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A Mathematical Model on Vacuum Chamber of a Multifunctional RH-degasser

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Abstract: A 3D-mathematical model was developed for the simulation of gas flow, combustion and heat convection in RH vacuum chamber. Under different conditions, the influences of the Kawasaki Oxygen Top Blowing system (KTB) on the gas flow, chemical reactions and temperature distributions were calculated based on the model. The optimum position of the lance is suggested for the RH-KTB degassing process.

Key words: RH-degasser; gas flow; combustion; mathematical model

RH equipment has been developed from having the single function of only degassing (H_2 and N_2) into possessing the multi-functions of degassing (H_2,N_2,O_2), decarburization, desulfurization, inclusion removal and temperature adjustment[1–4].

In the process of RH refining, there are many complicated physical changes and chemical reactions taking place, such as heat transfer, mass transfer and multiphase fluid flow etc. Especially when the RH vacuum chamber is taken as a semi-black box, its complex inner processes and reactions need to be investigated through physical simulation experiments and mathematical simulation. For example, water model experiment can emulate the processes of circulation flow, decarburization, degassing (O_2, N_2 and H_2), and so on, but it can do nothing about the processes of heat convection, combustion etc. The simulation of such the processes as post-combustion and heat convection are conducted only by means of mathematical model with computer.

1 Mathematical Model

The combustible gases in RH vacuum chamber usually escape from the molten steel in a circulation motion. The amount of the outcome gases follows the normal distribution of irregular patterns, with the up-leg as the symmetry center. Due to diffuse gradually during their up-rising process, the escaped gasses became uniformly distributed in the end. These gases are generally consisted of circulating carrying gas (Ar or N_2), decarburized products (CO) and degassing products (H_2 and N_2). If Ar is used as the circulating carrying gas, there will be only trace H_2 and N_2, with a ratio of Ar to CO being 1:5–1:10 during the peak period of decarburization. The temperature of the outcome gases is nearly the same as that of the molten steel. If oxygen is provided by a oxygen lance at the top of RH chamber, the high speed oxygen jet will move in the direction opposite to the escaped rising gases and bring a strong agitation to the liquid steel in the chamber. Meanwhile, the turbulent diffusing combustion reaction of CO and O_2 will take place in the chamber, where the combustion flame heats the molten steel and its heating efficiency depends on the lance position of KTB, from which the shape and position of the combusting flame usually result. The mathematical model was established on the basis of the above descriptions.

1.1 Basic assumptions

(1) It's supposed that the gases belong to the continuous medium when the degree of vacuum is below 133.322 Pa that means there are enough gases in the chosen minute volume.

(2) The outcome gases from the molten steel in the vacuum chamber follow with the patterns of the normal distribution, taking the up-leg as the symmetry center axis:

$$w=\frac{Q}{A}\times\frac{1}{2\pi b_1 b_2}e^{-\frac{(x-a_1)}{b_1^2}}\times e^{-\frac{(y-a_2)}{b_2^2}} \tag{1}$$

Where a_1, a_2 is x-axis and y-axis coordinate of the up-leg; b_1, b_2 x-axis and y-axis intensity value of Gaussian; Q circulation flow of molten steel; A cross section area of RH vacuum chamber.

(3) The combustion of CO in vacuum chamber is considered as turbulent diffusion combustion.

(4) To simplify the calculation, the trace amount of H_2 and N_2 in the gases is not taken into consideration.

