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ENHANCEMENT IN BATH MIXING AND PLUME AREA IN A NEW DEGASSING PROCESS – A COMPUTATIONAL FLUID DYNAMIC STUDY

ZWIĘKSZENIE MIESZANIA KĄPIELI I OBSZARU MIESZANIA W NOWYM PROCESIE ODGAZOWANIA – BADANIA OBLICZENIOWEJ DYNAMIKI PŁYNÓW

Reaction between the various species in slag and metal phase is usually mass transfer controlled. There have been continuous efforts to increase the reaction efficiency in slag-metal system, especially during decarburization of steel to produce the ultra low carbon steel (ULCS) in secondary steelmaking. It has been found that the surface reaction is a dominant factor in the final stage of decarburization. In the initial stage, the inner site reaction is major factor in the refining process. The mixing of bath affects the later reaction. However, the former reaction (surface reaction) is affected by the plume size area at the top of the metal surface. Therefore, a computational study has been made to understand the fluid dynamics of a new secondary steelmaking process called Revolutionary Degasser Activator (REDA) to study the bath mixing and plume area. REDA process has been considered as it is claimed that this process can reduce the carbon content in steel below 10ppm in a less time than the other existing processes such as RH and Tank degasser. This study shows that both bath mixing and plume area are increased in REDA process facilitating it to give the desired carbon content in less time. Qualitative comments are made on slag-metal reaction system based on this finding.

Keywords: REDA, decarburization, CFD, ultra low carbon steel

Reakcja pomiędzy różnymi składnikami w fazie żużlowej i metalowej jest zwykle kontrolowana przez transport masy. Ciągle dążono do zwiększenia wydajności reakcji w układzie metal-żużel, zwłaszcza podczas procesu odwęglania, przy produkcji stali o ultra niskiej zawartości węgla (ULCS) podczas obróbki pozapieciowej. Stwierdzono, że reakcja na powierzchni jest czynnikiem dominującym w końcowej fazie odwęglenia. W początkowym etapie, reakcja wewnątrz jest głównym czynnikiem w procesie rafinacji. Mieszanie kąpieli wpływa na późniejszą reakcję. Jednakże na poprzednią reakcję (reakcja na powierzchni) ma wpływ wielkość obszaru mieszania na powierzchni metalu. W związku z tym dokonano obliczeń, w celu zrozumienia dynamiki płynów nowego procesu metalurgii pozapiecowej, nazwanego Rewolucyjny Aktywator Odgazowania (REDA), do badania mieszania kąpieli i obszaru mieszania. Twierdzi się że proces REDA może zmniejszyć zawartość węgla w stali poniżej 10 ppm w krótszym czasie, niż inne istniejące procesy takie jak RH i odgazowanie w kadzi. Z niniejszych badań wynika, że zarówno mieszanie kąpieli i obszar mieszania zwiększa się w procesie REDA, ułatwiając uzyskanie żądanej zawartość węgla w krótszym czasie. Poczynione są jakościowe uwagi na temat reakcji w układzie żużel-metal, oparte na tych wynikach.

1. Introduction

With the growth of automobile industries, etc, the demand of ultra low carbon steel (ULCS) has increased. To meet this demand productivity of vacuum degassers such as RH (Rheinstahl-Heraeus), Ladle and Revolutionary Degasser Activator (REDA) should be increased. This may be achieved by enhancing the decarburization (reaction) rate in various part of the degasser and thus reducing the treatment time. However, before finding out the ways to enhance the reaction rates, one should have a proper idea of the various reactions which are occurring in the degassers at various stages.

In a steelmaking ladle, a layer of molten slag floats over the molten steel, and Ar gas is injected through a nozzle present at the bottom of the ladle for mixing and improving the metal-slag reaction. This Ar gas forms a region uncovered by slag at the surface—the so-called plume eye [1]. Broadly, there are three reaction sites which are:

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1. Reaction occurring at the free surface exposed to vacuum (surface reaction)
2. Reaction occurring at the surface of the injected Argon bubble rising through the steel bath (bubble reaction)
3. The evolution of CO gas from the bulk of steel bath due to the reaction between dissolved C and O (bulk reaction)

The plume eye plays an important role in the decarburization reaction rates in ultra low carbon region [1]. Although, the estimation of the gas-liquid reaction rate at the surface has been reported [2-4], the controlling factor of the surface reaction has not yet been identified, fully. Therefore, in order to improve the gas-liquid reaction rate in secondary steelmaking, it is important to quantify the surface reaction rate in the gas-stirred ladle system and identify the controlling factors[5-6].

Kitamura et al. [2] have studied the contribution of various reaction rates in decarburization process as it is shown in Figure 1.

