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Furnace structure analysis for copper flash continuous smelting based on numerical simulation

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Abstract: According to the innate characteristic of four types of furnace, the copper flash continuous smelting (CFCS) furnace can be considered a synthetic reactor of two relatively independent processes: flash matte smelting process (FMSP) and copper continuous converting process (CCCP). Then, the CFCS thermodynamic model was proposed by establishing the multi-phase equilibrium model of FMSP and the local-equilibrium model of CCCP, respectively, and by combining them through the smelting intermediates. Subsequently, the influences of the furnace structures were investigated using the model on the formation of blister copper, the Fe_3O_4 behavior, the copper loss in slag and the copper recovery rate. The results show that the type D furnace, with double flues and a slag partition wall, is an ideal CFCS reactor compared with the other three types furnaces. For CFCS, it is effective to design a partition wall in the furnace to make FMSP and CCCP perform in two relatively independent zones, respectively, and to make smelting gas and converting gas discharge from respective flues.

Key words: furnace structure; copper flash continuous smelting; numerical simulation; thermodynamic analysis

1 Introduction

For general copper production, there are two distinct steps, matte smelting and copper converting, in two separate furnaces.

The matte smelting of copper sulfide concentrates has been carried out in reverberatory furnace or electric furnace or blast furnace in earlier times, but it was revolutionized in the 1960s by the advent of the Outokumpu flash furnace [1−3]. Flash smelting has some significant advantages over conventional smelting, nevertheless, the matte produced in the flash smelting furnace is often transported to a separate converting furnace to produce blister copper. The periodic tapping and transportation of the matte from the flash smelting furnace cause fugitive emissions of SO_2 gases and some loss of heat energy.

So far, copper matte converting to blister copper is still dominated by Peirce-Smith converting, which is more than 100 years old. This technology is simple and reliable, but it has many well-documented disadvantages [4]. The Peirce-Smith converting of copper matte is a batch operation composed of several cycles in practice. Fugitive emission of SO_2 occurs during each cycle, and especially during discharging and charging the converter through the only one ‘mouth’ at the top of the furnace, which makes sulfur capture inefficient.

The flash converting technology developed by Kenne-cott Utah Copper Corporation (KUCC) and Outokumpu (now Outotec) has many advantages over conventional processing using Peirce-Smith converter [5]. Flash converting furnace can produce continuous off-gas flows at relatively high SO_2 contents because high levels of the oxygen enrichment can be utilized and the furnace is sealed. So it can achieve more than 99.8% sulfur capture [6]. However, the matte feed produced by other matte smelting furnaces, flash smelting furnace generally, must be granulated with water jets, ground and then dried thoroughly before entering the flash converting

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furnace, which involves additional energy [7,8].

Fortunately, some continuous copper smelting processes have been tried over the last few decades. Some of them are on a pilot plant scale and some are currently in operation. These processes are known as the Worcra, the Noranda, and the Mitsubishi processes.

For Worcra process [9], it is suggested to perform smelting and converting in a single furnace, with the matte and slag flowing countercurrent. However, there is no attempt to partition the furnace into distinct smelting and converting zones. After long pilot plant testing, the Worcra process failed to develop as an industrial process.

The Noranda process proposed the continuous production of blister copper and discardable slag in a cylindrical furnace equipped with tuyeres [10]. The proposed reactor is indicated as being composed of three zones (smelting, converting and slag cleaning), but without any distinct partition between these zones and under a common gas space throughout. However, industrial tests failed to produce discardable slags. Consequently, the Noranda process is not used to produce blister copper continuously, but high grade matte today.

The Mitsubishi process employs three inter-connected furnaces [11]. In this process, smelting is distinctly separated from converting, thus single stage converting is employed in a separate furnace in the presence of molten copper phase. However, the three-furnace concept maximizes heat losses. Further, the movement of molten materials from furnace to furnace leads to fugitive emission of SO_2 gas.

For today's copper production, a clean environment with low energy consumption is a desideratum. Based on these successful or failed experience for copper continuous smelting and the copper pyro-metallurgy principle, ZHANG [12] proposed a process and apparatus for continuous copper smelting, converting and producing blister copper in a single furnace, named copper flash continuous smelting technology (CFCST).

To understand the CFCST thoroughly and to design an efficient furnace for industrial application, massive researches have been done on the slag activities [13,14], the mathematic model, the metallurgical thermodynamics, the furnace structure and the technological parameters of the copper flash continuous smelting process.

