The Melting Properties of Tuyere Slags with and without Flux Injection into the Blast Furnace

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A laboratory study concerning the melting properties of tuyere slags has been conducted. The melting-point measurements of various specimens, consisting of coke ash, coal ash and fluxes (BOF slag, burnt lime and burnt dolomite), corresponding to the tuyere slags formed in front of the tuyeres with or without flux injection, have been performed in a high-temperature microscope. Theoretical estimations of melting points have been made based on the chemical composition of the tuyere slag specimens.

The results have shown that injection of fluxes has quite a positive effect on the melting properties of the tuyere slag. The melting point of the tuyere slag decreases and the temperature interval between softening and complete melting of the tuyere slag becomes narrower. Compared to the injection of burnt lime and burnt dolomite, the injection of BOF slag will result in still better tuyere slag properties in terms of lower flow point and narrower temperature interval between softening and melting. The differences in melting behaviour in the tuyere slag specimens indicate that injection of BOF slag will also give the tuyere slag a lower viscosity compared to injection of burnt lime or burnt dolomite at the same levels of slag basicity B₂.

KEY WORDS: flux injection; tuyere slag; melting-point measurements.

1. Introduction

In the blast furnace, reduction of iron ores and calcination of limestone proceed when the burden materials descend. Different types of slag will be formed at different locations:

- Primary slag—formed by the gangue in the pellets;
- Bosh slag—consisting of the primary slag, all the additives and fluxes dissolved in it and some ash from coke consumed for direct reduction and carburisation;
- Tuyere slag—formed by the ash content of coke and coal burnt in front of the tuyeres and, if injection of fluxes are used, the injected flux;
- Final slag—formed by a mixture of bosh slag and tuyere slag changed in composition by reduction of some SiO₂ to Si.

At the level of the cohesive zone, softening and melting of iron burden occur, accompanied by dissolution of fluxes. Normally, the bosh slag has a higher basicity compared to the primary slag and the final slag. If the pellet contains a very low amount of gangue and the ash content of the coke is quite high, the top-charged fluxes are mainly used to neutralise the coke ash at the tuyere level of the furnace. A slag of excessive basicity is formed in the bosh part, which was considered as one of the main causes of slag formation problems during testing of a new self-fluxed pellet at SSAB in 1995. A theoretical estimation of the changes in the basicity of the slag formed at different levels of the blast furnace showed that the basicity B₂=1 in the primary slag of the pellet increased to approximately 1.6 in the bosh slag.

The basicity of the tuyere slag was 0.05 and the final slag had a desired slag basicity of 1.2.¹⁾

To decrease the variations in slag basicity and the slag amount in the cohesive zone, Ma¹⁾ has proposed injection of fluxes through the tuyeres, instead of charging them from the top, to improve slag formation in the blast furnace. The basicity B₂ of primary slag of the pellet, bosh slag, tuyere slag and final slag will then be 1.0, 1.1, 0.9 and 1.2, respectively. In this case, a smooth slag formation process, increased productivity and decreased fuel rate can be achieved. In **Fig. 1** the basicity of slag formed at different locations in the blast furnace is compared for normal blast furnace operation and operation with injection of fluxes through the tuyeres when using self-fluxed pellets. The formation of high basicity slag when basic flux is added to self-fluxed pellets and the effect of this on melting behaviour of burden have been verified in laboratory tests. The positive effect of basic fluxes on melting properties of acid pellet is also evident when a certain amount of basic flux is added.^{2,3)}

Injection of iron ore and different fluxes has been tested in some blast furnaces to adjust the sulphur and silicon contents of hot metal.^{4–8)} In a study concerning the effect of tuyere injection of dolomite on the Si content of hot metal it was found that the increased MgO content of the tuyere slag decreased the SiO₂ activity in the slag and the generation of SiO gas decreased. The effect of MgO on the generation of SiO gas decreased with increased basicity B₂ of the slag.⁴⁾ The injection of iron-ore powder only, did not have any effect on the Si content of the hot metal, while a

