On the development of a viscosity model for molten multicomponent slag systems with several glass-forming, amphoteric and modifier oxides

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ABSTRACT

Viscosity of multicomponent slags is one of the crucial physicochemical properties for many industrial processes and technologies. While the viscosity-temperature relationship of completely molten slags can well be described by an Arrhenian-type law, the compositional dependence of viscosity is still not fully understood, especially in compositional regions with the lack of experimental data (e.g. at the glass-former concentration of 90 molar pct or higher). In the present work major compositional relationships of the activation energy of viscous flow have been revised for numerous binary and ternary slag systems on the basis of experimental data collected and stored in the viscosity database OxiVis. For example, it has been found that the activation energy relevant to the polymerisation effect in binary systems of the MO-GFO type, where MO is the modifier oxide (i.e. monovalent K_2O, Na_2O, Li_2O and bivalent CaO, MgO, BaO, MnO, PbO etc) and GFO is the glass-forming oxide (SiO_2 or B_2O_3) is not always proportional to the third power of X_{GFO} (contrary to the Urbain formalism) and can vary significantly dependent on the slag system. Also, the activation energy of the charge compensation effect has been revised for ternary systems of the AO-MO-GFO and AO-MO type, where AO is the amphoteric oxide (Al_2O_3, Fe_2O_3 or other). A simple polynomial model has been proposed on the basis of the carried-out analysis for estimation of viscosities of multicomponent slag systems. The model has been optimised against the experimental viscosities in the selected binary, ternary, and higher-order oxide systems, and has been shown reasonable agreement with the experimental data.

INTRODUCTION

Viscosity of molten oxide mixtures commonly known in industry as slags plays the critical role in many industrial and natural processes. The main problem with experimental determination of viscosity is a high melting point of various oxides (>1500°C) and extreme reactivity of oxides in the liquid state. Therefore, modelling of viscosity can be applied to avoid experimental difficulties.

A number of practical viscosity models have been developed over last 30-40 years to calculate viscosity of multicomponent oxide melts (e.g. Kondratiev 2002, Jung 2014). Among others, structural viscosity models are based on the melt structure usually described by concentrations of various structural units (e.g. bridging and non-bridging oxygens, silica tetrahedra, the second nearest neighbour bonds etc). However, these models are complicated, often cannot be used without additional data, and demonstrate good agreement mostly for multicomponent melts.

It is well known that, based on their effect on viscosity, all oxides can roughly be divided into three groups: glass-forming oxides (GFO), modifier oxides (MO) and amphoteric oxides (AO). Glass-forming oxide melts have much higher viscosity than the rest of oxide melts due to formation of interconnected, continuous structural network in the molten state. This continuous structural network is sometimes referred to as the “fully polymerised melt”. Modifiers usually break (or “depolymerise”) that continuous network into fragments and thereby lower the melt viscosity. Amphoteric oxides can either break the network or form a quasi-network structure depending on the other melt components.

One of the less complicated, polynomial models based on the above idea is the so called Urbain formalism (Urbain 1981), in which the Weymann-Frenkel equation (1) is used for the viscosity-temperature dependence, and the compositional dependence of the parameter *B* in the ternary Al_2O_3-CaO-SiO_2 system is expressed as the polynomial (2) of the molar fraction of SiO_2 and the ratio of Al_2O_3 and CaO:

$$\log\eta = \log A + \log T + \frac{B}{T}, \tag{1}$$

$$B = \sum_{i=0}^{3}\sum_{j=0}^{2} b_{ij}\left(\frac{X_{Al_2O_3}}{X_{Al_2O_3} + X_{CaO}}\right)^{j} X_{SiO_2}^{i}. \tag{2}$$

The Urbain-type models (e.g. Kondratiev 2001, Forsbacka 2007) demonstrate good agreement for calculating viscosity of the systems with one GFO (SiO_2), one AO (Al_2O_3) and a number of divalent MOs (CaO, MgO, MnO, etc). In the binary and ternary systems with monovalent modifiers (K_2O, Na_2O) this formalism is not generally capable to describe experimental data with a reasonable accuracy, and other, more complex models have to be developed(e.g. Jak 2009). To the authors' best knowledge the Urbainformalism has not been applied to the systems with two or more GFO. The major problem of development of phenomenological viscosity models is the experimental data, its existence, amount, and quality.

In the present work the OxiVis viscosity database (Kondratiev 2021) was used to extract and analyse experimental data for unary, binary and ternary systems. The OxiVis database is a big collection of the experimental viscosity data developed and maintained by one of the authors for 20 years. It contains over 50,000 experimental points for over 9,000 chemical compositions of 54 different oxides.

The main task considered in the present work is to construct a simplest possible polynomial model that is still capable to describe experimental data on viscosity of unaries, binaries, and ternaries with a reasonable accuracy. Thus, some non-linear viscosity effects other than polymerisation encountered in binary oxide systems, though be discussed, will not be taken into account during modelling. First, the available experimental data for binary systems will be analysed, and a polynomial model will be proposed for binary silicate, borate and other systems that takes into account different viscosity growth at the GFO concentrations approaching 1. Then additional terms will be proposed and discussed for the parameter B (equations 1-2) in the ternary systems of the AO-MO-GFO type. Finally the model will be tested on high-order systems.

EXPERIMENTAL EVIDENCE ON THE PRESENCE OF LINEAR REGIONS IN BINARY SYSTEMS

Viscosity of binary systems, in which one component is a GFO, are generally characterised by the so-called polymerisation effect, which results in a rapid growth of viscosity by several orders of magnitude as the GFO concentration tends to 1. In terms of the activation energy (proportional to the parameter B in Eq. 1) it results in an increase of the activation energy to the value that corresponds to the GFO parameter. In the Urbain formalism the polymerisation effect is expressed as the third power polynomial of the SiO_2 molar fraction (see Eq. 2). However, the exact form of the effect is not well investigated for most of binaries, especially at higher GFO concentrations (see, for example, Kondratiev 2021).

Analysis of the collected experimental data for binary silicates revealed the presence of a nearly linear region at the $\log\eta$ vs X_{GFO} dependence in each binary silicate system. The width of this region can expand from 0-0.3 to about 0.7-0.8 $X(SiO_2)$ and depends on a system. Figure 1 provides the experimental data for five silicate binary systems at constant temperatures against the molar fraction $X(SiO_2)$ (between 0 and 0.8) along with the linear fit for logarithm of viscosity. At $X(SiO_2) > 0.7$ a rapid growth of viscosity (the so-called polymerisation effect) usually takes place. At $X(SiO_2) < 0.3$ a similar, but less pronounced effect can be observed in systems like Al_2O_3-SiO_2 or PbO-SiO_2.

Interpolation of the linear fit of the viscosity logarithm against $X(SiO_2)$ was carried out for each system in selected silicate binaries (Al_2O_3-, BaO-, CaO-, K_2O-, MgO-, MnO-, Li_2O-, Na_2O-, and PbO-SiO_2). The interpolation procedure was applied to all the experimental viscosity values at $X(SiO_2)$ from 0.3 to 0.7, approximately, and to all the temperatures above the melting point. Table 1 shows the linear fit coefficients (log*A* & *B*) obtained for each system and the root mean squared errors (RMSE) of the interpolation. Also the coefficient of determination (R^2) is included. It can be seen that the fit "quality" ($R^2 > 0.8$, RMSE is low) is good for most of the systems, which implies that the quasi-linear regions exist at certain intervals of $X(SiO_2)$ in silicate binaries. Also, it can be seen that the parameters of the linear fit are similar to each other: the parameter log*A* is negative for all systems, and the parameter *B* is positive for all systems except for K_2O-SiO_2.