In this work, the innate characteristic of the copper flash continuous smelting process will be analyzed according to four possible types of furnace. Then the thermodynamic model of the copper flash continuous smelting process will be developed, and be used to discuss the advantages and disadvantages of the structure of the four furnaces for copper continuous smelting.

2 Furnace description

According to the different flowing way of the molten smelting slag and the gas, the copper flash continuous smelting furnace can be classified into following four types.

2.1 Furnace with one flue but no slag partition wall

The furnace with one flue but no slag partition wall is named type A furnace and shown in Fig. 1.

For type A furnace, the copper concentrates are blended with fluxes, oxygen-enriched blast and other materials necessary, and then fed to the reaction shaft through a central burner. In the reaction shaft, the concentrate particles are melted and oxidized into a mixture of matte and slag while falling towards the settler. In the settler, the whole mixture is oxidized continually to produce blister copper by the airflow from a row of tuyeres settled along the settler's side walls. Then the blister copper and the slag exit through their discharge outlets respectively at the end of the furnace, and the gas takes off from the flue. It is suggested to perform smelting and converting in two zones, but

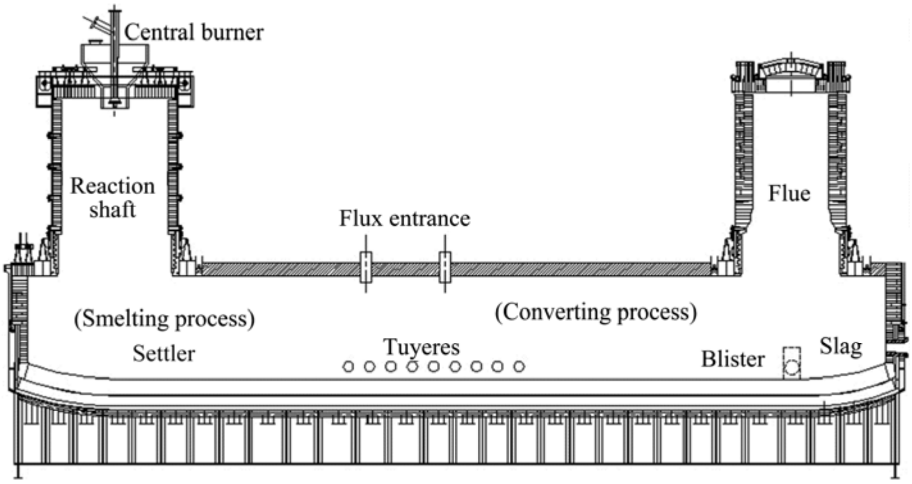

Fig. 1 Diagram of type A furnace with one flue but no slag partition wall

without any distinct partition between these zones and under a common gas space throughout, like the Noranda furnace.

2.2 Furnace with one flue and a slag partition wall

The furnace with one flue and a slag partition wall is named type B furnace and shown in Fig. 2.

Compared with type A furnace, there is a partition wall in the settler of type B furnace. The function of the partition wall is to prevent the smelting slag flowing into the right converting zone, but it cannot prevent the matte because there is a hole under the partition wall, neither can it prevent the gas due to the open space between the furnace roof and the partition wall. The smelting slag and the converting slag discharge from separated outlet located in smelting zone and converting zone, respectively.

2.3 Furnace with double flues but no slag partition wall

The furnace with double flues but no slag partition wall is named type C furnace and shown in Fig. 3.

For type C furnace, there is a partition wall in the settler, but the hole under the wall is so high that both the matte and the smelting slag can flow into the right converting zone, and there is no gap between the furnace roof and the partition wall, so the smelting gas can only takes off from the Flue 1, and the converting gas exits from the Flue 2.

2.4 Furnace with double flues and a slag partition wall

The furnace with double flues and a slag partition wall is named type D furnace and shown in Fig. 4. This type of furnace synthesizes the characteristics of type B and type C furnaces. For type D furnace, the partition wall can prevent the smelting slag and gas going through, so only the matte can flow into the converting zone.

