

Phosphorus Partition in an Industrial Basic Oxygen Furnace Process in Ukraine

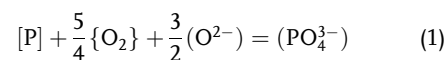
Olena Volkova, Nataliia Tinkova,* Rapuruchukwu Ifeyinwa Onaa, Lukas Neubert, Kostiantyn Niziaiev, and Dmytro Zotov

Dedicated to Professor Seshadri Seetharaman on the occasion of his 80th birthday

Phosphorus partition data from Ukrainian integrated steel plants are analyzed, focusing on the influence of parameters such as the basicity (CaO/SiO_2), optical basicity, tapping temperature, and the contents of (FeO), (MgO), and (Al_2O_3) in the slag. It is found that the phosphorus partition decreases with increase in tapping temperature and increases with the optical basicity. An increase in the phosphorus partition ($(\text{P})/[\text{P}]$) followed by a decrease with increase of (CaO/SiO_2) are observed. It is found that the optimal value, break point at which phosphorus partition changes its dependence to opposite, has a direct dependence on tapping temperature. At (CaO/SiO_2) = 1.9–2.1, ($(\text{P})/[\text{P}]$) increases linearly with increasing (FeO). However with higher value of (CaO/SiO_2) the breaking point when ($(\text{P})/[\text{P}]$) starts to decrease with increase in (FeO) is noticed. Thereby the optimal value of (FeO) decreases with increasing tapping temperature. In case of (Al_2O_3) there is only decreasing of ($(\text{P})/[\text{P}]$) with all (CaO/SiO_2) and tapping temperatures. Moreover, the effect of (MgO) varies with (CaO/SiO_2). These industrial results are supported by thermodynamic simulations using FactSage 8.1 and aligned with existing results from the literature.

hot-rolled high-strength sheet steel with 0.04 mass% $[\text{P}]$ and P-alloyed interstitial-free steel.^[1] In other steel grades, phosphorus may increase the probability of cold fractures, weldability, and ductility. The notched impact strength may also be decreased.^[2]

While the main source of phosphorus in steel production is iron ore, phosphorus can also be carried into molten metal from scraps, slag formers, or alloying compounds such as FeSi and FeMn . Phosphorus removal is an important task in primary steelmaking. The dephosphorization reaction between the molten metal and slag can be expressed in ionic form as^[3]



where $[\]$ is the molten metal, $\{\ \}$ is the gas, and $(\)$ is the slag. In general, the

molecular expression of the dephosphorization reaction is as follows.^[4]



The efficiency of phosphorus removal during primary steelmaking is generally evaluated using the phosphorus partition L_p (also referred to as the phosphorus distribution ratio or phosphorus distribution), phosphate capacity $C_{\text{PO}_4^{3-}}$, degree of dephosphorization, oxygen dephosphorization efficiency, and CaO dephosphorization efficiency.^[5,6] The results of industrial dephosphorization in a basic oxygen furnace (BOF) or electric arc furnace are generally analyzed using the phosphorus partition, L_p .

$$L_p = \frac{(\text{P})}{[\text{P}]^n} \quad (3)$$


where $n = 1$ for $(\text{P}) < (\text{P})_{\text{critical}}$ and $n = 2$ for $(\text{P}) > (\text{P})_{\text{critical}}$. The coefficient n depends on the chemical composition of the slag and the temperature. It also shows the form of the dephosphorization product. If $n = 1$, the product of the dephosphorization reaction is (P_2O_5) or a dimer $(\text{P}_2\text{O}_7^{4-})$. If the $n = 2$, the product of the dephosphorization reaction is $(\text{PO}_{2.5})$ or the monomer (PO_4^{3-}) . $(\text{P})_{\text{critical}} = 2$ mass% for the $\text{CaO-CaF}_2\text{-SiO}_2$ slag at

1. Introduction

Depending on the steel grade, phosphorus can be a useful alloy or harmful tramp element. In the presence of copper, phosphorus improves the resistance of structural steels to atmospheric corrosion. Examples of phosphorus alloying include

O. Volkova, N. Tinkova, R. I. Onaa, L. Neubert
Institute of Iron and Steel Technology
TU Bergakademie Freiberg
Leipziger Str. 34, 09599 Freiberg, Germany
E-mail: Nataliia.Tinkova@doktorand.tu-freiberg.de

K. Niziaiev, D. Zotov
Department of Iron and Steel Metallurgy
Ukrainian State University of Science and Technologies
av. Gagarin 4, 49005 Dnipro, Ukraine

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/srin.202400693>.

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1573 K and an oxygen partial pressure of 2.8×10^{-2} Pa.^[7] In the case of industrial dephosphorization, a real slag with $n = 1$ is used.

Since 1946, several researchers^[2,5,8–24] have experimentally investigated L_p . Consequently, many models have been developed for L_p as a function of the temperature and chemical composition of the slag components. A full review of the different L_p relations is provided in the literature^[25,26] and the experimental procedures for the determination of L_p are also reviewed.^[5] Previously reported experiments generally involve small metal or slag samples, typically weighing only a few grams. These samples were synthetic slags with varying metal/slag ratios, low (CaO/SiO₂) ratios, and oversaturation of MgO in a dense sintered MgO crucible. The experiments were conducted under inert gas atmospheres at temperatures below 1650 °C.^[5]

Most equilibrium studies of the phosphorus partition were conducted at temperatures of 1600 and 1650 °C, with (CaO/SiO₂) ratios of 1.5–2.5. Furthermore, the values calculated using the L_p equilibrium-based models were compared with the L_p values measured using real BOF slags.^[5] Thus, there were significant differences between the measured and calculated values of L_p , as well as between the calculated values obtained from different models. Moreover, studies on phosphorus partition with real industrial data have rarely been reported. Real industrial (P)/[P] ratios have been published by Hüttenwerke Krupp-Mannesmann GmbH (HKM, Germany)^[26] and BlueScope Port Kembla (Australia).^[25] Moreover, equilibrium-based models for L_p have been analyzed previously.^[25,26] Urban et al.^[26] concluded that equilibrium-based models do not represent industrial processes and that empirical models based on statistical evaluation must be developed to model and control dephosphorization in level-2 steel plants.

The objective of the present work is to study the phosphorus partition (P)/[P] of industrial heat from different integrated steel plants as a function of the tapping temperature, optical basicity, basicity (CaO/SiO₂), and (FeO), (Al₂O₃), and (MgO) content of the slags.

2. Industrial Dataset

A representative set comprising 25 710 BOF heats from Ukrainian integrated steel plants was selected for this study. Only heats with the following information were selected: 1) chemical composition of hot metal before charging; 2) chemical composition of crude steel and slag after oxygen blowing; 3) all masses of charged metallic materials and slag formers; 4) the temperature after oxygen blowing ends; and 5) oxygen consumption.

