Simulation on Gas Injection Refining Process with Mechanical Stirring

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Abstract
Basing on the new method of in-situ desulfurization with gas injection and mechanical stirring, the effect of bubble dispersion and disintegration of three type impellers are numerically simulated by commercial CFD software Ansys Fluent 12.0. Numerical simulations of three-dimensional multiphase turbulence in gas injection and mechanical stirring are performed by adopting unsteady SM method coupled with Eulerian multiphase model and two-phase turbulence model. The information of gas-liquid fluid flow, velocity, turbulent kinetic energy and the power consumption are investigated and the results show that the SSB impeller can make bubbles get best dispersion and disintegration, and its power consumption is lower than VB impeller. The disk on the impeller blades can weaken the swirl flow in the upper zone of the impeller. Therefore, the bubble residence time is extended, and the bubble dispersing zone is also increased.

Keywords: injection refining, mechanical stirring, in-situ desulfurization, bubble disintegration and dispersion, CFD

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1. Introduction
1.1 Gas Injection Refining
The injection technology was widely used in the metallurgical industry in recent decades. It is noteworthy that bubble disintegration and dispersion are indispensable for high refining efficiency and quality of products in gas bubble-liquid metal system, such as hot metal pretreatment process for desulfurization with magnesium and degassing process of aluminum melts.

In the magnesium desulfurization process, micronized bubbles can improve the efficiency of gas-liquid reaction, achieving the effect of deep desulfurization and improving steel quality. For aluminum degassing, evenly distributed bubbles can remove particle impurity in molten metal more conducively, reduce production cost and improve the quality of metal.

Production and wide dispersion of small bubbles in liquid are not difficult at low temperatures. For example, many sophisticated devices are used successfully for the purposes in chemical industry[1, 2] Since iron and steel refining processes are operated at very high temperatures, such sophisticated devices cannot be used in actual plants. Due to the restriction of high temperature and the refractor, it had to adopt the impeller with simple structure in this gas injection refining processes. So the ways to improve the refining effect mainly concentrated on changing operation conditions basing on impeller of simple structure.

1.2 In-situ Desulfurization Method
In-situ desulfurization of molten iron with mechanical stirring was presented on a basis of KR and magnesium granule injection method by Zhang etc[3]. This new method provide some new thoughts that magnesium vapor could generate from the pellets of dolomite and reductant in hot metal instead of injecting magnesium granule from the lance, then the magnesium vapor desulfurized directly with mechanical stirring. The new method has many advantages in getting high-activity magnesium vapor which has higher utilization rate and desulfurization efficiency, but there are some problems needed to be solved.
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Figure 1 shows the relation between the size of magnesium bubbles and the magnesium desulfurization efficiency. It has been proved by research of Masamichi Sano[4] that the bubble’s dispersion and disintegration can not only boost the desulphurization efficiency but also increase the utilization rate of magnesium. Obviously, the bubble’s dispersion and disintegration of magnesium vapor is the key problem in boosting the desulphurization efficiency and increasing the utilization rate of magnesium. Thus the research should be explored on bubble’s dispersion and disintegration on the base of refining process and gas-liquid mass transfer.

![Figure 1. Effect of bubble on desulfurization efficiency of magnesium(S=20ppm)](image)

In previous researches Liu etc[5-9] research the bubble’s dispersion and disintegration of stirring injection system using water model experiment method. Basing on the similarity principle, the cold water experiment was performed to investigate the influence on the bubble’s dispersion and disintegration with different stirring mode, eccentricity, nozzle structure and immersion depth, rotational speed and gas flow rate and some optimizational conditions were obtained.

1.3 CFD Simulation

The role of CFD (Computational Fluid Dynamics) in engineering predictions has become so strong that today it can be viewed as a new ‘third dimension’ in fluid dynamics, the other two dimensions being the classical cases of pure experiment and pure theory[10-12]. Currently, Ansys Fluent is the most widely used commercial CFD software. It provides various models of turbulent and multiphase flow for different simulation conditions. Specially, it has two ways, MRF and Sliding Mesh method, to deal with moving boundary, which could solve the rotation of impeller. In addition, many post processing tools are available in Fluent, which provide 2D or 3D information of flow field, meanwhile the results could be also reported quantificationally.

Water model physical simulation can provide relevant information for the improvement of process conditions in the industrial experiments. But it was difficult to get the information of velocity field and turbulent kinetic energy. Therefore, in this paper, on the basis of physics experiment, the stirring effects of three different impellers have been numerically analyzed by using commercial CFD software Ansys fluent 12.0.