It can be seen from what has been described above that, in essence, there are two interconnected processes, the flash matte smelting process (FMSP) and the copper continuous converting process (CCCP), in the copper

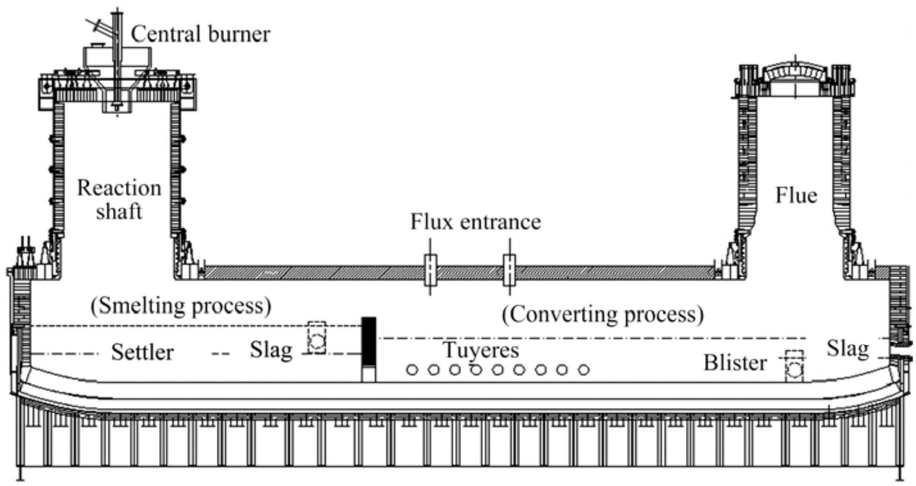

Fig. 2 Diagram of type B furnace with one flue and a slag partition wall

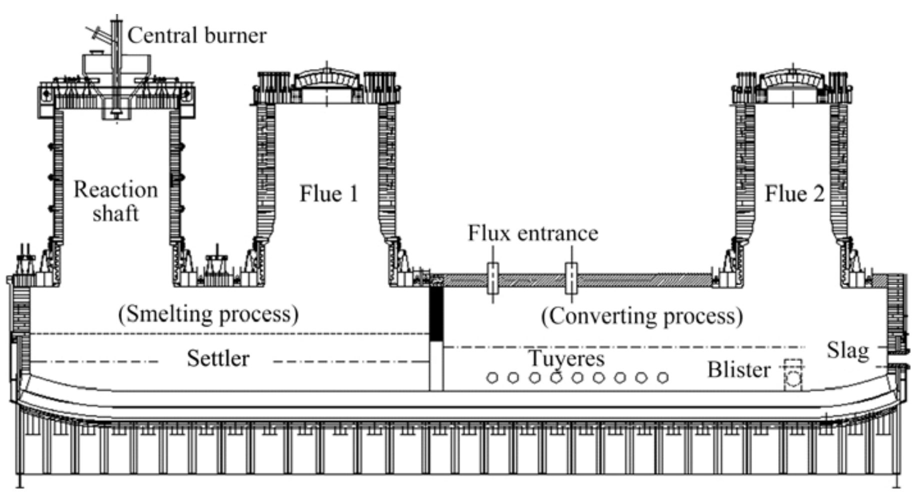

Fig. 3 Diagram of type C furnace with double flues but no slag partition wall

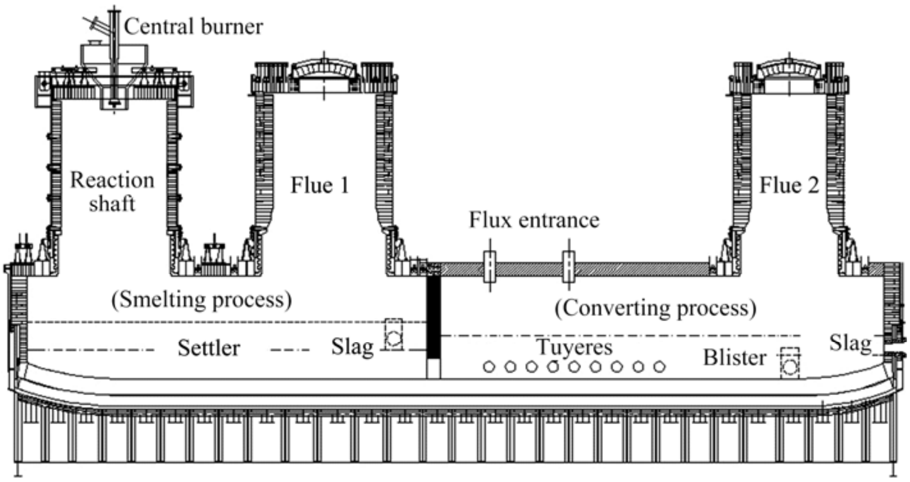

Fig. 4 Diagram of type D furnace with double flues and a slag partition wall

flash continuous smelting furnace. The two processes can perform continuously in two relatively independent partition zones. And the feed materials of the subsequent CCCP are all or part of the products of the preceding FMSP, depending on the structure of different furnaces.

