Numerical Investigation on Role of Bottom Gas Stirring in Controlling Thermal Stratification in Steel Ladles

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A two dimensional Computational Fluid Dynamics (CFD) model was developed to simulate the fluid flow and heat transfer of the molten steel in a ladle during the holding time, with gas purging from the bottom. Transient analysis of the temperature and the velocity distribution of the liquid steel during ladle standing and subsequent gas stirring was conducted, by employing a pressure-based fully-implicit finite volume approach. Stratification, which can adversely affect the quality of steel products, was seen to develop due to natural convection. Therefore, particular attention was paid to study the effect of bottom gas stirring in minimizing the thermal stratification. This was accomplished by introducing a novel approach of coupling the effects of natural convection and axisymmetric bottom gas injection. Various parametric studies was undertaken to examine the effects of standing time, gas flow rate and geometry of the ladle on the resultant thermal field. It was observed that bottom purging situation induces a strong recirculatory flow in the molten steel bath, with an increase in the order of turbulence giving rise to thermal homogenization. The results indicate that the thermal stratification can be effectively eliminated by a relatively gentle agitation. Homogenization takes place at a faster rate with an increase in the amount of bottom gas flow. The effect of ladle size was found to be inconsequential, in comparison to other parameters.

KEY WORDS: ladle; thermal stratification; natural convection; fluid flow; gas stirring; homogenization.
numerically simulated the effect of top slag cover on heat loss as well as liquid steel flow in a ladle before and during teeming to a continuous casting tundish. They established a two-dimensional CFD model for simulations of thermal stratification phenomena in steel ladles. Their work showed that significant temperature stratification occurs in the molten steel being held in the ladle with insulating slag layer at the top, and the degree of stratification increases with the holding time. For a thin slag layer with appreciable heat loss from the top, the liquid steel temperature was predicted to be somewhat homogenized due to much better bulk mixing. Olika et al. (2004) carried out a numerical simulation for the molten steel stratification in a ladle, using a commercially available CFD code. Influences of thermal status and geometrical shape of the ladle on the extent of thermal stratification were investigated. Grip et al. (2004) developed a three-dimensional CFD model to simulate the natural convection in a ladle. Thermal stratification phenomenon was investigated in their study and the simulation results were compared with experimental observations. In a recent study, Pan et al. (2004) established a physical model of industrial ladles in the laboratory and investigated the thermal stratification phenomena due to natural convection.

It can be noted here that most of the above-mentioned studies have typically addressed situations where the molten steel is held in a ladle without any external agitation, and thermal stratification occurs due to heat losses through the ladle walls. Studies concerning the suppression of stratification have largely been ignored. However, reduction of thermal stratification in the ladle and the means to prevent its occurrence have important applications and far-reaching consequences in the industry. This is primarily because of the fact that the progressively increasing emphasis on the quality of continuously cast products mandates much tighter tundish temperature control, which in turn, would require a more precise definition of extent of stratification in a ladle and the means to minimize the effect. Although some preliminary studies with similar objectives have been reported, a systematic study addressing this extremely significant issue is yet to be found in the literature.

The present study aims to numerically simulate the fluid flow and heat transfer of the molten steel in a ladle during the holding time, with gas bubbling from the bottom. This is accomplished by devising a suitable CFD model pertinent to this process. With heat losses occurring through the walls of the ladle containing molten steel during the holding time, natural convection set in, which give rise to thermal stratification. This thermal stratification, in turn, is strongly coupled with the turbulent fluid flow induced by the bottom gases. Therefore, particular attention is paid to study the effect of bottom gas stirring in minimizing the thermal stratification. This is accomplished by introducing a novel approach of coupling the effects of natural convection and bottom gas injection. In particular, the flow field and the resultant convection heat transfer, leading to thermal homogeneity on account of gas stirring, are thoroughly studied. Another significant feature of the present study is the transient simulation of the evolution of the velocity and thermal fields in the ladle. Various parametric studies are also undertaken to examine the effects of standing time, gas flow rates and geometry of the ladle on the thermal field. The combined model is expected to provide an effective quantification of thermal stratification in a ladle and the extent of agitation needed to eliminate the stratification, thereby facilitating the subsequent process control operations.