powder mixture of flux and iron ore did decrease the Si content. The positive effect of flux powder was explained by SiO absorption by the flux powder.⁵⁾ In another study on injection of iron ore fines it was found that the Si content was decreased as a result of increased partial pressure of oxygen in the end of the raceway. If sinter fines containing CaO was used the effect was higher.⁶⁾ In another study of the injection, a mixture of iron ore and coal or a water slurry containing iron ore resulted in decreased Si content of hot metal. The oxidation degree of the slag in the hearth and bosh was considered to be a key factor controlling Si content of hot metal.⁷⁾ The different results achieved in the iron ore injection studies might be explained by the particle size of the injected iron ore.⁸⁾ The original oxidation degree of slags in the bosh and the hearth will affect the result.⁵⁾ When a very fine grain size of iron ore is used, the reduction in the raceway will be efficient and the amount of residual FeO limited.

The use of injection of flux *via* tuyeres in order to obtain smooth slag formation in the blast furnace results in a decrease in the volume of bosh slag and prevents the formation of a bosh slag with excessive basicity.¹⁻³⁾ At normal blast furnace operation, the tuyere slag, formed by the ash content in fuels combusted in front of the tuyeres, is very acidic and has a high viscosity. The injection of fluxes *via* the tuyeres makes it possible to increase the basicity of the

tuyere slag to an appropriate level and improve its melting properties. A lower tuyere slag viscosity might improve the drainage of the slag through the voids in the coke bed.^{9,10)}

The aim of this laboratory study is to determine the influence of injected fluxes on the melting properties of the tuyere slag that normally consists of coal and coke ashes. The effect of BOF slag, burnt lime and burnt dolomite on the melting properties of tuyere slag is studied with the aid of melting-point measurements and estimations of melting points from phase diagrams and by model calculations.

The theoretical study by Ma,¹⁾ laboratory studies concerning slag formation in the cohesive zone^{2,3)} and this study of the effect of injection of basic fluxes on the melting properties of tuyere slag have been done to achieve an understanding of the effect of basic fluxes, top-charged or tuyere-injected, on slag formation. Based on the studies in this project, successful trials of injecting BOF slag into the LKAB (A Swedish pellet producer) experimental blast furnace at MEFOS (Metallurgical Research Centre in Luleå) have been done three times. The last two-week test was conducted in late November 2000.

2. Experimental Technique

In this study, the tuyere slag is considered to have been formed by a mixture of ash released from coke and coal combusted in front of tuyeres. When injection of flux is assumed, the flux injected is also included in the slag. To make the tested specimens similar to the real tuyere slag formed in front of the tuyeres, the specimens tested are made from a mixture of coke ash, coal ash and fluxes taken from SSAB Tunnsplåt in Luleå. Both coke and coal ash are obtained by combustion of coke and coal in a furnace slowly heated up to 800°C. The coal used is a highly volatile coal containing approximately 38–40 wt% of volatile matter. The ash contents are 10.6 and 5.8 wt% and the carbon content 89.5 and 78.2 wt% of coke and coal, respectively. The chemical compositions of coke ash, coal ash and the three types of fluxes used—BOF slag, burnt lime and burnt dolomite—are to be found in **Table 1**.

The ratio of coke ash, coal ash and fluxes used in specimens varies depending on coke rate, and the amount of coal and fluxes assumed to be injected. The operational conditions of blast furnace No. 2 at SSAB Tunnsplåt in Luleå, with a coal injection rate of 120–160 kg/thm and at the LKAB pilot blast furnace¹¹⁾ at MEFOS, with a coal injection rate of ~110 kg/thm, are the basis for determining the correct mixtures of the specimens. The amount of coke consumed in the raceway is calculated according to the different operational conditions with heat and mass balance used for BF No. 3 at SSAB. The estimated result shows that the ratios of coke ash to coal ash for the conditions as-

Fig. 1. Basicity of slags at different locations in the blast furnace.¹⁾

Table 1. Chemical compositions of coal ash, coke ash and fluxes used for preparation of specimens.

Sample	CaO	MgO	SiO ₂	Al ₂ O ₃	TiO ₂	V ₂ O ₅	MnO	P	Na ₂ O	K ₂ O	Fe ₂ O ₃	FeO	TFe
Coke ash	0.91	0.42	50.6	29.0	1.58			0.09	0.55	1.30	5.96		4.17
Coal ash	5.3	3.8	57.9	22.1	0.9			0.1	0.3	1.7	7.1		5.00
BOF-slag	41.1	13.0	9.84	0.95		4.31	3.99				8.08	16.40	18.4
Burnt lime	92.0	1.80	2.09	1.08									0.58
Burnt Dolomite	52.7	38.4	1.41	0.35									0.35

Table 2. Amounts of fluxes injected (kg/thm) corresponding to different injection levels assumed.

