Physical and Mathematical Modelling to Study the Effect of Ladle Shroud Mis-alignment on Liquid Metal Quality in a Tundish

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The present work involves the use of physical and mathematical modelling in order to study the effect of slight mis-alignments of the ladle shroud on liquid steel quality output from a delta shaped, four strand, continuous casting tundish. For the physical modelling, a full scale water model was used to observe the effects of ladle shroud alignment on steel quality in terms of “slag” entrainment into the individual moulds. The ladle shroud was purposefully biased by about 4 to 5 degrees off-vertical, and the number of “slag particles” entering individual strands of the 4 strand billet caster were measured during a ladle change, and compared with the “no bias” condition. A one third scale water model was also used to perform tracer dispersion experiments and to help visualize the effects of the biased shroud. Finally, a 3D mathematical model was developed and contours of velocity and/or turbulence were examined under a “biased shroud” condition. In the mathematical model, the shroud was biased in all directions. The mathematical predictions were in good agreement with physical modelling results. Given the great sensitivity of liquid metal quality to this slight misalignment during a ladle change, with the tundish “furniture” used, possible remedial measures are discussed for equivalent steel plant operations.

KEY WORDS: biased shroud; mathematical model; slag entrainment; ladle changes.

1. Introduction

The improvement of liquid steel quality during continuous casting operations has been the major goal for steelmakers. Much information on steel quality issues has been archived over the last four decades. Guthrie already emphasized the role of fluid flows in liquid metal processing and its effect on liquid metal cleanliness and quality. Sahai summarized work on the modelling of liquid steel flows in continuous casting tundishes. He emphasized the importance of contriving good melt flows within tundishes for achieving high quality clean steels, noting that this can be achieved by efficient tundish design and optimum volumetric flow rates of liquid steel. Tanaka and Guthrie reported on the modelling of steel cleanliness within a water model tundish using an aqueous inclusion sensor. Doutre and Guthrie developed an inclusion sensor for molten aluminium (Liquid Metal Cleanliness Analyser, or LiMCA Al), while Nakajima and Guthrie developed an inclusion sensor (LiMCA Fe) which could be used in liquid steel. Joo and Guthrie contributed greatly to characterising inclusion behaviour in model and real tundishes. They developed an in-house code, METFLO 3D, which could model fluid flows, heat transfer and inclusion floatation. They used the Aqueous Particle Sensor (APS II) which could continuously monitor the number of inclusions (hollow glass microspheres) exiting the strands on a full scale water model tundish available at Stelco, Ontario. A new version of this system APS III is now available for water modelling studies. Their numerical predictions were in good agreement with the aqueous model experiments. They reported that flow control devices could play a major role in enhancing steel cleanliness, especially for the intermediate (50 μm) to larger (120 μm) inclusions. They also mentioned the fact that the presence of thermal convection can generate secondary recirculating flows within a tundish, with increased fluid motions near the exit nozzles. These flows reduce separation efficiencies for inclusions. Another aspect they studied was an optimum tundish design which could result in better steel cleanliness and efficient inclusion removal. Sankaranarayanan and Guthrie mentioned that the diameter ratio of the outlet nozzle to the ladle diameter is important, and this ratio and the critical height for vortex formation, are proportional. For a constant ratio of outlet diameter to ladle diameter, the critical height becomes larger with higher initial bath heights for central draining. Understanding vortex mechanisms will be useful when designing simple and efficient devices to break down vortex flows during steel draining, even at very low metal residuals within the ladle. Sankaranarayanan and Guthrie also reported on vortex suppression regarding steel cleanliness and developed the VORTEX BUSTER. M. Javurek et al. considered the removal of non-metallic inclusions due to buoyancy forces in continuous casting tundishes. They explained the reasons why the particle separation is worse than the calculated maximum possible removal rate. The reasons were unsuit-
able fluid flow patterns and turbulent diffusion of particles. They also mentioned that RTD curves are not suitable for estimating particle separation in tundishes. The use of direct calculation and CFD simulation was recommended.

J. P. Rogler et al.\textsuperscript{11} mentioned the probability of inclusion removal in a tundish by gas bubbling. They\textsuperscript{12,13} also performed physical modelling of inclusion removal in a tundish by gas bubbling. They used water as the analogue of steel and linear low density polyethylene (LLDPE, \( \rho = 920 \text{ kg/m}^3 \)) as an analogue for inclusions. They concluded that the separation efficiency of inclusion particles within the flowing liquid within a tundish is influenced by a number of factors, such as the overall fluid flow behaviour, the chemical and physical nature of the inclusion, the size of the inclusions, and the rates and mechanisms of particle capture by various potential particle sinks. From their study, they showed that flow control devices could enhance particle separation efficiency, and that properly sized bubbles induced the highest particle separation efficiencies.