The melts omitted in these studies were as follows: 1) reblown according to the phosphorus content; temperature, etc. (re-blown heats); 2) blowing process interrupted; 3) oxygen-blowing process extended (overblown heats); and 4) unsatisfactory bottom mixing performance.

Table 1 shows the mean values and standard deviations of the hot metal set, phosphorus content of the hot metal, tapping temperature, slag amount, slag basicity (CaO/SiO₂), and chemical composition of the slag. Ukrainian steel producers use hot metal with phosphorus contents in the range of 0.045–0.085 mass%. The low phosphorus content of the hot metal and the availability of ladle furnaces allow Ukrainian steel plants to operate at low

Table 1. Mean values and standard deviations of some industrial parameters of 25 710 BOF heats investigated.

Parameter	Average value	Standard deviation
Hot metal set [kg/1 t crude steel]	854	34
Phosphorus content of hot metal [ppm]	585	70
Tapping temperature [°C]	1618	29
Slag amount [kg/1 t crude steel]	70	19
Slag Basicity	2.3	0.4
(CaO) [mass%]	46.85	2.70
(SiO ₂) [mass%]	20.97	2.82
(FeO) [mass%]	17.22	2.88
(P ₂ O ₅) [mass%]	1.25	0.17
(MgO) [mass%]	8.19	1.6
(Al ₂ O ₃) [mass%]	2.91	0.67
Phosphorus partition (P)/[P]	65	21

tapping temperature, low slag basicity, and high (MgO) content to protect the wear refractory lining of the BOFs. Because of bottom mixing, the FeO content is moderate. In addition, the low phosphorus content of the hot metal results in low slag amount. The slag amount in Table 1 was calculated from the Si balance of the 25 710 BOF heats investigated. This value is slightly distorted owing to the fluctuating chemical composition of the steel scrap used. The cumulative frequencies of the phosphorus content of the hot metal, tapping temperature, slag basicity, and phosphorus partition of the investigated 25 710 BOF heats are shown in **Figure 1**.

3. Results and Discussion

3.1. (CaO/SiO₂) and Optical Basicity

To analyze the influence of (CaO/SiO₂) on L_p , 4 978 BOF heats were selected at temperatures of 1595 to 1605 °C, 1645 to 1655 °C, and 1695 to 1705 °C with (CaO/SiO₂) varying from 1 to 4 (**Figure 2a**). As expected, the increase in (P)/[P] as the (CaO/SiO₂) ratio increased corresponded to a decrease in the elevated tapping temperature. Furthermore, the mean values of (P)/[P] as a function of (CaO/SiO₂) were calculated with a step of 0.25 for (CaO/SiO₂) and only for the datasets with at least ten heats (**Figure 2b**). Predictably, the optimum maximum value of (P)/[P] was found to depend on the (CaO/SiO₂). Thus, the maximum value of (P)/[P] shifts with increasing temperature in the range of higher (CaO/SiO₂) values. Specifically, the optimal value of (CaO/SiO₂) increased from 3.35 to 3.55 as the tapping temperature increased from 1595–1605 °C to 1645–1655 °C. Once the optimal value of (CaO/SiO₂) was attained, the (P)/[P] decreased significantly with a further increase in basicity. Similar equilibrium phosphorus partition behaviors from (CaO/SiO₂) at different (FeO) temperatures of 1600 and 1650 °C have been reported previously by Seetharaman et al.^[13,14] The optimum value of the (CaO/SiO₂) ratio for synthetic slag with (FeO) ≤ 15 wt% was found to be 2.5.^[13] In **Figure 2c**, the (P)/[P] values of Ukrainian integrated steel plants are compared with data from

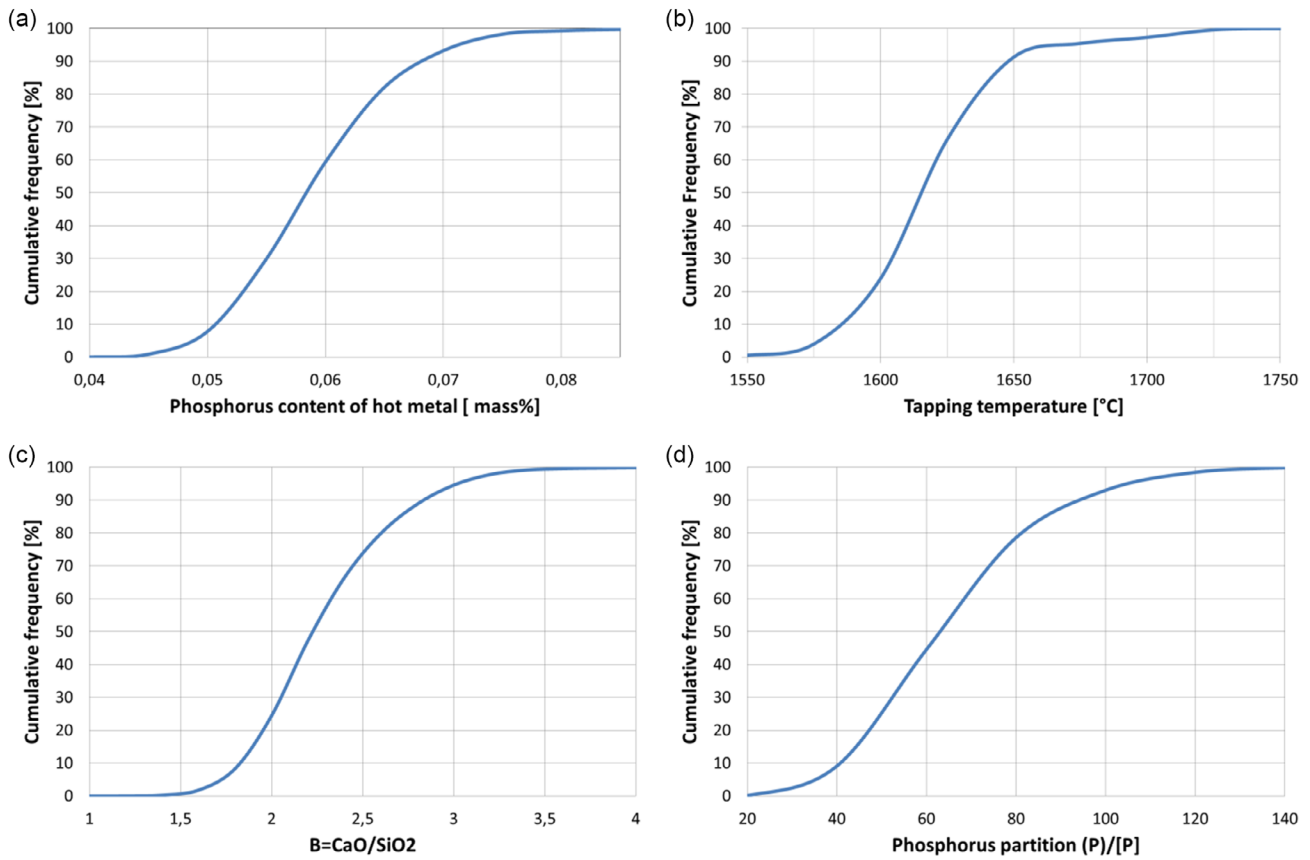


Figure 1. a) Cumulative frequency of phosphorus content of hot metal, b) tapping temperature, c) slag basicity, and d) phosphorus partition of the investigated 25 710 BOF heats.

