Research Article

Numerical Simulation of Multiphase Flow Behavior in Hot Metal Ladle Desulfurization with Bottom Powder Injection and Electric Field

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Received 4 June 2019; Revised 31 July 2019; Accepted 1 August 2019; Published 29 November 2019

Guest Editor: Qijun Zheng

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A computation fluid-coupled discrete phase model (CFD-DPM) was used to predict the motion characteristics of gas, particle, and liquid phases in the hot metal ladle. The influence of different voltage loading modes, voltage values, and powder injection speeds on the particle motion trail was investigated, while the effects on the particle concentration maximum difference in the stagnation region were discussed. The optimal injection and voltage parameters were proposed. The results are shown as follows: the loading voltage before injection is beneficial to the diffusion of particles in the molten pool. With the increase of voltage and injection speed, the distribution of particles in the upper part of the molten iron tends to be uniform. The bottom of the ladle is the stagnation region. Optimum voltage and injection speed were determined. Under the optimum conditions, particles are evenly dispersed and the particle concentration difference in the stagnation region is small. This research work will benefit greatly to the hot metal ladle desulfurization technology.

1. Introduction

As well known, sulfur is the main harmful element affecting the quality and performance of steel. So, ladle desulfurization has become a necessary part of producing high quality steel [1, 2]. In the past 10 years, the steel production capacity in China has increased rapidly. At the same time, new desulfurization techniques have emerged one after another to fulfil high efficiency and low-cost smelting [3–5]. The most widely used desulfurization process currently is powder injection technology [6]. Powder injection technology has received importance as a means to improve refining reactions due to the intimate contact between the particle and metal. In addition, the carrying gas provides stirring of the molten metal to achieve chemical homogeneity.

The powder can be injected to the ladle from the ladle top or bottom. The top injection desulfurization technology,

inserting the lance into the molten pool, has some serious problems such as the splashing phenomenon, low utilization rate of desulfurizer, pollution of molten steel by lance refractory material, long treatment period, and high cost [2]. Therefore, Pan et al. proposed a hot metal bottom powder desulfurization process in which calcium oxide powder particles were injected into ladle baths through the slot plug and the particle motion trail in the slot plug was simulated [7, 8]. Liu proposed electrolytic magnesite desulfurization technology and verified its feasibility through thermodynamic experiments [9]. In this article, a new bottom powder desulfurization process with electricity field, the process is shown in Figure 1. With calcium oxide as the main component, lime is used as the desulfurizer blown into the molten pool by nitrogen gas through the bottom purging plug of the ladle. The voltage is used to destroy the stability of the compound and improve the dynamic condition in the

FIGURE 1: Schematic diagram of new technology of ladle bottom powder injection with electricity field.

ladle, so as to promote the reaction of the powder particles with the molten iron, and the desulfurization efficiency can be maximized.

Most studies of the hot metal powder desulfurization process have focused on top injection metallurgy technology [10–15], while the study of multiphase behavior in the process of ladle bottom powder injection with electric field is few. In addition, it is extremely hard or impossible to measure experimentally the particle trajectories in metallurgical systems, so mathematical simulation become an important method to understand this process [16–18]. The aim of the current work is to understand the movement of the calcium oxide particle under the condition of electricity. With Fluent software used, a CFD-DPM coupled model was established to describe and simulate the multiphase flow behavior in the 300 t ladle bottom powder injection process. The effectiveness of the injection technique is related to the hydrodynamics of the system and the particle trajectories. Therefore, the influence of different voltage loading modes, voltage magnitudes, and powder injection speeds on the particle trajectories was investigated. The effect on the particle concentration in the low-velocity area was discussed. The determination of optimum blowing parameters provides a theoretical basis for the establishment of the theoretical model of the bottom injection desulfurization process. The present study will greatly benefit advances in hot metal ladle desulfurization technology.

2. Model Description

With the chemical reaction neglected, the discrete phase model (DPM) is used to describe the motion behavior of the calcium oxide particles. As a transporting particle gas, the nitrogen and molten iron interact with each other. The gas-liquid interface is obvious and affected by the liquid flow.