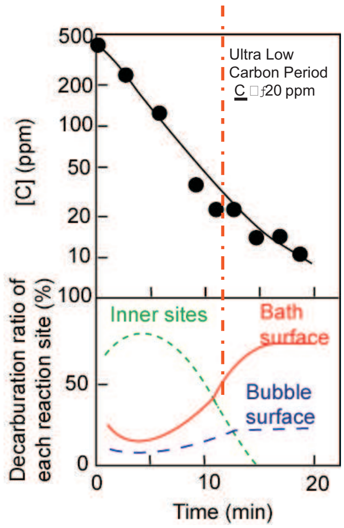


Fig. 1. Contribution of various reaction during decarburization of steel

This figure clearly shows that during the initial period of decarburization, inner sites reaction is predominant in the vessel. However at the later stage of decarburization, bath surface reaction becomes predominant along with some contribution from bubble surface reaction. The reaction of oxidation of carbon practically does not take place at the slag-metal interface because of the difficulty in nucleating gas bubbles at the interface. In reality the reaction takes place at the gas-metal interface. Recent studies [5] show that plume area plays an important role in mass transfer. Our recent research [6] shows that plume area plays an important role in determining the surface reaction rate. This clearly indicates that in order to increase the decarburization rate at the later stage of decarburization, one should try to increase the bath surface reaction. One of the ways to do this is to increase the plume eye surface area (gas – metal surface area) reaction. In fact, this concept has given the birth of a new process called/known as Revolutionary Degasser Activator (REDA) [7-9].

REDA process consists of one large cylindrical snorkel immersed into the molten steel bath and Argon gas is purged through a nozzle in to the ladle from the bottom of the ladle [7-9]. The schematic diagram of REDA process is shown in Fig. 2. It differs a little from RH and tank degasser in the sense that design features were conceptualized based on logical thinking of reaction kinetics. Such as, in order to increase the decarburization efficiency at the later stage of decarburization, surface area should be increased to increase the reaction rate which means increase in snorkel area. Certainly it works to achieve the low C content at the later stage of decarburization; however, proper design is not based on theoretical basis. Therefore, it is believed that CFD study would be very helpful to give better design aspects of the process in terms of mixing, plume area, etc [10].

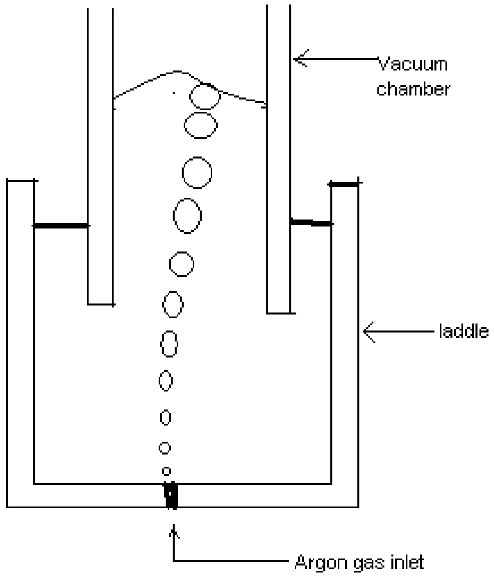


Fig. 2. Schematic diagram of REDA process

In order to study the mass transfer phenomena, which are occurring at various places in the ladle, knowledge of fluid flow behavior becomes a necessary precursor. Therefore, from numerical view point it becomes important to study both fluid flow and mass transfer phenomena which are occurring in the vessel simultaneously during the operation. Recently, Monal et al. [10] have made some attempts to study this process using computational fluid dynamics (CFD) and have shown some interesting results in terms of its design. The aim of this paper is to find out the mixing efficiency and estimation of plume eye areas at the gas-metal interface under various operating conditions for REDA process.

2. Mathematical description

Fluid flow

From mathematical modelling viewpoint, the REDA process is also similar to tank degasser except that it has one large snorkel [10]. Therefore, many features of tank degasser model [4, 11-14] can be incorporated into REDA process. For the simulation of REDA process, two dimensional (2-D) Cartesian coordinate system is considered. Unsteady state condition has been assumed. It has also been assumed that there is no slag present at the free surface of the liquid.

Liquid and gas phase have been modeled using Eulerian-Eulerian approach. The Eulerian multiphase model is based on multiple separate, yet interacting phases tracked in an Eulerian frame of reference. In this approach, pressure and turbulence fields are shared among phases whereas basic equations are solved for continuity and momentum equations. Each phase is described by its volume fraction such that at any point in space, volume fractions of two phases are unity.

$$(1-\alpha)+\alpha=1 \tag{1}$$

$\alpha$is the volume fraction of the liquid.

Equation of continuity and motion for each phase (liquid and gas) can be written in generalize form as follows:

Equation of continuity for α phase

$$\frac{\partial}{\partial t}(\alpha\rho)+\nabla.(\alpha\rho\vec{u})=0 \tag{2}$$

Where ρ and u are density and velocity of α phase.