Therefore, the thermodynamic model of the copper flash continuous smelting process can be developed by establishing the FMSP model and the CCCP model, respectively, and then combining them through the smelting intermediates.

3 Model description

3.1 Modeling principle

The model structure of the copper flash continuous smelting process is shown in Fig. 5.

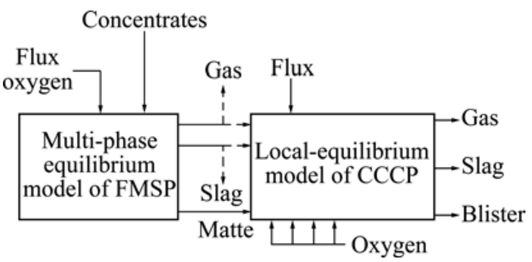

Fig. 5 Thermodynamic model structure of copper flash continuous smelting process

For the flash matte smelting process (FMSP), the matte reactions in the shaft are so fast and complete that it can be considered to be an approximate equilibrium system, which has been verified by many researches [15,16]. Therefore, based on the principle of Gibbs energy minimization [17,18], the multi-phase equilibrium model of FMSP can be established to predict the compositions of matter, slag and gas of FMSP.

For the copper continuous converting process (CCCP), it is assumed that all of the entering feed from the preceding FMSP is $\sum M_i$, forming a small system, within the time of Δt. When the converting process is ongoing continuously, at the macroscopic level, the overall system will move together towards the blister copper outlet at the end of the furnace while reacting with the flux and oxygen ceaselessly.

As to the kinetics of converting reaction, the practical data of some converting processes, such as Pierce-Smith converting, flash converting and fixed continuous converting, confirm that the copper converting reactions are complete and the oxygen utilization coefficient is more than 98% [19]. Thus, if Δt is little enough, it can be ensured that the $\sum M_i$ feed reacts completely with the fluxes and oxygen and achieves thermodynamic equilibrium continuously as moving towards the blister copper outlet.

Therefore, the copper continuous converting zone can be divided into a number of small parts along the flowing direction, and each of these parts is an equilibrium system. Thus the thermodynamic model of CCCP can be developed by establishing the multi-phase equilibrium models of each part.

3.2 Mathematical description

For the FMSP multi-phase equilibrium system or each equilibrium part of CCCP, the Gibbs energy is depicted as follows:

$$G=\sum_{p=1}^{P}\sum_{c=1}^{C_p}[x_{pc}G_{pc}^{\Theta}+RT\ln(\frac{\gamma_{pc}x_{pc}}{\sum_{k=1}^{C_p}x_{pk}})] \quad (1)$$

where P is the number of phases; C_p is the number of components in phase p; x_{pc} is the mole fraction of component c in phase p; G_{pc}^{Θ} is the molar Gibbs function at the standard state; γ_{pc} is the activity coefficient of the component c in phase p.

According to the principle of Gibbs energy minimization, the Gibbs energy G will reach its minimum value when the system achieves chemical equilibrium under the condition of constant temperature and constant pressure. Therefore, to solve the minimization problem of Eq. (1) can acquire the compositions of FMSP or each part of CCCP by means of Rand iteration algorithm [20] or element potential algorithm [21].

3.3 Calculation flowchart

The calculation flowchart of copper flash continuous smelting model is shown in Fig. 6.

For the multi-phase equilibrium model of FMSP, there are two layer iterations, one for the compositions x_{pc} and another for the activity coefficient γ_{pc}. The composition iteration is terminated when $\left|x_{pc}^{(n+1)} - x_{pc}^{(n)}\right| < \varepsilon_1$, where $\varepsilon_1 = 10^{-5}$, and the activity coefficient iteration is terminated when $\left|\gamma_{pc}^{(m+1)} - \gamma_{pc}^{(m)}\right| < \varepsilon_2$, where $\varepsilon_2 = 10^{-4}$.