2. Simulation Method

2.1 Geometric and Mesh Model

The size of simulation geometric model was the same as the experimental apparatus. The diameter and height of the vessel were 0.433 and 0.51 m respectively. The bath depth of water was 0.35m. The diameter of the impeller shaft was 30mm. Figure 2 shows the mesh
model of the string vessel Figure 3 shows different structure of three impellers. The four-blade impeller used in the previous experiment is shown in Figure 3 (a), which is named VB impeller. Figure 3 (c) illustrates the sloped swept-back blade impellers named SSB impeller. The side wall between the blades was sloped and in addition swept back oppositely to the direction of rotation. The central part of the impeller was in the form of square plate and four blades were attached to the side of the plate. In this paper, a circular disk was put on the top side of the blade, then we get SSB impeller with disk, which is named SSB-D impeller, which is shown in Figure 3 (b). In order to improve the accuracy and efficiency of the numerical prediction, a local mesh encryption method is used in the stirring region. 148974 meshes are used in the SSB-D model shown in Figure 2.167530 meshes are used in SSB impeller model. 147034 meshes are used in VB model.

![Figure 2. Mesh model](image)

![Figure 3. Geometric model of three impellers](image)

2.2 Mathematical Model

For simulating the liquid surface and vortex in stirred vessels, a two-fluid model based on Eulerian-Eulerian was used in this work. The mass and momentum balance equations may be written as:

Continuity:

\[
\frac{\partial}{\partial t} (\alpha_s \rho_s) + \nabla \cdot \left( \alpha_s \rho_s \vec{u}_s \right) = 0
\]

\[
\alpha_s + \alpha_l = 1
\]

where, \( \alpha_s \) is gas volume fraction, \( \rho_s \) is gas volume fraction averaged density; \( \vec{u}_s \) is gas velocity; \( \alpha_l \) is liquid volume fraction.
where, \(d_b\) is bubble diameter, \(C_o\) is drag coefficient that is based on the relative Reynolds number \((\text{Re})\). The relative Reynolds number for the primary phase \(l\) and secondary phase \(g\) is obtained from:

\[
\text{Re} = \frac{\rho |u_l - u_g| d_p}{\mu_i}
\]

where \(\mu_i\) is steel viscosity.

The standard \(k\)-\(\varepsilon\) turbulence model is used in the present study for simulating turbulent gas-liquid flows in stirred vessels. The governing equations for turbulent kinetic energy, \(k\), and turbulent energy dissipation rate, \(\varepsilon\), is solved only for the liquid.

Turbulent kinetic energy:

\[
\rho \frac{\partial (u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ (\mu + \frac{\mu_i}{\sigma_k}) \frac{\partial k}{\partial x_i} \right] + G - \rho \varepsilon
\]  

Rate of dissipation of \(k\):

\[
\rho \frac{\partial (u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ (\mu + \frac{\mu_i}{\sigma_\varepsilon}) \frac{\partial \varepsilon}{\partial x_i} \right] + C_1 \frac{\varepsilon}{k} G - C_2 \rho \frac{\varepsilon^2}{k}
\]

where, \(G\) is turbulence generation; \(\mu_i\) is turbulence viscosity.

\[
G = \mu_i \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
\]

\[
\mu_i = \rho C_\mu \frac{k^2}{\varepsilon}
\]

and \(C_1 = 1.44\), \(C_2 = 1.92\), \(C_\mu = 0.09\), \(\sigma_k = 1.0\), \(\sigma_\varepsilon = 1.3\).

### 2.3. Boundary Condition

In order to achieve the coupling between the blade rotation and the fluid momentum, Sliding-mesh (SM) method is adopted. The whole bath is divided into an inner region and an outer region. The inner region is set to rotating reference frame and the rotational speed of the inner region need to be specified. The outer region is set to stationary reference frame. The two regions will move relative to each other along the mesh interface. This mesh interface allows the momentum and energy transfer between inner region and outer region.

This paper doesn’t consider the temperature changes in the mixing process. The top of hot metal ladle and water model are set to pressure-out boundary condition. The gas volume fraction is 100%. That means no liquid overflow in this surface.

All of the fixed walls, which include the bottom of the tank, tank wall, blades, and shaft, are set up as standard wall function.
The pose algorithm is used to solve coupled equations of pressure and velocity. The time step is 0.005s.

3. Results and Discussion
3.1 Gas Dispersion Results
Figure 4 and Figure 5 show the comparison of the experimental and simulation results of gas-liquid distribution under the same conditions. The condition is that: eccentric stirring mode, rotation speed of 150 rpm, gas flow rate of 4.5 m$^3$/h with four holes nozzle, immersion depth of 25 cm, eccentricity of 0.4. The experimental results agree well with the simulation results on the gas-liquid fluid flow. Through the contradistinction, it can be confirmed that these models can really reflect the fluid flow in the bath. As shown in the Figure4 and Figure 5, the bubbles were not dispersed widely in the bath with VB impeller. Because improvement of SSB-D impeller and SSB impeller, it is seen that the bubble dispersion was tremendously improved. The widest bubble dispersion appears on the SSB-D impeller.

This improvement can be explained as follows, in the case of VB impeller, the relatively clear vortex indicated by white lines was formed by the strong swirl flow-2. In this case, the bubble density near the vortex was very large.