Therefore, the volume of fluid (VOF) multiphase model is selected to simulate gas-liquid two phase flow behavior, with molten iron as the main phase, nitrogen as the second phase, and calcium oxide as the discrete phase. The mathematical mode of each phase includes the momentum equation, the electric field force control equation, the energy equation, and the equation of turbulence kinetic energy and its dissipation rate. The standard $k - \epsilon$ turbulence model is selected. For the solution, considering the influence of the motion of the discrete phase on the continuous phase flow, a phase-to-phase coupled calculation model is adopted. Firstly, the flow field of gas-liquid two-phase flow without calcium oxide particles is calculated, and then the flow field results of molten iron are used as the calculation domain of particles. After the particle trajectory is computed, the flow field of gas-liquid is calculated again with the interaction and momentum exchange between the discrete and continuous phase considered. The aforementioned steps would be repeated until the convergence results are obtained. The model is outlined below for completeness.

2.1. Gas-Liquid Phase Flow Equations in Ladle (VOF).

The tracking of the gas-liquid interface was carried out by using the VOF model originated from the research of Hirt and Nichols [19]. In this model, α is used to describe the volume fraction of different phases. Each calculation cell contains gas and liquid phases, in which the sum of the volume fractions of the phases is equal to 1, shown as follows:

$$\sum_{i=1}^n \alpha_i = 1, \quad (1)$$

where α is the volume fraction and i is for phase category. If $\alpha_i = 0$, there is no i th phase in the cell, and if $\alpha_i = 1$, the cell is full of the i th phase fluid.

The interface between gas and liquid phases was tracked by the solution of a continuity equation. For the i th phase, the conservative equation can be expressed as follows:

$$\frac{\partial(\rho_i \alpha_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i u_i) = 0, \quad (2)$$

where ρ_i and α_i are the density (kg/m^3) and the volume fractions of the i th phase, respectively.

In the VOF model, all the fluids were simulated by the momentum equation as shown in equation (3). The velocity field is shared by both phases. Concurrently, all variables and properties are represented by the volume fraction-averaged values.

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u u) = -\nabla p + \nabla \cdot [\mu_{\text{eff}}(\nabla u + \nabla u^T)] + \rho g + F, \quad (3)$$

$$\rho = \alpha_{\text{gas}} \rho_{\text{gas}} + \alpha_{\text{liquid}} \rho_{\text{liquid}}, \quad (4)$$

$$\mu = \alpha_{\text{gas}} \mu_{\text{gas}} + \alpha_{\text{liquid}} \mu_{\text{liquid}}, \quad (5)$$

where u is the velocity vector (m/s), p is the pressure (Pa), g is the gravity (m/s^2), ρ is the density (kg/m^3), and μ_{eff}

$(\mu + \mu_t)$ is the effective viscosity (Pa·s). p is the pressure (Pa), and F is interfacial forces between the gas and liquid phases (N).

Similarly, the energy equation is also shared among the phases shown as follows:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot [u(\rho E + p)] = \nabla \cdot ((\lambda_{\text{eff}} \nabla T) + S_h), \quad (6)$$

where the energy E and the temperature are treated as a mass-averaged variable.

$$E = \frac{\sum_{i=1}^n (\alpha_i \rho_i E_i)}{\sum_{i=1}^n (\alpha_i \rho_i)}, \quad (7)$$

where E_i is based on the specific heat of the i th phase. The source term S_h in equation (6) is the volumetric heat source. $\lambda_{\text{eff}} (= \lambda + \lambda_t)$ is the effective thermal conductivity ($\text{W} \cdot \text{m}^{-1} \text{K}^{-1}$):

$$\lambda = \alpha_{\text{gas}} \lambda_{\text{gas}} + \alpha_{\text{liquid}} \lambda_{\text{liquid}}. \quad (8)$$

