In the blast furnace process, material losses occur due to mechanical wear between charged iron ore pellets and are exhausted in the form of dust in the off-gases. A redesigned tribometer combined with a ventilation chamber was developed to identify the dust emission from the mechanical wear contact of pellets. In order to obtain a better understanding of the measurement results, a coupled drift flux with a unified Eulerian deposition model was adopted to investigate particle dispersion and deposition during tests. Two influential factors, namely the air condition (5–20 L/min) and particle size (1–20 μm) were examined. The predicted results were presented by introducing two parameters, namely the measurable fraction and the deposition fraction. For each air condition, the measurable fraction declines while the deposition fraction rises as particle size grows. The critical size of the particles that becomes airborne and captured at the outlet was identified to be around 20 μm. In addition, a high airflow rate supplied at the inlet was observed to be favorable for improving the measurable fraction. Nevertheless, the results show that nearly 50% of emitted particles (1–20 μm) that failed to be captured during tests. Thus it could be expected that these generated particles would be transported deeply in a blast furnace if they are not efficiently removed from the off-gas. As a consequence, they may influence the quality of the products. Furthermore, the validation of the simulation results against the experimental data was achieved by using the predicted measurable fraction.

**KEY WORDS:** particle; pellet; off-gas; particle size; deposition; computational fluid dynamics; wear.

1. Introduction

In the blast furnace process, material losses are caused by particles that are exhausted from the top of the blast furnace within the off-gas. To reduce the losses, the off-gas dust formation source needs to be identified. Iron ore pellets are widely used as raw materials in the blast furnace process. During the feeding processes, such as handling, transportation and charging, pellets typically undergo a mechanical wear which is reported as being one important source for the dust formation. However, it is unclear to what extent wear which is reported as being one important source for the dust formation.

During the feeding processes, such as handling, transportation and charging, pellets typically undergo a mechanical wear which is reported as being one important source for the dust formation. However, it is unclear to what extent.
experimental data from a previous study. The objective of this work is to provide a good understanding of the air conditions and particle movements during the tests in an effort to evaluate the measurement results of the particle generation from the wear contact between pellets. The influence of the particle size and air inflow rate on the particle sampling is examined by a set of calculations. Numerical results with respect to airflow pattern, deposition velocity, deposition fraction and measurable fraction are presented.

2. Materials and Method

2.1. Experimental Set-up

A schematic diagram of the experimental setup is illustrated in Fig. 1. It can be seen that the redesigned disc tribometer is situated in a cylindrical chamber (I) with an air inlet (B) and an outlet (H). The clean air is taken from a compressed gas tank through the inlet (B) into the chamber. The inflow rate at the inlet is controlled by using an air flowmeter (A). Furthermore, the whole air supply system is connected by flexible tubes to avoid the leakage. The test samples (E. pellets) are placed between a rotational disc (D) and a porous plate (F). The wear contacts between the pellets wear contact are transported by the air ventilation to the outlet (H), where the particle counter and collection instrument is situated. The Electrical Low Pressure Impactor (ELPI+, Dekati Ltd., Finland) is used to acquire the particle size distribution and concentration as well as to collect the generated particles. The operating principle of the ELPI+ is that the particles are firstly charged by a corona changer and then they are classified by using a low pressure cascade impactor combined with an electrical detection by using a multi-channel electrometer. The ELPI+ consists of 14 stages in total, which enables a collection of particles in the aerodynamic diameter range from 6 nm to 10 μm. During the tests, the generated particles were collected separately during these 14 stages on grease aluminum filters according to their different sizes. Moreover, three layers of iron ore pellets (E) were charged for all tests. The rotational speed of the plate (D) was fixed at 240 rpm and three air flow rates at the inlet (B), namely 5, 8 and 10 L/min were examined. For each test, it was repeated twice.