2. Mathematical Modelling

2.1. The Physical Problem

The problem domain considered here is a cylindrical ladle of radius $R$, containing molten steel to a depth $H$. This is illustrated in Fig. 1. Heat is transferred from the molten steel to the surrounding refractory surfaces. A gravitational instability associated with these fluid elements gives rise to natural convection. The convection is responsible for forming colder layers of fluid at the bottom of the ladle and warmer layers at the top. This results in formation of thermally stratified layers of the molten steel, which is undesirable from manufacturing point of view. To alleviate this problem, gas purging is used. In this process, argon gas is purged from the bottom into the liquid steel bath. The gas, while rising as a plume to the free surface, induces recirculatory fluid flow in the vessel, thereby helping to regain thermal homogeneity. The velocity fields and the associated temperature fields are calculated as a function of time. It can be noted here that following major assumptions are made in developing the present mathematical model:

(i) the free surface is flat and frictionless
(ii) axial symmetry exists about the centerline
(iii) gas–liquid mixture in the rising plume region is modeled using the quasi single phase approach, as described subsequently
(iv) the molten steel is initially at a uniform temperature.

2.2. Governing Equations

The governing transport equations describing the flow field and the heat transfer in cylindrical (axisymmetric) coordinates can be written in the following conservative form:
(a) Continuity Equation
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad \text{...........................................(1)} \]

(b) Momentum Conservation Equations
\[ \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = -\nabla P + \nabla \cdot (\mu + \mu_s)\nabla \mathbf{v} + \nabla F_u + F_v \]
\[ \text{...........................................(2)} \]

(c) Energy Conservation Equation
\[ \frac{\partial (\rho T)}{\partial t} + \nabla \cdot (\rho \mathbf{v} T) = \nabla \cdot \left( \left[ \frac{k_i}{c_p} + \frac{\mu_s}{\sigma_s} \right] \nabla T \right) + G \quad \text{.................................(3)} \]

(d) Governing Equations for \( k \) and \( \epsilon \)

The governing equations for \( k \) and \( \epsilon \) in the present context can be written as:
\[ \frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho \mathbf{v} k) = \nabla \cdot \left( \mu_s \nabla k \right) \]
\[ + G - \frac{\mu_s}{\sigma_s} \frac{\partial T}{\partial z} - \rho \epsilon \quad \text{...........................................(4)} \]
\[ \frac{\partial (\rho \epsilon)}{\partial t} + \nabla \cdot (\rho \mathbf{v} \epsilon) = \nabla \cdot \left( \mu_s \nabla \epsilon \right) + C_{\epsilon} G \frac{\epsilon}{k} \]
\[ - C_{\epsilon_i} \rho \epsilon^2 \frac{\partial \rho}{\partial k} - C_{\epsilon_s} \frac{\mu_s}{\sigma_s} \frac{\partial T}{\partial z} \frac{\epsilon}{k} \quad \text{...........................................(5)} \]

In the above system of coupled equations, \( \mu_s \) is defined as:
\[ \mu_s = C_{\mu_s} \rho k^2 \epsilon \quad \text{...........................................(6a)} \]
\( \sigma_s \) is the turbulent Prandtl number and a value of \( \sigma_s = 0.9 \) is used for the present calculations.

Further, \( G \) is the turbulence generation term, defined as:
\[ G = \mu_s \left[ \frac{1}{2} \left( \frac{\partial T}{\partial z} \right)^2 + \left( \frac{\partial T}{\partial r} \right)^2 + \left( \frac{V_r}{r} \right)^2 \right] \]
\[ + \left( \frac{\partial \rho}{\partial r} \right)^2 + \left( \frac{\partial \rho}{\partial z} \right)^2 \quad \text{...........................................(6b)} \]

In the above system of equations, \( C_{\mu_s} = 0.09, \quad C_{\epsilon} = 1.44, \quad C_{\epsilon_i} = 1.92, \quad \sigma_s = 1.0 \) and \( \sigma_s = 1.3 \), as per standard \( k-\epsilon \) turbulence model.