1.2 Mathematical model

The k–ε two-equation turbulent model was used to carry out the numerical calculation of the fluid field. The model includes continuous equation, momentum equations in x, y and z directions, turbulent kinetic energy k equation and turbulent kinetic dissipation ε equation. In the vacuum chamber the post combustion of CO belongs to turbulent diffusion combustion. And the quick reaction model is applied to the simple chemical reaction system in the turbulent diffusion combustion. It presented as follows:

Mixture fraction is defined:

$$\bar{f} \equiv \frac{\phi_M - \phi_A}{\phi_F - \phi_A} \quad (2)$$

Pulse dissipation of mixture fraction is defined:

$$g \equiv \overline{f'^2} \equiv \int_0^1 (f-\bar{f})\cdot P(f)\mathrm{d}f \quad (3)$$

Where ϕ is the conservation value in the system, and subscript A, F and M represent oxygen, CO and product stream respectively, $P(f)$ the PDF of mixture fraction.

After the mixture fraction and the pulse dissipation were defined as mentioned above. Their control equation similar to that in turbulent kinetic energy equation can also be obtained. As well as coupling energy T equation and concentration M_i equation make up the whole mathematical model. The universal equation for all these is that:

$$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial}{\partial x}(\rho u\phi)+\frac{\partial}{\partial y}(\rho w\phi)+\frac{\partial}{\partial z}(\rho w\phi)=$$
$$\frac{\partial}{\partial x}\left(\Gamma_\phi\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_\phi\frac{\partial\phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_\phi\frac{\partial\phi}{\partial z}\right)+S_\phi \quad (4)$$

The variables of parameters for each respective equation are given in **table 1**.

In table 1 subscript i represents CO, CO_2 and O_2, and Q is releasing heat value by combustion, r the rate of chemical reaction.

Table 1 Parameter variables of the general equation

Equation	ϕ	Γ_ϕ	S_ϕ
Continuous equation	1	0	0
x momentum equation	u	μ_e	$-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu_e\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial z}\left(\mu_e\frac{\partial w}{\partial x}\right)$
y momentum equation	v	μ_e	$-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu_e\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_e\frac{\partial w}{\partial y}\right)$
z momentum equation	w	μ_e	$-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left(\mu_e\frac{\partial u}{\partial z}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial v}{\partial z}\right)+\frac{\partial}{\partial z}\left(\mu_e\frac{\partial w}{\partial z}\right)$
Turbulent kinetic energy equation	K	$\frac{\mu_e}{\sigma_k}$	$G_K-\rho\varepsilon$
Turbulent kinetic dissipation equation	ε	$\frac{\mu_e}{\sigma_\varepsilon}$	$\frac{\varepsilon}{K}(c_1G_K-c_2\rho\varepsilon)$
Mixture fraction equation	f	$\frac{\mu_t}{\sigma_f}$	0
Pulse dissipation of mixture fractin equation	g	$\frac{\mu_t}{\sigma_g}$	$c_{g1}\mu_e\left[\left(\frac{\partial\bar{f}}{\partial x}\right)^2+\left(\frac{\partial\bar{f}}{\partial y}\right)^2+\left(\frac{\partial\bar{f}}{\partial z}\right)^2\right]-c_{g2}\rho\varepsilon\frac{g}{K}$
Energy equation	T	$\frac{\mu_e}{\sigma_T}$	Q
Concentration equation	m_i	$\frac{\mu_e}{\sigma_m}$	r

1.3 Boundary conditions

(1) Boundary of velocity field.

At the molten steel plane on the bottom of the vacuum chamber where u=0, v=0, but w is the same as equation (1).

At the top and on the walls of the vacuum chamber where $\frac{\partial v_i}{\partial x_j}=0$, i=1, 2, 3, j=1, 2, 3, $j\neq i$.

(2) Boundary of temperature field.

On the molten steel surface in vacuum chamber where $q=\alpha\times(T_s-Y_g)$.

At the top of the flow and on the walls where $q_i=0$ (i=1,2,3).

(3) Boundary of concentration field.

On the molten steel surface in vacuum chamber where $m_i = m_{i0}$ (i=CO, H_2, N_2, O_2, Ar).

At the top of the flow and on the walls where $m_i = 0$ (i=CO, H_2, N_2, O_2, Ar).