However, for the local-equilibrium model of CCCP, there is a loop before two layer iterations similar to those in FMSP model. The loop is used to ensure the equilibrium, the calculation of each part of CCCP is processed. Here, the part number N_L can be deduced from the following formula:

$$N_L = \frac{V_{\text{total}}}{V_{\text{instant}}} \tag{2}$$

where V_{total} is the total consumption of oxygen during the converting process (m^3), and V_{instant} is the amount of oxygen blasted into the furnace from these tuyeres in just one second (m^3).

In the calculation process, the activity of some components or the quality of some phases will be used to judge whether one phase generates or disappears. For example, the blister phase can be regarded exists when the activity of Cu in matte is greater than 1.0, but the phase will disappear when its quality approaches 0.

4 Simulation results and discussion

Based on the thermodynamic model described above, the multi-factor coupled simulation of the copper flash continuous smelting process was carried out for the mixed feed shown in Table 1 under the operation parameters shown in Table 2.

4.1 Formation of blister copper

The effect of different furnace structures on Cu activity α(Cu) in matte is shown in Fig. 7.

It can be seen from Fig. 7(a) that, when the converting temperature is 1523 K, the Cu activity α(Cu) is increased with the increasing oxygen volume per ton concentrate (OVPTC), that means the entering feed flows towards the blister copper outlet at the end of the furnace. Interestingly, α(Cu) can reach 1.0 for type C and

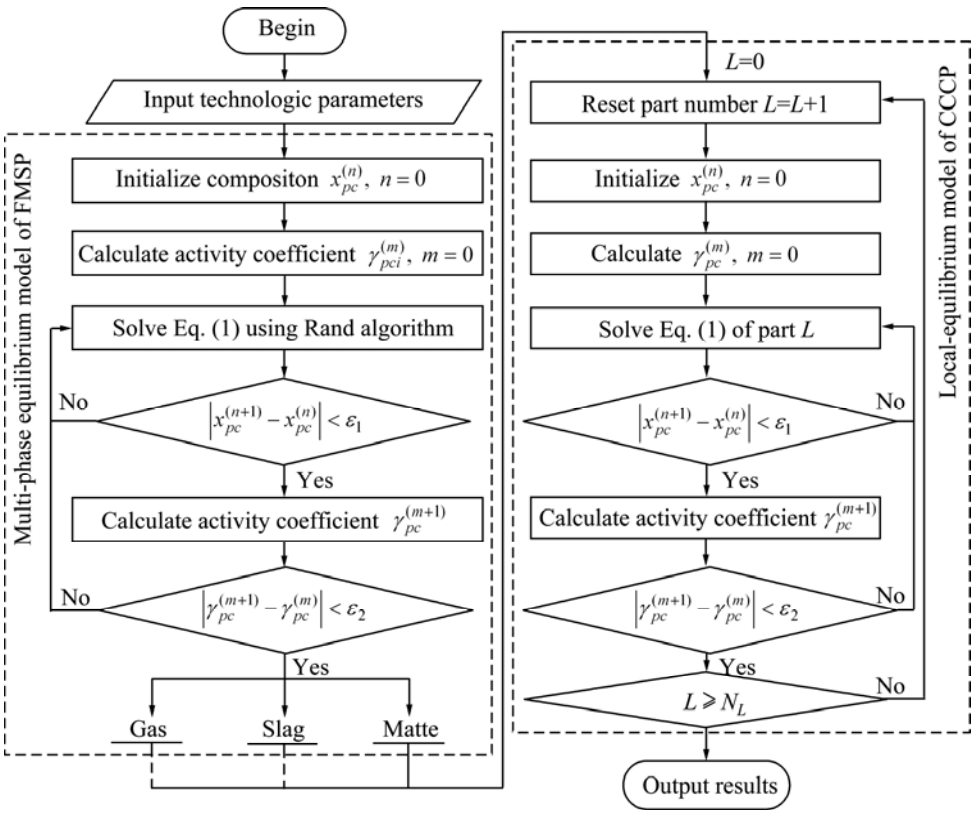

Fig. 6 Calculation flowchart of copper flash continuous smelting model

Table 1 Composition of mixed feed (mass fraction, %)

Cu	S	Fe	SiO_2	Other
28.40	28.01	26.26	6.82	7.99

Table 2 Operation parameters of CFCS

Feed loading rate/($t\cdot h^{-1}$)	Smelting temperature /°C	Matte grade/%	Converting temperature/°C
137.9	1190	64	1250, 1300