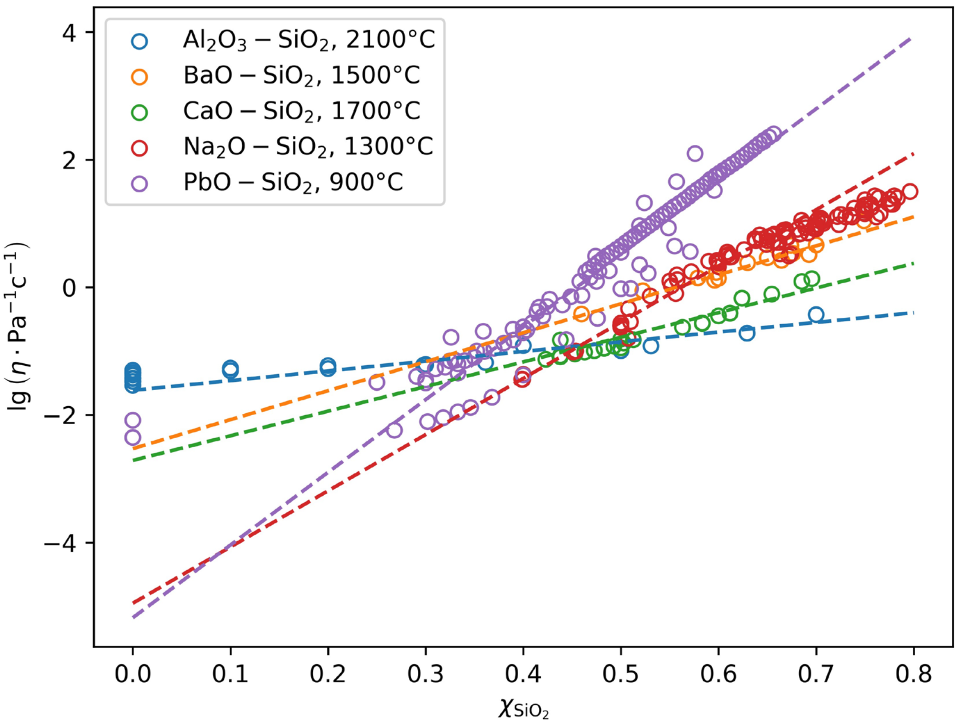


FIG 1 – The quasi-linear regions in the (Al_2O_3, BaO, CaO, Na_2O, PbO)-SiO_2.

Table 1. Linear fit parameters and errors for selected silicate systems (equation 1).

System	End-member	log(A/Pa*s)	10^3·B, kK	RMSE	R^2
Al_2O_3-SiO_2	Al_2O_3	-2.538	2.189	0.104	0.833
	SiO_2	-4.792	11.146		
BaO-SiO_2	BaO	-5.029	4.430	0.062	0.987
	SiO_2	-5.157	12.708		
CaO-SiO_2	CaO	-6.839	8.137	0.172	0.834
	SiO_2	-3.292	8.756		
K_2O-SiO_2	K_2O	-6.302	-0.896	0.172	0.973
	SiO_2	-5.540	17.028		
Li_2O-SiO_2	Li_2O	-5.775	3.065	0.103	0.969
	SiO_2	-3.227	9.411		
MgO-SiO_2	MgO	-2.801	0.524	0.101	0.987
	SiO_2	-6.454	15.189		
MnO-SiO_2	MnO	-6.601	6.812	0.118	0.811
	SiO_2	-0.110	2.925		
Na_2O-SiO_2	Na_2O	-6.923	3.100	0.153	0.983
	SiO_2	-3.319	11.289		
PbO-SiO_2	PbO	-8.468	3.857	0.293	0.921
	SiO_2	-1.606	9.175		

Figure 2 shows the "log(Viscosity) vs 1/T" dependences of the pure SiO_2 obtained during interpolation for each silicate binary system. It can be seen that only two systems do not follow the mean trend: K_2O-SiO_2 and MnO-SiO_2. And PbO-SiO_2 is also slightly out at higher temperatures. A possible reason for deviation of the K_2O-SiO_2 and MnO-SiO_2 systems is the lack of experimental data at $X(SiO_2) < 0.5$ for K_2O-SiO_2 and at $X(SiO_2) > 0.5$ for MnO-SiO_2. The PbO-SiO_2 system can be characterised by a large scatter in the experimental data at $X(SiO_2)$ from 0 to 0.5. On the basis of the above analysis one set of parameters can be selected for the pure SiO_2 end (shown in Fig.2 as the mean line).

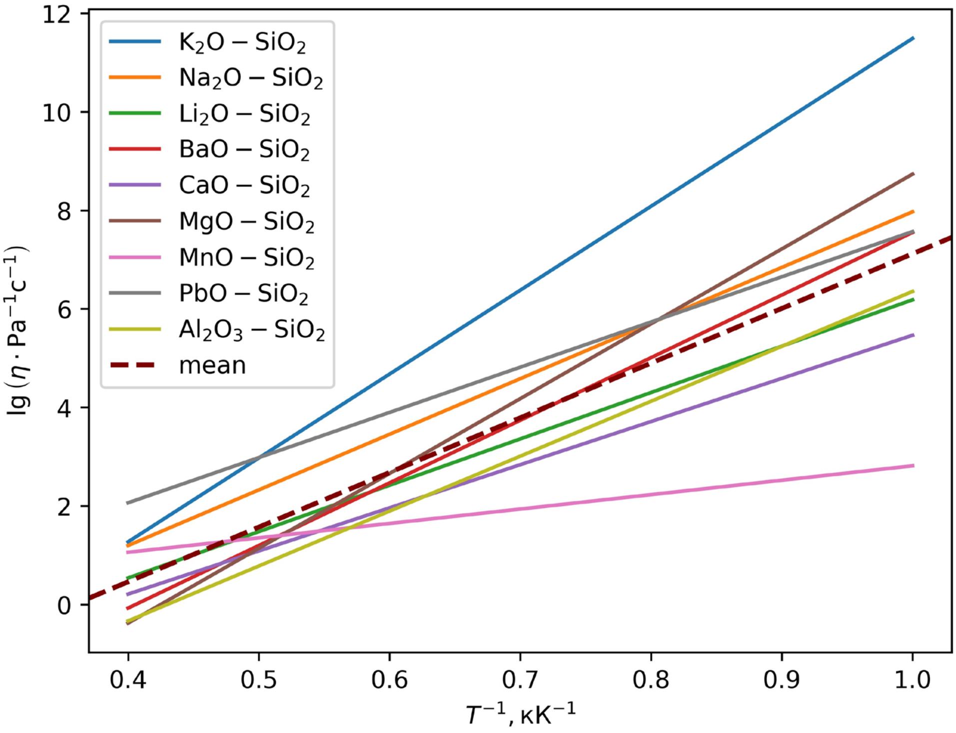


FIG 2 – Viscosity of pure SiO_2 obtained from each system optimisation.

Among all binaries molten silicates are by far the most investigated systems due to their significance for industry and geology. Binary borates, germanates and phosphates are less investigated, although these systems may also be important for glass-making industry or nuclear waste vitrification. Nevertheless, a lot of silicate systems are investigated only in a narrow compositional range (e.g. the CaO-SiO_2 viscosities are measured only in the range $0.4 \leq X(SiO_2) \leq 0.7$), at relatively low melting temperatures (Kondratiev 2021). In the present study a number of binary silicate and borate systems will be analysed as well as few other GFO-containing systems.

MODEL CONSIDERATIONS

In the present study the classical Arrhenius equation (in a logarithmic format) is used to describe the temperature dependence of viscosity of molten oxide systems:

$$\log \eta = \log A + \frac{B}{T}, \tag{3}$$

where the parameters *A* and *B* depend on chemical composition. The B parameter is linked to the activation energy of viscous flow.

Parameters of Eq. (3) can easily be calculated for those pure oxides, for which the experimental data is available. For the rest of pure oxides it is possible to use estimations from various viscosity models or molecular dynamics simulations (Kondratiev 2024).

The compositional dependence of viscosity in a binary system consists of two parts (called "ideal" and "excess" by the analogy to thermodynamics):

$$\log\eta = \log\eta^{id} + \log\eta^{ex} \tag{4}$$

$$\log\eta^{id} = X_1\log\eta_1^{id} + X_2\log\eta_2^{id} = X_1\log A_1^{id} + X_2\log A_2^{id} + \frac{X_1B_1^{id} + X_2B_2^{id}}{T} \tag{5}$$

$$\log\eta^{ex} = X_1^{\alpha_1}\log\frac{A_1^0}{A_1^{id}} + X_2^{\alpha_2}\log\frac{A_2^0}{A_2^{id}} + \frac{X_1^{\alpha_1}\left(B_1^0 - B_1^{id}\right) + X_2^{\alpha_2}\left(B_2^0 - B_2^{id}\right)}{T} \tag{6}$$

Consequently, the following dependence can be written for the parameter *B* in a binary system MO-GFO:

$$B = B_1^{id}X_1 + B_2^{id}X_2 + \left(B_1^0 - B_1^{id}\right)X_1^{\alpha_1} + \left(B_2^0 - B_2^{id}\right)X_2^{\alpha_2}, \tag{7}$$

where indices 1 and 2 refer to the first and second components of a binary system, B^{id} describe the linear part of the experimental data and B^0 are the pure oxide values.

One of relatively well investigated binary systems without GFO is Al_2O_3-CaO, in which viscosity as a function of composition has a maximum approximately at Al_2O_3/CaO = 1. This non-monotonous behaviour is due to formation of quasi-tetrahedra $(AlCa_{0.5})O_4^{4-}$ that are linked together and generate a network similar to the silica tetrahedral network. This effect is usually referred to as the charge compensation effect in ternary systems, while it is not investigated in similar binary systems such as Al_2O_3-K_2O or Al_2O_3-Na_2O.