1.4 Numerical solution method to the equations

The equations listed above were dissipated on the control units to be turned into difference equation group, then, the numerical solutions to the variables were obtained from using the method of SIMPLER calculation.

2 Calculation Results and Discussions

2.1 Velocity field

The velocity field in RH chamber is generally characterized by the followings: The fluid field speed is very high and the vertical height is comparatively tall, so the horizontal branch velocity of the gases escaped from the vacuum chamber is low compared with that in the vertical direction. Especially the velocity along the up-leg is remarkably high and it turns out to be uniformly distributed on the whole intersections of the RH chamber later with the increase of the altitude. If there exists an oxygen stream, it will give rise to a vigorous agitation zone. The gas flow fields on the across section of up-leg and down-leg in the vacuum chamber are described in **figure 1**. After the comparison of (a) with (b), (c) and (d), it can be found out that the influence of KTB arrangements on the flow field at the bottom of the vacuum chamber is obvious. The oxygen stream has a strong impulsive force to cause a compulsion zone of 3–4 m tall in altitude in the environment of rising gases. Comparing (b) with (c) and (d), in the situation of (b) when the position of oxygen lance is at 1 m to the molten steel surface, the high-speed jet goes down too quickly to diffuse before reaching the surface of the molten steel in the vacuum chamber, with bringing about a lot of steel drop and excess oxidization of