2.2. Computational Fluid Dynamic Model

2.2.1 Drift Flux Model and Deposition Model

A simplified drift-flux model which considers gravitational separation and diffusion was adopted to simulate the particle transport and concentration in this study. The governing equation for particle transport in turbulent flow field is,

$$\frac{\partial C_i}{\partial t} + \frac{\partial}{\partial x} \left[ (u + v_f) C_i \right] = \frac{\partial}{\partial x} \left[ \left( D_{B_i} + \epsilon_{B_i} \frac{\partial C_i}{\partial x} \right) \frac{\partial}{\partial x} C_i \right] + S_i \quad \text{(1)}$$

where $C_i$ is the particle mass concentration, kg/m$^3$, $u$ is the fluid velocity and $v_f$ is the particle settling velocity, m/s, with respect to different diameters, $\epsilon_B$ is the particle eddy diffusivity (assumed to equal to the carrier fluid turbulent diffusivity, $v_0$. In addition, $D_B$ is the Brownian diffusion coefficient and $S_i$ is the source term.

The detailed description of the Eulerian deposition model can be found in (9-11), so the equations are not reproduced here. A brief description of the drift flux model and deposition model is given in the Appendix.

For the estimation of the deposition velocity, the only input parameter is the friction velocity, which can easily be calculated based on the numerical results of the wall shear stress,

$$u_t = \sqrt{\tau_w / \rho} \quad \text{.................................. (2)}$$

where $\tau_w$ is the wall shear stress and $\rho$ is the density of the air.

The particle flux towards the wall due to the deposition is taken into account as a sink term ($S_i$) in the area adjacent to the corresponding walls. The deposition particle flux at each unit area ($dA$) of the walls can be estimated by the following equation,

$$J_i = v_f C_i \rho dA \quad \text{.................................. (3)}$$

where $v_f$ is the deposition velocity of particles close to each cell, $C_i$ is the particle mass concentration at the cells adjacent to the walls, and $dA$ is the area of the wall.

2.2.2 Model Geometry

The model is built in a cylindrical-polar coordinate system. The dimension of the model geometry is the same as the experimental setup, which is shown in Fig. 2, specifically, the angular degree ($\theta$) × radius ($r$) × height ($z$) = $2\pi \times 0.0635 \times 0.26208$ m. The diameter of the inlet and the outlet are 0.016 m and 0.02 m, respectively. Also, three layers of pellets (221 in total) are placed between the rotating plate and the porous plate (Fig. 2).

2.2.3 Boundary Conditions and Assumptions

Non-slip boundary conditions and the generalized logarithmic wall functions(12) were employed for the air at all walls and surfaces of the objects. The air flow was supplied...
at the inlet with different volumetric flow rates of 5, 8, 10 and 20 l/min, corresponding to air change rates of 110, 176, 220 and 440/h, respectively. The pressure boundary condition at the outlet was set as a prescribed value of the atmospheric pressure. The rotational speed of the rotating disc was 240 rpm and it was active over the entire test duration. A zero concentration condition of particles was specified at the initial moments in the chamber. The particles (source) were released continuously from each pellet with a constant mass flux of \(5 \times 10^{-5}\) kg/s, which is in total corresponds to a flux of \(1.105 \times 10^{-3}\) kg/s. Also, a particle flux due to the deposition effect at areas of interest was considered as a sink term in the particle concentration calculation. Besides, the drift flux model was deactivated for the region below the porous plate. This is due to that the computational domain is divided into a number of zones by hundreds of pellets. As a consequence, it is not easy to define the boundary condition for the drift flux term in this region. Overall, these assumptions may to some degree limit the simulation to a macro scale study.

Air is treated as an incompressible fluid, which has a 20 degree temperature and a 1 atm pressure. Thus, the density of air is 1.189 kg/m³ and the kinematic viscosity is \(1.544 \times 10^{-5}\) m²/s. All objects of the redesigned triboimeter and all walls of test container were defined as materials consisting of solid steel. All the pellets were assumed to be spherical with a uniform diameter of 0.01 m. Moreover, the generated particles were supposed to have a spherical shape with a uniform density of \(5 \times 10^5\) kg/m³. However, the motions of the pellets (e.g. rotation or sliding) and the interactions between emitted particles were not considered in order to reduce the complexity of the calculation as well as the related computational time. The surfaces of the redesigned triboimeter body and internal walls of the cylindrical chamber were assumed to have a constant roughness of 70 µm.