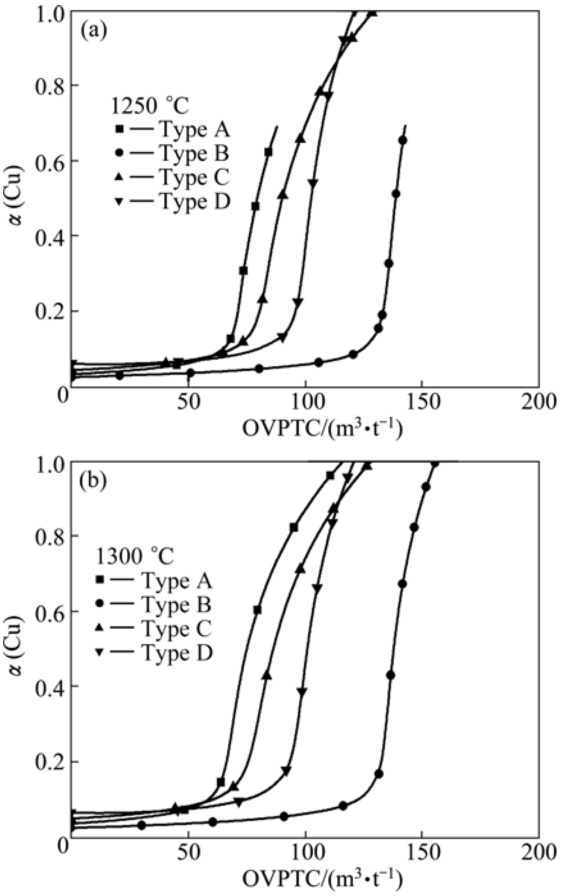

Fig. 7 Effect of furnace structure on Cu activity in matte

type D furnaces, but cannot for types A and B furnaces. The data indicate that the blister copper can be produced in types C and D furnaces but cannot in types A and B furnaces at 1523 K.

However, when the converting temperature rises to 1573 K, the blister copper can be produced in all four type furnaces seen from Fig. 7(b). That means the increase of temperature is useful for the formation of blister copper during converting process.

Consequently, the blister copper can form in types C and D furnaces more easily than types A and B furnaces under the same conditions. Take their structures into account, as shown in Figs. (1−4), to make smelting gas and converting gas discharge from separated flues is effective for copper flash continuous smelting.

4.2 Fe_3O_4 activity in converting slag

The effect of different furnace structures on the Fe_3O_4 activity in converting slag is shown in Fig. 8.

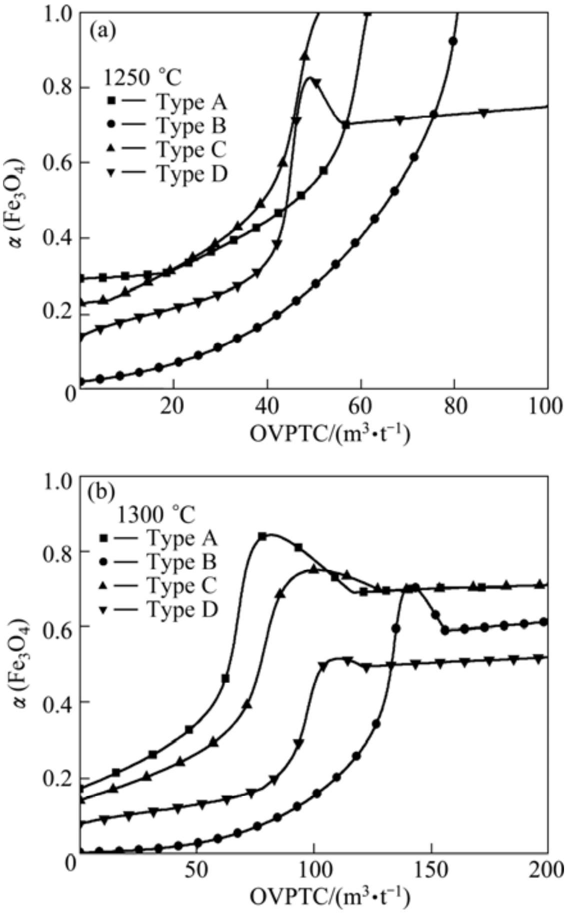

Fig. 8 Effect of furnace structure on Fe_3O_4 activity in converting slag

It can be seen from Fig. 8(a) that, when the converting is ongoing at 1523 K, only in type D furnace cannot the Fe_3O_4 activity $\alpha(Fe_3O_4)$ reach 1.0. In other words, Fe_3O_4 will be deposited during the converting process in types A, B and C furnaces, but not in type D furnace.