Injection levels of fluxes	Coal injection rate								
	110 kg/thm			123 kg/thm			150 kg/thm		
	BOF slag	Lime	Dolomite	BOF slag	Lime	Dolomite	BOF slag	Lime	Dolomite
None	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Low	8.3	4.2	6.8	8.8	4.4	7.1	9.5	4.7	7.1
Medium	16.7	8.3	13.4	17.5	8.8	14.1	18.9	9.5	14.1
High	33.5	12.5	20.1	35.2	13.2	21.2	37.8	14.2	21.1
Very High	50.1	16.7	26.7	52.8	17.5	28.2	56.4	18.9	28.1

Table 3. Main chemical composition, wt%, and basicities of the tuyere slag specimens used for melting point measurements.

	BOF slag					Burnt lime				Burnt dolomite			
	None	Low	Medium	High	Very high	Low	Medium	High	Very high	Low	Medium	High	Very high
CaO	1.92	11.6	17.5	24.2	27.9	14.7	24.2	31.7	37.6	13.6	21.1	26.4	30.3
MgO	1.18	4.11	5.88	7.89	9.00	1.27	1.34	1.39	1.43	9.10	14.2	17.7	20.4
SiO ₂	52.3	41.7	35.4	28.1	24.1	45.1	39.8	35.6	32.3	41.3	34.2	29.3	25.6
Al ₂ O ₃	27.5	20.9	16.9	12.4	9.87	23.7	20.9	18.7	17.0	21.7	18.0	15.4	13.5
TiO ₂	1.42	1.54	1.61	1.69	1.73	1.23	1.09	0.97	0.88	1.12	0.93	0.80	0.70
V ₂ O ₅		1.24	1.99	2.85	3.32					0.01	0.02	0.02	0.03
MnO		0.99	1.59	2.27	2.65								
FeO		4.07	6.5	9.3	11								
Fe ₂ O ₃	6.24	6.69	7.0	7.3	7.5	5.5	4.9	4.4	4.1	5.0	4.2	3.7	3.3
Fe _{met}		0.93	1.9	3.7	1.9								
Fe _{tot}	4.36	7.84	9.95	12.3	13.7	3.82	3.42	3.11	2.86	3.50	2.95	2.56	2.27
B2*	0.04	0.28	0.49	0.86	1.17	0.33	0.61	0.89	1.16	0.33	0.62	0.90	1.18
B4**	0.05	0.32	0.57	0.99	1.35	0.28	0.50	0.72	0.93	0.49	0.91	1.33	1.75

Fig. 2. Schematic drawing of high temperature microscope.

sumed are almost the same. This means that the following results could still be valid, even if some changes in operational condition occur. Five levels of flux injection—none, low, medium, high and very high—are considered for BOF slag, burnt lime and burnt dolomite, respectively. **Table 2** shows the different amounts of fluxes to be injected; corresponding to the different injection levels. The coke ash and coal ash obtained are first mixed according to the ratios obtained from the calculation results. To make a specimen representing the tuyere slag at a certain level of flux injection, corresponding amounts of the ash mixture obtained and slag former are mixed and ground in a mortar. The chemical compositions of the specimens stated in **Table 3**, corresponding to different injection levels of fluxes, are obtained from the weight and chemical analyses of materials used. The chemical composition is also analysed and the table is corrected based on this.

The test method used is a standard method used to determine the melting properties of the slag in coal and coke.¹²⁾ **Figure 2** shows a schematic drawing of the high-temperature microscope used. A control unit controls the temperature. The difference between the temperature demanded by the heating programme and the one measured by the thermocouple is used to adjust the electrical current that should

be supplied to the furnace. The furnace can be heated up to a maximum temperature of about 1640°C and a heating rate of 10°C/min is used at temperatures exceeding 700°C. A small specimen, about 2 mm square and 3 mm high, is used for each test. The sample is placed on an alumina plate on the sample-holder, in which the thermocouple is positioned, and observed with the microscope during heating in a nitrogen atmosphere. To prove that the specimen is not oxidised during the test, one specimen of α -iron is melted in the furnace using the same procedure. The oxygen analysis shows that no substantial oxidation occurred. The oxygen content of the iron is 0.014% before the test and 0.15% after the test.

