Numerical Analysis of Molten Steel Flow in Ladle of RH Process

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As the result of the analysis of molten steel flow in a ladle during 310 t RH treatment by the use of a three-dimensional fluid analysis program, the following facts have been found:

(1) In the actual ordinary operational conditions of the flow velocity of molten steel discharged out of a down snorkel, by-pass flow does not take place between the down snorkel and up snorkel, and also the effect of a center-to-center distance of the snorkels on the generation of such by-pass flow is little.

(2) When the sectional area of the snorkel is small, a stagnating phenomenon occurs over the whole surface of ladle bath. Whilst, when a circulation rate is increased by enlarging the sectional area of the snorkel, the mixing of the bath in the ladle is improved.

(3) As for the equipment characteristics, it is more advantageous to increase RH decarburization rate when the snorkel sectional area is large.

KEY WORDS: vacuum degassing; numerical analysis; RH; fluid dynamics.

1. Introduction

Heretofore in each iron and steel making company, the technology of manufacturing an ultra-low carbon steel by a BOF or a secondary refining process has made enormous progress and what is more, a great number of results of research and development of RH process have been reported,1,2) In RH decarburization process, it can be thought that reaction sites are near the interface of molten steel and atmosphere in vacuum vessel and near the interface of molten steel and argon injected from the up snorkel, and that no reaction takes place in molten steel in a ladle. However, the mixing condition of molten steel in a ladle has an effect on the concentration of carbon in molten steel flown into the vacuum vessel from the up snorkel and exert a great influence on RH decarburization rate.

There is a report indicating that as the technology of manufacturing an ultra-low carbon steel by RH process, enlargement of the sectional area of RH snorkel is effective to increase the circulation rate and decarburization rate.3) However, with the increase in sectional area of RH snorkel, the center-to-center distance of snorkels becomes short, which brings about the possibility of the generation of by-pass flow of molten steel from the down snorkel toward the up snorkel without reaching the bottom of the ladle and decreasing the reaction efficiency.

It can also be deemed that the change in the mixing in a ladle according to the enlarged sectional area of RH snorkel has an effect on the decarburization rate. It is understood from the above viewpoint that there is a need to examine the flow and mixing con-
ditions of molten steel in a ladle during RH treatment. Up to the present, there is a few examples4,5) of such analysis as mentioned above, but not the detailed report. Therefore in this research, with particular attention to such factors as the discharging velocity of molten steel from the down snorkel, snorkel diameter (circularizing rate), center-to-center distance of snorkels, etc., numerical analysis has been made on a three-dimensional flow and mixing characteristics of molten steel in a ladle during RH treatment process.

2. Calculation Theory

Calculations of the flow of molten steel and the concentration of a tracer for mixing in the ladle were made by the following manner. Generally, the bath flow in the ladle at a time of RH treatment becomes a turbulent flow and it is difficult in fact to analyze a non-steady turbulence phenomenon as it is viewed from a time as well as a space.

Thus, by the use of a turbulent flow model6) (k & e equation model) which is available in calculating a turbulent flow characteristic averaged with time, the following mass conservation equation, momentum conservation equation, specific values of turbulent flow (k & e) and tracer concentration equation were solved simultaneously.

(1) Basic Equations
Mass conservation equation:

\[ \text{div} \, \vec{U} = 0 \] ..................................(1)

Momentum equation:

\[ \text{div} \left( \vec{U} \phi - \mu \text{grad} \phi \right) = -\text{grad} P \] ...........(2)

\[ \phi = u, v, w \]
$k$ & $c$ equation:

$$\begin{align*}
\text{div} (\tilde{U} k - \mu_{rel} / \sigma_v \text{grad} k) &= G_{4}(p - e) \quad \text{(3)} \\
\text{div} (\tilde{U} e - \mu_{rel} / \sigma_v \text{grad} e) &= z / k (C_{G_{4}} p - e z) \\
\mu_{rel} &= \mu_{tan} + \mu_{arb} \quad \text{(4)} \\
\mu_{tan} &= C_{p} \rho e / k \quad \text{(5)} \\
G_{4} &= \mu_{rel} \sum \partial u / \partial x_{j} + \partial u / \partial x_{i} \partial u / \partial x_{j} \quad \text{(6)} \\
C_{G_{4}} &= \mu_{rel} \sum \partial u / \partial x_{j} + \partial u / \partial x_{i} \partial u / \partial x_{j} \cdot \partial a / \partial c \quad \text{(7)}
\end{align*}$$