As mentioned above, viscosity in the ternary systems of the AO-MO-GFO type is also characterised by the charge-compensation effect, when an amphoteric cation (e.g. Al^{3+}) coupled with a mono- or divalent modifier cation (e.g. Na^+) form additional quasi-network interlinked to the silica tetrahedral network, which results in an increase of viscosity. This effect is much more pronounced for monovalent cations (K^+, Na^+, Li^+), but also found in systems with divalent cations (e.g. Ca^{2+}, Mg^{2+}).

In a binary system AO-MO and a ternary system AO-MO-GFO the charge compensation term is proposed in the following form:

$$B \sim B^{ChC}\cdot\left(\frac{X_{AO}}{X_{AO} + X_{MO}}\right)^{\gamma_1}\cdot\left(\frac{X_{MO}}{X_{AO} + X_{MO}}\right)^{\gamma_2}, \tag{8}$$

where γ_1 and γ_2 are the adjustable parameters.

Thus, in the ternary system AO-MO-GFO, the parameter B (the Arrhenius activation energy reduced by the universal gas constant R) has the following general form:

$$\begin{gathered} B = B_{AO}^{id}X_{AO} + B_{MO}^{id}X_{MO} + B_{GFO}^{id}X_{GFO} + \left(B_{AO}^0 - B_{AO}^{id}\right)X_{AO}^{\alpha_{AO}} + \left(B_{MO}^0 - B_{MO}^{id}\right)X_{MO}^{\alpha_{MO}} + \\ \left(B_{GFO}^0 - B_{GFO}^{id}\right)\left[\frac{X_{AO}}{X_{AO}+X_{MO}}X_{GFO}^{\beta_{AO}} + \frac{X_{MO}}{X_{AO}+X_{MO}}X_{GFO}^{\beta_{MO}}\right] + \\ B_{AO\cdot MO}^{ChC}\left(\frac{X_{AO}}{X_{AO}+X_{MO}}\right)^{\gamma_{AO}}\left(\frac{X_{MO}}{X_{AO}+X_{MO}}\right)^{\gamma_{MO}}. \end{gathered} \tag{9}$$

RESULTS AND DISCUSSION

Only a part of the results obtained for binaries and ternaries is presented and discussed here. Other results are still to be obtained and might be included into the conference presentation.

Viscosities of binary silicates

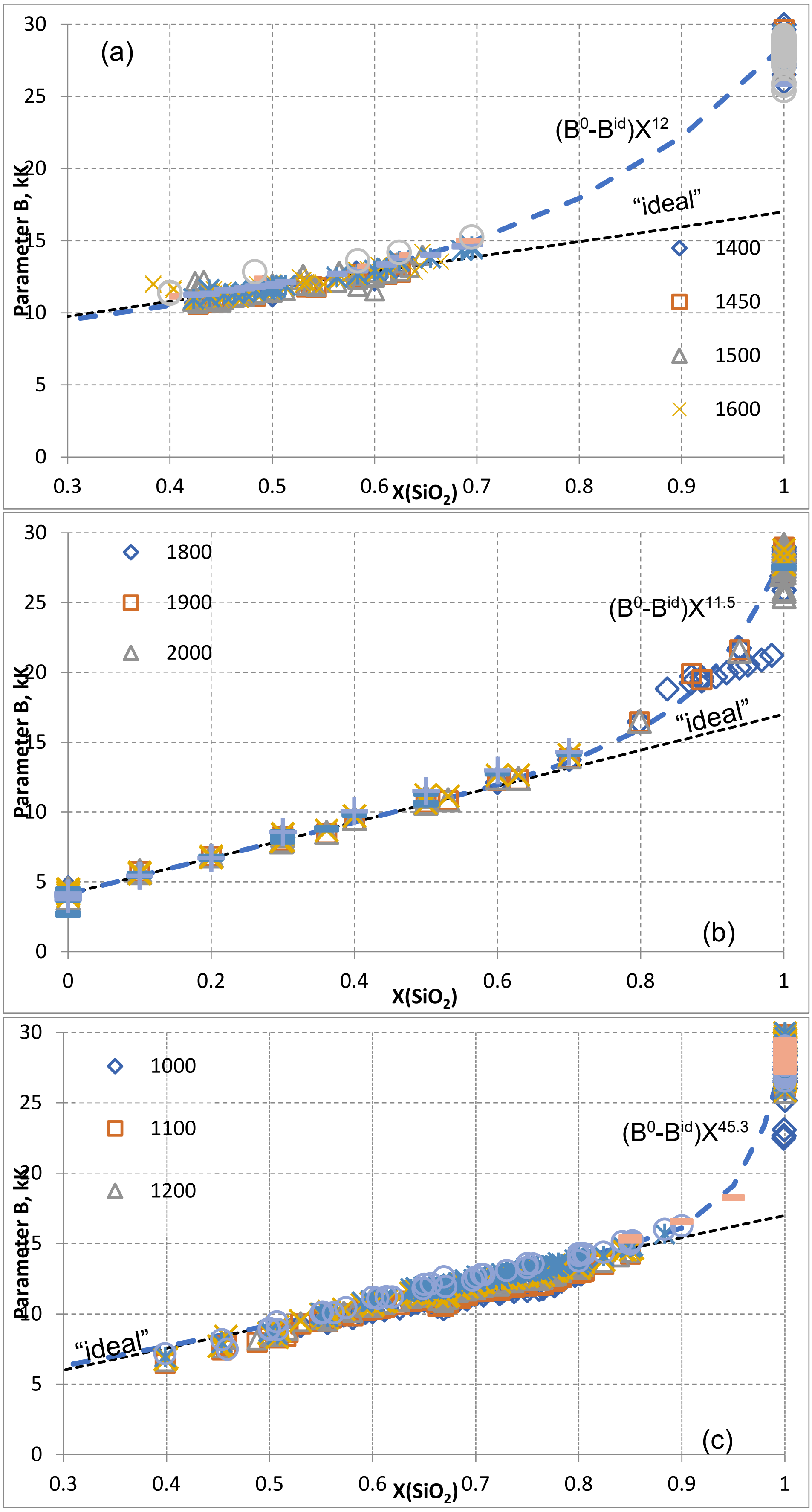
Tables 2-3 represent the model parameters for unary systems and binary silicate systems, respectively. Parameters for several pure oxides were taken from the review by Kondratiev (2024). In the present work the parameters of those pure oxides, for which no experimental data are available, were made equal to the corresponding linear parameters obtained as described above. Also, the α parameters for these oxides were not calculated, since it is not possible without experimental data. The "ideal" SiO_2 parameters listed in Table 3 were calculated as the average for all systems from Table 1 except K_2O-SiO_2 and MnO-SiO_2.

TABLE 2 – Model parameters for pure oxide melts.

	Al_2O_3	PbO	SiO_2	BaO	CaO	K_2O	Li_2O	MgO	MnO	Na_2O
log(A^0/Pa*s)	-3.20	-4.02	-7.73	-5.86	-6.18	-8.56	-4.31	-5.21	-3.73	-6.83
B^0 (kK)	4.13	2.30	28.54	5.24	5.85	7.49	0.06	4.53	0.74	4.50
Reference	Kondratiev 2024			This work						

TABLE 3 – Model parameters for binary silicate melts obtained in this work.

System	**Coefficients**			
	log(A^{id}/Pa*s)	**B^{id} (kK)**	**α_1**	**α_2 (SiO_2)**
SiO_2	-3.72	10.85	-	-
Al_2O_3-SiO_2	-3.07	1.63	3.46	11.46
BaO-SiO_2	-5.86	5.24	-	14.69
CaO-SiO_2	-6.18	5.85	-	12.00
K_2O-SiO_2	-8.56	7.49	-	67.98
Li_2O-SiO_2	-4.31	0.06	-	23.51
MgO-SiO_2	-5.21	4.53	-	12.00
MnO-SiO_2	-3.73	0.74	-	10.00
Na_2O-SiO_2	-6.83	4.50	-	45.26
PbO-SiO_2	-5.52	1.22	8.66	9.23


(a)
Parameter B, kK
X(SiO2)
$(B^0-B^{id})X^{12}$
"ideal"
1400
1450
1500
1600
(b)
1800
1900
2000
$(B^0-B^{id})X^{11.5}$
"ideal"
(c)
1000
1100
1200
$(B^0-B^{id})X^{45.3}$
"ideal"
0
5
10
15
20
25
30
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8