2.2.4. Numerical Procedure

The steady airflow field was solved first by using the commercial software PHOENICS, where the turbulence was calculated by using the re-normalized group RNG k-ε model. The flow field calculation was assumed to reach a steady state, within a cut off error of \(1 \times 10^{-5}\) which occurring after 10 000 sweeps. The convection and diffusion terms for the pressure and velocity were discretized using the HYBRID scheme. Also, the friction velocity \(\beta_m\) was estimated from the solved flow field and it was used as the input parameter for the deposition velocity calculation, which was done by the commercial software MATLAB. Thereafter, a transient simulation was carried out for the released particles from pellets into the cylindrical chamber during a time period of 300 s with the consideration of the particle deposition as a sink term at the areas of interest.

3. Results and Discussion

3.1. Independence of the Grid System and the Time Step Size

As known, the grid system and the time step size may influence numerical results to some extent. To study the grid independence three grid systems, were examined in the flow field calculation for the air inflow rate of 8 l/min, namely grid 1 (coarse), grid 2 (medium) and grid 3 (fine). The corresponding number of grids were 408 156 (113 \times 42 \times 86), 593 640 (159 \times 45 \times 110) and 787 050 (166 \times 55 \times 138), respectively. Figure 3 shows a comparison of the z-velocity magnitude along Line 1 for three grid systems: Grid 1, 2 and 3.

<table>
<thead>
<tr>
<th>Grid 1, coarse</th>
<th>Grid 2, medium</th>
<th>Grid 3, fine</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.24</td>
<td>0.21</td>
<td>0.20</td>
</tr>
<tr>
<td>0.20</td>
<td>0.18</td>
<td>0.17</td>
</tr>
<tr>
<td>0.16</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>0.12</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>0.08</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The average percentage deviation (APD) was used. The APD value is defined as the difference of the studied variable between two compared cases divided by the magnitude of the variable for an observed case at a chosen distance or a given time period. To be specific, the APD values for grid 1 and grid 3 to grid 2 are 12.46% and 5.15%, respectively. Although the deviation of grid 1 to grid 3 is not so small, it should be noted that the deviation mainly occurs in a small magnitude range of the velocity, namely 0.02–0.05 m/s. Thus, the overall grid independence is deemed to be acceptable. Therefore, the medium mesh (grid 2) system was selected and used by considering the computational time and the accuracy (Fig. 2).

Based on the medium mesh in Fig. 2, four different time step sizes, 0.01, 0.1, 0.5 and 1 s were examined to evaluate the independence of the time step on the numerical results. The related study case was that 1 µm particles were continuously released from each pellet with a constant mass flux, \(5 \times 10^{-6}\) kg/s, over a time period of 120 s for an air flow field of 8 l/min. The amount of particles exhausted from the outlet was monitored during the calculations. The measurable fraction was calculated as follows:

\[
\beta_m = \frac{M_r}{M_s} \tag{4}
\]

where \(\beta_m\) is measurable fraction, \(M_r\) is the released particle amount from the pellets and \(M_s\) is the exhausted particle amount from the outlet (Fig. 1(H)). As illustrated in Fig. 4, the deviation of the measurable fraction was rather small from the initial to the end of time among the cases of time step, 0.01, 0.1 and 0.5 s. The deviation from the cases of the time steps 0.01, 0.5 and 1 s to 0.1 s was evaluated at the specific time moments of 30, 60 and 120 s to have values of 0.13%, 2.53%, 9.57%; 0.05%, 0.32%, 1.50%; 0.03%, 0.09%, 0.25%, respectively. According to that, the time step size independence is reasonable. Considering the computational load, the time step 0.1 s was selected as the time step size.