Lifeng Zhang et al.\textsuperscript{15} proposed three modes of inclusion removal from molten steel in the tundish viz. floatation to the free surface, collision and coalescence of inclusions to form larger ones, and adhesion to the tundish linings solid surfaces. Those researchers studied the 3D fluid flow with, and without, flow control devices. The results indicated that flow control devices could effectively control the strong stirring energy field within the inlet zone. Flow control devices were also beneficial for inclusion removal. They reported that the total removal ratio was 51\% without flow control devices, wherein inclusions with radii greater than 72 microns were totally removed. This increased to 79\% with flow control devices where inclusions with radii greater than 61 microns were totally removed. Of the 79\% eliminated, removal by floatation was 49.5\% and removal by adhesion was 29.5\%. The collision and coalescence mode was a better way to remove smaller size inclusions as the number of collisions per unit time per unit volume of steel was much higher for smaller inclusions than for bigger inclusions.

Thomas and Bai\textsuperscript{14} summarized mechanisms of formation, methods of detection, and ways to prevent, tundish nozzle clogging, focusing on the role of computational models in quantifying the non-composition-related aspects. They classified mechanisms for tundish clogging into four main types: viz. the transport of oxides present in the steel to the nozzle wall, air aspiration into the nozzle, chemical reaction between the nozzle refractory and the steel, and lastly, steel solidified in the nozzle. However, in practice, a clog can be a combination of two or more of the above types. They mentioned that clogging can be best detected during casting by simultaneous monitoring of several different parameters, such as argon back pressure, nitrogen pickup by the steel, mould level fluctuations, and flow control position relative to casting speed. Solutions to reducing clogging problems were also discussed. They include minimizing inclusions by improved steelmaking practices, optimizing fluid flow and melt transfer processes, controlling steel alloy additions, slag and refractory compositions, improving nozzle material design, and avoiding air aspiration.

However, concerning the entrainment of tundish slag, a very important phenomenon during ladle changes, this has not been considered in most cases. Henrik Solhed et al.\textsuperscript{15,16} included slag entrainment in their work, but the majority of the work to date has been done at the McGill Metals Processing Centre by R. I. L. Guthrie and co workers.\textsuperscript{17,18} Similarly, slag entrainment was a very important parameter in designing new flow modifiers for the steel industry. Chattopadhyay et al.\textsuperscript{19} did some preliminary work to study the effect of ladle shroud mis-alignment on steel quality. They used a 2D mathematical model, coupled with full scale water model experiments. Slag entrainment was used as a parameter to evaluate liquid metal quality during a ladle change operation. They also discussed some remedial measures that should be followed in equivalent steel plant operations. However, the authors felt that there was scope to study this phenomenon in greater detail, using a 3D mathematical model and full scale and one third scale water model tundish experiments. In the present 3D numerical model, the shroud was biased in all possible lateral directions by 4–5 degrees off the vertical. Similarly, the 3D mathematical model was used to predict residual ratios of inclusions and inclusion trajectories under biased shroud conditions. In the one third scale model, tracer dispersion studies were performed, and filmed with high definition cameras, to study the effects of the bias.

2. Physical Modelling

Physical modelling was performed using a full-scale water model of a twelve tonne, delta shaped, four strand tundish, and its one third scale equivalent. A schematic diagram of the full scale water model tundish is given in Fig. 1. The key dimensions of the tundish are given in Fig. 2. The slag phase was simulated by using polyethylene beads of density ~920 kg/m$^3$. A water inflow rate of 0.17 m$^3$ per minute was used to maintain a steady state height of 500 mm of water from the inner base of the tundish. The
A ladle change operation was simulated by stopping the flow of water passing through the shroud for three minutes while the tundish drained, and then fully opening the slide gate to achieve a refilling rate of around 0.4–0.5 m³ per minute, in order to regain the height of 500 mm as quickly as possible. During this operation, owing to the high degree of turbulence generated by the plunging free jet of liquid from the ladle, the slag layer adjacent to the entry region is severely disrupted. Many “slag droplets” are entrained within the “steel”, and many of these can then pass through each strand. By counting the numbers of slag beads collected in each strand, the relative performances of the exit strands were assessed, using the full scale water model tundish. Seven slag entrainment experiments were performed for each tundish configuration and the average was taken. Table 1 shows an example of a data set of seven experiments performed, and the average and standard deviation reported for slag entrainment tests in a full scale water model tundish fitted with the standard impact pad. As mentioned, the ladle shroud was purposefully biased by 4–5 degrees off the vertical and this is shown schematically in Fig. 3. The shroud was biased towards SENs 1 and 2. In the small scale water model, mineral oil (density = 870 kg m⁻³, viscosity = 0.017 Pa. s) was used to simulate the slag layer. A red tracer was injected and its mixing behaviour was studied under the biased shroud conditions.