Sketches of the samples are constantly drawn to show the changes in the shapes of the samples during heating. The temperatures of softening, active melting and flow point are registered. The definitions of these temperatures are as follows.

- Softening: The contour of the sample gets smooth and no sharp border can be distinguished.
- Active melting: The melting is rapid and the shape of the specimen changes quickly.
- Flow point: The material flows out and the height of the specimen decreases to 1/3 of its original height.

Fig. 3. Contour of sample at start of test (a), softening (b), active melting (c) and flow point (d).

Figure 3 shows an example of the course from softening to flow out of a specimen. In fact, the shapes of the specimens are different for different specimens during softening and melting depending on the viscosity, surface tension and wetting behaviour of the slag formed during melting. The specimens sometimes swell and sometimes shrink in addition to softening. Some specimens kept their shape during early melting, while others very quickly became bell-shaped.

To find out if the method produced results comparable to other data some samples were also tested by DTA—differential thermal analysis. In general, the two methods give approximately the same results, except in the case of high viscosity samples that flow out at a temperature considerably higher than the melting temperature. The melting temperature of BOF slag measured in an air atmosphere is 1 310–1 330°C when measured with DTA; measured in the high temperature microscope, the temperatures are 1 310°C, 1 340°C and 1 350°C for softening, melting and flow point, respectively. The melting points of three samples, corresponding to a high injection level of BOF slag, burnt lime and burnt dolomite, respectively, are also measured by DTA in an air atmosphere. The melting temperatures measured with DTA are in the same temperature interval as those measured in the high temperature microscope, except for the sample containing BOF slag. The lower melting temperature measured by DTA as compared to that measured by the high-temperature microscope might be explained by the fact that an air atmosphere was used in the DTA, while an N_2 atmosphere was used in the high temperature microscope. The sample with BOF slag contains both Fe_{met} and Fe^{2+} that can be oxidised in the air atmosphere. The reproducibility of measurement in the high temperature microscope is good with homogeneous samples of low viscosity; the difference between repeated samples is less than 10°C.

3. Theoretical Estimations

Melting temperatures are estimated by calculations done by the computer program Chemsage¹³⁾ using a thermodynamic data file^{14–19)} for multi-component slags. The model used has no data for P_2O_5 or V_2O_5 . The N_2 atmosphere is assumed to be as in the laboratory measurements. Estimations are made both with and without a metallic iron phase present and the calculation results are found to be the same for both conditions. Estimations are made for the chemical compositions of tuyere slag stated in Table 3.

Table 4. Temperatures for softening, active melting and flow out of measured in the high temperature microscope.

Sample	Softening	Active melting	Flow point	Melting interval
Coke ash	1567	1593	1608	41
Coal ash	1331	1350	1430	99
BOF slag	1305	1347	1364	59
No inj. of fluxes	1435	1477	1570	135
Low BOF slag	1215	1245	1290	75
Medium BOF slag	1200	1223	1245	45
High BOF slag	1207	1217	1225	18
Very high BOF slag	1196	1203	1241	45
Low lime	1206	1298	1408	202
Medium lime	1193	1203	1337	144
High lime	1163	1198	1219	56
Very high lime	1185	1213	1250	65
Low dolomite	1200	1215	1253	53
Medium dolomite	1185	1200	1290	105
High dolomite	1163	1229	1330	167
Very high dolomite	1210	1297	1395	185

4. Results

4.1. Melting-point Measurements

The results of melting-point measurements are summarised in Table 4. The coke ash has the highest softening and melting range—from 1 567 to 1 608°C, while that of the coal ash is much lower—from 1 300 to 1 430°C, and the BOF slag from 1 305 to 1 364°C. A sample consisting of a mixture of coke ash and coal ash has higher softening and melting points than a sample of coal ash, while the softening and melting points are lower than those of coke ash on its own.