It also can be seen from Fig. 8(b) that $\alpha(Fe_3O_4)$ cannot reach 1.0 in all the four type furnaces when the temperature increases to 1573 K (1300 °C). That means the increase of temperature is also useful to preventing Fe_3O_4 depositing during converting process.

But it can also be found from Fig. 8(b) that $\alpha(Fe_3O_4)$ in type D furnace is the smallest. That means the Fe_3O_4 content in the converting slag of type D furnace is the lowest.

The reason may be that, compared with the other three type furnaces, the two flues in type D furnace can make the SO_2 partial pressure in converting zone lower, and the partition wall can reduce greatly the amount of converting slag and the FeO activity.

4.3 Copper loss in converting slag

The effect of furnace structures on the copper content in converting slag is shown in Fig. 9.

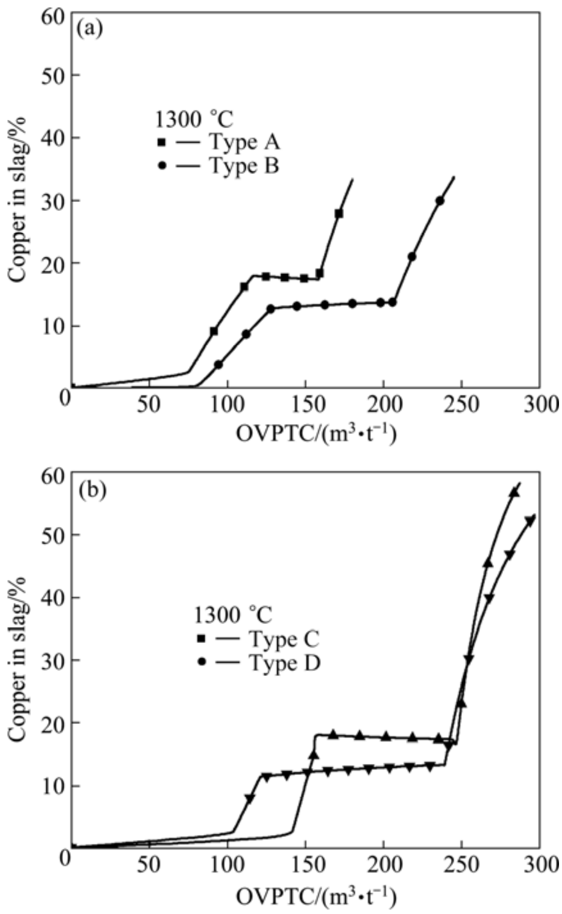

Fig. 9 Effect of furnace structure on copper content in converting slag

The data in Figs. 9(a) and (b) show that the copper content in converting slag in type D furnace is the lowest during the period of producing blister copper, about 10% (mass fraction), the content in type B furnace is about 15%, and the contents in types A and C furnaces are higher than 20%.

The effect of different furnace structures on the amount of converting slag is shown in Fig. 10.

It can be found clearly from Fig. 10 that the converting slag amounts in types D and B furnaces are small, while that in types A and C furnaces are very high. It follows that, according to their structures, the furnace with a slag partition wall preventing smelting slag flowing into the right converting zone is so efficient to reduce the amount of converting slag.

Taking the copper content and the amount of converting slag into consideration overall, the copper loss in slag is the lowest for type *D* furnace.

4.4 Recovery rate of copper

The effect of different furnace structures on the copper recovery rate of the whole copper flash continuous process is shown in Fig. 11.