3. Mathematical Modelling

The domain of calculation was drawn using GAMBIT 2.4.6, as shown in Fig. 4. The shroud was biased by 5 degrees off the vertical in the lateral and width planes, as shown clearly in Fig. 4.

The ladle shroud was not submerged, as in real life plant practise, during a ladle change operation. The simulations were carried out using ANSYS 12.0. The fluid (water) in the tundish and shroud were considered as Newtonian and incompressible. The standard k-ε turbulence model of Launder and Spalding was used, where k is the kinetic energy of turbulence per unit mass and, ε is the rate of turbulence energy dissipation. Thus,

\[ k = \frac{1}{2} \sum \mu_i \] ........................(1)

So, in addition to the continuity and momentum equations, two extra equations for k and ε are solved.

\[ \frac{Dk}{Dt} = \frac{\nu}{\sigma_k} (\nabla \cdot )^{2}k + G_k - \varepsilon \] ..................(2)

\[ \frac{D\varepsilon}{Dt} = \frac{\nu}{\sigma_\varepsilon} (\nabla \cdot )^{2}\varepsilon + \frac{k}{\varepsilon} (C_1G_k - C_2\varepsilon) \] ..................(3)

Here G_k is the rate of production of k and is given by the following equation:

\[ G_k = \nu_\parallel \left( \frac{\partial v_x}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \frac{\partial v_i}{\partial x_j} \] ..................(4)

The turbulent and effective viscosity is calculated by the following equations:

\[ \mu_t = \frac{c_1 \rho k^2}{\varepsilon} \] ..................................(5)

\[ \mu_{\text{eff}} = \mu + \mu_t \] ..................................(6)

The recommended values of the constants adopted in this study were C_1 = 1.44, C_2 = 1.92, C_1 = 0.09, C_2 = 1 and \( \alpha_t = 1.3 \), as proposed by Launder and Spalding.

The velocity inlet boundary condition was used for the

![Fig. 3. Schematic representation of a mis-aligned shroud.](a) Perfectly aligned shroud (b) Biased shroud

![Fig. 4. Tundish with a biased shroud drawn in GAMBIT 2.4.6](a) 5° in YZ plane (b) -5° in XY plane (c) 5° in XY plane.
inlet, and outflow boundary conditions were used for the outlets. The top surface was set as a free surface, and all other surfaces were walls with the no-slip condition. To model the non-submerged shroud, which occurs during refilling of the tundish, a free jet condition was considered.

For predicting inclusion and bubble trajectories, the discrete phase model was used. Along with the standard k-ε turbulence model, the discrete phase model (DPM) was used where inclusions were tracked in a Lagrangian frame of reference. In the discrete phase modelling procedure, the fluid phase is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles, bubbles, or droplets, through the previously calculated flow field. The dispersed phase can then exchange momentum, mass, and energy with the fluid phase. A fundamental assumption made in this model is that the dispersed second phase occupies a low volume fraction (less than 10 pct by volume). The particle or droplet trajectories are computed individually at specified intervals during the fluid phase calculation.

The equations involved in the DPM\textsuperscript{(21)} enlisted, are given below.

\[ \frac{d u_p}{dt} = \frac{18 \mu C_g R_s}{24 \rho_p d_p^2} u_{rel} + \frac{g (\rho_p - \rho)}{\rho_p} + \frac{1}{2} \rho \frac{d}{d t} u_{rel} \]  \hspace{1cm} (7)

\[ Re = \frac{\rho_d u_{rel}}{\mu} \] \hspace{1cm} (8)

\[ u_{rel} = u - u_p \] \hspace{1cm} (9)

\[ C_p = a_1 + \frac{a_2}{R_s} + \frac{a_3}{R_s^2} \] \hspace{1cm} (10)

Inclusions were simulated using hollow glass microspheres (50–300 μm) with approximate densities of 400 kg/m\textsuperscript{3} to 450 kg/m\textsuperscript{3}. They were injected into the ladle shroud and then their trajectories were monitored using the mathematical model. For bubbles, discrete air bubbles in the observed size range of 3.5–5 mm, were injected into the shroud.