The results also show that the presence of BOF slag, burnt lime or dolomite in the specimens lowers the melting temperature significantly. The BOF slag also decreases the softening and melting temperature interval for all injection levels, while the lime gives some decrease only in the two cases, with high and very high injection rate, and the dolomite gives a decrease only in the case with a low injection level. The result is shown in Table 4 and Fig. 4. For the specimens corresponding to low and medium injection levels of burnt lime and high and very high injection levels of dolomite, the samples started softening at rather low temperatures and the temperature intervals between softening and flow out were much wider than for other samples. On the contrary, the specimens containing BOF slag, especially the one corresponding to the high injection rate, melted very quickly and actively. Some of the specimen material even ripped off during melting, indicating a very low melt viscosity. The samples containing BOF slag normally formed a flat bell during melting, while the samples containing lime formed a hemisphere. All samples start to melt at the top of specimens and the slag melt formed is wetting the alumina substrate for all specimens tested. The differences in the melting properties of the specimens with BOF

slag, lime and dolomite can also be clearly seen in Fig. 4. The introduction of BOF slag has a more beneficial effect on the decrease in the softening and melting temperature interval than the introduction of burnt lime and dolomite

As shown in Table 3, the amounts of BOF slag and burnt lime have been chosen equitably to generate tuyere slags with the same basicity B2 ($B2 = \text{wt\%CaO}/\text{wt\%SiO}_2$). However, if the MgO and Al_2O_3 contents in the slags are included and considered as CaO and SiO_2 on a molar basis, the values of basicity B4 ($B4 = [(\text{wt\%CaO} + 1.4\text{wt\%MgO})/(\text{wt\%SiO}_2 + 0.59\text{wt\%Al}_2\text{O}_3)]$) for the slags formed will be quite different for the specimens containing BOF slag, burnt lime and dolomite, respectively. Due to a high MgO content, especially the specimens containing dolomite, but also the ones containing BOF slag, will have much higher basicity B4 than the specimens containing lime. For instance, three samples with almost the same basicity B2, 1.17 for the BOF-doped specimen, 1.16 and lime-doped specimen and 1.18 for the dolomite-doped specimen, differ considerably with respect to basicity B4; 1.35 for the BOF-doped specimen, 0.93 for the lime-doped specimen and 1.75 for the dolomite-doped one. This means that injection of BOF slag, lime and dolomite will give different basicity B4 in tuyere slag, although basicity B2 is the same.

Fig. 4. Measured softening and flow out temperatures of the specimens based on no injection and injection of BOF slag (a), burnt lime (b) and burnt dolomite (c). The basicity B4 on the x-axis corresponds to the different injection levels.

Injection of BOF slag will give the tuyere slag an intermediate basicity B4, compared to lime and dolomite, but still with a rather low melting point and a narrow temperature interval. This implies that the injection of BOF slag, as compared to injection of lime, might also be more beneficial for desulphurisation in front of the tuyeres. If the softening and melting temperatures are compared based on approximately the same basicity B4, the addition of BOF slag gives the same or lower flow point as compared to addition of lime or dolomite. The softening and melting temperature interval of the specimens containing BOF slag is also narrower.

4.2. Theoretical Estimations

As can be seen in Table 5 the estimations show that the BOF slag decreases the melting temperature for all injection levels assumed, while burnt lime and burnt dolomite increase the temperature of start of melting. The temperatures corresponding to 85% melt formed from the mixture decrease for all additions of fluxes. The temperature interval for melting is narrower when fluxes are added to the mixture of coal and coke ash. The proportion of melts formed at 1650°C increases when fluxes are added. Examples of this can be seen from the melting curves in Figs. 5, 6 and 7 shows the chemical composition of the slag melt formed. The first melt formed is in general a low-basicity slag melt, which contains the main part of the manganese and iron oxides. When an increased temperature is assumed, mainly CaO, but also MgO and Al_2O_3 , are dissolved into the slag melt. The final basicity achieved in the tuyere slag depends on the assumed injection level of fluxes.

