Numerical simulation of sticking phenomena in an industrial-scale shaft furnace and process intensification

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Highlights

- A moving bed porous medium model for the countercurrent gas-solid flow of industrial-scale shaft furnaces.
- Rate constants from Tsay et al and Takahashi et al predict the reduction of Contrecoeur shaft furnace well.
- Decreased bed permeability for pellet sticking hinders reduction more than limited gas diffusion for grain sticking.
- Increase reducing gas flow rate and prevent cooling gas from rising to the reduction region promotes reduction.

1. Introduction

As a kind of hydrogen metallurgy technology, MIDREX and ENERGIRON shaft furnaces have been newly adopted by global iron and steel companies in the past three years to achieve low CO_2 emissions. Numerical simulation can visualize shaft furnace black box for process intensification. The authors recently reviewed the modeling for shaft furnaces and strategies to increase reduction performance.[1] As mentioned in that paper, (1) the porous medium model widely used to describe packed beds has not been developed for moving bed cases; (2) the rate constants have large differences from different researchers attributing to pellet structure and impurities; (3) pellet sticking results from iron whiskers and solid diffusion and grain sticking in pellets due to sintering have not been considered in modeling. Apart from modeling, we also test the combined effect of reducing gas flow rate and pressure at cooling gas outlet on iron ore reduction intensification.

2. Methods

The porous medium model is expended to characterize the gas (upward)-solid (downward) moving bed process. Convective terms, which do not exist in packed bed simulations, are added to the continuity, energy, and species mass fraction equations of solid. Among them, the solid continuity equation is solved to estimate varying solid densities during reduction, while solid descending velocity is obtained in advance through an empty tower flow. Three-interface unreacted shrinking core model (USCM) is applied to estimate the gas-solid reduction process $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$. The increased permeability in the Ergun equation predicts the improved pressure drop when pellet sticking occurs. Based on the expression of reaction rate, the decreased gas diffusivity in pellets describes the effect of grain sticking, and rate constants given by different researchers[2-4] are used. Effects of the above factors as well as process intensification are discussed from the perspective of metallization rate (MR).

3. Results and discussion

The Contrecoeur shaft furnace with operating conditions of Hamadeh et al[4] is assumed as the base case. They used a grain model to predict gas-solid reactions. However, with three-interface USCM, as shown in Fig.1, their rate constants significantly underestimate MR, while those from Tsay et al[2] and Takahashi et al[3] estimate the MR at the furnace bottom close to the industrial value as 0.938. Regarding sticking phenomena, in Fig.2, if pellet sticking increases bed permeability 1.67 and 2.86 times, the product MR decreases around 15% and 30%, respectively. In comparison, the product MR hardly decreases even if the internal gas diffusivity reduces 5 times as presented in Fig.3. With the internal gas diffusivity resisted by over 10 times, the product MR appears obvious decrease. In addition, process intensification in case of bed permeability decrease due to pellet sticking is discovered. We find the combined effect of reducing gas flow rate and outlet pressure of cooling gas. The reducing gas flow rate is given in the STP state, and the real flow rate is $Q=Q_{STP}\cdot(T/273)/p$. When Q further rises to against the decrease caused by the local pressure and the outlet pressure of cooling gas maintains values at which bottom cooling gas does not slip to the upper reduction zone (see Fig.4b), iron ore pellets are completely reduced with less than 1/3 of the reduction region used. This means that, in this case, solid production can be further improved to balance the additional cost from the increased flow rate within the reduction ability.

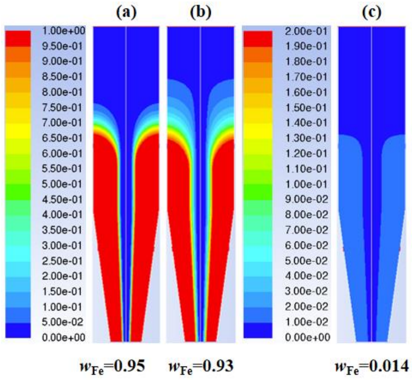

Figure 1. Metallization rate under rate constants from Tsay et al (a), Takahashi et al (b), and Hamadeh et al (c).

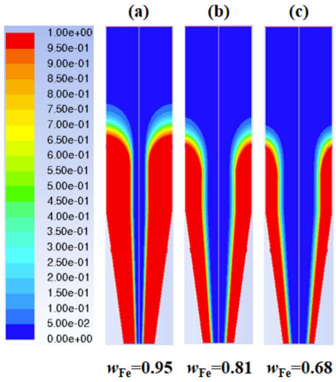

Figure 2. Metallization rate against bed permeability: base case (a), decreasing 1.67 (b) and 2.86 (c) times.

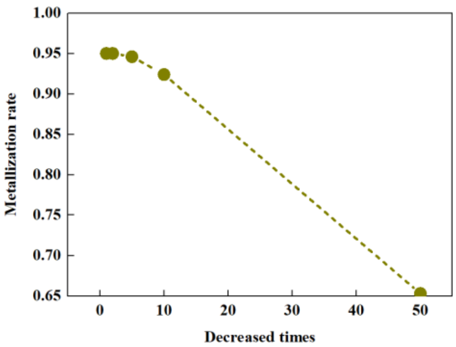

Figure 3. Product metallization rate with decreased times of gas diffusivity in pellets.

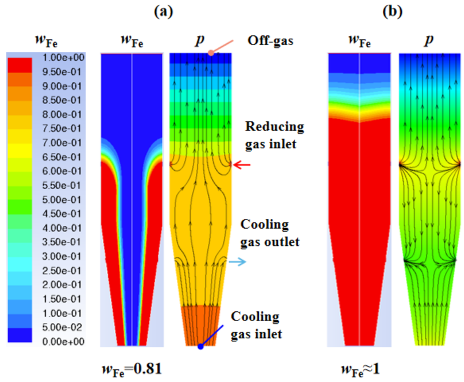

Figure 4. Metallization rate and flow field: base case (a) and improved case (b).

4. Conclusions

We develop a porous medium moving bed model. The rate constants from Tsay et al and Takahashi et al obtain reasonable MR under three-interface USCM. Compared with hindered gas diffusion in pellets due to grain sticking, hindered gas flow across the bed owing to pellet sticking has far more influence on MR. As for process intensification, increasing reducing gas flow rate and preventing cooling gas from rising upward to the reduction region by controlling its outlet pressure promotes MR significantly. However, CH_4-H_2O reforming is not considered due to its overreaction together with gas-water shift reaction in the present simulations. Its strong endothermic effects on temperature and MR will be discussed later.

References

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Keywords

Shaft furnace; Bed permeability; Reduction kinetics; Process intensification