Equation of motion in unsteady state form would be

$$\frac{\partial}{\partial t}\left(\rho\alpha\vec{u'}\right)+\nabla.(\alpha\rho\vec{u}\vec{u})=\mu_{eff}\nabla^2(\alpha\vec{u})-\nabla(\alpha p)-\nabla\left(\alpha\rho\vec{u'}\vec{u'}\right)+S \tag{3}$$

Where, $\vec{u}$ and $\vec{u'}$ are time smoothed and fluctuating vectors of the liquid velocity respectively and ρ is the density of the liquid steel. S is the source term which should be zero for liquid phase. μ_{eff} is the effective viscosity of the fluid, which is a combination of molecular and turbulent viscosity and is defined as.

$$\mu_{eff}=\mu+\mu_t \tag{4}$$

μ_t The turbulent viscosity is defined according to the k-epsilon (ε) model as

$$\mu_t=\frac{C_D k^2}{\varepsilon} \tag{5}$$

Where, C_D is a constant, k is the turbulent kinetic energy and ε is the rate of turbulent energy dissipation.

As such the fluid flow is turbulent in nature in ladle degasser; therefore, k-ε turbulent flow model is used in conjunction with the above equations in order to get the complete fluid flow behavior. k-ε model is used to get the turbulent viscosity and it is a standard model details of which can be found elsewhere [15].

For solving the gas phase, α is substituted by (1- α) and source term S should be ρ(1-α)g.

Mixing time (Mass transfer)

To study the mixing in REDA process, a tracer (NaCl) is introduced and its concentration with time is calculated computationally by solving mass transfer equation along with fluid flow equations. The mass transport of tracer is due to the convection and diffusion processes along with the reaction rate, if any, which are occurring at various sites in the process. The generalized form of the equation for species balance may be expressed as:

$$\frac{DC_1}{Dt}=D_{eff}\nabla^2 C_1+\dot{r} \tag{6}$$

where, C_1 is concentration of tracer, D_{eff} is effective diffusion coefficient of tracer which includes turbulent viscosity and turbulent Schmidt number. $\dot{r}$ is the rate at which tracer is generating or disappearing. In the present case it is zero.

As for the boundary conditions, top of the snorkel leg is defined as out let to maintain the vacuum chamber pressure. Velocity inlet is defined at nozzle portion and it is calculated from the gas flow rate. Volume fraction is unity at the gas inlet. Wall functions [15] are employed to represent the near wall regions. At the free surface, the normal gradients of the parallel velocity components, turbulent kinetic energy, kinetic dissipation rate and tracer concentration are set to be zero. At the solid wall, free slip boundary condition is set for velocity, pressure and concentration. Initially, the concentration in bath is assumed zero.

3. Computational procedure

Fluent® CFD software was used to solve the governing equations along with their boundary conditions. In Uniform grid size 25mm is used throughout the domain. Mesh/grid was created using Gambit software (version 2.0.4). All the computations were performed on the Intel based PC with 3 GB ram. Quad-map mesh is used. All the results presented here are independent of grid size and time step. The final value of time step is

0.001s. The problem is solved in two-dimension. Standard values of physical properties of Ar gas, molten steel and water are used. Diameter of the vessel is 4m and heights of liquid in vessel and snorkel are 3.24 and 1.5m respectively. Porous plug diameter is 5cm and it is situated 0.1m away from the center of the vessel bottom. Air flow rate, snorkel diameter and chamber vacuum pressure are variables and their values are mentioned in the respective figures.

4. Results and discussion

As this is a new process, no experimental data are available in the open literature. Therefore, the developed computer code on fluid flow was validated against RH and Tank degassers in a previous study [10]. The same computer code has been used here with the incorporation of mass transfer. In the current study snorkel diameter was taken 2.6m, snorkel submerged depth in liquid was 0.65m; Ar gas flow rate was 6.1×10^{-4} Nm^3/s. Gas injection position is 0.1m away from the center of the vessel at the bottom. Vacuum pressure in the chamber is 0.032 atm. Results obtained under these conditions are shown below.

Figure 3 shows a typical concentration profile of the tracer (NaCl) in REDA process with time. This gives an idea of mixing time in the vessel. It is obvious from this figure that one gets almost complete mixing at 25s except a little difference in concentration at the top right corner in the tank. However, theoretically, complete mixing is achieved at 32s.

In order to compare the theoretical complete mixing time of REDA process with RH and tank degassers, simulations were carried out for these processes under the similar operating conditions. The results are shown in Table 1. This table also shows the results of complete mixing time using various available correlations in curly bracket. As there is no correlation available for REDA process to calculate the mixing time, RH degasser correlation has been used for the same.