Tracer concentration equation:

$$1 / \rho \frac{\partial C}{\partial t} + \text{div}(\tilde{U} C - \mu_{rel} (\rho \cdot a_{c}) \text{grad} C) = 0$$

(8)

In Eqs. (3), (4) and (8), 5 universal constants are given by Launder and Spalding as shown below:

$$\begin{align*}
C_{e} &= 0.09, \quad C_{1} = 1.44, \quad C_{2} = 1.92, \\
\alpha_{e} &= 1.0, \quad \alpha_{1} = 1.3, \quad \sigma_{e} = 1.0
\end{align*}$$

(2) Boundary Condition

Table 1 shows the boundary conditions adopted in this calculation. A wall function was employed for the refractory surface, by taking a steep flow velocity gradient nearby the wall into account.

(3) Numerical Calculation Technique

By differentiation of Eqs. (1) to (8) on the basis of a control volume method as a spatial discretization, a differential equation was derived by integrating a volume with each control volume. Further, a simplest method was adopted in order to solve the flow velocity and pressure in a compound manner.

3. Calculation Conditions

Table 2 shows the configuration of an actual 310 t RH and its operating conditions. Effect of discharging velocity of molten steel from the down snorkel was examined by comparing the condition of A-I with that of A-II, in the same way, effect of center-to-center distance of snorkels by comparison of Conditions B and C, and effect of snorkel diameter by comparing Conditions A-II and B in which center-to-center distances are nearly equal. Velocity of molten steel from down snorkel, snorkel diameter, center-to-center distance of snorkels are independent to each other. Moreover as a circulation rate, a value calculated from Eq. (9) was used.

$$W = 22 \times (H^{0.3} Q^{0.18} D_{p}) \quad \text{(9)}$$

Assuming that a molten steel in a ladle has a columnar form of 4.0 m in diameter and 3.5 m in height, it was divided into 20, 15 and 15 sections, respectively, in X, Y and Z directions to calculate as 4 500 meshes in all as shown in Fig. 1. Moreover, the dipping depth of the snorkel is 0.47 m in each condition.

In addition, the mixing condition of molten steel in a ladle was examined by discharging molten steel of 0.5 wt% solute concentration out of the down snorkel continuously together with the added molten steel whose initial solute concentration in the ladle was assumed to be zero in Conditions A-I, B and C and from calculations of the concentration distribution of molten steel in the ladle after a certain time. The concentration distribution of the molten steel in the ladle was shown by dividing equally the concentration of 0 to 0.5 wt% into 20 parts.

4. Calculation Results and Discussion

4.1. Effect of Flow Rate of Molten Steel Discharged from Down Snorkel on Flow of Molten Steel in Ladle

Figs. 2 to 5 show the calculation results of the flow of molten steel in a ladle for Conditions A-I and -II. Figs. 2 and 4 show a longitudinal section (hereinafter referred to as M section) passing through the
center of each section of the up snorkel and down snorkel, and Figs. 3 and 5 show a longitudinal section (hereinafter referred to as N section) which is perpendicular to the M section. Although there is a tendency that the main flow route of molten steel from the down snorkel to the up snorkel becomes somewhat short with the decrease in the flow velocity of molten steel discharged from the down snorkel from 1.68 to 0.5 m/s, the flow of molten steel coming out of the down snorkel is reaching the ladle bottom and in either case, no by-pass flow of molten steel is formed from the down snorkel toward the up snorkel. According to the analysis of the flow of molten steel in a ladle during RH treatment made by Shirabe and Szekely, it is different from such a result that the by-pass flow of molten steel is induced from the down snorkel toward the up snorkel when the flow velocity of molten steel discharged from the down snorkel is 0.72 m/s. The reason can be ascribed to the difference between the mass balance of molten steel in a ladle obtained by two dimensional analysis proposed by Shirabe and Szekely and the present three dimensional analysis. Though there is a possibility of the generation of by-pass flow of molten steel from the down snorkel toward the up snorkel when the flow velocity of molten steel coming out of the down snorkel is further reduced, it can be reasoned that no by-pass flow of molten steel comes up because the flow velocity of molten steel discharged out of the down snorkel is generally in excess of 1 m/s in the range of an actual routine operation.

4.2 Effect of Snorkel Diameter and Center-to-center Distance of Snorkels on Flow of Molten Steel in Ladle

Figs. 6 & 7 and Figs. 8 & 9 show the calculation results obtained in cases of Conditions B and C.