3.2. Flow Field

Figure 5 shows the air flow field inside the test chamber by means of fluid streamlines. Two initial positions as illustrated in Fig. 5, the horizontal centerline of the inlet and a circle line above the top layer of pellets, were selected to draw hundreds of streamlines. They were colored by the velocity magnitude in the given scale. As can be seen in Figs. 5(a)–5(d), the airflow pattern inside the test chamber becomes more complicated as the air flow rate increases from 5 to 20 l/min. The injected air from the inlet seems to experience two scenarios, either it merges into the bottom.
rotational flow or it travels towards the outlet. Moreover, the injected air that runs into the bottom part decreases as the air inflow rate increases. Meanwhile, more air can approach the outlet. As reported by Nazaroff, the airflow pattern plays a key role for the airborne particle in an enclosed space. It seems that the airflow pattern formed in the case of a higher air inflow rate would be beneficial for the particle sampling at the outlet on one hand. On the other hand, one can speculate that the strong rotation that exists at the bottom together with some turbulence, which appears in certain areas, would cause a drop of the measurable fraction of the particle emission at the outlet. The deductions inferring from Figs. 5(a)–5(d) are further supported by the results in Figs. 5(e)–5(h). If the generated dust particles are supposed to reach the position just above the top layer of the pellets and thereafter to follow the air stream, one can find that a portion of particles would be forced backward to the bottom part of the chamber.

Also, it indicates that these particles may remain in the bottom region for a long time. In all likelihood, they would deposit either on the surface of pellets, the bottom plate, or eventually on chamber walls. In addition, more general information can be extracted from the streamlines. Specifically, that high velocities only reside in the bottom area (close to the inlet and the rotational plate) and in the vicinity of the outlet. Furthermore, a large region of the test chamber (especially for the region above the porous plate to the outlet) is occupied with rather low velocities. This velocity distribution is further illustrated in Fig. 6. The Z-velocity along Line 1 (above the porous plate to the center of the outlet) for four different air inflow rates shows that the magnitude of the velocity is low. Specifically, it has a value below 0.1 m/s at a distance 0.16 m from the porous plate (Fig. 2). Thereafter, it increases sharply at the vicinity of the outlet to a maximum value of 0.56, 0.86, 1.05 and 1.98 m/s for 5, 8, 10 and 20 l/min, respectively. This low local velocity (\( < 0.1 \text{ m/s} \)) seems to be unable to transport the generated particles with a diameter of larger than 30 \( \mu \text{m} \) (the gravitational settling velocity is around 0.12 m/s) to the outlet.

3.3. Deposition Velocity

The friction velocity, \( u_f \), was calculated by using Eq. (2) with values from the solved flow field in the turbulent region. A comparison of the measurable fraction for the following different time step sizes: 0.01, 0.1, 0.5 and 1 s.

![Fig. 4. A comparison of the measurable fraction for the following different time step sizes: 0.01, 0.1, 0.5 and 1 s.](image)

![Fig. 5. A comparison of the streamlines starting from the horizontal centerline of the inlet for different air inflow rates: (a) 5 l/min, (b) 8 l/min, (c) 10 l/min, (d) 20 l/min for different air inflow rates, and from a circle above the pellets: (e) 5 l/min, (f) 8 l/min, (g) 10 l/min, (h) 20 l/min. (Online version in color.)](image)
boundary layer adjacent to i) the vertical inner wall of the uppcyl (Fig. 2), ii) the vertical outer wall of the load arm (Fig. 2) and iii) the horizontal wall at the horizontal top surface of the porous plate (Fig. 2). The extracted friction velocities from the numerical results are listed in Table 1. The fitted expressions for the deposition velocity data as a function of the friction velocity can be illustrated by using the following expression:

\[ f(x) = p_1 \cdot x^6 + p_2 \cdot x^5 + p_3 \cdot x^4 + p_4 \cdot x^3 + p_5 \cdot x^2 + p_6 \cdot x + p_7 \]

\[ \log_{10}(V_{dep}), x = \log_{10}\left(\frac{u}{u_{in}}\right) \]