It can be noted here that in the equation of motion, there are two driving buoyancy forces \( F_u \) and \( F_v \), due to thermal gradient and gas stirring respectively. Here \( F_u \) represents a body force due to thermal gradients existing inside the domain, and can be expressed as:
\[ F_u = \rho g (1 - \beta (T - T_{ref})) \quad \text{...........................................(7)} \]

It is also important to note here that \( \rho \) in the above expression represents a volume-averaged continuum density, and is evaluated in a manner to be described subsequently. The other momentum source term \( \left( F_v \right) \), which takes into account the momentum transfer due to gas purging, can be defined taking into consideration the hydrodynamics of gas stirring. This, however, demands a separate fluid-dynamic consideration, to be described as follows.

2.2.1. Hydrodynamics of Bottom Gas Stirring

The physical processes associated with gas stirred system are quite complex. These are due to the multi-dimensional and multiphase (gas-metal and slag) nature of the system. When the gas is introduced into a cylindrical vessel containing liquid metal (through a tuyere located at the bottom and placed along the axis of the vessel), a two-phase region consisting of gas bubbles and liquid steel forms and moves upward. This is known as plume. Upward movement of bubbles in the plume leads to circulation of liquid steel in the vessel. Such a liquid motion is called as ‘recirculatory flow’, and it is turbulent as well. The interaction of the plume with its surrounding liquid metal forms an important part of all the modelling techniques of the gas injection phenomena. In the numerical procedure adopted for the present study, gas injection is treated as a pseudo single-phase flow phenomenon (quasi single phase approach\(^{(11)} \)), in which the gas–liquid metal plume is characterized by a region of lower density steel. The definition of the plume region is based on the experimental studies of vertically injected gas bubbles into water performed by Castillejos and Brimacombe\(^{(12)} \) and followed by various other researchers\(^{(13)} \). Accordingly, the shape of the plume region is taken to be conical\(^{(10)} \) with an apex angle of 20 degree.\(^{(12)} \) The bubble size here is not a constant, but is strongly dependent on the local surface tension coefficient prevailing at the liquid–vapour interface and the pressure differential between its exterior and interior. Since the numerical method adopted for the present study is based on an equivalent single-phase continuum approach, bubbles need not to be separately tracked, and the bubble size is not explicitly set in the present model. Also, in the quasi single phase approach\(^{(11)} \) adopted for the present study, specification of tuyere diameter is not explicit, but implicit through the specification of the plume geometry that eventually influences the overall flow pattern. The gas voidage, \( \alpha \), within a rising gas–liquid plume is accounted for by introducing a buoyancy term, \( F_{b} \), in the momentum equation and is given by
\[ F_{b} = \rho g \frac{\bar{r}}{r} \alpha \quad \text{...........................................(8)} \]

The gas voidage, \( \alpha \), can be calculated by applying the principle of volume continuity as follows:
\[ \alpha = \frac{Q}{\rho U_{p}} \quad \text{...........................................(9)} \]

where \( r_{av} \) is the average plume radius and is given by\(^{(14)} \)
\[ r_{av} = \left( \frac{1}{\sqrt{\pi}} \right) \text{radius at surface} \quad \text{...........................................(10)} \]

Sahai and Guthrie\(^{(15)} \) provided an algebraic equation to calculate the plume rising velocity, \( U_{p} \) such that

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where the constant $K$ is estimated to be 4.17 in SI system of units. The continuum density of the plume can then be obtained by

$$
\rho = \alpha \rho_0 + (1-\alpha) \rho_1 \quad \text{..........................(12)}
$$

The above approach correctly depicts the relative and proportional significance of buoyancy and shear forces in gas-driven recirculating flows. In fact, it has been confirmed through many experiments to be an effective way of treating pseudo-single phase problems of identical nature.