When the cases of Conditions B and C wherein the snorkel sectional area was increased were compared with the case of Condition A-I in Figs. 2 and 3, it is found that despite the flow rate of molten steel discharged from the down snorkel being lower than that in Condition A-I, the molten steel flow rate at the
ladle bottom is rather high, and that no marked change is macroscopically seen in the direction of the flow line of molten steel though there is a difference in the flowage.

As stated above, the flow rates of molten steel at the ladle bottom in Conditions B and C are higher than that in Condition A-I. The reason is that although the flow velocities of molten steel coming out of the down snorkel in Conditions B and C are lower than that in Condition A-I, the snorkel sectional area is large and the circulation rate (t/min) is about double that in Condition A-I, and consequently, a difference can arise in the kinetic energy of molten steel discharged out of the down snorkel.

Again, as a difference in the effect of the center-to-center distance of snorkels on the flow of molten steel in both Conditions B and C where the snorkel has a large section, the flow rate of molten steel going up along the side wall of ladle in Condition C is higher than that in Condition B at both down snorkel and up snorkel sides. This can be reasoned as follows. Namely, it will be that in the case of Condition C, the position of the down snorkel is near the center of the ladle and attenuation of the jet velocity of molten steel coming out of the down snorkel is little on the side wall of ladle at the up snorkel side and further on the side wall of ladle at the down snorkel side, the interference is minor between the jet of molten steel coming out of the down snorkel and the rising flow of molten steel on the side wall of ladle at the down snorkel side. Moreover, because the center-to-center distance of snorkels is short in Condition C, no generation of bypass flow of molten steel from the down snorkel toward the up snorkel is seen, nor be a difference between Condition B and the above.

4.3. Effect of Circulation Rate and Center-to-center Distance of Snorkels on Mixed Condition in Ladle

In Conditions A-I, B and C, as described before, a molten steel having 0.5 wt% solute concentration was added to a molten steel whose initial concentration in the ladle was assumed to be zero and the molten steel was discharged continuously from the down snorkel. Figs. 10 to 12 show the concentration distribution of
molten steel in the ladle at each M section in 30 s after the beginning of discharge. It is found from these figures that in Condition A-1, a part where a

![Diagram of snorkel distribution](image)

**Fig. 10.** Distribution of concentration in ladle in 30 s after adding solute in Condition A-1. (M section)

molten steel having concentration of 0.05 % or less is stagnating (hereinafter, a stagnant part) is formed over the whole surface of the ladle bath in 30 s after the commencement of discharge, whereas in Conditions B and C, the stagnant part exists only in the vicinity of a zone between the up snorkel above the ladle bath and side wall of ladle. The reason why the stagnant part is formed around the down snorkel above the ladle bath in Condition A-1 but not in Conditions B and C can be considered as follows; since the circulation rate is high, the flow rate of molten steel at the ladle bottom just beneath the down snorkel, in its turn the flow rate of molten steel going up along the side wall of ladle is high and as a result, molten steel existing between the down snorkel and side wall of ladle is stirred up. On the other hand, at a zone between the up snorkel and side wall of ladle, the stagnant part is formed in Conditions A-1, B and C. It is however presumed that although the rising flow velocity of molten steel on the side wall of ladle at the up snorkel is high in Conditions C, B and A in this order, since a considerable volume of the rising flow of molten steel on the side wall of ladle is drawn into the up snorkel in either case, the molten steel on the bath surface between the up snorkel and side wall of ladle is not stirred sufficiently. In other words, as far as the position of the stagnant part formed on the bath surface at the up snorkel side is concerned, no big difference is recognized even though the center-to-center distance of snorkels is short.

Fig. 13 shows the condition that the average concentration on the bath surface inside the up snorkel changes with the lapse of time in Conditions A-1, B and C. Also, Fig. 14 indicates the change in concentration with the lapse of time at a typical position C_1 (the position at a distance of 6.7 cm from the wall of up snorkel and 11.7 cm under the surface of molten metal) of the aforesaid stagnant part shown in Figs. 10 to 12.

As is apparent from Figs. 13 and 14, when Condition B where the snorkel sectional area is large to increase the circulation rate in comparison with Condition A-1, not only the change in the average concentration on the bath surface inside the up snorkel but also the change in the concentration at the stagnant part quickens and RH treatment charac-

![Graph of concentration change](image)

**Fig. 13.** Change in average concentration ($C_{av}$) of bath in up snorkel with lapse of time in Conditions A-1, B and C.
Characteristics are improved.