5. Discussion

5.1. Differences between the Specimens Containing BOF Slag, Lime and Dolomite

According to the laboratory results obtained, the improvement of slag formation in front of the tuyeres can be expected if injection of fluxes into the blast furnace is used. Although BOF slag, lime and dolomite can decrease the melting point of the tuyere slag significantly, it seems that the injection of BOF slag improves the properties of the tuyere slag more than does the injection of lime or dolomite, in terms of lower melting point and narrower temperature interval between softening and flow out and possibly also a lower viscosity, at all injection levels studied.

This may be explained by the following reasons.

(a) The BOF slag contains a larger amount of components such as FeO, MnO, TiO_2 and V_2O_5 that are included

Table 5. Estimated temperatures for first melt formed and the ratio of melt at 1650°C.

	BOF slag			Burnt lime			Burnt dolomite		
	First melt, temperature °C	> 85% melt temperature °C	Ratio of melt at 1650°C	First melt, temperature °C	> 85% melt temperature °C	Ratio of melt at 1650°C	First melt, temperature °C	> 85% melt temperature, °C	Ratio of melt at 1650°C
None	1100	1500	86%	1100	1500	86%	1100	1500	86%
Low	1050	1250	91%	1100	1400	89%	1100	1350	92%
Medium	1000	1300	97%	1250	1350	94%	1100	1350	99%
High	1000	1250	100%	1250	1400	99%	1150	1400	98%
Very high	1000	1350	98%	1250	1400	99%	1150	1450	99%

Fig. 5. Ratio of slag melt and main chemical composition of the slag melt formed at the high injection level. From top to bottom injection of BOF slag (a), burnt lime (b) and burnt dolomite (c) respectively.

Fig. 6. Estimated ratio (%) of melt formed, at different temperatures, in tuyere slag specimens corresponding to no injection of fluxes and low injection level of fluxes.

in neither the basicity formulas nor in the phase diagrams. These components could further decrease the melting point or/and the viscosity of the slag formed. Estimations in Chemsage show that the first slag melt formed is a low basicity slag containing the main part of the iron and manganese oxides.

(b) The BOF slag injected is a slag already formed in the converter and having a comparatively low melting point, while the burnt lime used has a high content of CaO and the dolomite used has a high content of CaO and MgO, both of which have a much higher melting point. Therefore, the former will be re-melted and dissolved into other components much easier than the latter two, which probably require more time and an even higher temperature for dissolution.

(c) The concentration of alumina in the tuyere slag will be lower in the case of BOF slag injection than in the case of lime injection, because a larger amount of BOF slag is needed compared to that of lime to give the same basicity B2 in the tuyere slag. The concentration of alumina will also be lower with BOF slag injection as compared to dolomite injection, although the difference is smaller.

5.2. Comparison of Measured Melting Temperatures and Melting Temperatures Estimated with Chemsage

The results from melting-point measurements and from

Fig. 7. Estimated ratio (%) of melt formed, at different temperatures, in tuyere slag specimens corresponding to no injection of fluxes and high injection level of fluxes.

estimations of melting points with Chemsage are compared in Fig. 8. The flow-out temperature is compared with the estimated temperature for >85% of melt formed in the computer calculations. When comparing these results it is important to realise that the relationship between the amount of melt formed and flow out is effected by the viscosity of melt just above the melting temperature. The correlation is quite good for BOF slag. For burnt dolomite the tendency of the curves for measured and estimated values is the same, but the estimated temperatures are higher, except for the case without injection of fluxes. The correlation for the cases with low and medium injection level of burnt lime is good, but the difference is quite large in the case of high and very high injection levels. The reason might be a partial dissolution of burnt lime into the slag melt. It could be expected that the BOF slag dissolves into the slag melt better than burnt lime and burnt dolomite, as a result of the lower melting temperature of the former. There is a risk that the burnt lime and burnt dolomite are not totally dissolved into the slag melt and therefore the melting temperature interval will correspond to a lower injection level than assumed.

5.3. Quaternary Systems of $\text{Al}_2\text{O}_3\text{--CaO--MgO--SiO}_2$ and of $\text{Al}_2\text{O}_3\text{--CaO--FeO}_x\text{--SiO}_2$

The chemical compositions of the specimens according to Table 3 are transferred into four main oxides; CaO, MgO, SiO_2 and Al_2O_3 and CaO, FeO, SiO_2 and Al_2O_3 , respectively. Estimations of melting temperatures according to the phase diagrams²⁰⁾ and by calculations in Chemsage are listed in Table 6.