2.2. Turbulence Model. The governing transport equations for turbulence kinetic energy k and its dissipation rate ε are shown as follows:

$$\frac{\partial(\rho k)}{\partial t} + \nabla(\rho u k) = \nabla \cdot \left(\frac{\mu_t}{\sigma_k} \nabla k \right) + G_k - \rho \varepsilon, \quad (9)$$

$$\begin{aligned} \frac{\partial(\rho \varepsilon)}{\partial t} + \nabla(\rho u \varepsilon) = & \nabla \cdot \left(\frac{\mu_t}{\sigma_\varepsilon} \nabla \varepsilon \right) + \frac{\varepsilon}{k} (C_{1\varepsilon} G_k - C_{1\varepsilon} C_{3\varepsilon} G_b) \\ & - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}, \end{aligned} \quad (10)$$

where μ_t is the turbulent viscosity and is described as

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}. \quad (11)$$

G_k ($\text{kg/m}^3 \text{s}^3$) in equation (9) is the generation of turbulence kinetic energy due to the mean velocity gradients. In equations (10) and (11), the value of $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, σ_k , σ_ε , and C_μ are 1.44, 1.92, 0.8, 1.0, 1.3, and 0.9, respectively.

2.3. Equation of Motion for Calcium Oxide Particles (DMP). In the discrete phase model (DPM), the analysis of the particle was performed by the Lagrangian approach. The time rate of change of velocity of a discrete particle and the position are the results of various forces acting on the particle. The particle trajectories were obtained by the solution of Newton's second law, shown as follows:

$$\frac{du_p}{dt} = \frac{18\mu C_D R_e}{\rho_p D_p^2 24} (u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_g} + F_x, \quad (12)$$

where, u and u_p are the speed of liquid hot metal and the calcium oxide particles, respectively (m/s), ρ_p is the density of the calcium oxide particles (kg/m^3), D_p is the particle diameter (m), and F_x is the force including virtual mass

force, pressure, gradient force, and Lorentz force (N) induced by electricity field.

The drag coefficient C_D is defined as

$$C_D = \beta_1 + \frac{\beta_2}{\text{Re}} + \frac{\beta_3}{\text{Re}^2}, \quad (13)$$

where β_1 , β_2 , and β_3 are constant under several ranges of Re , and Re is the relative Reynolds number, which is expressed as

$$\text{Re} = \frac{\rho D_p |u_p - u|}{\mu}. \quad (14)$$

2.4. Simulation Conditions. Table 1 gives the ladle size and the physical parameters of molten iron, nitrogen gas, and calcium oxide powder. The ladle capacity is 300 t. Nitrogen oxide is used as a carrier gas to blow the calcium oxide powder into the molten pool through bottom purging plug. The position of the purging plug is at 1/2 of the bottom radius, and the double nozzle is symmetrically arranged. The bottom and sides of the ladle are set as no slip boundary condition and a standard wall function to describe the turbulence characteristics at the near wall of the fluid. At the inlet of the gas-powder, the velocity inlet condition is adopted, the powder is sprayed at a uniform rate, and the gas phase volume ratio is 1. The top surface of the ladle is set at pressure outlet conditions, which is 0.1 MPa. The initial velocity of the entire fluid domain except the boundary is zero.

3. Results and Discussion

3.1. Typical Multiphase Flow Behavior Predicted in Hot Metal Ladle Desulfurization with Bottom Powder Injection. Figure 2 shows the flow field in the hot metal ladle with the bottom powder injection. Figure 2(a) is the typical trajectories of the gas and the particle phase predicted by DPM, while Figure 2(b) is the velocity vector of molten iron. There is no electric field, and the molten pool temperature is 1400°C . The gas-powder blowing speed is 4 m/s , and the blowing time is 2 s . It can be seen from Figure 2(a) that the gas and particle phases enter the ladle with an upward momentum, and the molten iron velocity increases due to gas buoyancy, as shown in Figure 2(b). From Figure 2(b), it can be seen that the liquid vortexes are formed between the gas column and the ladle wall for the big velocity gradient, which improves the uniformity of composition and the desulfurization rate. Under the action of the vortex, buoyancy, and liquid turbulence, gas and particle phases move upward for a distance and then toward the beside wall, rise up, and diffuse in the ladle as shown in Figure 2(a). By the aforementioned process, the purpose of desulfurization can be completed finally. However, the velocity at the bottom of the ladle (1, 2, 3 zone) is small, which is named as the stagnant region. This region has a negative effect on the uniformity of composition and desulfurization rate.