In addition, when the calculation results of Conditions B and C where the snorkel sectional area is large and the center-to-center distance of snorkels differs are compared with each other, there is a tendency that the initial changes in the average concentration of the bath inside the up snorkel and in the concentration at the stagnant part are quicker in Condition C where the center-to-center distance of snorkels is short. However, since the difference is small, the effect of the center-to-center distance of snorkels on RH treatment characteristics should be little. Next, to make clear the mixed characteristics of molten steel in a ladle available as a refining vessel, the characteristics in Conditions A-I, B and C were compared with each other by the use of a complete mixing bath flow model. The result is shown in Fig. 15. It is found from Fig. 15 that in Condition A-I, the mixed characteristics are approximate to a complete mixed flow and in Conditions B and C, the same behavior as a complete mixing bath flow with 2 baths is exhibited.

In other words, it can be said that when the snorkel sectional area has been enlarged to increase the circulation rate, the response at out side relative to in side of the ladle deteriorates as a refining vessel viewed from the same time ratio (t/t*).

As for RH decarburization treatment, however, it is supposed that a large difference between the concentration of molten steel drawn into the up snorkel and that of molten steel discharged out of the down snorkel promises a great reaction accelerating effect.

And as a refining reaction equipment, it can be said that an equipment providing higher efficiency when the circulating rate is increased by enlarging the snorkel sectional area is preparable.

5. Conclusion

The analysis of the flow and mixing conditions of molten steel in a ladle during 310 tRH treatment undertaken by the use of a three-dimensional fluid analysis program has revealed the following facts:

(1) Even if the flow rate of molten steel discharged out of a down snorkel is reduced from 1.68 to 0.5 m/s, by-pass flow exerting an aggravating influence upon the RH treatment effect is not produced between the down snorkel and up snorkel. In the routine operating conditions of actual equipment, it can be guessed that no bypass flow comes out at a part between the down snorkel and up snorkel even though the flow rate of molten steel discharged is low.

(2) Even when the center-to-center distance of snorkels is reduced from 1.6 to 1.15 m, the above bypass flow does not generate at a part between the down snorkel and up snorkel, and the effect of the center-to-center distance of snorkels on the generation of by-pass flow between the down snorkel and up snorkel becomes to be minor.

(3) When the sectional area of the snorkel is small, a stagnant part is generated over the whole surface of the ladle bath, whereas in case where a circulation rate is increased by enlarging the snorkel sectional area, the stagnant part becomes to exist only at a part between the up snorkel above the ladle bath and side wall of ladle, and the mixing of molten steel in the ladle is improved.

(4) A comparison of the two made by the use of a mixing model, the one is that the snorkel sectional area is small and the other is that the area is large, manifests that in the former case, almost a complete mixing flow can be obtained, and that in the latter case, the molten steel flow is approximate to a bath flow with 2 baths. As the equipment characteristics, the enlarged sectional area of the snorkel is more advantageous because the change in concentration at the same time ratio (t/t*) is slow and a difference in the concentration of molten steel becomes great be-
between the up snorkel and down snorkel sides.

**Nomenclature**

- $C_{in}$: Average concentration (wt%) at in side to ladle from down snorkel
- $C_{out}$: Average concentration (wt%) on bath surface in up snorkel
- $D$: Inside diameter of snorkel (m)
- $D_s$: Viscosity dissipation item (g/cm$^2$s$^3$)
- $H$: Suction height of molten steel (m)
- $k$: Turbulent flow energy (cm$^2$/s$^2$)
- $P$: Pressure (dyn/cm$^2$)
- $Q$: Ar gas flow rate (Nm$^3$/min)
- $r$: Coordinates in radial direction (cm)
- $t$: Time required from start of mixing (min)
- $t^*$: Amount of molten steel in ladle/circulation rate (min)
- $U$: Flow rate vector ($u$, $v$, $w$) (-)
- $u$: Flow rate component in $x$ direction (cm/s)
- $v$: Flow rate component in $r$ direction (cm/s)
- $W$: Circulation rate (t/min)
- $w$: Flow rate component in $z$ direction (cm/s)
- $x$: Coordinate in circumferential direction (rad)
- $z$: Coordinates in axial direction (cm)
- $\varepsilon$: Dissipation rate of turbulent flow energy (cm$^2$/s$^3$)
- $\mu_{lam}$: Laminar flow viscosity coefficient (g/cm$\cdot$s)
- $\mu_{turb}$: Turbulent flow viscosity coefficient (g/cm$\cdot$s)
- $\mu_{eff}$: Effective viscosity coefficient (g/cm$\cdot$s)
- $\rho$: Density (g/cm$^3$)

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