the German steel plant HKM GmbH at comparable tapping temperatures and (FeO) values. Steel plants in Europe use Fe-rich iron ores from Brazil, Canada, and Australia. This yielded a hot metal phosphorus content between 0.060 and 0.090 mass%.^[26] The higher phosphorus content of the hot metal demands slags with higher basicity (CaO/SiO₂), higher tapping temperatures, and higher slag amounts. However, as shown in Figure 2c, the phosphorus partition (P)/[P] data from different Ukrainian and German integrated steel plants operating under different conditions complemented each other perfectly.

The equilibrium phosphorus partition (P)/[P] of industrial heats was calculated with FactSage 8.1 (FTOxid, all “Base-Phase”) using Macro Processing Program.

For estimation purposes, the chemical compositions of the crude steel, slag after oxygen blowing, and masses of crude steel and slag in real proportions were used. Moreover, the real tapping temperature was used in the calculations. Figure 2d shows a comparison between the actual industrial phosphorus partition and the calculated equilibrium (P)/[P] as a function of the (CaO/SiO₂) ratio. The estimated equilibrium values of (P)/[P] increased significantly with the (CaO/SiO₂) ratio. At (CaO/SiO₂) < 1.6, the calculated equilibrium (P)/[P] was lower than the industrial value. In contrast, at (CaO/SiO₂) > 3, the calculated equilibrium values were 3–9 times higher than those for industrial (P)/[P].

To analyze the change in (P)/[P] based on the optical basicity, the optical basicity was first determined using the coefficients for individual oxides reported by Mills and Sridhar.^[27] The optical basicity of the industrial slags examined was in the range between 0.7 and 0.84 (Figure 3a). In addition, the (P)/[P] increased with increasing optical basicity (Figure 3a). Here too, the mean values of (P)/[P] as a function of the optical basicity were determined with optical basicity in steps of 0.01 (Figure 3b). Thus, no maximum value of (P)/[P] from the optical basicity was observed for the investigated industrial heats.

3.2. Tapping Temperature

To investigate the influence of the tapping temperature on (P)/[P], only the heats with (CaO/SiO₂) ratios of 1.9–2.1, 2.4–2.6, and 2.9–3.1 were selected (Figure 4a). This corresponds to 9 823 BOF heats. The mean values for (P)/[P] as a function of temperature were calculated with steps of 10 °C (Figure 4b). The (P)/[P] decreased exponentially with increasing tapping temperature. Figure 4c shows a comparison of the (P)/[P] values of Ukrainian integrated steel plants based on the tapping temperature with previously reported values^[26] for comparable (CaO/SiO₂). As discussed, owing to the different [P] contents of hot metal, the tapping temperatures of Ukrainian and European steel plants