5.3.1. Estimations Based on Phase Diagrams

The values estimated from phase diagrams²⁰⁾ of the $\text{Al}_2\text{O}_3\text{--CaO--MgO--SiO}_2$ and $\text{Al}_2\text{O}_3\text{--CaO--FeO}_x\text{--SiO}_2$ systems are generally higher than the measured results, except for the estimations made with the latter system for two specimens corresponding to a high injection level of BOF slag or burnt dolomite. Estimations based on the quaternary system $\text{Al}_2\text{O}_3\text{--CaO--FeO}_x\text{--SiO}_2$ differ less from the measured values compared to estimations based on the $\text{Al}_2\text{O}_3\text{--CaO--MgO--SiO}_2$ system. The considerable influence

of FeO on the melting point may explain the better correlation between the estimated and measured results when using the quaternary system $\text{Al}_2\text{O}_3\text{--CaO--FeO}_x\text{--SiO}_2$.

5.3.2. Estimations Made by Chemsage

The same data—normalised chemical composition based on four oxides—as used in the estimation of melting points by phase diagrams are used in estimations with the computer program Chemsage. The results can be seen in Table 6. In general, the data estimated by the phase diagrams are found in the melting interval calculated in Chemsage. One exception is the estimation for the chemical composition corresponding to no injection of fluxes. The calculations indicate that MgO and CaO increase the temperature for start of melting, but decrease the temperature of final melt out. If FeO is present, an increase in CaO content will decrease the start of melting temperature at low basicities and decrease the temperature for final melt out. If both the FeO content and the CaO content increase, the start of melting temperature will decrease at the same time as the temperature for final melt out is kept at a low and constant level.

6. Conclusions

A study has been carried out concerning the effect of tuyere-injected fluxes on the melting properties of tuyere slag using theoretical calculations and laboratory experiments. The results indicate that injection of fluxes improves the melting properties of tuyere slag in terms of increased basicity, decreased softening and melting temperatures and decreased softening and melting temperature interval. This will improve the drainage of slag from the raceway area of the BF. The results also show that, as compared to lime or dolomite, injection of BOF slag generally has approximately the same or a better effect on the tuyere slag properties mentioned for all injection levels tested.

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Fig. 8. Comparison of measured and estimated flow points.

Table 6. Comparison between the measured flow points obtained in this study and estimated values from phase diagrams (*) and estimations by calculations in Chemsage (**) of the quaternary systems of $\text{Al}_2\text{O}_3\text{--CaO--MgO--SiO}_2$ and $\text{Al}_2\text{O}_3\text{--CaO--FeO}_x\text{--SiO}_2$.

Tuyere slag mixture	Based on $\text{Al}_2\text{O}_3\text{--CaO--MgO--SiO}_2$		Based on $\text{Al}_2\text{O}_3\text{--CaO--FeO}_x\text{--SiO}_2$		Measured flow point, °C
	Estimated* melting point, °C	Estimated** melting interval, °C	Estimated* melting point, °C	Estimated** melting interval, °C	
No injection of fluxes	1640	1200-1500	1680	1200-1500	1570
Low injection of BOF slag	1400	1200-1400	1390	1150-1350	1290
Medium injection of BOF slag	1350	1250-1350	1320	1150-1350	1245
High injection of BOF slag	1360	1300-1400	1210	1100-1350	1225
Very high injection of BOF slag	1460	1300-1400	1330	1050-1350	1241
Low injection of burnt lime	1500	1250-1450	1450	1150-1450	1408
Medium injection of burnt lime	1390	1250-1450	1370	1150-1400	1337
High injection of burnt lime	1350	1350-1400	1300	1300-1400	1219
Very high injection of burnt lime	1440	1350-1450	1350	1300-1450	1250
Low injection of burnt dolomite	1400	1200-1350	1450	1150-1450	1253
Medium injection of burnt dolomite	1390	1300-1450	1380	1150-1400	1290
High injection of burnt dolomite	1495	1400-1550	1300	1300-1400	1330
Very high injection of burnt dolomite	1680	1450-1550	1450	1300-1450	1395

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