where \( f(x) \) and \( x \) are the corresponding coefficients. Subsequently, the fitted coefficients and the correlated expressions were patched at the layer near the walls to store the deposition velocity, namely the inner wall of uppcyl (Fig. 2, \( I_Y = 42 \)), the outer vertical wall of the load arm (Fig. 2, \( I_Y = 6 \)) and the top horizontal wall of the porous plate (Fig. 2, \( I_Z = 25 \)). It can be seen from Table 1 that the friction velocity near the walls of three objects increases with a larger inflow rate of the air. The reason is simple that a high air flow speed produces a larger shear stress near the walls. This, in turn, increases the friction velocity. Also, the maximum value of the friction velocity for each object with different air supply rates is two or three orders higher than the minimum value. It reveals that an uneven distribution of the friction velocity exists near the walls of these three objects. A comparison of the deposition velocity, \( v_d \) contours for particles with diameters corresponding to 1, 2, 4, 6 and 8 \( \mu m \) at the layer, \( I_Y = 42 \), adjacent to the object of uppcyl (Fig. 2) is shown in Table 2. The scale of the deposition velocity for each graph was set to \( 0 - 1 \times 10^{-7} \) m/s. The results show that the deposition velocity, \( v_d \), apparently increases with an increased air inflow rate for a given particle size. This can be explained by that a higher air inflow rate produces a larger friction velocity at the boundary layer adjacent to the inner vertical wall of uppcyl (Fig. 2) as illustrated in Table 1. Moreover, the deposition velocity declines with an increased particle diameter for each value of the air inflow rate. This is attributed to that the gravitational settling effect becomes predominant for large particles compared to the diffusion effect. Thus, they would fall downwards parallel to the vertical walls. On the contrary, the turbulent diffusion is more significant for small particles and it enhances the chances for them to deposit on the vertical walls. Moreover, it is worth noting that the magnitude of the deposition velocity is very small, namely in the order of \( 10^{-7} \) or even as small as \( 10^{-8} \). As a consequence, one can estimate that the relevant deposition flux is rather small, i.e. few particles would be deposited on the vertical inner wall of uppcyl (Fig. 2). Also, it suggests that a similar trend can be found for the deposition velocity near the outer vertical wall of the object of the load arm (Fig. 2). Therefore, the related deposition velocity distribution is not shown here. When calculating the deposition velocity near the top horizontal wall of the porous plate (Fig. 2), the gravitational settling effect was incorporated. The results show that the deposition velocity is very close to the particle settling velocity and that it has magnitudes that are several orders larger than that of the vertical walls of the uppcyl (Fig. 2) and the load arm (Fig. 2). As expected, it indicates that most of particles would deposit onto the top

![Figure 6](image)

**Fig. 6.** A comparison of the z-velocity magnitude along Line 1 for the following four different air inflow rates: 5, 8, 10 and 20 l/min.

<table>
<thead>
<tr>
<th>Objects</th>
<th>Friction velocity, m/s, for different air inflow rates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 l/min</td>
</tr>
<tr>
<td></td>
<td>0.01055</td>
</tr>
<tr>
<td></td>
<td>0.03732</td>
</tr>
<tr>
<td></td>
<td>0.06478</td>
</tr>
</tbody>
</table>

© 2016 ISIJ
Table 2. The deposition velocity, $v_d$, distribution near the vertical inner walls of the object, uppcyl, for studied particle with a diameter of 1 to 8 $\mu$m, and for different air supply conditions ranging from 5 to 20 l/min. (Online version in color.)

<table>
<thead>
<tr>
<th>Air inflow rate at the inlet, l/min</th>
<th>5</th>
<th>8</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle diameter, $\mu$m</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

3.4. Measurement Efficiency

In order to evaluate the influence of particle size and air condition on the efficiency of the measurement system, two parameters are introduced. They are the measurable fraction and the deposition fraction. The measurable fraction, $\beta_m$, is defined as shown in Eq. (4). Likewise, the deposition fraction is calculated as follows:

$$\beta_d = \frac{M_d}{M_r} \quad \text{(6)}$$

where $\beta_m$ is the measurable fraction, $M_r$ is the released particle amount from the pellets and $M_d$ is the deposited particle amount at three considered areas: i) the vertical inner wall of the uppcyl (Fig. 2), ii) the vertical outer wall of the load arm (Fig. 2) and iii) the horizontal wall at the horizontal top surface of the porous plate (Fig. 2). The particle deposition in the region below the porous plate (Fig. 2) is not taken into account in the present study. The reason is that a complex situation exists in this region which contains hundreds of pellets that are influenced by a strong rotation. Also, the particle deposition on the downward side of the top lid was not included. This is due to that only a few particles would reach the downward side of the top lid (as shown in Fig. 5).

