 3 | 44.6% | 30% | 9.3% | 8.3% | 4.2% | 2.0% |

The results were illustrated in figures 4 to 5. The calculations after Riboud model (fig. 4) show that for slag made of FeO = 10% (1400 °C) the slag viscosity equals to 0.604 *Pa·s*. For FeO = 20% and the same temperature the viscosity was 0.13 *Pa·s*, and for FeO = 30% it was 0.028 *Pa·s*. At lower temperatures (1400 – 1500 $^0$C) and higher FeO content in slag will result in its higher liquidity.

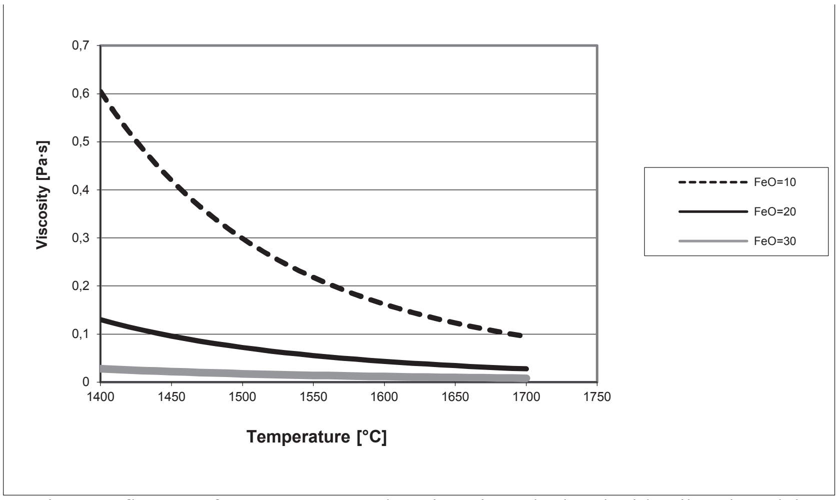


Fig. 4. Influence of temperature on slag viscosity calculated with Riboud model, for various chemical composition of FeO

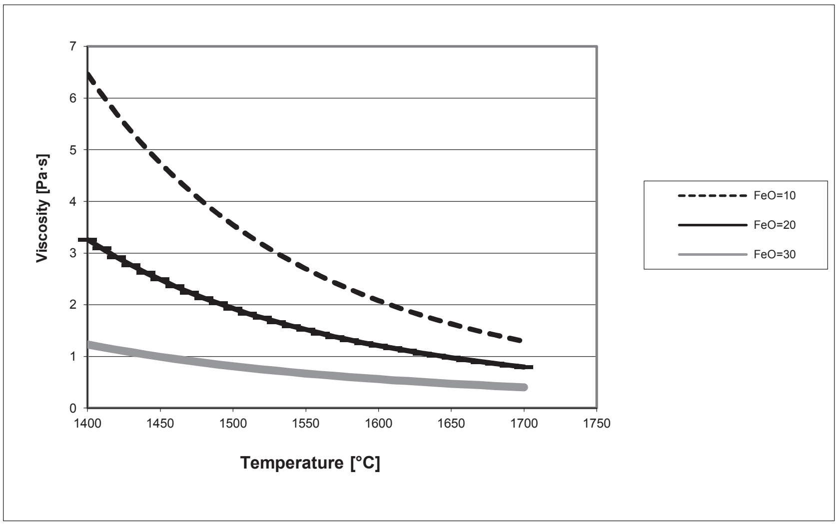


Fig. 5. Influence of temperature on slag viscosity calculated with Urbain model, for various chemical composition of FeO

Figure 5 illustrates the results of calculations with Urbain model. For a 10% FeO content and temperature of 1400 °C the calculated viscosity equaled to 6.462 *Pa·s*. For FeO = 20% and he same temperature the slag viscosity was 3.62 *Pa·s* and for FeO = 30% it equaled to 1.231 *Pa·s*. The results of calculations performed with Urbain model are one order higher as compared to the results obtained with the Riboud model.

## 4. Conclusions

The applied empirical models can be used for calculating slag viscosity in a function of temperature and chemical composition. The influence of FeO content in converter slag on its viscosity has been discussed in this paper. The calculations performed after Riboud model, Urbain model and FactSage software showed considerable discrepancies between the obtained results, especially at lower temperatures. This was mainly caused by the assumptions of empirical models which were made for calculations of slag viscosity in liquid phase, although the liquid and solid phases may co-exist in slag at a temperature of 1400 $^0$C. All the results prove that with an increase of temperature T (*°C*) the viscosity η (*Pa·s*) lowers. A similar effect on viscosity has a higher FeO content in slag.

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# Modelowanie lepkości żużla konwertorowego

## Streszczenie

Obecna praca poświęcona jest jednemu z najważniejszych czynników wpływających na pracę konwertora tlenowego - lepkości dynamicznej żużla. Znając typowy skład chemiczny żużla uzyskany po wytopie w piecu wykonano obliczenia lepkości żużla przy pomocy empirycznych modeli Ribouda i Urbaina w zakresie temperatur od 1400 °C do 1700 °C. Wykonano również analizę porównawczą wyników obliczeń przy pomocy modeli z wynikami symulacji uzyskanymi z kalkulacji wykonanych za pomocą programu FactSage.