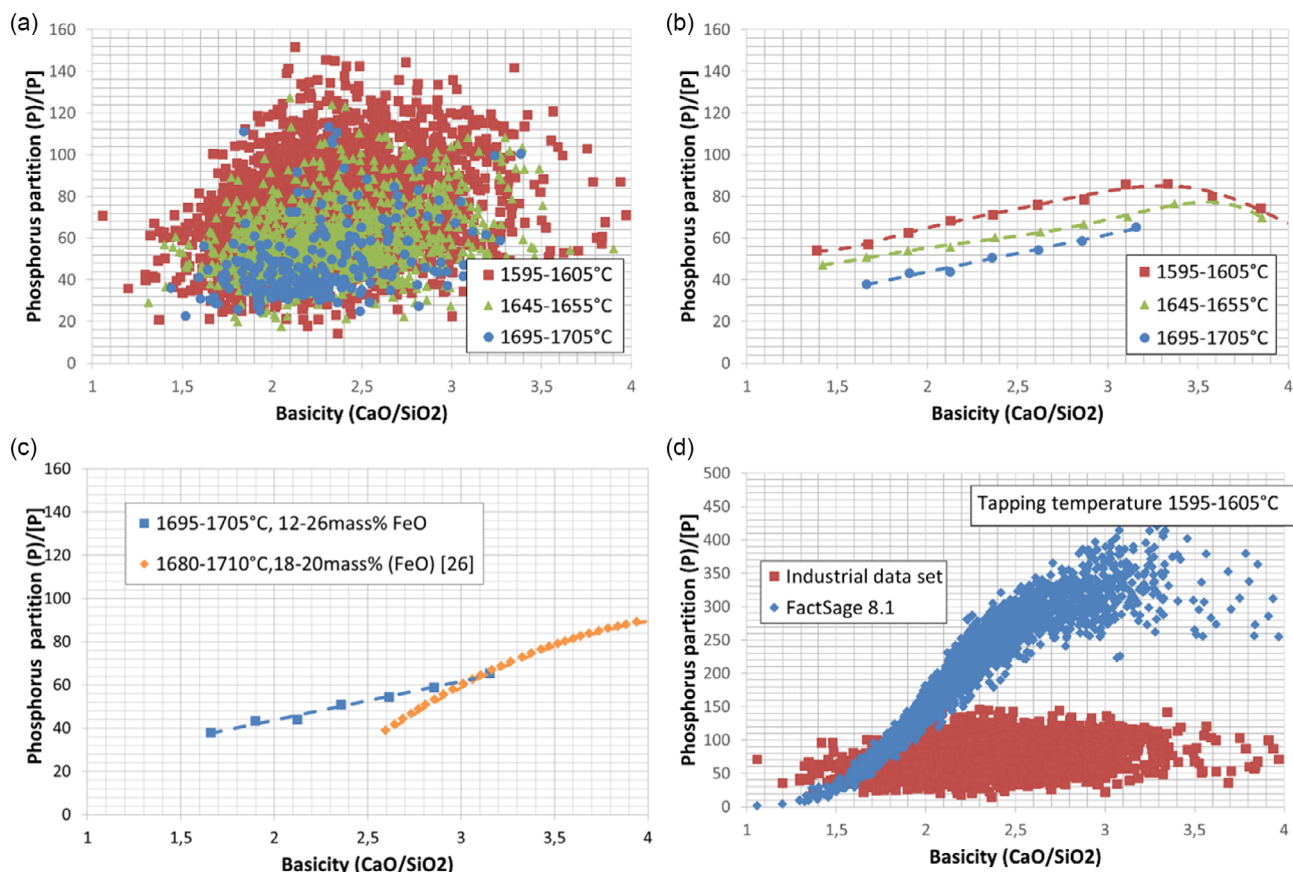


Figure 2. Phosphorus partition $(P)/[P]$ as a function of the basicity (CaO/SiO_2) . a) $(P)/[P]$ of industrial heats as a function of the (CaO/SiO_2) ratio and tapping temperature. b) Mean values of $(P)/[P]$ of industrial heats as a function of the (CaO/SiO_2) ratio and tapping temperature. c) Comparison of the mean values of $(P)/[P]$ of industrial heats in terms of tapping temperatures of 1695–1705 °C with literature values. d) Comparison of industrial $(P)/[P]$ with those calculated with FactSage 8.1 in tapping temperatures of 1595–1605 °C.

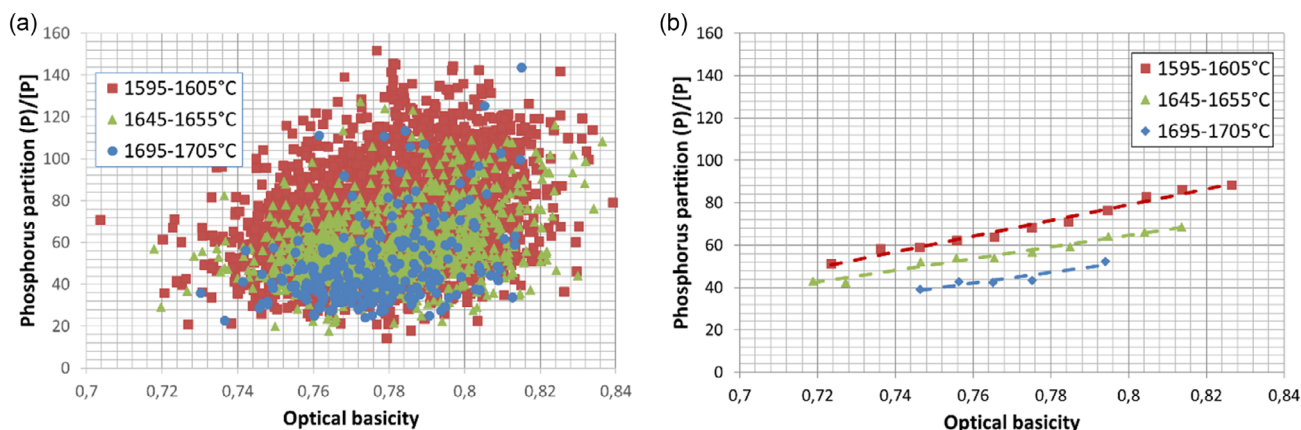


Figure 3. Phosphorus partition $(P)/[P]$ as a function of optical basicity. a) $(P)/[P]$ of industrial heats as a function of the optical basicity and tapping temperature; b) mean values of $(P)/[P]$ of industrial heats as a function of the optical basicity and tapping temperature.

differ significantly. However, the $(P)/[P]$ values based on the tapping temperatures fit perfectly and complement each other. Figure 4d shows a comparison between the calculated equilibrium phosphorus partition values and the industrial $(P)/[P]$. At tapping temperatures higher than 1675 °C, the calculated

equilibrium $(P)/[P]$ was less than or equal to the industrial values. Based on the results from Figure 2d and 4d, it can be concluded that the influence of (CaO/SiO_2) and the tapping temperatures on phosphorus partitioning in the FactSage 8.1 computations are overestimated.