**Figure 7** depicts the predictions of the measurable fraction ($\beta_m$) and the deposition fraction ($\beta_d$) for particles with diameters corresponding to 1, 2, 4, 6, 8, 10 and 20 $\mu$m and for the following four different air inflow rates: 5, 8, 10 and 20 l/min. A clear trend can be found that the measurable fraction declines while the deposition fraction rises with an increased particle size from 1 to 20 $\mu$m for each air supply condition. To be specific, for the air inflow rate of 5 l/min case, the measurable fraction of 1 $\mu$m to 20 $\mu$m particles are 44.42% and 0%, respectively. It is worth noting that the measurable fraction of both 1 $\mu$m and 2 $\mu$m particles is more than 10 times and 60 times higher than that of 8 $\mu$m and 10 $\mu$m particles, respectively. This large gap shows that gravitational settling effects become more predominant for bigger particles (8, 10 $\mu$m) compared to smaller particles (1, 2 $\mu$m).

The sedimentation influences the particle dispersion in a
non-linear way, so that the magnitude of the gravitational settling velocity is proportional to the square of the particle size (Eq. (A13) in Appendix). As a consequence, large particles would drop to the bottom part of the chamber. This indicates that few of them can reach the outlet and be measured at the outlet. Correspondingly, the deposition fraction is observed to increase dramatically from 1.17% to 56.16% as the particle size increases from 1 to 20 μm. In addition, it can be seen in Fig. 7 that a higher air inflow rate results in a larger measurable fraction and a lower deposition fraction for a given particle size. Specifically, the measurable fraction of 1 μm particles experiences a slight rise from 44.42 to 48.73% as the air inflow rate increases from 5 to 20 l/min. However, a sharp increase from 0.69% to 21.91% appears for 10 μm particles. Overall, the results show that the motion of 4–10 μm particles is very sensitive to the strength of the air flow condition. However, this influence becomes less significant for smaller particles (1 and 2 μm) and super large particles (≥20 μm). As indicated by the measurable fractions of 20 μm particles in Fig. 7, they seem to be too large to become airborne in the test chamber. Therefore, they cannot be measured during the tests.

By summing up the measurable fractions and the deposition fractions for 1–10 μm particles, one can see that nearly 50% of the released particle amount is neither registered at the outlet nor at the deposition zones. Two scenarios of these released particles can be expected, namely that they either travel inside the test chamber for a long residence time or drop to the bottom part of the porous plate (Fig. 2). This deduction can be explained by the results of the concentration profiles. As illustrated in Fig. 8, a non-uniform concentration distribution of 8 μm particles is observed in the test chamber for all four air conditions. Specifically, a heavy particle concentration level builds up below the porous plate (Fig. 2) and at the bottom region around the pellets. This observation is in accordance with that the missing 50% of the large particles would very likely fall down below the porous plate (Fig. 2) as a result of gravitational settling effects. Thereby, they would accumulate at the vicinity of the pellets, the bottom plate, and at immediate neighbor walls as a lack of upwards air streams in this region. Besides this observation, the particle concentration level at the accumulated region is also found to gradually be reduced with an increased airflow rate.

### 3.5. Validation

To obtain a feasibility analysis of the model, experimental and simulation data were compared with respect to the particle mass flux close to the outlet. During the experiments, the particle mass concentration was acquired by the particle counter instrument of ELPI+. Therefore, the mass flux can be calculated based on from the product of the mass concentration and the air flow rate, when particles are assumed to be spherical and to have a uniform density,

\[ \dot{m}_{pi} = C_{mi} \dot{V} \]

where \( C_{mi} \) represents the measured mass concentration in
each diameter interval, $V$ is the air flow rate (10 l/min), and $n_{mpi}$ is the relevant mass flux for an identified particle size.