TABLE 1: Size of 300 t ladle and purging plug and physical parameters of materials.

Parameter	Value
Top diameter	3942 mm
Bottom diameter	3438 mm
Height	5196 mm
Liquid level depth	4800 mm
Purging plug diameter	57 mm
Hot metal density	7800 kg/m ³
Calcium oxide particle density	3320 kg/m ³
Blowing pressure	0.4 MPa

3.2. Effect of Voltage Loading Mode. Figure 3 shows the particle trajectories comparison under the different voltage loading modes, when the initial temperature of molten iron is 1400°C and the injection speed is 2 m/s. Figure 3(a) is the result of no voltage load and Figures 3(b) and 3(c) are the results of 4 kV voltage load before and after the powder injection, respectively. When there is no electricity field, the two particle streams are symmetrically distributed in the molten pool, move up from the bottom in the form of a cylinder to some height distance (this distance is named as the particle core region), and then diffuse toward the center and afterward move to the wall, go up, and spread toward the top surface. From the Figure 3(b), it can be seen that the voltage load before injection has little effect on the length of the particle core region. However, the voltage load can weaken the rotation of the particles toward the wall and make the particles move upward with a higher kinetic energy. Compared with the results of no voltage, much more particles rise to the top and the particle concentration distribution is more uniform at the same ladle position. Figure 3(c) shows that the distribution of particles in the ladle is not improved when the electricity is loaded after blowing for 2 s. Within 2 s blowing time, the particle concentration distributions in the stagnation region (1, 2, 3) under (a) and (b) mode were 750.362, 1142.53, and 803.64 kg/m³ and 760.35, 1200.36, and 804.35 kg/m³. From aforementioned analysis, it can be known that the voltage of 4 kV before injection can promote the diffusion of particles in the upper part of the ladle, but the particle concentration distribution in the stagnation region is not improved significantly.

3.3. Effect of Voltage Value. In order to investigate the effect of the voltage value on the particle concentration distribution in the bath, all of the model parameters are identical except for the voltage value loaded on the hot metal iron before bottom blowing. The value of voltage is 4 kV, 12 kV, and 20 kV, respectively, while the DPM-predicted results are shown as Figures 4 and 5. Figure 4 provides the comparison of the simulated trajectories of particle under the condition of different voltage values. It can be seen that with an increase of voltage value, the maximum height of the particle can increase. The particle concentration distribution in the upper region tends to be

uniform. The reason is that the higher voltage value leads to the bigger electric field force on the liquid iron, which accelerates the circulation of the liquid phase and diffusion of the particles. The increase in the voltage value also can strengthen the bath mixing in the stagnation region of the ladle. As shown in Figure 5, the particle concentration in this region increases with the increasing voltage. It is apparent that the particle concentration in regions 1 and 2 is less than that in the region 3, while the particle concentration in region 3 is influenced by the value of voltage significantly.

3.4. Effect of Injection Speed. Under the different bottom injection speeds, the predicted results of the particle trajectories and the particle concentration in the stagnation region are shown in Figures 6 and 7, respectively. In this section, the voltage value is 20 kV, the temperature of the molten iron is 1400°C, the gas-particle injection speed is 2 m/s, 3 m/s, and 4 m/s, respectively, and the blowing time is 2 s. It can be seen that with an increase in the injection speed, the length particle core region (green color zone in Figure 6) increases, and much more particles concentrate in the middle region of the ladle. This is because that initial kinetic energy of the particles increases with the raising injection speed and results in an increase of the particle instantaneous blowing height. The particle concentration on the upper of the ladle bath increases when the injection speed increases from 2 m/s to 3 m/s, but decreases when the injection speed changes from 3 m/s to 4 m/s. The reason of that is higher injection speed causes more vortex between the particle stream and liquid, which transports the particles move toward the wall, and then rise up and go down. Owing to that, a larger injection speed is beneficial to the bath mixing effect. As shown in Figure 7, compared with the injection speed of 2 m/s and 3 m/s, the particle concentration in the stagnation region increases significantly at the 4 m/s injection speed, and the particle concentration difference between the three stagnation regions decreases obviously. It can be known that the injection speed is the main factor for affecting the uniformity of the particle concentration distribution.