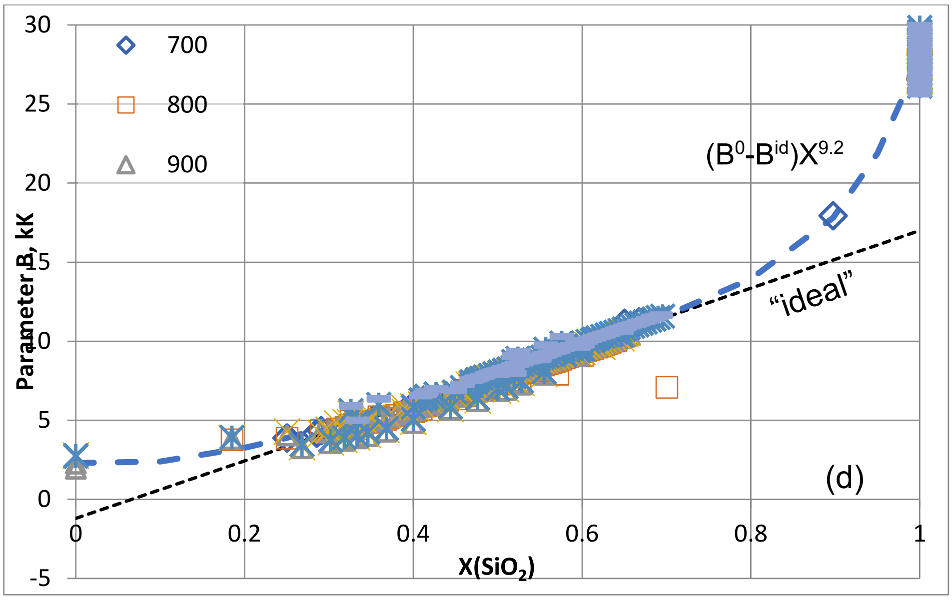


FIG 3 – The parameter *B* as a function of the SiO_2 molar fraction for (a) CaO-SiO_2, (b) Al_2O_3-SiO_2, (c) Na_2O-SiO_2, (d) PbO-SiO_2.

The parameter *B* in binary silicate systems is expressed by Equation 7, and the values of the parameters of Eq. 7 can be found in Table 3. The polymerisation effect is introduced into the model simply as the difference between the pure oxide and linear ("ideal") *B* parameters multiplied by the SiO_2 concentration to a certain power (the α parameter). Figures 3(a-d) show four examples of the compositional dependence of the parameter *B* (Eq. 7) for the CaO-SiO_2, Al_2O_3-SiO_2, Na_2O-SiO_2 and PbO-SiO_2 systems. Different symbols denote different temperatures (in °C). It can be seen that the polymerisation effect is more pronounced in the Na_2O-SiO_2 than in the Al_2O_3-SiO_2 or PbO-SiO_2 systems. The region that corresponds to the polymerisation effect in the CaO-SiO_2 is not investigated, so it is problematic to assume the exact form of the compositional dependence with increasing X(SiO_2). Therefore the parameter B was chosen arbitrarily from 10 to 15. For the PbO-SiO_2 system two structural effects can be observed: the polymerisation effect at higher SiO_2 and similar but less pronounced at lower SiO_2, with the quasi-linear region at intermediate SiO_2.

This linear region at intermediate SiO_2 concentrations in binary silicate systems may be considered as the compositional region, in which no structural rearrangement takes place. Increasing SiO_2 leads to the polymerisation effect, while SiO_2 decreasing results in other, similar to polymerisation, effect of structural rearrangement. Both effects result in viscosity increasing. Polymerisation is a type of clustering, structural network formation. At the other end also some clustering occurs.

Figures 4-12 represent the experimental and calculated viscosities in the Al_2O_3-SiO_2, CaO-$SiIO_2$, K_2O-SIO_2, Li_2O-SiO_2, MgO-SiO_2, MnO-SiO_2, Na_2O-SiO_2, and PbO-SiO_2 systems. It can be seen that the model describes the experimental data with a reasonable accuracy, although only 2-3 model parameters are used for each binary system.

Figures 4-12 demonstrate reasonably good agreement with the available experimental data. Perhaps, a poorest, but still reasonable agreement among all systems is shown in the Al_2O_3-SiO_2 system (Figure 4). This is mainly due to slightly lower values of the SiO_2 ideal parameters than for the Al_2O_3-SiO_2 system (see Table 1), and also because a low-temperature experimental data is described with a better agreement that the viscosity data at higher temperatures.

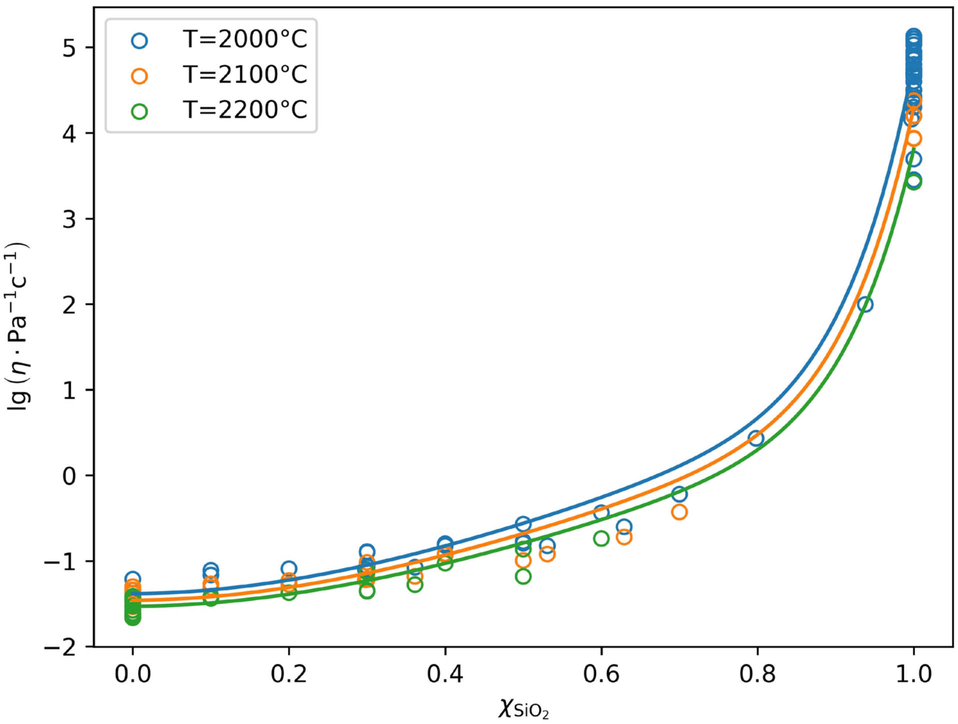


FIG 4 – Viscosities of the Al_2O_3-SiO_2 system.

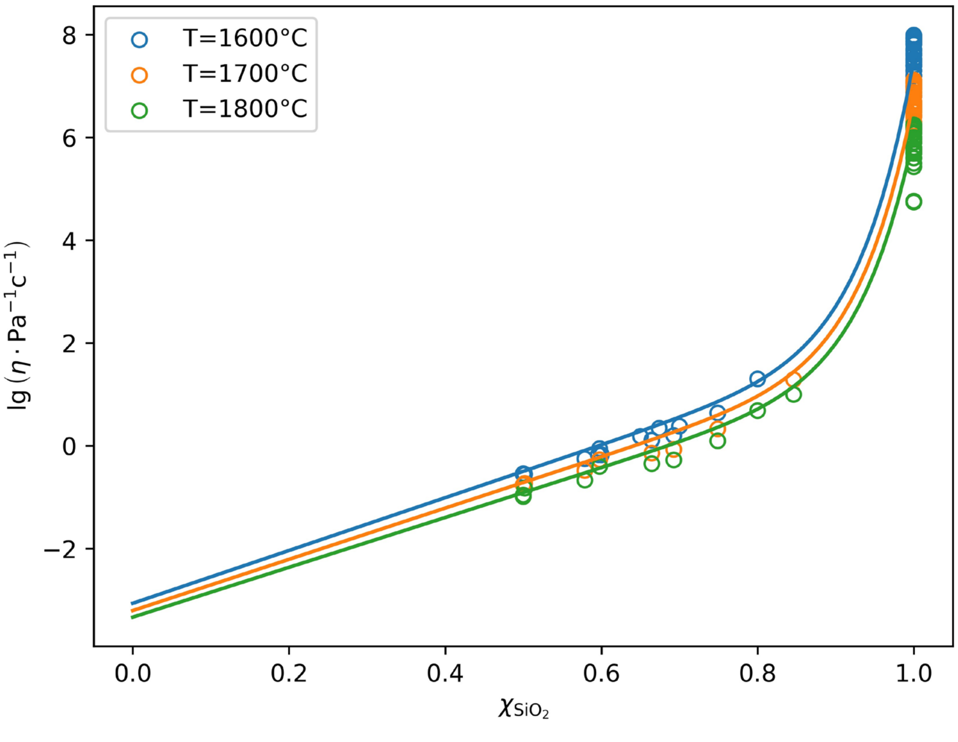


FIG 5 – Viscosities of the BaO-SiO_2 system.