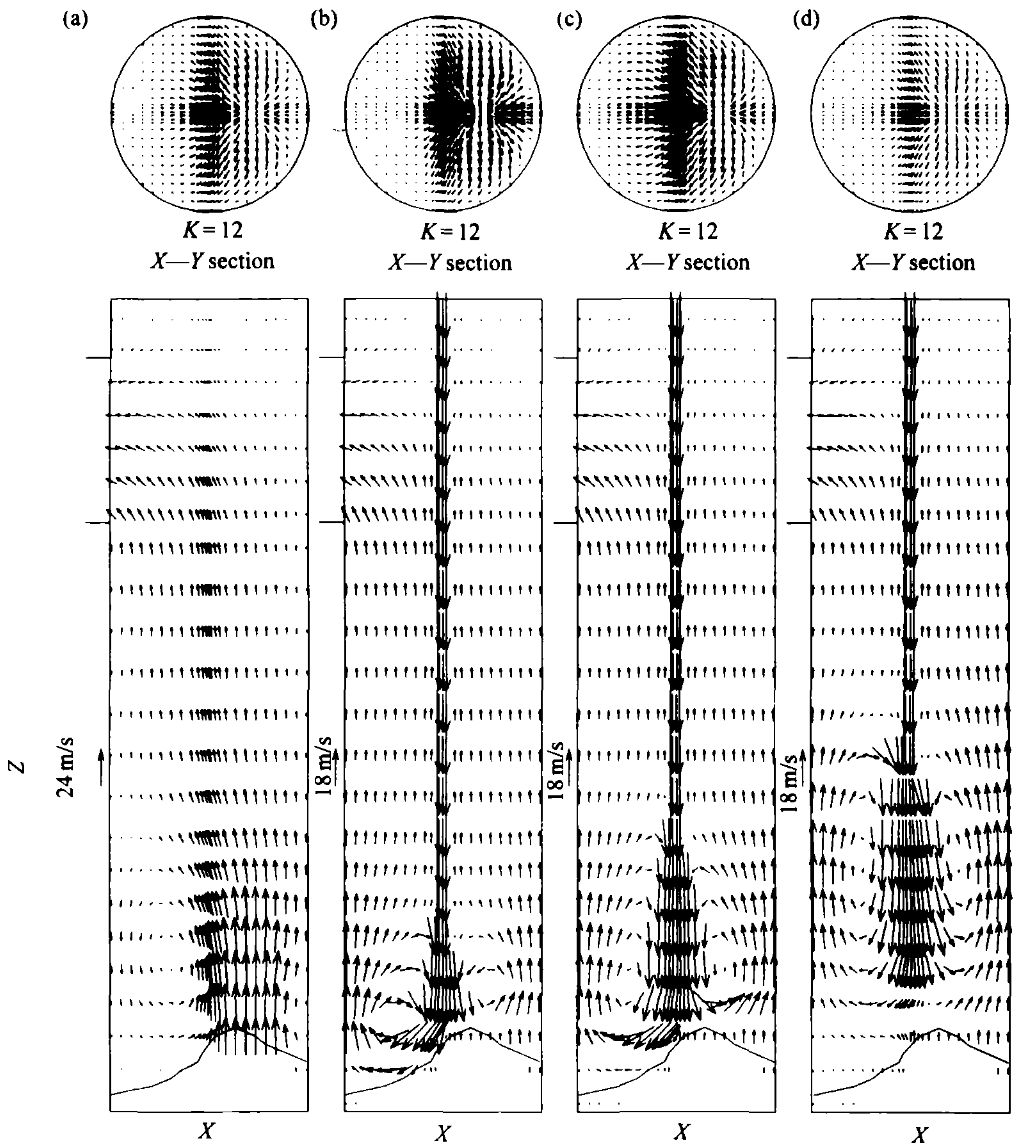

Figure 1 Velocity field in RH vacuum chamber (j=2), (a) no oxygen lance; (b) 1 m position of oxygen lance; (c) 2 m position of oxygen lance; (d) 3 m position of oxygen lance.

the molten steel. In figure 1(d), the position of oxygen lance of KTB is at 3 m to the molten steel surface, the compulsive kinetic energy of the oxygen jet has run without reaching the molten steel surface and the oxygen stream returns bark while being brought up by the gases flowing in the reverse direction. Although the excess oxidization may not take place at this moment, it is very difficult to heat the molten steel surface by the way of the combustion of CO because the oxidizing zone is away from the surface region of the molten steel under this condition. Finally, the position of KTB being at 2 m to the molten steel surface, not only it can be carried out with easy to heat the molten steel by combustion of CO, but the molten steel can avoid being necessary excessively oxidized by the oxygen stream. In a word, the optimum arrangement of KTB is to put the oxygen lance at the altitude of 2 m in RH vacuum chamber to conduct the heating and heat insulation of the molten steel by means of post combustion.

2.2 Temperature field

When O_2 is provided by KTB, the characteristic of gases' temperature field in the vacuum chamber is considered as "low–high–low". That means, at first the low temperature center is formed around the top of oxygen lance, then the temperature is rising gradually toward the peripheral part to reach the highest in the combustion and diffusion zone of CO and O_2, and later turns lower continuously towards the further peripheral region. The post combustion in the vacuum chamber is a high-speed flame in motion of turbulence and diffusion to lead to an irregular curve-like interface.

Figure 2 displays three temperature fields corresponding to the three flow fields respectively with the same position of oxygen lance. The compared results of the three temperature fields prove that there is no obvious change in temperature near the molten steel surface after falling the position of oxygen lance from at 2 m down to at 1 m. This is because there will be no chance for the oxygen jet to come into contact fully with the up-rising CO to get enough combustion when the lance position is too low. In this case, post combustion takes place mostly in the upper part of the vacuum chamber. Comparing the case of the temperature field of oxygen lance position at 2 m with that at 3 m. In conclusion, the lower is the position, the higher is the temperature next to the surface of the liquid steel. These analyses assure that the position of oxygen lance at 2 m is the best one for heating the molten steel by way of post combustion.