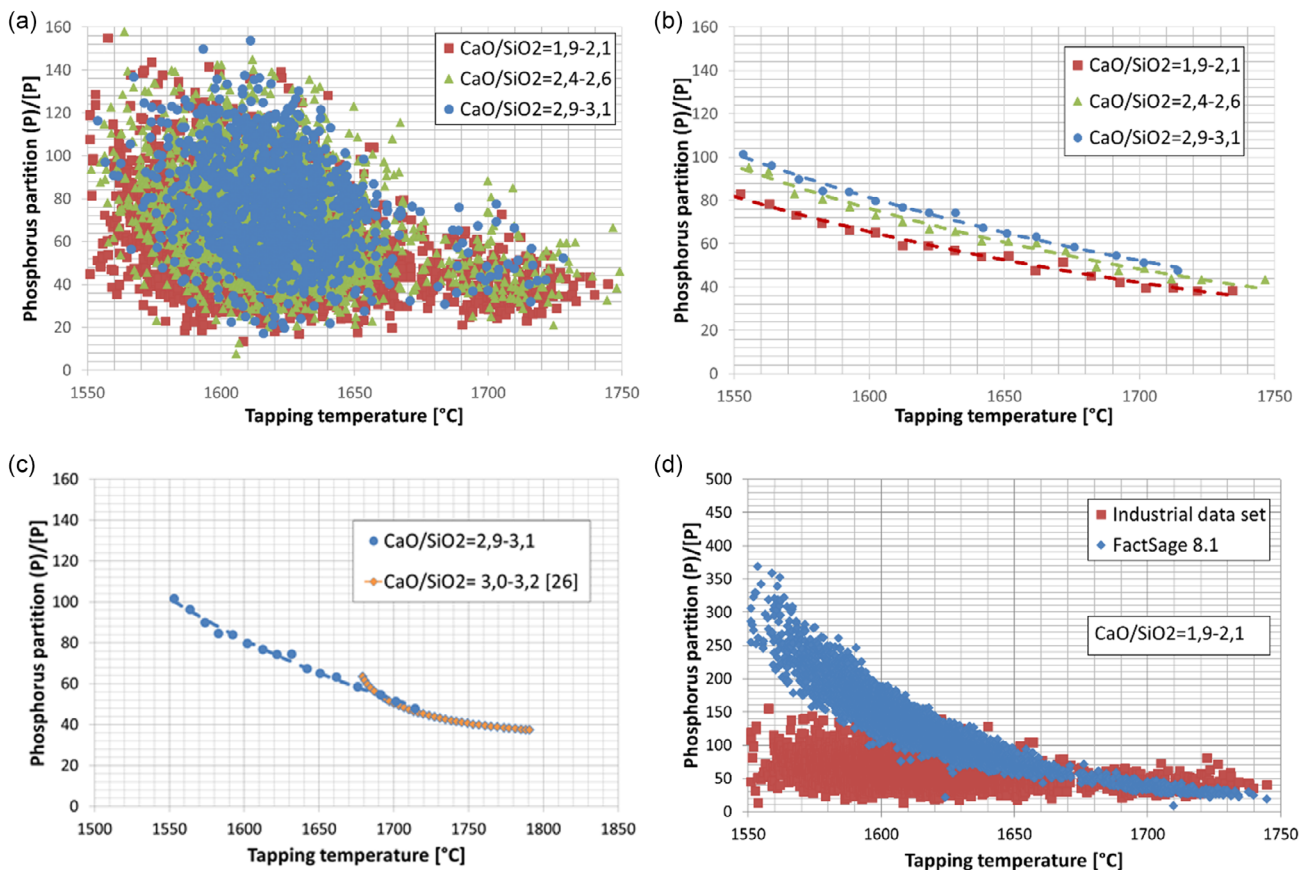


Figure 4. Phosphorus partition (P)/[P] as a function of the tapping temperature. a) (P)/[P] of industrial heats as a function of the tapping temperature and (CaO/SiO₂); b) mean values of (P)/[P] of industrial heats; c) comparison of mean values of (P)/[P] of industrial heats with (CaO/SiO₂) = 2.9–3.1 with previously reported values; d) comparison of industrial (P)/[P] with calculated with FactSage 8.1 with (CaO/SiO₂) = 1.9–2.1.

3.3. (FeO) of the Slag

To investigate the influence of (FeO) on (P)/[P], data were considered only for (CaO/SiO₂) of 1.9–2.1, 2.4–2.6, and 2.9–3.1 at tapping temperatures of 1595–1605 °C, 1645–1655 °C, and 1695–1705 °C. This corresponds to 1 887 BOF heats. The (FeO) content of the investigated industrial heats varied from 11 to 30 mass%. The mean (FeO) and (P)/[P] values were calculated using a step size of 1 mass% (FeO). However, the set with (CaO/SiO₂) = 2.9–3.1 and tapping temperature between 1695 and 1705 °C did not have sufficient heats. Therefore, mean values of (FeO) and (P)/[P] were not estimated for this set.

At (CaO/SiO₂) = 1.9–2.1, (P)/[P] increased linearly with the (FeO) content of the slag at all temperatures (Figure 5a,b). At higher (CaO/SiO₂) ratios, the maximum value of (P)/[P] was observed as a function of (FeO) (Figure 5c,d). Thereby the maximum value of (P)/[P] moves with increasing tapping temperature in the range of low (FeO). At (CaO/SiO₂) = 2.4 to 2.6, the optimal value of (FeO) decreases with increasing tapping temperature from 1595–1605 °C to 1695–1705 °C from 25 to 17 mass%. Similar (P)/[P] behavior from (FeO) has been reported by Basu et al.^[14] At (CaO/SiO₂) < 1.6, the phosphorus partition was practically independent of the (FeO) in the slag.^[14]

The variation of (P)/[P] with the (FeO) of the slag for (CaO/SiO₂) > 2.0 attained a maximum of ≈18–20 mass% (FeO) at 1600 and 1650 °C.^[14] An optimum (P)/[P] ratio, depending on the (FeO) of the slag between 25 and 30 mass% for a (CaO/SiO₂) ratio between 3.9 and 4.2, has been reported by Kovtun et al.^[5] The industrial data for (P)/[P]^[26] showed the maximum (FeO) between 22 and 24 mass%. The values of (P)/[P] computed with FactSage 8.1 at tapping temperatures between 1595 and 1605 °C as well as (CaO/SiO₂) = 1.9–2.1 indicate the same dependence on (FeO) as that of industrial (P)/[P] (Figure 5e). At higher tapping temperatures of 1695–1705 °C, the computed and industrial (P)/[P] are equivalent, which indicates an overestimation of influence of the temperature on (P)/[P] in the simulation using FactSage 8.1.

3.4. (Al₂O₃) of the Slag

When analyzing the influence of (Al₂O₃) on the (P)/[P] of industrial heats, the same 1 887 BOF heats were used as for (FeO) analysis. The (Al₂O₃) content in the industrial heats varied from 1.5% to 5%. The (Al₂O₃) in the slag mainly formed from the [Al] of the steel scrap used in the BOF. The mean values for the phosphorus partition were calculated with a step of 0.5 mass%