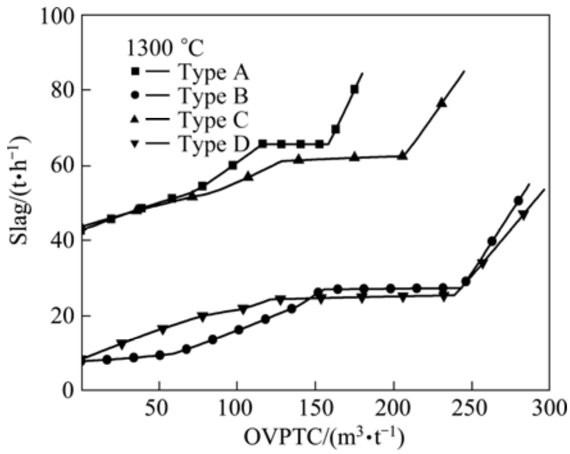

Fig. 10 Effect of furnace structure on converting slag amount

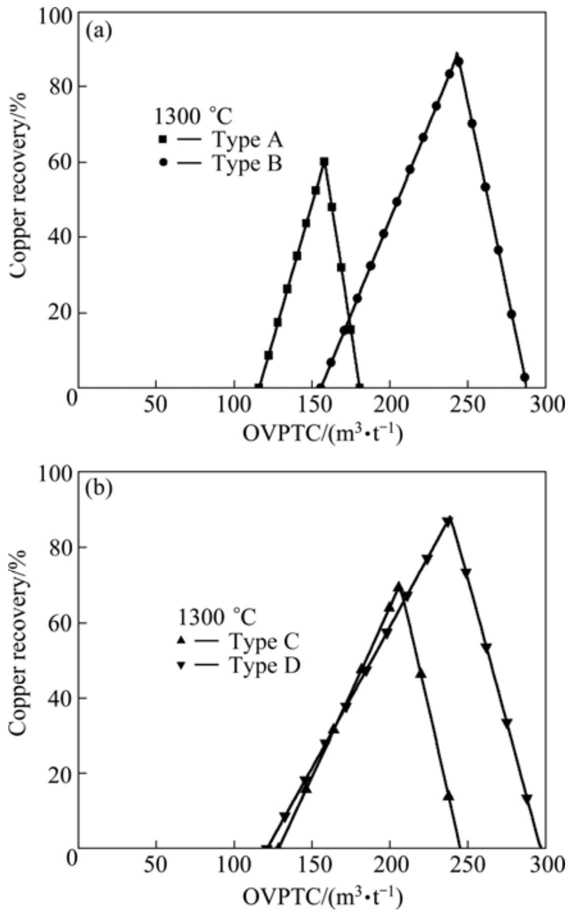

Fig. 11 Effect of furnace structure on copper recovery rate

It can be seen from Figs. 11(a) and (b) that the copper recovery rate for types D and B furnaces can be higher than 90 %, but it is so low for types C and A furnaces, about 70% and 60%, respectively. The main reason is that there is a slag partition wall in types D and B furnaces, which can prevent smelting slag flowing into the converting zone, and then the copper loss in slag is reduced.

5 Conclusions

1) According to the innate characteristic of four types of furnace, a thermodynamic model of the copper flash continuous smelting (CFCS) was established by building the multi-phase equilibrium model of the flash matte smelting process (FMSP) and the local-equilibrium model of the copper continuous converting process (CCCP), respectively, and then combining the two models through the smelting intermediates.

2) Compared with other three types of furnaces, the type D furnace is an ideal reactor for CFCS. Type D furnace has many advantages over other furnaces, such as easier formation of blister copper, lower content of Fe_3O_4 in converting slag, and higher copper recovery rate.

3) It is efficient for CFCS to design a slag partition wall and double flues in the furnace. The wall can partition the furnace into two relatively independent zones, prevent smelting slag flowing into the converting zone, and make smelting gas and converting gas discharge out of the furnace from the separated flues, which reduce the copper loss in slag and the SO_2 partial pressure in converting zone.

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基于数值模拟的闪速连续炼铜炉型结构研究

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摘 要：分析 4 种闪速连续炼铜炉型的本质特性，提出将闪速连续炼铜过程视为由相对独立的闪速造锍熔炼过程和连续吹炼造铜过程构成，分别建立闪速造锍熔炼多相平衡数学模型和连续吹炼造铜局域平衡数学模型，并通过中间物料的传递将两模型有机结合，从而构建完整的闪速连续炼铜过程热力学模型。运用此模型，考察炉型结构对闪速连续炼铜过程的粗铜生成条件、Fe_3O_4 行为、铜在渣中损失以及铜直收率等因素的影响。结果表明：相对于其他 3 种炉型，甩渣吹炼双烟道 D 型炉是比较理想的连续炼铜炉体；对于闪速连续炼铜，造锍熔炼段和铜锍吹炼段宜在相对独立的分区进行，各自炉渣和烟气也应分开排出炉体。

关键词：炉型结构；铜闪速连续炼铜；数值模拟；热力学分析

(Edited by Chao WANG)