The SIMPLE\textsuperscript{(22,23)} algorithm, along with the first order upwind scheme for momentum, k, and ε equations, was used. The values of the under relaxation factors used were unity for body forces, density and turbulent viscosity; 0.7 for the k, ε equations; 0.6 for the momentum equation. For pressure, the standard scheme was used, with an under relaxation of 0.3.

4. Results and Discussion

4.1. Slag Entrainment

Slag entrainment tests were carried out in the full-scale water model tundish. Two tundish configurations were considered, viz. the bare tundish, and the tundish with an impact pad. The impact pad was a very large and shallow piece, 1.16 m in length and 0.152 m in height. The location of the pad is shown in Fig. 2. Figure 5 shows the amounts of “slag” entrained in each SEN during a ladle change operation using a perfectly aligned shroud. Symmetry can be clearly seen in the amounts of slag particles entrained in individual strands on either side of the shroud. For the bare

Fig. 5. Number of slag beads collected in each SEN of the tundish with a perfectly aligned shroud (a) bare tundish (b) impact pad arrangement.

Fig. 6. Number of slag beads collected in each SEN of the tundish with a biased shroud (a) bare tundish (b) impact pad arrangement.

Fig. 7. Schematic representation of a biased shroud (−5° in YZ plane).
tundish (Fig. 5(a)) there are many more slag particles reporting to the inner strands as compared to the outer ones. For the impact pad arrangement (Fig. 5(b)), there were more slag particles reporting to the outer strands as compared to the inner strands. These trends are perfectly normal, because with the use of an impact pad, there is a recirculation in the inner strand zone and slag particles are carried upwards. As such, the amount of slag entering the inner SENs is much less as compared to the outer ones. If the y axes of the plots are examined carefully, it is seen that for the tundish fitted with the impact pad, the number of beads collected was much less (60 times) than those collected in a bare tundish. The number of beads collected does not correspond to a specific weight of slag entrained in the real plant, but indicates relative amounts of slag entrained in each strand and follows the same trend as those happening in the plant, where measurements are far more difficult.

The results of slag entrainment with a biased shroud are shown in Fig. 6. For the bare tundish (Fig. 6(a)), the effect of the bias is not clearly seen, because of the high amounts of beads entrained in the inner strands. However, if carefully observed, there are more slag particles reporting to SEN 1 than to SEN 4, and also more to SEN 2 than to SEN 3. In other words, for both the inner and outer strands, more slag is entrained in the SENs in the direction of the bias. For the impact pad arrangement (Fig. 6(b)), it is clearly seen that much more slag is entrained in SEN 1 compared to SENs 2, 3, and 4. From the above results, it can be inferred that there must be biased flows to one side of the tundish i.e. towards SENs 1 and 2 and this causes more slag entrainment.

4.2. Tracer Dispersion and ‘Exposed Eye’

In the one third scale water model tundish, the shroud was

![Tracer dispersion under a biased shroud condition.](image1)

![Tracer dispersion under an aligned shroud condition.](image2)

![Exposed ‘eye’ with a biased shroud for (i) 4% (ii) 6% gas injection by volume.](image3)

![Exposed ‘eye’ with a perfectly aligned shroud for (i) 4% (ii) 6% gas injection by volume.](image4)
biased by 4–5 degrees off the vertical towards SENs 3 and 4 as shown in Fig. 7. A red dye was injected through the biased shroud at steady state, to observe the mixing behaviour. It was seen that the dye mixes faster in one half of the tundish i.e. in the direction of the bias. However, when the bias was eliminated and then the dye injected, symmetrical mixing patterns are observed. These are shown in Figs. 8(a) and 8(b) respectively.

Compressed air was injected through the biased shroud at volumetric flow rates of 4–10 pct of the water entry flows and the movements of the slag layer were recorded. Mineral oil was used to simulate the slag phase. Figure 9(a) shows the shape of the ‘exposed eye’ with a mis-aligned shroud. The ‘eye’ is not concentric with the shroud; rather it is more towards the direction of the bias. However, when the shroud is perfectly aligned and the experiment is repeated, it can be seen that the exposed ‘eye’ is now concentric (Fig. 9(b)). All these observations correspond to the fact that there are biased flows in one half of the tundish, as a result of a slight mis-alignment of the shroud.