2.3 Concentration field

In RH vacuum chamber the gases are mainly consisted of CO, CO_2 and O_2 whose distributions are characterized by the followings: CO is concentrated mostly on the molten steel surface, especially on the area round the up-leg, disappearing quickly with the increase of the distance away from the surface. The concentration of CO_2 increases with the increase of height and there is a comparatively low concentration place near the head of the oxygen lance. O_2 is distributed in an as symmetrical curve-like zone with the head as its center, and the oxygen concentration turns lower from the center to the peripheral region. The three distributions of the gases CO, CO_2 and O_2, each with three arrangements of lance respectively at 1 m, 2 m and 3 m, are shown in **figures 3, 4** corresponding to that of the same arrangement of lance in figure 1. The analytical results of these figures indicate that when the lance position is at 1 m, the oxidized zone extends to the liquid steel surface and causes the direct oxidization of the liquid steel by oxygen stream, so more deoxidizer was consumpted and more deoxidized products was produced. Under the condition of the lance at 3 m the oxidized zone is far away from the molten steel surface, that is the failure in the heating and insulation of the liquid steel. While the lance at 2 m, the peripheral part of the oxidized zone lies on the liquid steel surface, which can both keep the liquid steel from excess oxidization and make the heating of the molten steel is carried out well by post combustion.

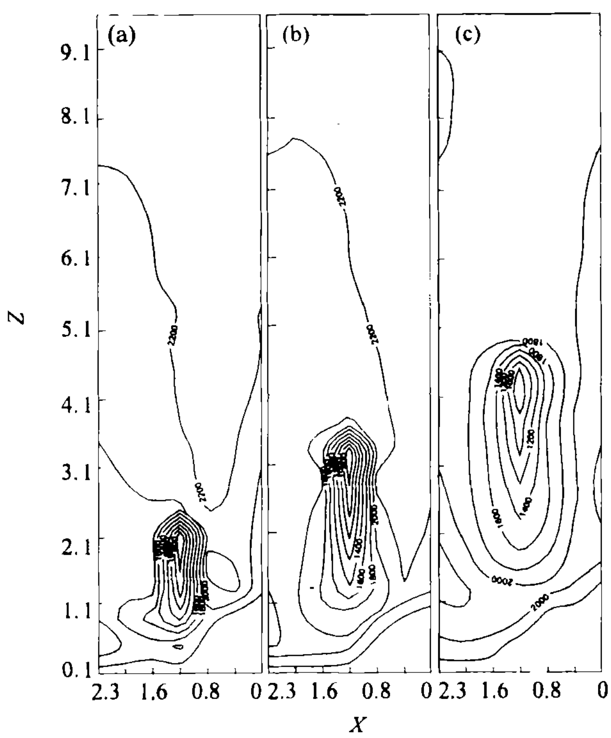

Figure 2 Temperature field in the RH vacuun chamber, (a) 1 m position of oxygen lance; (b) 2 m position of oxygen lance; (c) 3 m position of oxygen lance.