For the simulation cases, the particle amount was released as an average mass flux from the experimental data divided by a factor. The considered particle sizes (1, 2 and 3 μm) represent the three stages of 12, 13 and 14 of the used particle counter instruments (ELPI+). The mean geometry stoke diameters of stage 12, 13 and 14 is, 1.294, 1.926 and 3.195 μm, respectively, if the particle density is assumed to be 5 000 kg/m³. For 1 and 2 μm particles, the factor value can be taken from prediction results of the measurable fraction, 0.4698 (46.98%), 0.453 (45.30%) and 0.4769 (47.69%) for cases representing 8 and 10 l/min flow rates, respectively. Notwithstanding no direct simulation results for 3 μm particles, the factor value can be extrapolated from Fig. 9. Here, the measurable fraction and deposition fraction is plotted as a function of the particle size for different air inflow rates. Moreover, two relationships were obtained for the correlation between the particle size and the measurable fraction for flow rates corresponding to 8 and 10 l/min, by using the polynomial curve fitting. The corresponding polynomial functions and related R-square values ($R^2 = 1$) are provided in Fig. 9. Therefore, it is reasonable that an accurate measurable fraction of any specific particle size in this range, 1 to 10 μm, can be extrapolated from the polynomial functions. For example, the measurable fraction of 3 μm particles is 0.4390 (43.90%) and 0.4033 (40.33%) for a flow rate of 8 and 10 l/min, respectively.

In Fig. 10, the simulation results and the experimental data of the mass flux are compared with respect to particles with a stoke diameter of 1, 2 and 3 μm over a test duration of 300 s. It can be seen that a reasonable agreement is obtained for all six cases during 300 s. However, a distinct difference is observed for the particle mass flux curve at the initial stage after the release. The time delay of the concentration growth at the outlet for simulations is shorter than that during the experiments. Also, a gap appears from 30 s to 60 s between the measured particle mass flux and the simulation data after the running-in process is completed. This can be explained by that the particle source in the

![Fig. 9.](image-url) The measurable fraction and the deposition fraction to the release particle amount as a function of the studied particle diameters for the following four air supply systems: 5, 8, 10 and 20 l/min. In addition, two fitting curves and the corresponding expressions are included for the measurable fraction for cases of 8 and 10 l/min. (Online version in color.)

![Fig. 10.](image-url) A comparison the particle mass flux at the outlet between the simulation results and the available experimental data for particles with diameters corresponding to 1, 2 and 3 μm for the following air inflow rates: 8 and 10 l/min, (a) 1 μm, 8 l/min, (b) 1 μm, 10 l/min, (c) 2 μm, 8 l/min, (d) 2 μm, 10 l/min, (e) 3 μm, 8 l/min, (f) 3 μm, 10 l/min.
simulation study is released continuously with a constant mass flux, whose value is equal to the average particle mass flux during a 300 s test. However, it may not be the case for the experiments during the very beginning of the test. The release strength in the beginning of the simulation is indeed higher than the real generation amount during tests. Over elapsed time from 60 s to 300 s, the APD values of the particle mass flux from simulation to experimental data are 5.52%, 4.93%, 11.40% for 1, 2 and 3 μm particles, respectively, when the air inflow rate is 8 l/min. Moreover, the APD values are 8.14%, 6.83%, 12.02% when the air inflow rate is 10 l/min.

Inferring from the validation results, the used drift-flux model in the present study is adequate to evaluate the efficiency of this kind of particle measurement systems in a macro scale, by predicting the measurable fraction and the deposition fraction.

4. Conclusions

In the CFD simulation, a drift flux model combined with a unified Eulerian deposition model is used to illustrate the particle transport behavior inside the test chamber. It shows an advantage when large or heavy particles are involved in an air system compared to a traditional transport model of a contaminant concentration is used. In the meanwhile, this model is capable to predict the zones where depositions take place as well as the resulting amount of deposited particles. Moreover, it is easy to extend this model by integrating other effects, such as thermophoresis.

Considering the different stages of an iron making process, the dust particles can be generated from iron ore pellets during loading, unloading and charging. The dust particle generation during charging, i.e. on the conveyor belt has a great likelihood to enter the furnace. The present simulation study can be used to estimate the critical size of particles, which are being transported deeply into the furnace. Moreover, the transport manner of dust particles within the exhaust hot off-gas can probably be elucidated by extending the present model by integrating the thermophoresis effect into the current model. This, in turn, can provide more information to how to use of the off-gas for different applications.

According to the simulation results, the following conclusions may be drawn:

• The flow field inside the test chamber shows a complicated airflow pattern with a marked velocity difference. This airflow pattern influences the particle transport to the outlet.