3.5. Matching Analysis of Injection Speed and Voltage. In order to determine the optimum match of injection speed and voltage, the particle concentration in the stagnation region (1, 2, and 3) is predicted under different voltages and injection speeds, the results are shown in Figure 8. It can be seen that the particle concentration at the stagnation region 3 increases significantly with the raise of the injection speed and the voltage. However, the voltage value has little effect on the particle concentration at the stagnation region 1 and 2 when the injection speed is less than 4 m/s. Figure 8(a) shows that when the voltage value is more than 12 kV, the maximum concentration difference between three stagnation regions is larger (the larger slope of the curve). So, the voltage loaded should be less than 12 kV when the injection speed is 2 m/s. Similarly, as shown in Figure 8(b), when the blowing speed is 3 m/s, the

FIGURE 2: Trajectories of gas and particle phases (a) and velocity vectors in the hot metal ladle (b).

FIGURE 3: Trajectories of particle under the condition of no electric field (a). Voltage loading before injection (b). Voltage loading after injection (c).

FIGURE 4: Trajectories of the particle under the condition of voltages of 4 kV (a), 12 kV (b), and 20 kV (c).

voltage value also should be between 4 kV and 12 kV. When the injection speed is 4 m/s, the particle concentration at the stagnation region (1, 3) increases with the raising voltage, while the particle concentration difference between regions 1 and 2 reduces. Therefore, at 4 m/s

injection speed, the loading voltage should be 20 kV. Overall, based on the aforementioned analysis, 20 kV voltage and 4 m/s injection speed can be used as the optimal parameter for the 300 t hot metal ladle desulfurization process.

FIGURE 5: Effect of voltage value on particle concentration in the stagnation region.

FIGURE 6: Trajectories of particle under the condition of 20kv voltage and with the injection speed of 2 m/s (a), 3 m/s (b), and 4 m/s (c).

FIGURE 7: Effect of injection speed on particle concentration at the stagnation region.

FIGURE 8: The effect of loading voltage on particle concentration in the stagnation region when the injection speed is 2 m/s (a), 3 m/s (b), and 4 m/s (c).

4. Conclusions

A CFD-DPM coupled model was carried out to describe the gas-particle-liquid multiphase flow in hot metal ladle desulfurization with bottom powder injection and electric field. With the coupled model used, the effect of voltage load mode and its value, and injection speed on the particle concentration in the bath was investigated. The results show that the voltage loaded on the liquid iron contributes to the uniform diffusion of the calcium oxide particles in the ladle. Furthermore, the loading voltage before injection is more favorable for the particles diffusing in the ladle. When the injection speed is constant, the larger the voltage value is, the more uniform the particle distribution is in the upper part of the ladle. When the voltage is constant, the particle distribution not only in the upper part of ladle but also in the stagnation region is improved with the increasing injection speed. Considering the effect of voltage value on the maximum difference of the particle concentration in the stagnation region, the voltage should be 4 kV to 12 kV when the injection speed is 2 m/s or 3 m/s, and the voltage should be about 20 kV

when the injection speed is 4 m/s. Overall, the voltage of 20 kV and the injection speed of 4 m/s are suggested for the 300 t hot metal ladle desulfurization process, because the difference of particle concentration in the stagnation region is small, and the particle is evenly dispersed under this condition.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was funded by the National Key R&D Program of China (2017YFC0805100), the State Key Laboratory of Marine Equipment and Applications-University of Science

Technology of Liaoning United Fund (SKLMEA-USTL-201903), Liaoning Province Natural Science Foundation (2019-ZD-0271), and Excellent Talent Project of University of Science Technology of Liaoning (2017RC01).