The disk on the impeller blades can weaken the swirl flow in the upper zone of the impeller, and the vortex is formed farther from the shaft. Therefore, no clear vortex can be seen. Moreover, the sloped swept-back blade impeller can strengthen the downward and the radial flow to make the bubble dispersing zone larger.

![Figure 4. Simulation results of distribution of gas volume fraction](image1)
![Figure 5. Experimental results of distribution of gas and liquid](image2)

3.2 Velocity Results
Figure 6 shows the velocity distribution of the injection bath under different impeller. The velocity around the blade of SSB-D impeller is significantly greater than the other two kinds of impeller. When under the same rotation speed, the higher velocity indicates that SSB-D impeller can transform kinetic energy to liquid velocity more effectively, which is benefit in reducing
energy consumption. By increasing liquid velocity, the bubbles will be put in motion in the injection bath, and enlarge the bubble distribution area, so as to improve the utilization of gas.

3.3 Turbulent Kinetic Energy Results
Turbulent kinetic energy distribution is one of important factors contributing to the efficiency of mixing. Because the fluid micelles size is controlled by turbulent kinetic energy, it is extremely important to mixing process. Figure 7 is the distribution of turbulent kinetic energy in the injection bath under different impellers. The turbulent kinetic energy around the blade of SSB-D impeller is obviously larger than four-blade impeller. As turbulent kinetic energy is the main factor in bubble refining, that is to say, the tangent plane of SSB-D impeller has the advantage in bubble refining, and the disk above the blade has a downward force on the bubbles, which can increase the retention time of bubbles, so as to improve the utilization of gas in injection bath.

3.4 Liquid Flow Path Line Results
Figure 8 shows the macroscopic flows in the injection bath under the same condition with different impellers. It can been seen that, the flow filed include two kinds of circulation flow: tangential flow and radial flow. The tangential flow is circulation flow around the shaft. The axis flow is circulation flow along the axis of the impeller. As shown in the Figure8(b), the liquid flow path line induced by SSB-D impeller is quite different from the other impellers. There are two small voters below the disk. It is good for the bubble disintegration and dispersion, so as to improve the utilization of gas in injection bath.

3.5 Power Consumption Results
Power is the cost for the mixing required and it is one of the standards to measure the performance of stirring system. Stirring power required by liquid depended up the flow speed and the turbulent desired. Specifically, the stirring power was related to the shape and size of
the impeller, the rotational speed, viscosity and density of the fluid, the size of the tank, the internal structure(such as baffle or other obstacle), the position of the impeller, and etc.

In this gas-liquid two phase flow, the main power consumption was caused by the resistance from liquid phase. The total moment torque can be computed by integrating the torque on the impeller, and the value of power could be calculated by (11):

\[ P = M \omega = \frac{2\pi n M}{60} \]  

where, \( P \) is the power consumption of the impeller, W; \( M \) is drag torque of the impeller from the liquid phase, Nm; \( \omega \) is the rotational angular velocity of the impeller, rad/s; \( n \) is rotational speed, r/min.

The power consumption is different with the different impeller structure. The power of impeller directly affects the effective energy utilization rate and production capacity efficiency. Studying power of each impeller has a very important significance on industrial production.

We tested many kinds of impeller structure, but here present the results for three impellers shown in Figure 3. The simulation condition is that: eccentric stirring mode, rotation speed of 150 rpm, immersion depth of 25 cm, and eccentricity of 0.4. The power consumption for the different impeller is shown in Figure 9. The black points means experimental results and the red points means simulation results. The experimental results agree well with the simulation results with the same impeller. Both the two figures show that the maximum power consumption appears on the VB impeller. After blowing gas, because gas density is much smaller than that of water, stirring power decreased remarkably. At the same time, the greater the gas holdup in the bath is, the smaller the stirring power required is. Stirring power of SSB impeller is obviously less than the VB impeller, thus it can be seen that this impeller structure has a very good energy-saving effect. The power consumption for the SSB impeller with disk was larger than that for that without disk. It seems that the tangential flow, which reduced the power consumption, was stronger for the impeller without disk.

![Figure 8. Liquid flow path line in the injection bath](image_url)

![Figure 9. Effects of different impeller on power consumption](image_url)
4. Conclusion

In this paper, a mathematical model of injection bath is developed. It is used to investigate gas-liquid fluid flow, velocity, turbulent kinetic energy and the power consumption in the injection bath. The results have been validated against water model experiment. More specifically, the predictions using analytical equations have been found to agree well with the experimental results on the gas-liquid fluid flow and power consumption. The conclusions are as follows:

1. The SSB-D impeller is better for bubble disintegration and dispersion, and can effectively reduce the power consumption in injection refining bath.
2. The disk on the impeller blades can weaken the swirl flow in the upper zone of the impeller. Therefore, the bubble residence time is extended, and the bubble dispersing zone is also increased.

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