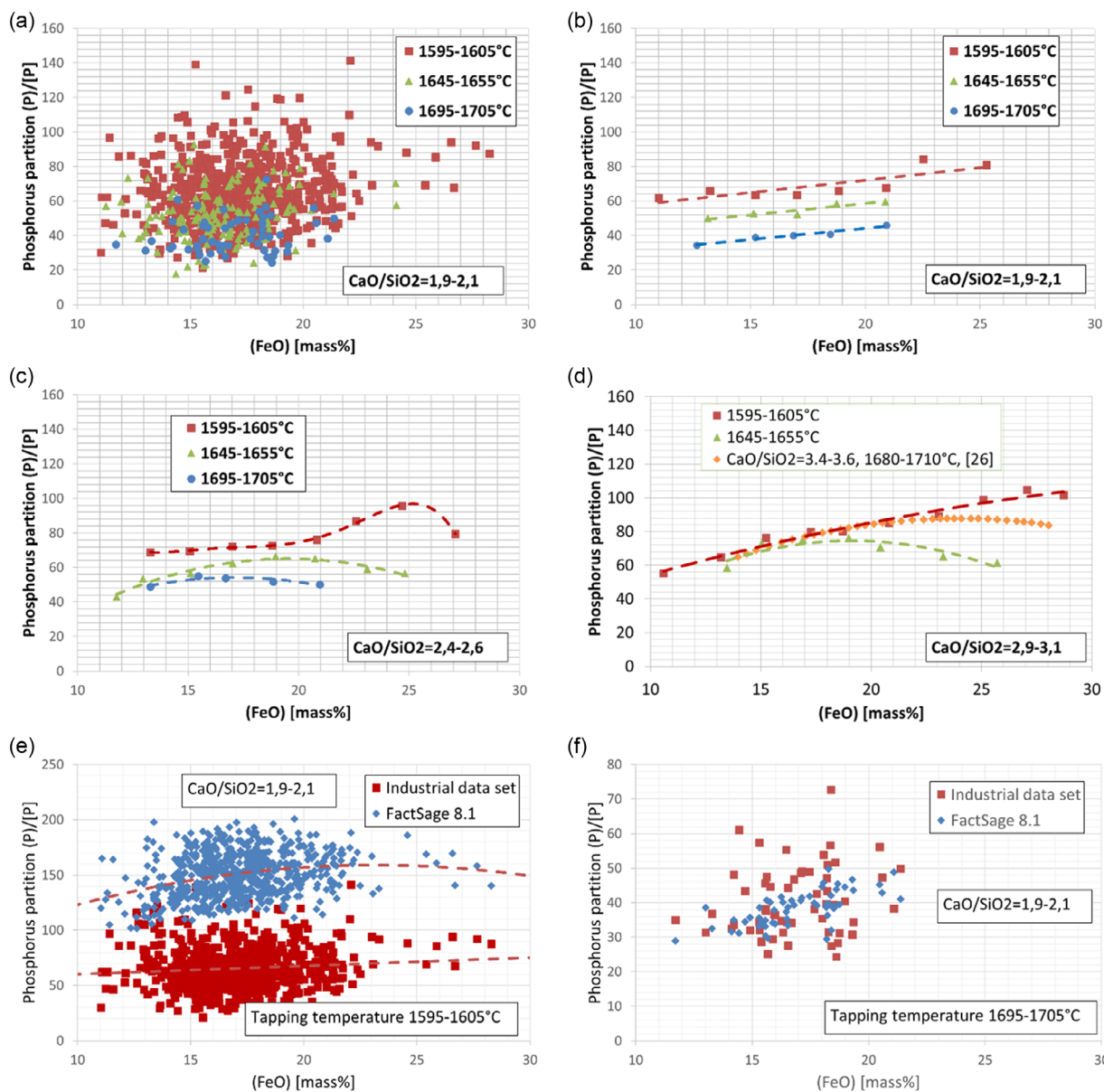


Figure 5. Phosphorus partition (P)/[P] as a function of (FeO). a) (P)/[P] of industrial heats as a function of the tapping temperature with $(\text{CaO}/\text{SiO}_2) = 1.9\text{--}2.1$. b) Mean values of (P)/[P] of industrial heats with $(\text{CaO}/\text{SiO}_2) = 1.9\text{--}2.1$. c) Mean values of (P)/[P] of industrial heats with $(\text{CaO}/\text{SiO}_2) = 2.4\text{--}2.6$. d) Mean values of (P)/[P] of industrial heats with $(\text{CaO}/\text{SiO}_2) = 2.9\text{--}3.1$ and (P)/[P] reported previously. e) Comparison of industrial (P)/[P] with that calculated using FactSage 8.1 with $(\text{CaO}/\text{SiO}_2) = 1.9\text{--}2.1$ and tapping temperature of 1595 to 1605 °C; f) Comparison of industrial (P)/[P] with that calculated using FactSage 8.1 with $(\text{CaO}/\text{SiO}_2) = 1.9\text{--}2.1$ and tapping temperature of 1695–1705 °C.

(Al_2O_3). From Figure 6a–d, it can be seen that (P)/[P] decreases with increasing (Al_2O_3) at all temperatures and $(\text{CaO}/\text{SiO}_2)$. At $(\text{CaO}/\text{SiO}_2) = 1.9\text{--}2.1$, (P)/[P] varied slightly with the (Al_2O_3) content of the slag. The trend lines for (P)/[P] were approximately parallel depending on the temperature. With increasing slag $(\text{CaO}/\text{SiO}_2)$, the influence of (Al_2O_3) on the (P)/[P] increases (Figure 6d). The same tendency in the variation of the influence of (Al_2O_3) on the phosphorus partition with the basicity of slag has been reported previously (Figure 6e). Figure 6e shows the equilibrium phosphorus partition for the slags with

$(\text{CaO}/\text{SiO}_2) = 2$ and $(\text{CaO}/\text{SiO}_2) = 3.9\text{--}4.2$ at the temperature of 1600 °C from.^[5,28] Thus, the dependence of the equilibrium phosphorus partition on (Al_2O_3) of the slag increases with increasing $(\text{CaO}/\text{SiO}_2)$ (slope of the red and blue trend lines). Figure 6f shows the comparison of the industrial phosphorus partition with the equilibrium values computed using FactSage 8.1 at tapping temperatures of 1595–1605 °C and $\text{CaO}/\text{SiO}_2 = 1.9\text{--}2.1$. Thus, the industrial (P)/[P] showed a similar tendency of variation with (Al_2O_3) as that of the equilibrium phosphorus partition calculated with FactSage 8.1.