2.3 Initial and Boundary Conditions

The set of governing equations described above can be simulated effectively only on the prescription of appropriate initial and boundary conditions. Initially, the entire volume of the domain is considered to be occupied by molten steel, at a specified initial temperature. The flow boundary conditions are essentially no slip at all the bounding surfaces, i.e., the velocities are zero at the wall. At the nodes adjacent to the ladle wall, logarithmic wall functions are used to calculate the shear stresses, turbulent kinetic energy, energy dissipation, and the velocity components parallel to the ladle wall. Details regarding the wall functions are described by Launder and Spalding. Heat losses from the side walls of the ladle are used to form the transient boundary conditions. The particular transient form of the heat loss boundary condition used in the present model are taken from the literature and are reproduced here in Table 1 and mentioned below.

$$
q = ae^{-bt} + c \quad \text{...............................(13)}
$$

where $q$ is the boundary heat loss flux, $t$ is the time and $a$, $b$ and $c$ are constant parameters related to temperature regions defined by Fig. 2. The parameters used in the above equation are given in the literature and are reproduced here in Table 1. The heat loss from the top slag surface is 8923 W/m² as quoted in the literature and is used here for model validation.

3. Numerical Solution Procedure

The basic framework of the present numerical method rests on a pressure based finite volume method according to the SIMPLER algorithm. Accordingly, the governing equations are discretized and a power-law scheme is used to evaluate the finite-volume coefficients. The resultant system of algebraic equations are iteratively solved by a line-by-line tridiagonal matrix algorithm (TDMA) solver. With this method, the boundary information is quickly transmitted to the interior of the domain by direction alteration of ‘sweeping’, resulting in quick convergence. Also, as an aid for handling non-linearities, the convergence is achieved by the introduction of suitable under-relaxation parameters in the iterative scheme. The computational domain is taken to be an axisymmetric cylindrical one and numerical simulations are performed with molten steel as the constituent material initially present in the problem domain. The thermo-physical properties and processing parameters for the problem are listed in Table 2.

| Parameter | Value |
|-----------|-------|
| Thermal expansion coefficient ($\beta$) | 0.0002 $1/°C$ |
| Density ($\rho_s$) | 7000 kg/m³ |
| Specific heat ($c_p$) | 787 J/kg°C |
| Viscosity ($\mu$) | 0.005 Pa.s |
| Prandtl number($\sigma$) | 0.9 |
| Density of Argon gas | 1.6 kg/m³ |

A uniform grid size of 30 is employed along the axial direction ($z$) and a uniform grid size of 20 is employed along the radial direction ($r$). Grid independence study confirms that a finer grid system does not alter the results appreciably. Transient simulations are performed using a time step...
size of $\Delta t = 1$ s, till a quasi-steady state with regard to thermal and velocity fields can be attained. Although in the implicit time-discretization scheme employed for the present formulation, a coarser time-step could be used, it is observed that a time step size which is coarser than that chosen for the present simulation disturbs accuracy of the solution considerably.

3.1. Convergence Criteria

Within a particular time step, all the primitive variable ($\bar{u}$, $\bar{T}$, $k$, $\varepsilon$) values are checked after each iteration. Convergence is declared upon satisfying the following condition at each grid point:

$$\left| \frac{\phi - \phi_{\text{old}}}{\phi_{\text{max}}} \right| \leq 10^{-4}$$

where $\phi$ is the value of any primitive variable at a particular grid point at current iteration level, $\phi_{\text{old}}$ is the value of the same variable at the same grid point at the previous iteration level, and $\phi_{\text{max}}$ is the maximum absolute value of the same over the entire domain.

4. Results and Discussions

4.1. Model Validation

For the purpose of validation of the present numerical code, computations are first performed to simulate the conditions described in Olika et al.\textsuperscript{5)} The cylindrical ladle considered for the study is 2.6 m in diameter, with a molten steel height of 2.8 m. One of the important boundary conditions used here is the time and geometry dependent heat loss rate (Eq. (13)) through the ladle walls, which is the major cause of natural convection. Ladle wall is divided into different regions and is described in Fig. 2. Details regarding the parameters used in the calculation are described in Olika et al.\textsuperscript{5)} and are listed here in Table 1.