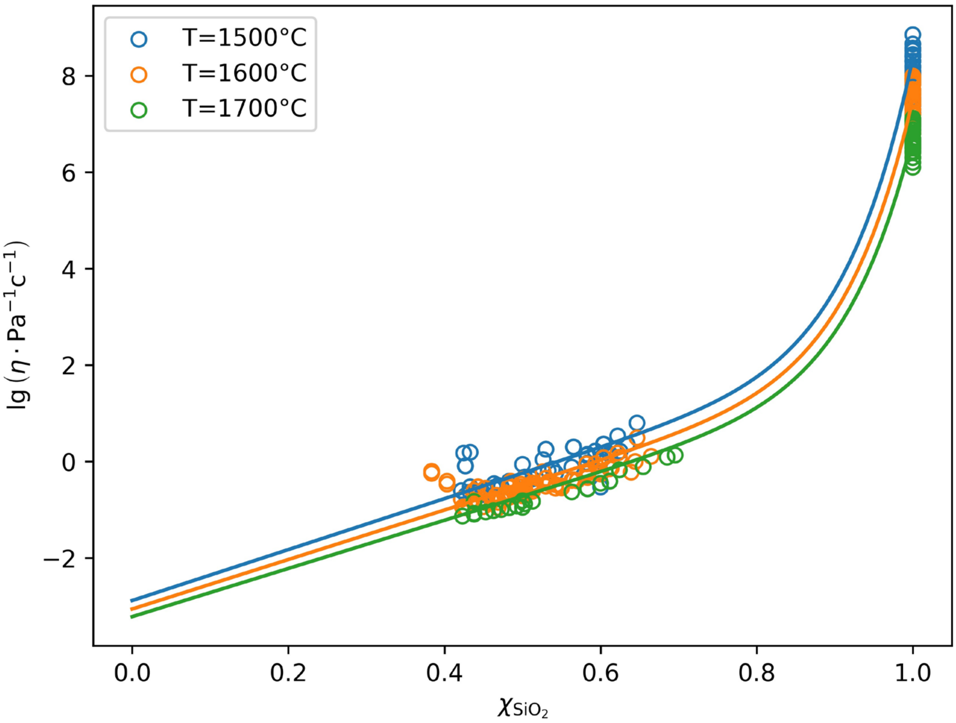


FIG 6 – Viscosities of the CaO-SiO_2 system.

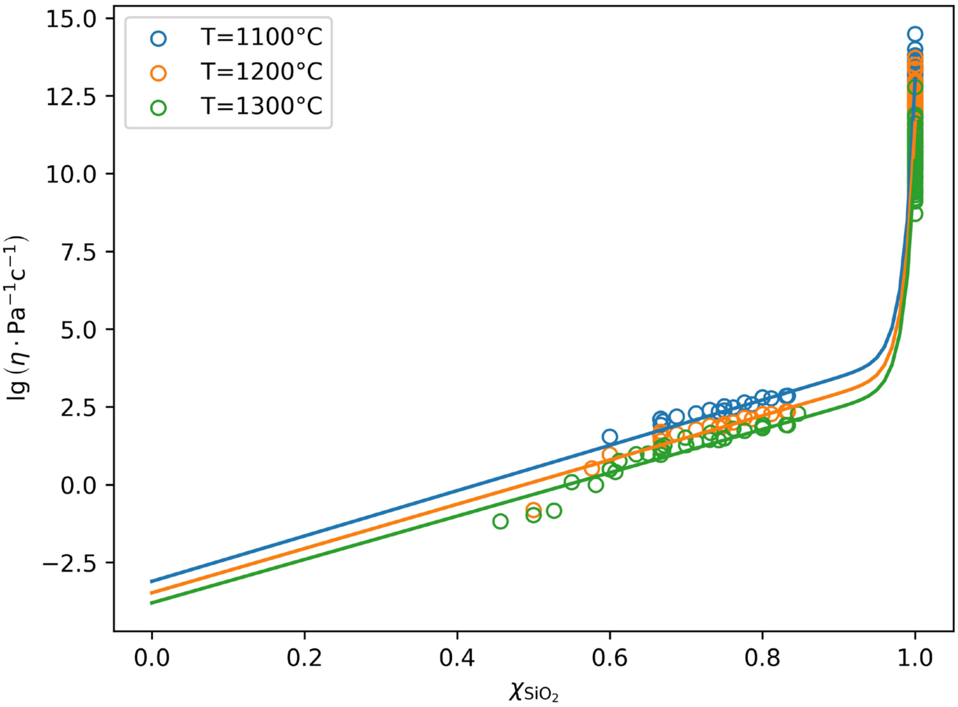


FIG 7 – Viscosities of the K_2O-SiO_2 system.

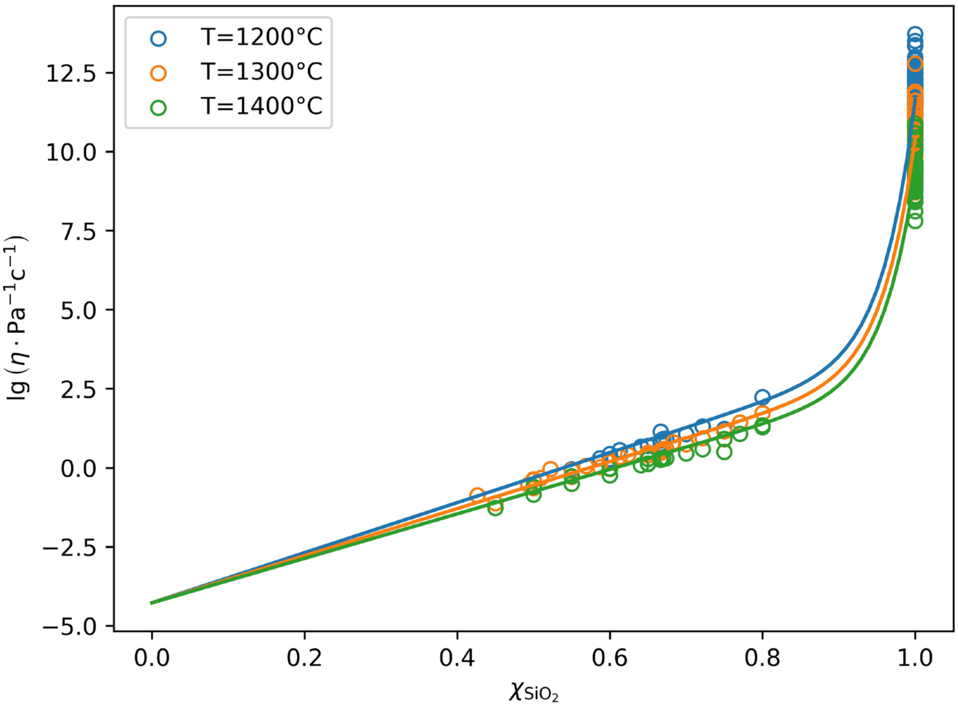


FIG 8 – Viscosities of the Li_2O-SiO_2 system.

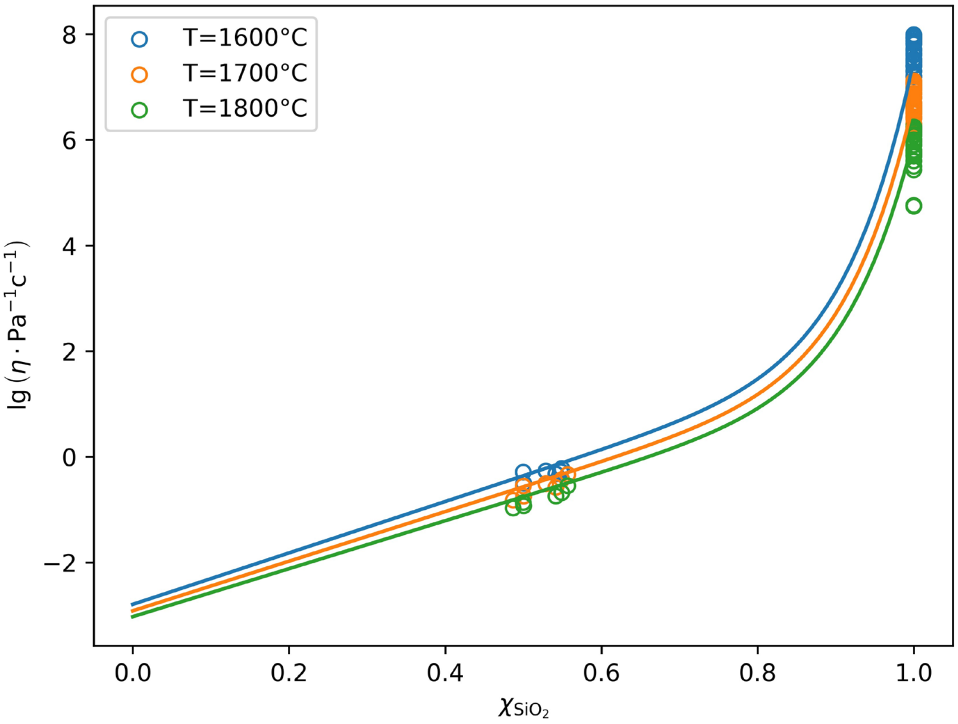


FIG 9 – Viscosities of the MgO-SiO_2 system.