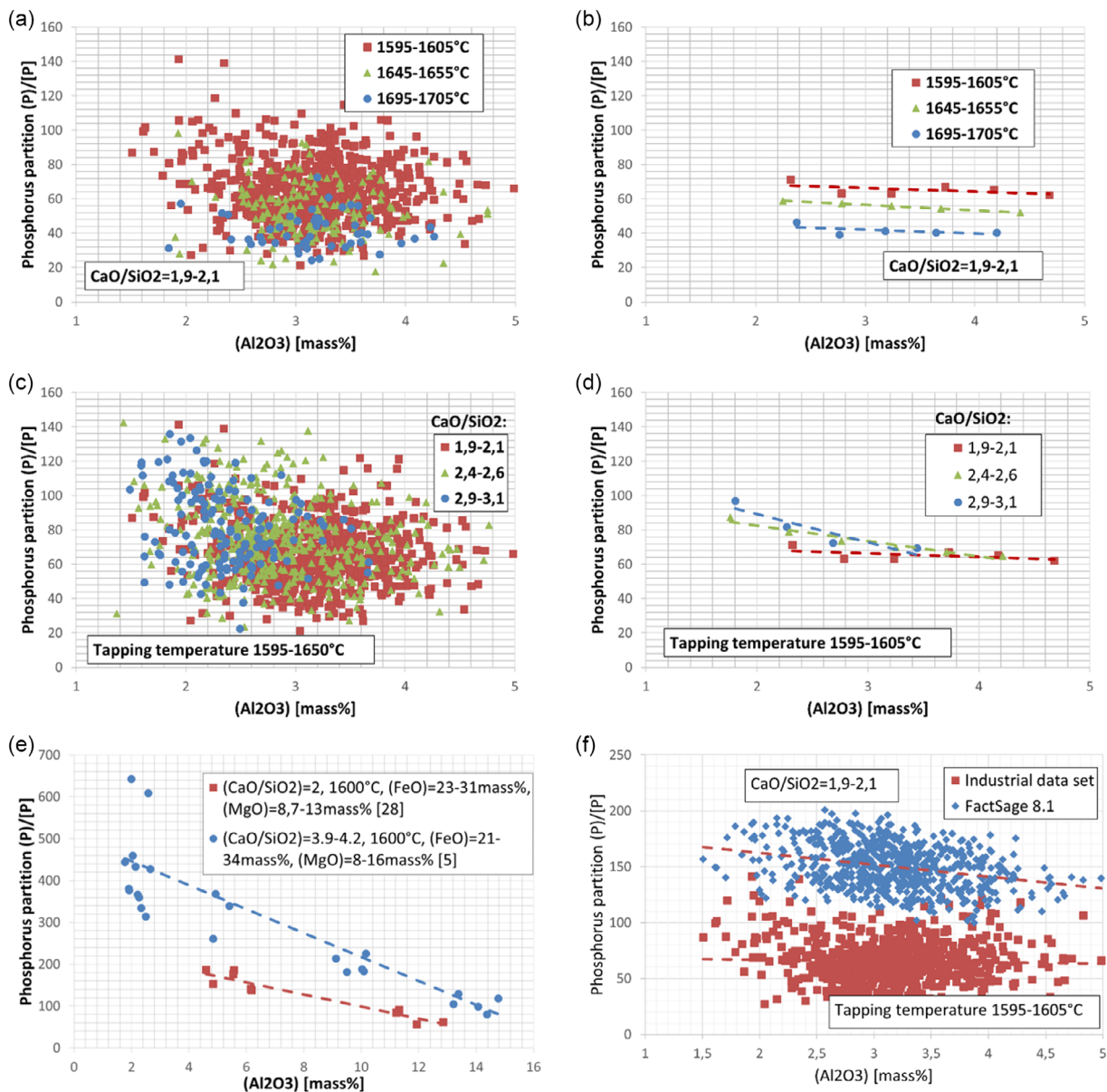


Figure 6. Phosphorus partition $(P)/[P]$ as a function of (Al_2O_3) . a) $(P)/[P]$ of industrial heats as a function of the tapping temperature with $(CaO/SiO_2) = 1.9-2.1$; b) mean values of $(P)/[P]$ of industrial heats with $(CaO/SiO_2) = 1.9-2.1$; c) $(P)/[P]$ of industrial heats as a function of (CaO/SiO_2) with tapping temperatures of 1595–1605 °C; d) mean values of $(P)/[P]$ of industrial heats as a function of (CaO/SiO_2) with tapping temperatures of 1595–1605 °C; e) $(P)/[P]$ as a function of (Al_2O_3) as reported previously; f) comparison of industrial $(P)/[P]$ with that calculated using FactSage 8.1.

3.5. (MgO) of the Slag

When analyzing the dependence of $(P)/[P]$ on (MgO) , the same 1 887 BOF heats were used as that for the (FeO) and (Al_2O_3) analyses. The (MgO) content of industrial heat varies from 1 to 16 mass%. (MgO) in the slag is attributed to slag formers and the dissolution of the wear refractory material of the BOF. The mean values of the phosphorus partition were determined with 1 mass% steps of (MgO) . At $(CaO/SiO_2) = 1.9-2.1$, the phosphorus partition decreased slightly with the (MgO) content of the slag at all tapping temperatures (Figure 7a–b). With

increasing (CaO/SiO_2) , the dependence of the phosphorus partition on (MgO) changed. At $(CaO/SiO_2) = 2.9-3.1$, the phosphorus partition increased with (MgO) of the slag at all tapping temperatures (Figure 7a,c). Such diverse influences of (MgO) on $(P)/[P]$ align with the findings in previous studies, as shown in Figure 7d, which shows the phosphorus partition of the slag with $(CaO/SiO_2) = 1.3$ to 2.5 and $(CaO/SiO_2) = 3.9$ to 4.2. Moreover, the phosphorus partition decreased with the slag (MgO) content at $(CaO/SiO_2) = 1.3$ to 2.5, and the $(P)/[P]$ of the slag increased with the (MgO) composition at $(CaO/SiO_2) = 3.9$ to 4.2. Figure 7e shows a comparison between the