4.3. Bubble and Inclusion Trajectories

The 3D mathematical model along with the DPM was used to predict bubble tracks and inclusion trajectories with-

Fig. 10. Inclusion trajectories (at steady state) within the tundish with a biased ladle shroud (a) bare tundish (b)impact pad arrangement.

Fig. 11. Bubble tracks (at steady state) in the tundish with a biased shroud shown in (a) isometric view (b) top view.

Fig. 12. Bubble tracks (at steady state) in the tundish with a perfectly aligned shown in (a) isometric view (b) top view.

Fig. 13. TKE contours (m²/s²) within the tundish with a perfectly aligned submerged shroud (a) plane of the shroud (b) plane of the outlets (c) transverse plane through the centre of the shroud (d) free surface.
in the tundish with a biased shroud. Figures 10(a) and 10(b) show predicted inclusion trajectories within the tundish at steady state. It is clearly seen that inclusions spread much more to one half of the tundish in the direction of the bias. For the bubbles, a similar argument applies, as represented in Fig. 11. The bubble column becomes biased, and the

Fig. 14. TKE contours (m²s⁻²) within the tundish with a perfectly aligned non-submerged shroud (a) plane of the shroud (b) plane of the outlets (c) transverse plane through the centre of the shroud (d) free surface.

Fig. 15. TKE contours (m²s⁻²) in the bare tundish with a biased non-submerged shroud (a) plane of the shroud (b) plane of the outlets (c) free surface.

Fig. 16. TKE contours (m²s⁻²) in the tundish fitted with the impact pad under a biased non-submerged shroud condition (a) plane of the shroud (b) plane of the outlets (c) free surface.
bubbles rise up in one half of the tundish. This also explains the fact that the ‘exposed eye’ of slag is formed on one side of the shroud, as observed in our physical model experiments. However, when simulations were done using a perfectly aligned shroud, then the bubble column was concentric with the shroud, as represented in Fig. 12. The results shown in Figs. 11 and 12 are at steady state.

4.4. Contours of Turbulence

Given all these observations, it is believed that any slight mis-alignment of a ladle shroud definitely affects the flow within the tundish, and that the amount of turbulence is dissimilar in either half of the tundish. Turbulent Kinetic Energy (TKE) is a good measure of turbulence, and so using the 3D mathematical model, contours of TKE were examined within the tundish. First a simulation was performed with a perfectly aligned shroud (submerged and non-submerged) and the results are shown in Figs. 13 and 14.

It is evident that in the non-submerged condition, the turbulence is much higher within the tundish because of the free impinging jet of liquid. However, with a perfectly aligned shroud, the turbulent kinetic energy is similar in both halves of the tundish.

The shroud was then biased in two possible planes and TKE was examined on the free surface, the plane of the shroud and the plane of the outlets. Figure 15 represents contours of TKE within the bare tundish with a biased shroud in the YZ (vertical longitudinal) plane. It is clear that there is more TKE in the direction of the bias and the TKE is not distributed uniformly. The same logic applies for the tundish fitted with an impact pad, whose TKE contours are shown in Fig. 16.

As seen, the effect of the bias is quite prominent when the shroud is biased in the YZ plane. Figures 17–20 represent TKE contours within the tundish when the shroud was biased in the XY (vertical cross width) plane.

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Fig. 17. TKE contours (m²s⁻²) in the bare tundish when the shroud (non-submerged) is biased in the vertical cross-width plane by +5° (a) transverse plane through the centre of the shroud (b) free surface.

Fig. 18. TKE contours (m²s⁻²) in the tundish with an impact pad when the shroud (non-submerged) is biased in the vertical cross-width plane by +5° (a) transverse plane through the centre of the shroud (b) free surface.

Fig. 19. TKE contours (m²s⁻²) in the bare tundish when the shroud (non-submerged) is biased in the vertical cross-width plane by −5° (a) transverse plane through the centre of the shroud (b) free surface.
In all cases, the TKE contours are not symmetrical but the effect of the bias is less pronounced. So a small bias along the length of the tundish is far more sensitive than a bias across its width. There is more turbulence in the direction of the bias, and hence there is more slag disruption in that region, leading to higher amounts of slag entrainment. In all the above cases, the shroud was not submerged.