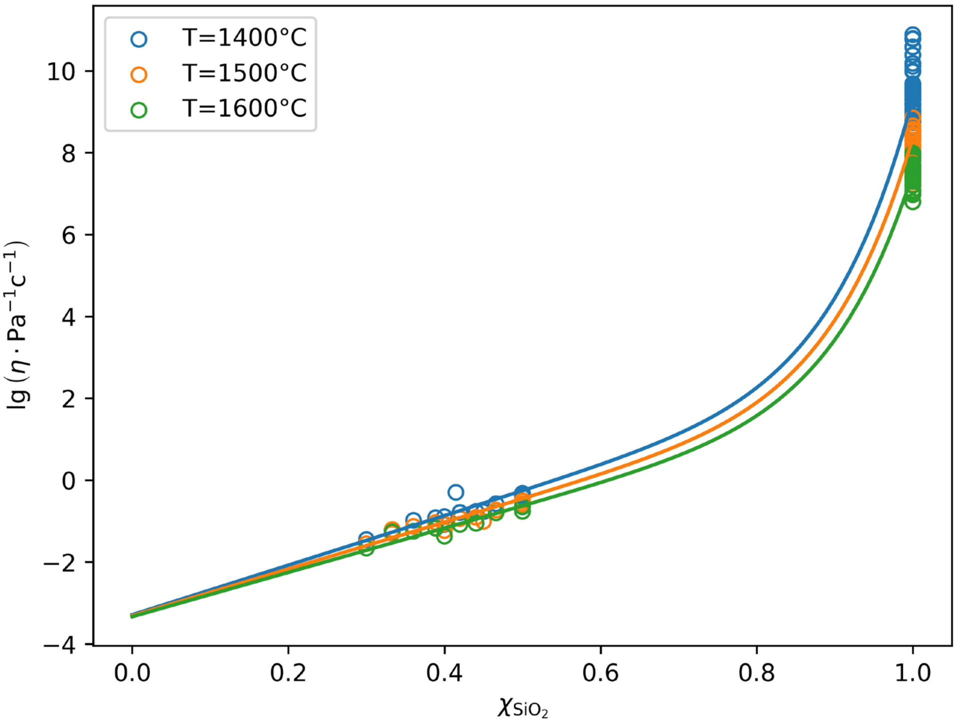


FIG 10 – Viscosities of the MnO-SiO₂ system.

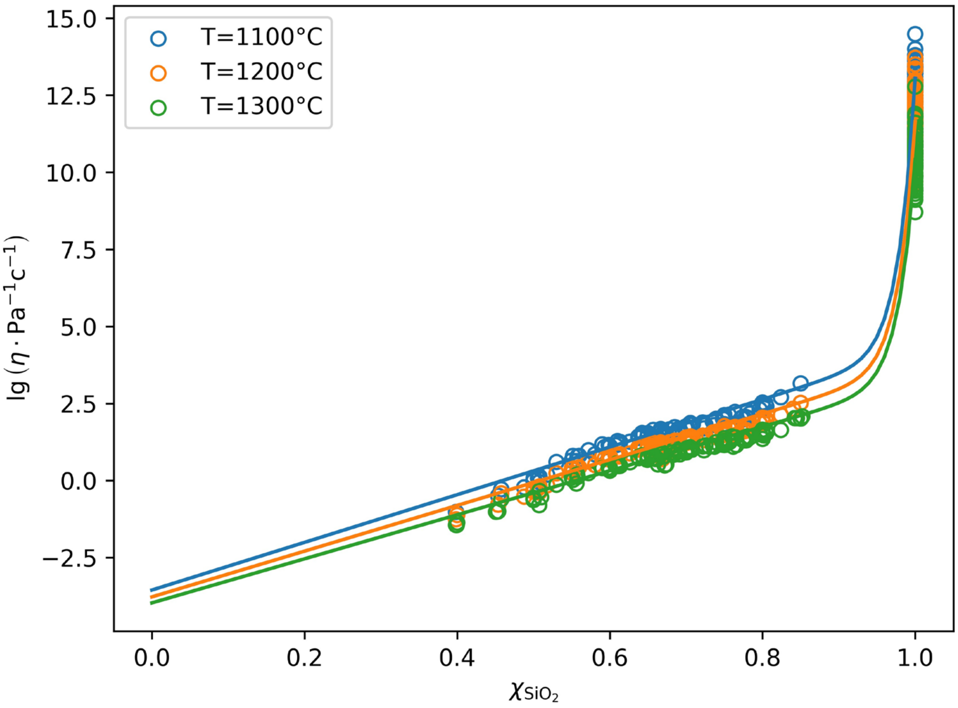


FIG 11 – Viscosities of the Na₂O-SiO₂ system.

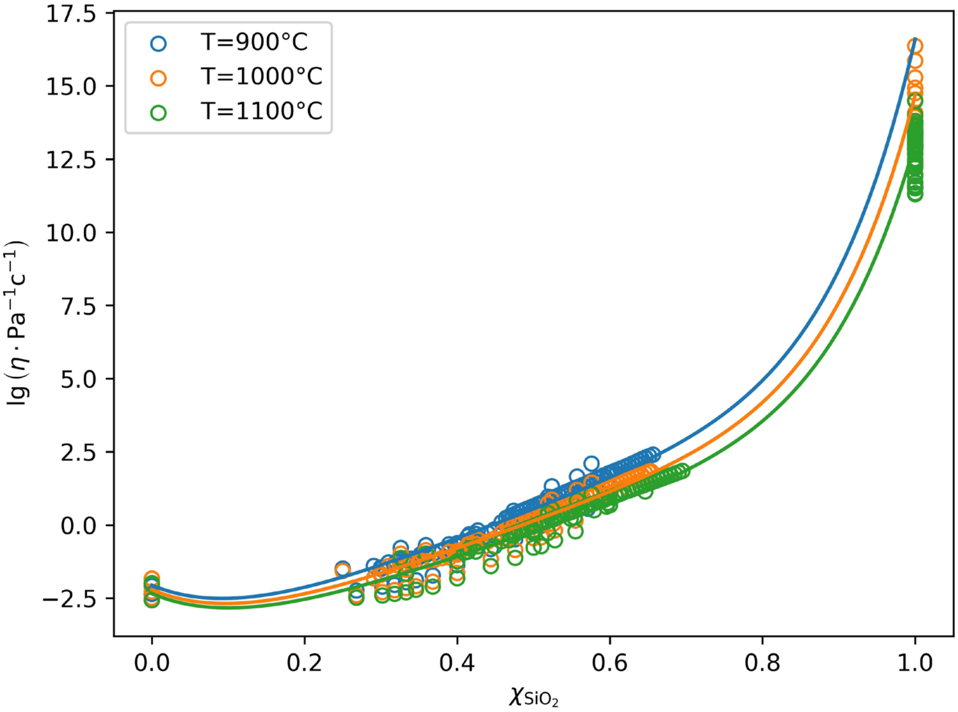


FIG 12 – Viscosities of the PbO-SiO$_2$ system.

Viscosities of binary borates and other binaries

Table 4 represent the model parameters for B_2O_3 and B_2O_3-SiO$_2$. The parameters for pure B_2O_3 are calculated using the experimental data at temperatures above the melting point and the Arrhenius equation (1). The experimental data for borates are scarce and controversial, the only reliable data is found to be present in the B_2O_3-SiO$_2$ system. The B_2O_3 “ideal” parameters were optimised mainly on the basis of B_2O_3-SiO$_2$. The other end-member parameters for molten B_2O_3-BaO, B_2O_3-Na$_2$O, B_2O_3-PbO were taken from the corresponding silicates listed in Table 3.

TABLE 4 – Model parameters for binary borate melts.

System	Coefficient					
	log(A^0/Pa*s)	B^0 (kK)	log(A^{id}/Pa*s)	B^{id} (kK)	α_1	α_2
B_2O_3	-2.14	3.96	-0.83	2.06	-	-
B_2O_3-SiO$_2$	-	-			4.64	4.61

Figures 13-15 represent the results of model calculation for two borate systems (B_2O_3-PbO and B_2O_3-Na$_2$O). Borate melts are less investigated and are characterised by larger experimental scatter than silicate melts. It can be seen that the model cannot describe complex compositional effects present in the borate binary systems. It should be mentioned that the model parameters for PbO and Na$_2$O (the linear part) were taken from the corresponding silicate binaries, while the model parameters for B_2O_3 were obtained on the basis of the B_2O_3-SiO$_2$ system.