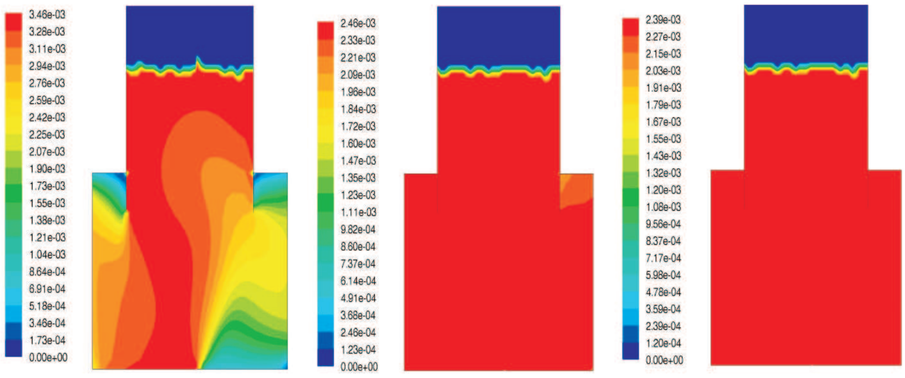
This table shows some interesting results. Based on the results obtained from correlation and simulation, the REDA process takes lowest mixing time amongst all the three processes. Tank degasser takes more than four times than REDA process to achieve theoretical complete mixing. This is one of the reasons that REDA process takes less time in lowering the C content in steel than the other existing processes.

TABLE

Mixing time calculations at constant submerged depth of snorkel for RH and REDA (0.65 m), vacuum pressure (0.032 atm) and gas flow rate (Nm^3/s) 6.1×10^{-4}

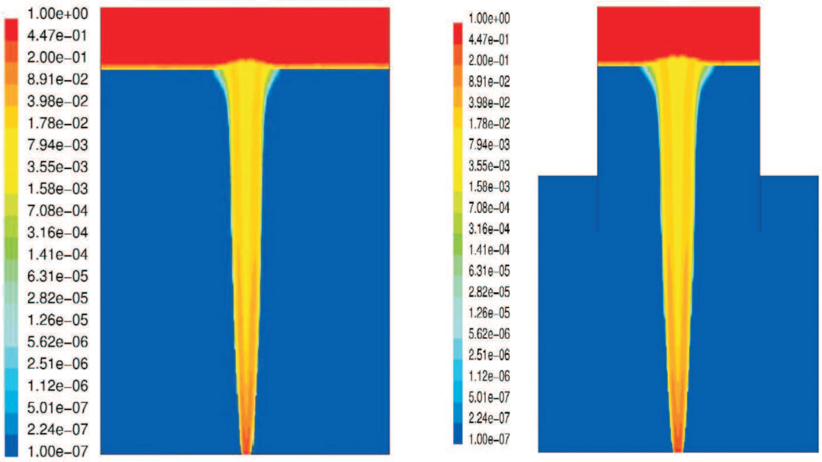
Name of the process	Complete mixing time (s) [computational]
RH	42 {12.4} [16-17]
REDA	32 {8.77} [16-17]
Tank (no vacuum)	140 – under vacuum {315} [18]

Figure 4 shows the shape of plume for tank degasser and REDA process under the similar operating conditions. RH process does not have a well developed plume therefore, it has been excluded. From this figure it is noticed that plume eye area at the top of the gas-metal interface has increased in case of REDA process which is necessary to reduce the C content in steel at the later period of decarburization (i.e. enhancement in bath surface reaction) as discussed before. Plume eye diameter in case of tank degasser is 0.9m and for REDA it is 1.16m. Theoretically, surface plume eye area has increased by about 66% of tank degasser. This is another reason that REDA process is more efficient than other existing processes in lowering the C content in steel in less time.



12s 25s 32s

Fig. 3. Concentration contours of the tracer (NaCl) at different time interval in REDA process



Tank degasser REDA

Fig. 4. Plume eye diameters for tank degasser and REDA process are 0.9m and 1.16m respectively

As discussed by Kitamura et al. [1] that at the later stage of decarburization surface reaction is predominant therefore, it becomes essential to know the contribution of plume eye area (i.e. uncovered metal portion) at the top and covered area (i.e. area covered with slag layer) at the top surface towards the reaction kinetics. The above findings would also be applicable for the slag-metal system which can be used to improve these processes efficiency by enhancing the reaction rates at various reaction sites during decarburization.

5. Conclusions

Revolutionary Degasser Activator (REDA) process, a new secondary refining process, has been studied to know the mixing time and plume eye area using commercial available computational fluid dynamics software Fluent®. REDA process takes less time for complete mixing and plume eye area is also increased in comparison to tank degasser and RH process. Due to these reasons, it achieves lower content of carbon in steel at less time than the other existing processes. It is believed that same findings/procedure could be used to enhance the reaction rates in slag-metal system during decarburization.

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