References

- [1] B. Deo, R. K. Lingamaneni, A. Dey, and R. Boom, "Strategies for development of process control models for hot metal desulfurization: conventional and AI techniques," *Materials and Manufacturing Processes*, vol. 20, no. 3, pp. 407–419, 2005.
- [2] W. F. Geng, "Development of hot metal furnace desulfurization technology," *Iron and Steel*, vol. 26, no. 10, pp. 68–72, 1991.
- [3] B. Y. Liu, "Applied effects of different hot metal desulfurizing processes," *Iron and Steel*, vol. 39, no. 6, p. 24, 2004.
- [4] M. Vargas-Ramirez, A. Romero-Serrano, R. Morales, M. Angeles-Hernandez, F. Chavez-Alcala, and J. Castro-Arellano, "Hot metal pretreatment by powder injection of lime-based reagents," *Steel Research*, vol. 72, no. 5-6, pp. 173–181, 2001.
- [5] C. J. Long, J. S. Cheng, D. P. Zhan, and J.-F. Wan, "Development of compound passivated magnesium powder for hot metal pre-desulfurization at Baosteel," *Iron and Steel*, vol. 42, no. 12, p. 29, 2007.
- [6] S. Zhi, B. Y. Zhang, and S. H. Lou, "Jet metallurgy-ladle powder injection technology abroad," *Iron and Steel*, vol. 15, no. 7, pp. 59–68, 1980.
- [7] S. S. Pan and M. Y. Zhu, "Motion Characteristics of injection Powder through Porous brick module in the bottom of refining ladle," *Acta Metallurgica Sinica*, vol. 43, no. 5, pp. 553–556, 2007.
- [8] Z. F. Chen and M. Y. Zhu, "Theoretical analysis and experiment of liquid metal penetration into slot plug applied for refining ladles," *Metallurgical and Materials Transactions B*, vol. 45, no. 5, pp. 1695–1705, 2014.
- [9] Z. C. Lv and K. Liu, "Feasibility study on high temperature electrolytic desulfurization in hot metal pretreatment," *Metallurgija*, vol. 57, no. 1-2, pp. 39–42, 2018.
- [10] J. A. Zhou, Z. Q. Sun, D. P. Zhan et al., "Comparative experimental study on Desulfurization of top and bottom powder injection in molten iron ladle," *Journal of Northeast University (Natural Science Edition)*, vol. 33, no. 1, pp. 93–96, 2012.
- [11] P. Tang, G. H. Wen, W. F. Xue et al., "Study on optimization of desulfurization parameter of hot metal by Powder injection," *Journal of Iron and Steel Research*, vol. 32, no. 5, p. 9, 2004.
- [12] M. Numata and Y. Higuchi, "Effect of changes in sulfur and oxygen concentration in liquid steel during CaO-CaSi powder blowing under reduced Pressure," *ISIJ International*, vol. 52, no. 11, pp. 2019–2025, 2012.
- [13] N. Wang, L. B. Zhang, and Z. S. Zou, "Three basic parameters determining desulfurization efficiency of powder injection in ladle," *Journal of Iron and Steel Research*, vol. 12, no. s1, pp. 10–15, 2000.
- [14] S. Ghoral, G. G. Roy, and S. K. Roy, "Physical simulation of impurity removal through submerged liquid slag injection in steel melt," *ISIJ International*, vol. 44, no. 1, pp. 37–42, 2004.
- [15] D. E. Langberg, S. Avery, and M. Nilmani, "The separation of the solids from the carrier gas during submerged powder injection," *Metallurgical and Materials Transactions B*, vol. 27, no. 5, pp. 773–779, 1996.
- [16] N. Wang, Y. S. Zou, and Z. S. Zou, "Mathematical simulation of magnesium-calcium carbide composite powder desulfurization by hot metal ladle injection," *Journal of Iron and Steel Research*, vol. 9, no. S, pp. 16–21, 2000.
- [17] L. R. Farias and G. A. Irons, "A multi-phase model for plumes in powder injection refining processes," *Metallurgical Transactions B*, vol. 17, no. 1, pp. 77–85, 1986.
- [18] S. Ohguchi and D. G. C. Robertson, "Kinetic model for refining by submerged powder injection: part 1 transitory and permanent-contact reactions," *Ironmaking Steelmaking*, vol. 11, no. 5, pp. 263–273, 1984.
- [19] C. W. Hirt and B. D. Nichols, "Volume of fluid (VOF) method for the dynamics of free boundaries," *Journal of Computational Physics*, vol. 39, no. 1, pp. 201–225, 1981.

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