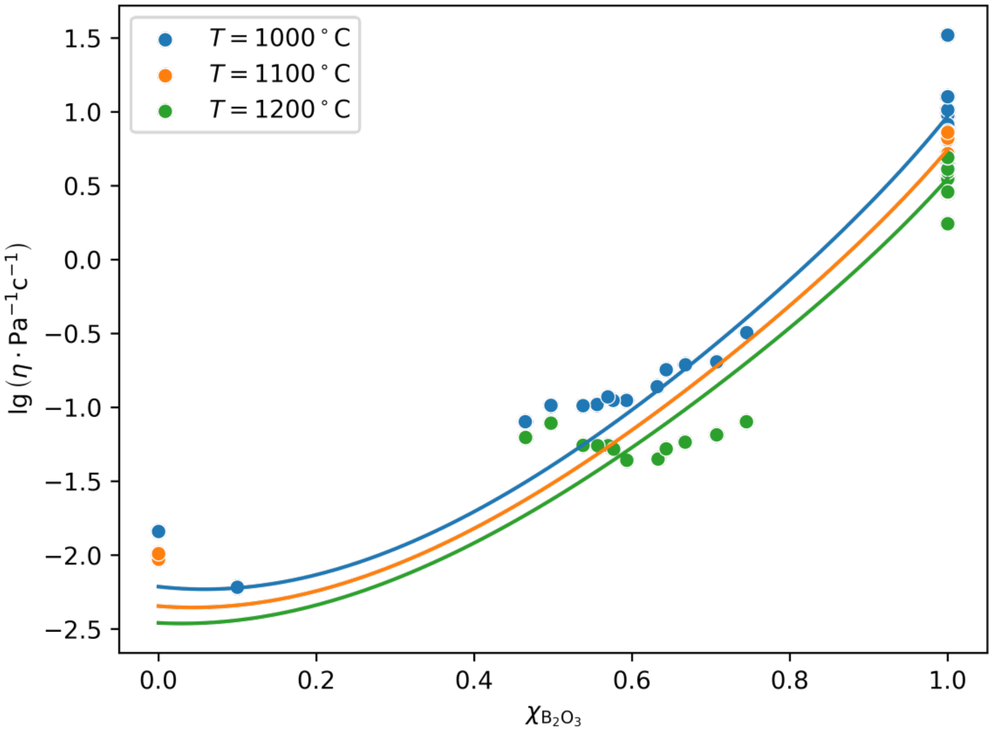


FIG 13 – Viscosities of the B_2O_3-PbO system.

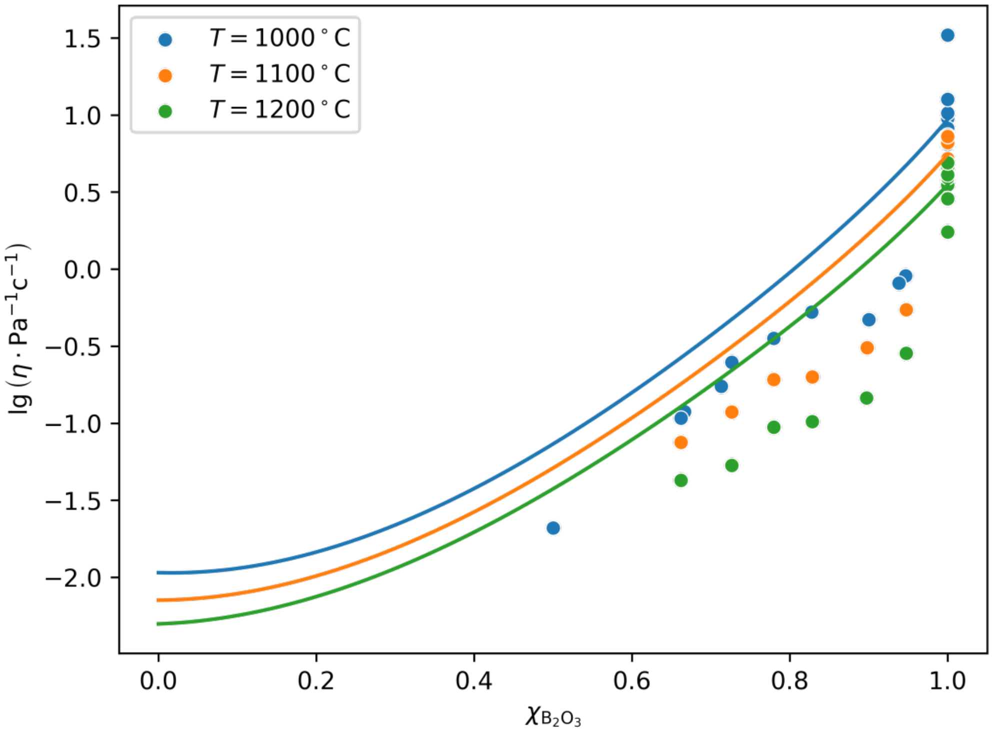


FIG 14 – Viscosities of the B_2O_3-Na_2O system.

Viscosity of the B_2O_3-SiO_2 melt is shown in Figure 15. It can be seen that agreement between the experimental and calculated viscosities is reasonably well.

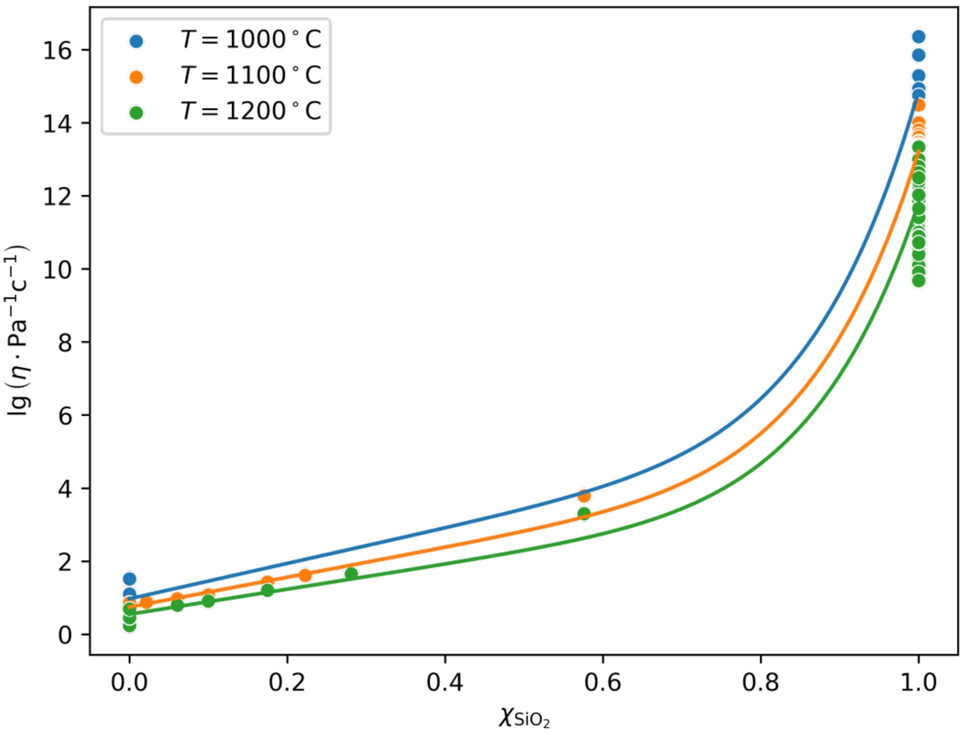


FIG 15 – Viscosities of the B_2O_3-SiO_2 system.

Viscosity of the Al_2O_3-CaO system is shown in Figure 16 as a function of the $Al_2O_3/(Al_2O_3+CaO)$ ratio. Parameters are listed in Table 5. The agreement between the experimental and calculated values is reasonable.