Figure 3 shows predicted isotherm fields and velocity vectors for a 105 tonne ladle after 5 min holding time. The isotherms are flat, except for the regions near the ladle walls where there is a strong heat flux to the walls. The isotherms clearly illustrate the counteracting effects of melt circulation and the steep temperature gradients in the regions near the wall, where the cooling takes place. The pattern of temperature contours and velocity field shows a very good agreement with the results obtained in Olika et al.\textsuperscript{5)}

Thermal stratification, as a function of time, is depicted in Fig. 4, in which a comparison is made between numerical predictions from different researchers. The difference between the liquid steel temperature at two axial heights $h_1 = 0.3$ m (near the bottom wall) and $h_2 = 2.4$ m (near the top surface) is taken as a representative value for the “temperature difference” in this study. It is seen that slight dif-
ferences exist between predictions from different investigators. However, as a general trend, the present work compares well with the results of Olika et al. and suggests that the rising rate of thermal stratification is proportional to the holding time.

4.2. Effect of Gas Stirring on Thermal Stratification

In order to study the effect of gas stirring on thermal stratification in a steel ladle, simulations are carried out for a 105 tonne ladle. The calculation starts with a quiescent bath of liquid steel with homogeneous temperature of 1580°C, the heat loss boundary conditions from the side wall are same as described in Eq. (13). The top surface is assumed to be completely insulated by the thick slag layer. The coupled thermal and velocity fields are calculated and the effect of gas stirring is examined by comparing the resultant flow and temperature fields with and without gas stirring.

Figure 5 shows the computed temperature profiles, velocity field and turbulent kinetic energy distribution, after a standing time of 10 min. The isotherms clearly indicate the existence of a steep temperature gradient in the vicinity of the ladle wall. Near the walls, the fluid, being colder and consequently denser, sinks under the influence of gravity, thereby producing a layer with colder (and hence, heavier) steel at the bottom of the ladle. The centerline velocity field shows an upward flow of warmer steel because of its lower density. The turbulent kinetic energy has maximum value near the side wall and low value around the center of the ladle. The predicted fields are in close agreement with the results obtained in literature.

Figures 6 and 7 depict the evolution of the temperature profiles, corresponding velocity profiles and turbulent kinetic energy distribution when the ladle is stirred with a 130 NL/min flow of Argon gas, after a holding time of 10 minutes from the secondary treatment station. Figure 6 shows the situation immediately after start of gas stirring. Due to the thermal gradients in the wall, the velocity near the side wall is relatively high. The molten steel with low temperature near the bottom moves toward the top surface and the temperature field in the ladle is being homogenized by Argon bubbling. The maximum kinetic energy is distrib-

Maximum Velocity: 4 cm/sec

Fig. 5. Predicted (a) isotherm fields, (b) velocity vectors and (c) kinetic energy contours after 10 min standing time.

Maximum Velocity: 0.9 m/sec

Fig. 6. Predicted (a) isotherm fields, (b) velocity vectors and (c) kinetic energy contours after 10 min standing time with Ar stirring.
uted near the plume zone and the side wall. Figure 7 shows the homogenized flow and thermal field 1 min after the start of gas purging. It is observed that the anticlock-wise rotating vortex in the main bulk of liquid is initially (i.e. immediately after start of gas purging) small in size (Fig. 6(b)) and moving with a relatively slow speed. With gas bubbling continued, the flow within the vessel intensifies and eventually produces a large recirculating vortex (Fig. 7(b)) which is the characteristic flow pattern of an axisymmetric, gas bubble driven system.