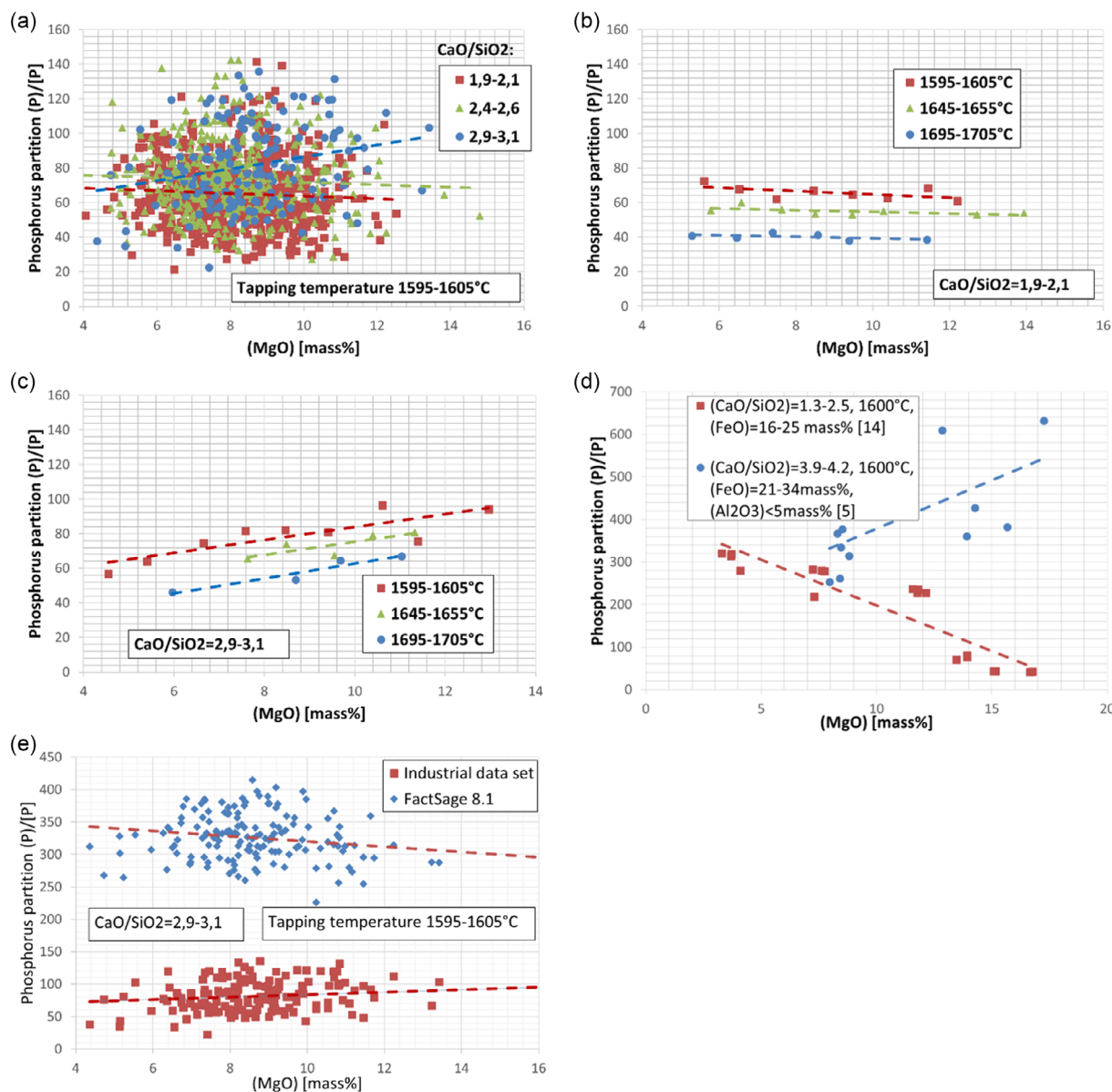


Figure 7. Phosphorus partition (P)/[P] as a function of (MgO). a) (P)/[P] of industrial heats; b) mean values of (P)/[P] of industrial heats with $(\text{CaO}/\text{SiO}_2) = 1.9\text{--}2.1$; c) mean values of (P)/[P] of industrial heats with $(\text{CaO}/\text{SiO}_2) = 2.9\text{--}3.1$; d) (P)/[P] as function of (MgO) from previous reports; e) comparison of industrial (P)/[P] with that calculated using FactSage 8.1.

industrial phosphorus partition and (P)/[P] computed using FactSage 8.1 with $(\text{CaO}/\text{SiO}_2) = 2.9$ to 3.1. Thereby the industrial and calculated tendencies of the (P)/[P] with change of (MgO) do not match each other.

It can be seen from Figure 2d, 4d, 5e, 6f, and 7e that the values of (P)/[P] calculated with FactSage 8.1 and industrial ones are very different from each other. It can be explained by lack of sufficient data of database FToxid which was used for equilibrium calculation. Thus, according to ref. [29], there are phase diagrams only for $\text{Al}_2\text{O}_3\text{--P}_2\text{O}_5$, $\text{CaO--P}_2\text{O}_5$, $\text{FeO}_x\text{--P}_2\text{O}_5$, $\text{MgO--P}_2\text{O}_5$, $\text{MnO--P}_2\text{O}_5$, $\text{CaO--Fe}_2\text{O}_3\text{--P}_2\text{O}_5$, $\text{CaO--MgO--P}_2\text{O}_5$, $\text{CaO--SiO}_2\text{--P}_2\text{O}_5$ systems, while industrial slags contain (CaO), (SiO_2) , (FeO_x) ,

(Al_2O_3) , (MgO), (TiO_2) , (MnO), and (P_2O_5) . Moreover, some of the available phase diagrams have a data for only temperatures: 1000, 1300, or 1600 °C. The unavailability of thermodynamic data in FToxid for different temperatures and for multicomponent oxidic systems can lead to strong differences between calculated and industrial (P)/[P] values and to discrepancy of the expected trends.

4. Conclusion

The effects of operating parameters such as the tapping temperature, $(\text{CaO}/\text{SiO}_2)$, optical basicity, and (FeO), (Al_2O_3) ,

and (MgO) compositions of slag on the phosphorus partition of 25 710 industrial heats from Ukrainian integrated steel plants with bottom stirring were investigated. Ukrainian integrated steel plants work with Ukrainian low-phosphorus iron ore, which results in low-phosphorus content in the hot metal. Due to this, steel plants operate within the BOF at low tapping temperature, low slag basicity, and moderate (FeO) and high (MgO) contents to protect the wear refractory lining. The industrial (P)/[P] were compared with phosphorus partitions of other integrated steel plants from previous studies. In addition, the influences of (CaO/SiO₂), (FeO), (Al₂O₃) and (MgO) were compared with those of known equilibrium values from literature. Moreover, the phosphorus partition of industrial heats was simulated using FactSage8.1 under oxygen blow-end conditions. The following conclusions are drawn from the results and discussion. 1) The phosphorus partition initially increases with increasing (CaO/SiO₂) slag but appears to decrease when (CaO/SiO₂) increases above an optimal value. The optimal value of (CaO/SiO₂) is a function of the tapping temperature. Moreover, optimal value of (CaO/SiO₂) relative to (P)/[P] increased with increasing temperature. The industrial (P)/[P] values at low and medium CaO/SiO₂ from Ukrainian integrated steel plants perfectly aligned with the (P)/[P] values at higher CaO/SiO₂ obtained from the HKM steel plant. 2) Increasing the optical basicity had a strong linearly increasing effect on phosphorus partition. 3) Similar to the equilibrium phosphorus partition, (P)/[P] of the industrial heats changed exponentially with the tapping temperature. With an increase in the tapping temperature, the phosphorus partition decreased exponentially. The industrial (P)/[P] values fit perfectly as a function of the tapping temperature and complemented the (P)/[P] values of other integrated steel plants operating at higher tapping temperatures. 4) The phosphorus partition at (CaO/SiO₂) = 1.9 to 2.1 increased slightly with the (FeO) content of the slag. With increasing (CaO/SiO₂), the dependence of (P)/[P] on (CaO/SiO₂) increased. Thus, optimum phosphorus partition depending on (FeO) was observed. The optimal value of (FeO) is a function of the tapping temperature and (CaO/SiO₂). With increase in the (CaO/SiO₂), the optimal value of (FeO) increased. With increasing tapping temperature, the optimal value of (FeO) decreased. 5) The phosphorus partition at (CaO/SiO₂) = 1.9 to 2.1 increased slightly with the (Al₂O₃) composition of the slag at all tapping temperatures. With an increasing (CaO/SiO₂), the dependency of (P)/[P] on (Al₂O₃) increased. 6) The influence of (MgO) changed with increasing (CaO/SiO₂). In case of (CaO/SiO₂) = 1.9–2.1 the phosphorus partition decreased with the (MgO) content of the slag. In other case, (P)/[P] increased with (MgO) at (CaO/SiO₂) = 2.9–3.1. 7) A comparison of the industrial (P)/[P] with equilibrium (P)/[P] estimated using FactSage 8.1 showed that the influence of the tapping temperature and (CaO/SiO₂) on (P)/[P] is over-estimated in the simulation using FactSage 8.1. The computed equilibrium (P)/[P] at higher tapping temperatures and lower (CaO/SiO₂) were smaller than those of the real industrial (P)/[P]. The computed equilibrium (P)/[P] at (CaO/SiO₂) > 3 was up to nine times higher than the real industrial phosphorus partition.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Keywords

basic oxygen furnace slags, CaO/SiO₂, phosphorus partitions, tapping temperatures

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