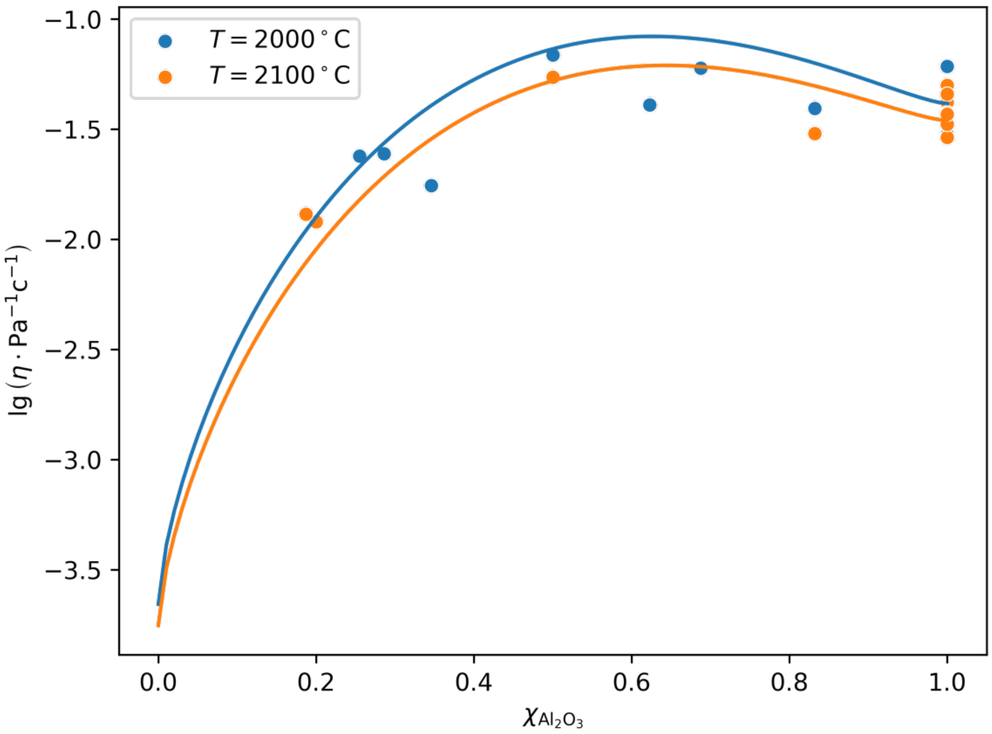


FIG 16 – Viscosities of the Al_2O_3-CaO system.

Viscosities of ternary systems

Table 5 provides the model parameters for the charge compensation term in one binary system, Al_2O_3-CaO, and two ternary systems, Al_2O_3-Na_2O-SiO_2 and Al_2O_3-CaO-SiO_2.

TABLE 5 – The charge compensation model parameters for Al_2O_3-CaO and ternary oxide melts.

System	**Coefficient**		
	B^{ChC} (kK)	γ_1	γ_2
Al_2O_3-CaO	10.66	0.64	1.12
Al_2O_3-Na_2O-SiO_2	829.45	4.53	3.20
Al_2O_3-CaO-SiO_2	3.57	1	1

Viscosity of the Al_2O_3-Na_2O-SiO_2 is presented in Figure 17. The agreement between the calculated and experimental values is good.

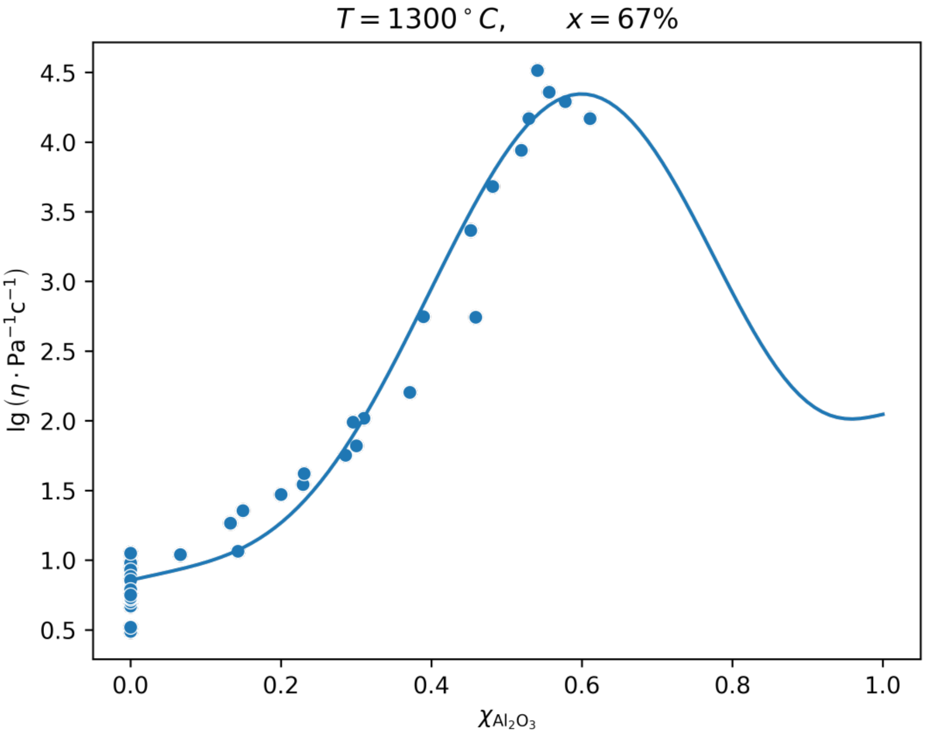


FIG 17 – Viscosities of the Al_2O_3-Na_2O-SiO_2 system at $X(SiO_2)=0.67$ and T=1300°C.

Experimental viscosities of Al_2O_3-CaO-SiO_2 are shown in Figure 11 with preliminary coefficients of the charge compensation term. It can be seen that agreement between calculated and experimental viscosities is reasonable.

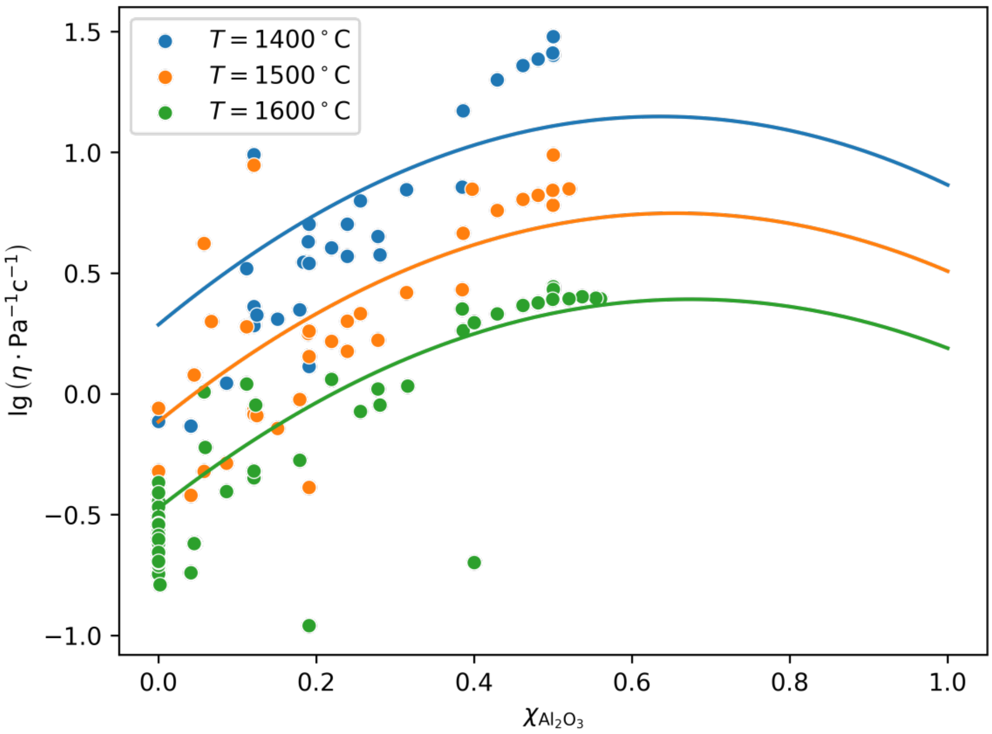


FIG 18 – Viscosities of the Al_2O_3-CaO-SIO_2 system at X(SiO_2)=0.5 and T=1400, 1500, 1600ºC.

The experimental data and calculated viscosities for the other AO-MO-GFO systems (e.g. Al_2O_3-K_2O-SiO_2, Al_2O_3-Li_2O-SiO_2, Al_2O_3-MgO-SiO_2) might be added to the conference presentation.

CONCLUSIONS

The simple polynomial model is constructed on the basis of analysis of experimental data in binary silicate systems. The model introduces a linear compositional dependence and polymerisation effect for silicate systems. In ternary systems a charge compensation term is added to describe the experimental data.

A significant rise of viscosity with approaching pure SiO_2 (the so-called polymerisation effect) is described reasonably well in different binary silicate systems.

The presence of viscosity maximum in ternary systems of the AO-MO-GFO type (the charge compensation effect) is described reasonably well in two ternaries (Al_2O_3-Na_2O-SiO_2 and Al_2O_3-CaO-SiO_2) systems.

More complex viscosity effects (e.g. in binary borates) are not described. However, viscosity in the B_2O_3-SiO_2 system is described reasonably well.

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