4.2.1. Influence of Standing Time

It is of interest to examine how the ladle standing time would affect the extent of stratification and how gas stirring can homogenize the steel temperature in such cases. Figure 8 depicts the predicted isotherm field and velocity field after standing time of 15 min. It is seen from the figure that the low temperature layer is formed near the bottom wall and significant stratification takes place with an increase in standing time. The thermal and flow fields shown in the figure correspond to the instant just before the start of purging. As a thermal homogenization mechanism, Argon bubbling is subsequently applied. Figure 9 shows the computed results of Argon bubbling at a rate of 130 NL/min, for the ladle with a standing time of 15 min. The flow field develops quite fast and the basic flow becomes steady within a very short time.

Figure 10 shows the variation of complete homogenization time of the molten steel bath with standing time when a gas flow rate of 130 NL/min is applied from the bottom. It is to be mentioned here that in the present study, “completely homogenized” state in the ladle indicate a situation when the difference between the numerically predicted molten steel temperature at two axial heights, \( h_1 \) and \( h_2 \) (as described before) is around 3°C. As expected, with an increase in stratification with standing time, the time needed for complete homogenization also increases. However, the increase is not very significant. For a maximum standing time of 1 hr as shown in the figure, the bath gets homogenized within 3.5 min after start of purging.

4.2.2. Effect of Gas Flow Rate

A systematic and consistent study concerning the comparison of effect of gas stirring with different gas flow rate in reducing thermal stratification in steel ladles has not
been reported so far. The present work might be the first attempt to analyze such a situation with numerical solution. Simulations were carried out with Argon flow rate varying in the range of 0.5 to 150 NL/min, a typical flow rate for industrial applications.

Figures 11(a) through (d) represent the predicted thermal field of the molten metal in the ladle, when the ladle is stirred with 0.5, 10, 100 and 150 NL/min flow of Argon gas, after a standing time of 20 minutes from the secondary treatment station. The figures show the thermal field 1 min after the start of gas purging.

The flow patterns in all the four different cases of Argon flow rate (flow rate varying from 0.5 to 150 NL/min) are qualitatively similar, exhibiting an overall recirculatory flow. Figure 12 shows the predicted flow field for a gas flow rate of 150 NL/min. It is seen that the molten metal move up toward the top surface under the influence of an externally induced flow from the bottom. Velocity in the plume zone, near the sidewalls and free surface are relatively large compared to the bulk flow, in the case of axisymmetric blowing from the bottom center. It is also observed that the characteristic velocity increases with an increase in gas flow rate, from 0.75 m/s (corresponding to a gas flow rate of 0.5 NL/min) to 1.2 m/s (corresponding to a gas flow rate of 150 NL/min). The turbulent mixing brought about by this recirculating flow will diminish the temperature stratification as shown by the isotherm contours. Figure
11(a) depicts a situation when the thermal field in the ladle started to homogenize with a gas flow rate of 0.5 NL/min from the bottom. The liquid steel with low temperature from the bottom flows up and in the process, reduces the extent of stratification present inside the ladle. Due to increased amount of purging, thermal mixing is enhanced. This is caused due to an enhanced turbulent kinetic energy field and the corresponding dissipation rate. The effect of increased gas flow rate on temperature field can be seen from the Figs. 11(a) through 11(d), where the thermal field is seen to homogenize fast with an increase in the rate of purging.

In Fig. 13 the time taken by the liquid steel bath to get completely homogenized is plotted as a function of the gas flow rate. Two situations are considered; the gas stirring has started after the ladle has undergone a standing time of 20 min or 60 min. It can be seen from the figure that the homogenization time decreases with increasing gas flow rate and follows the same trend for both cases of stand time considered. This occurred with all other ladle standing time studied. During the initial period of gas stirring, the effect is more pronounced and the bath starts to get homogenized at a faster rate with an increase of gas flow rate. It is also seen from the figure that gas stirring can homogenize the thermal field in the ladle in just few minutes.

4.2.3. Effect of Ladle Geometry

It is of interest to examine how the geometry of the ladle would affect the rate of homogenization being brought about by the bottom gas stirring in a stratified ladle. Numerical simulation was done for different ladle shapes. In all cases ladles were taken to be of equal volume and their heat content was assumed to be identical. The ratio between ladle height and diameter (aspect ratio) was used to simulate the different shapes.