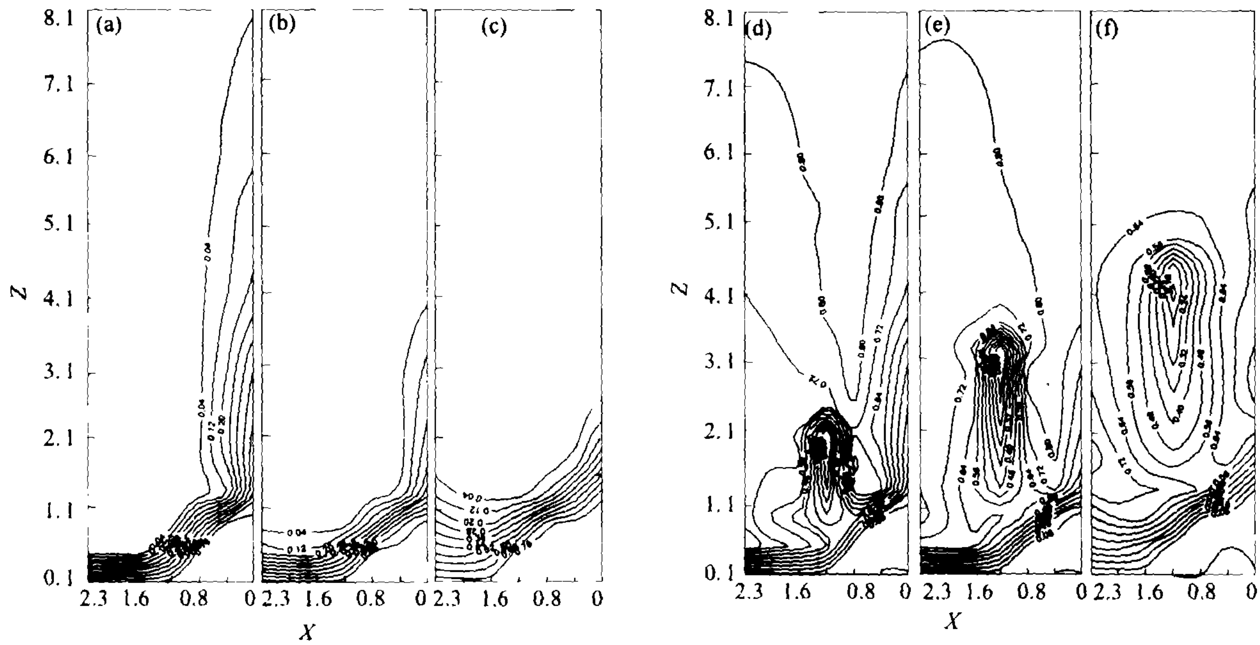

Figure 3 CO (a–c) and CO_2 (d–f) concentration field in RH vacuum chamber, (a) and (d)1 m position of oxygen lance; (b) and (e) 2 m position of oxygen lance; (c) and (f) 3 m position of oxygen lance.

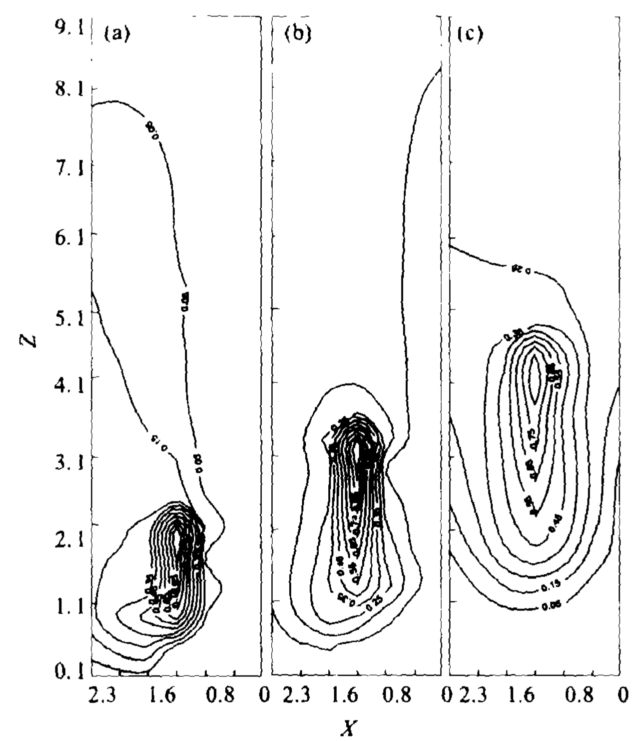

Figure 4 O_2 concentration field in RH vacuum chamber, (a) 1 m position of oxygen lance; (b) 2 m position of oxygen lance; (c) 3 m position of oxygen lance.

3 Conclusion

(1) Oxygen jet in post combustion can render a vigorous agitation to the fluid field at the bottom of the RH vacuum chamber and the agitation contributes much to the uniform distribution of gases on the cross-sections of RH vacuum chamber.

(2) The optimum arrangement of KTB for carrying out the heating and insulation of the molten steel is to put the oxygen lance at the altitude of 2 m in RH vacuum chamber.

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