A simulation was carried out with a biased submerged shroud in the YZ plane. The results are shown in Figs. 21 and 22.

It is clearly seen that the effect of the bias is much less now. Although there is more TKE in the direction of the bias, it is still evenly distributed, as compared to the non-submerged condition. So a ladle change operation with a submerged ladle shroud is preferred, but practical difficulties do not always allow this practice in industry.

4.5. Preventive Measures

The above computations revealed that a slight mis-alignment of an un-submerged (exposed) ladle shroud can be catastrophic in terms of liquid metal quality to the strands. Clearly, some preventive measures are called for. From the 3D numerical predictions, it is clear that in the submerged condition, a biased shroud has much less effect on the TKE fields. Furthermore, slag is not entrained when the shroud is submerged. This suggests that opening up a new ladle when the ladle shroud is not submerged in the tundish, should be avoided. That procedure is possible with bell-shaped ladle shrouds which can accommodate gas pockets, but not with the straight nozzles more frequently used in the industry. For these, one opens up a new ladle with the ladle shroud clear of the melt. This precaution avoids exploding ladle shrouds and/or dangerous sub-surface gas explosions. Given that the collector nozzle shroud is reset from one ladle to another, the nozzles are invariably slightly biased (e.g., >90%). So the time period during which the shroud is exposed, and slag is entrained, must be minimised. In this regard, a three plate slide gate shroud is superior to the two plate slide gate system, since the latter precludes lateral movements during operations. Assuming normally designed shrouds with a two-plate system is being used, the first measure is to minimise exposure times prior to re-submergence of the shroud, so as to limit the amount of slag entrainment. One technique would be to raise the steel level in the tundish above the normal operating height (500 mm in the case modelled), a few minutes before the end of a ladle pour. This allows time for the collector nozzle to be de-coupled from the emptied ladle, the turret rotated to the new ladle, and the collector nozzle re-fitted to the collector nozzle of the new ladle with a gasket. This procedure would be carried out such that the level of steel in the tundish would be just below the end of the shroud collector nozzle once ended. As soon as the level of
steel within the tundish drops below the end of the ladle shroud, the new ladle should be opened immediately, and the ladle shroud quickly re-submerged. Ladle change times should be reduced from the current 3–4 minutes to 1–2 minutes. This can be done using efficient handling systems which are already used by large steel companies in Asia. Also, proper instrumentation (like laser levels) should be installed in the plant, in order to check the alignment of the shroud during each casting sequence.

5. Conclusions

It is very clear that ladle shroud mis-alignments is an important issue and should be given high priority in the industry to maintain steel quality. Ladle change times should be reduced to minimize shroud exposure times and thus try to circumvent the effects of a biased shroud. The physical modelling results correspond very well to our mathematical predictions. The 3D mathematical model enabled us to visualize bubble tracks and inclusion trajectories within the tundish to predict TKE contours on the free surface, the plane of the shroud, and the plane of the outlets. The 3D model also helped us to find the fact that a mis-alignment of the shroud along the length of the tundish is more harmful than a bias along its width. These predictions were not possible in the previously developed 2D model. A submerged shroud operation would be better than the non submerged operation during a ladle change, as indicated from the 3D numerical model predictions, but practical difficulties do not normally permit for this.

Nomenclature

\( k \): Kinetic energy of turbulence per unit mass, \( \text{m}^2/\text{s}^2 \)
\( \varepsilon \): Rate of energy dissipation, \( \text{m}^2/\text{s}^3 \)
\( G_k \): Rate of production of \( k \), \( \text{kg/m}^3\text{s} \)
\( C_1, C_2, \sigma_\varepsilon, \sigma_k \): Empirical Constants
\( u_p \): particle velocity, \( \text{m/s} \)
\( u \): Fluid Velocity, \( \text{m/s} \)
\( g \): acceleration due to gravity, \( \text{m/s}^2 \)
\( d_p \): diameter of the particle, \( \text{m} \)
\( \mu \): viscosity of the fluid, Pa. s
\( \mu_{ef} \): Effective viscosity of the fluid, Pa. s
\( \rho \): density, \( \text{kg/m}^3 \)
\( C_D \): Drag Coefficient
\( Re \): Reynolds Number
\( DPM \): Discrete Phase Modelling
\( SEN \): Submerged Entry Nozzle
\( TKE \): Turbulent Kinetic Energy
\( IP \): Impact Pad

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