Figure 14 shows how homogenization time varies with gas flow rate for two different ladle shape. The aspect ratio used to simulate different ladle shapes are H/D=0.9 and H/D=1.4. In both the cases, the ladle is considered to undergo a standing time of 10 min before gas stirring commences. It is seen from the Fig. 14 that the variation of the degree of homogenization with different ladle shapes for varying gas flow rate can be neglected. This happens for all other geometries considered. With an increase of standing time, the difference increases somewhat, but is still too small to be considered worthwhile. This corresponds well with the previous findings reported in literature.

5. Conclusions

A two-dimensional CFD model was developed to simulate the fluid flow and heat transfer of molten steel in a ladle during the holding time with gas purging from the bottom. A series of numerical study was carried out to investigate the combined effects of natural convection and gas injection on the resultant flow and thermal field. The influences of various parameters on the homogenization effect being brought about by inert gas stirring were studied. Some of the important findings of the study may be summarized as follows:

- In the absence of any external source of agitation, thermally stratified layers develop in a ladle holding molten steel. The extent of stratification increases with an increase in holding time.
- Bottom purging of argon through the melt bath induces strong buoyant forces in the plume region. Energy gets transferred to the liquid steel from the rising gas mainly through the momentum convection and eddy diffusion. There is a strong recirculatory flow in the bath with an
increased order of turbulence giving rise to thermal homogenization.

- With an increase in the amount of bottom gas flow, thermal homogeneity is achieved at a faster rate irrespective of the ladle standing time. This is due to the fact that with an increase in gas flow rate the level of turbulence also increases with enhanced transport rates for momentum and energy.
- For a particular ladle holding situation and associated stratification, a minimum gas flow rate (\( \sim 0.5 \text{NL/min} \)) can be identified which can get rid of the thermal stratification in the ladle within a short duration.
- The effect of ladle shape on the rate of homogenization is small compared to other parameters.

The study illustrates the effectiveness of gas purging in homogenizing the stratified bath in a ladle holding molten steel. The model successfully reveals some of the important physical issues pertaining to turbulent transport in a gas-stirred melt bath. Future studies with extension of the present work to three-dimensional situations along with more realistic boundary conditions can be performed for a detailed characterization of the flow physics.

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Nomenclature

- \( c_p \): Specific heat at constant pressure
- \( C_{\mu}, C_{\varepsilon_1}, C_{\varepsilon_2} \): Constants used in turbulence model
- \( F_B \): Buoyancy force due to thermal gradients
- \( F_G \): Buoyancy force due to gas stirring
- \( g \): Gravitational acceleration vector
- \( H \): Liquid steel height
- \( k \): Turbulent kinetic energy
- \( k_t \): Thermal conductivity
- \( p \): Pressure
- \( Q \): Volumetric gas flow rate
- \( r_p \): Average radius of the plume
- \( r \): Radial coordinate
- \( R \): Ladle radius
- \( T \): Temperature
- \( T_{\text{ref}} \): Reference temperature
- \( t \): Time
- \( u \): Velocity
- \( U_p \): Plume rise velocity
- \( \bar{V}_r \): Axial component of mean velocity
- \( \bar{V}_z \): Radial component of mean velocity

Greek symbols

- \( \alpha \): Gas volume fraction
- \( \varepsilon \): Dissipation rate of turbulent kinetic energy
- \( \mu \): Dynamic viscosity
- \( \phi \): General scalar variable
- \( \rho \): Density
- \( \sigma_r \): Prandtl number
- \( \sigma_k \): Turbulent prandtl number
- \( \sigma_m \): Prandtl number for turbulence kinetic energy
- \( \sigma_e \): Prandtl number for dissipation rate of turbulent kinetic energy

Subscripts

- \( \text{av} \): Average
- \( L \): Liquid phase
- \( G \): Gaseous phase

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