• The prediction of the deposition velocity shows that a particle deposition would mainly take place at the upward horizontal surface of the porous plate above the pellets rather than at the inner vertical walls of the cylindrical chamber.

• For a specific air condition, the bigger particle sizes result in a small measurable fraction and a large deposition fraction. The critical size of the particles that becomes airborne and can be captured at the outlet is around 22 μm. Also, it is worth noticing that a high air inflow rate enables more particles to be measured in such a test system. Correspondingly, the measurable fraction rises while the deposition fraction declines as the air inflow rate increases from 5 to 20 l/min. However, one can see that particle sampling at the outlet only successfully captures less than 50% of the generated particles in the size ranges from 1 to 20 μm, for all studied cases.

• The measurable fraction is used as a factor for validation of the simulation results against experimental data. A reasonable agreement of the mass flux (4.93% < APD < 12.02%) for 1, 2 and 3 μm particles over a test period from 60 s to 300 s is obtained for flow rates of 8 and 10 l/min, respectively.

Based on these results from the simulation, it is concluded that the particle loss due to deposition should be considered when evaluating such experimental measurements. Also, it may lead a way to optimize the experimental set-up and to improve the measurement efficiency in the future: This can, for example, be done by replacing the air side blown air supply system by a bottom blown system.

Acknowledgement

One of the authors, Hailong Liu wants to thank CSC (China Scholarship Council) for the financial support of his study at KTH.

REFERENCES


Appendix

Deposition Model

In general, the deposition velocity, \( v_d \), is defined as the particle mass transfer rate to the wall, \( J \), which is normalized by the mean concentration, \( C \), in the flow:

\[
\frac{v_d}{C} = \frac{J}{C} = \frac{\dot{m}}{C} = \frac{\dot{m}}{\rho C v} = \frac{1}{\tau} = \frac{1}{\tau_T} = \frac{1}{\tau_c} \tag{A1}
\]

The particle relaxation time, \( \tau \), is a measure of particle inertia and denotes the time scale for which any slip velocity between the particles and the fluid is equilibrated:

\[
\tau = \frac{2 \rho_p u^2}{9 \mu} \tag{A2}
\]

where \( \rho_p \) represents the density of pure particulate material, \( r \) is the particle radius, and \( \mu \) is the dynamic viscosity of air. By using the fluid friction velocity, \( u_f \), the dimensionless expressions of \( v_d \) and \( \tau \) can be derived as follows:

\[
\eta = \frac{u}{u_f} \tag{A3}
\]

\[
\tau' = \frac{u^2}{v} = \frac{2}{9} \left( \frac{\rho_p}{\rho_f} \right) \frac{r^2 u_f^2}{v^2} \tag{A4}
\]
\[ u_e = \sqrt{\frac{\tau_w}{\rho_f}} \] ........................ (A5)

where \( v = \frac{\mu}{\rho_f} \) is the kinematic viscosity of air and \( \rho_f \) is the density of air, \( \tau_w \) is shear stress in the near-wall layer and obtained from numerical results.

The flux of particles in the y direction (perpendicular to the wall) is expressed as follows:

\[ J = -(D_B + \epsilon) \frac{\partial C_p}{\partial y} - C_s D_T \frac{\partial \ln T}{\partial y} + C_s \frac{\partial V_{py}}{\partial y} \] ........................ (A6)

where \( D_B \) and \( \epsilon \) represents the Brownian diffusivity and turbulent diffusivity, \( C_p \), the particle concentration, \( D_T \), the coefficient of temperature gradient dependent diffusion and \( V_{py} \), the particle convective velocity in the y direction. In the present study, no temperature gradients conditions are assumed in the near wall region. As a result, the second term on the right hand side of Eq. (A6) is neglected.

Using Eq. (A1) substitute into Eq. (A6) and the non-dimensional deposition velocity, \( v_{de} \) can be derived as follows:

\[ \frac{v_{de}}{v} = \left( \frac{D_B + \epsilon}{v} \right) \frac{\partial C_p}{\partial y} + C_s \frac{\partial V_{py}}{\partial y} \] ........................ (A7)

The particle eddy diffusivity, \( \epsilon \), is assumed to equal to the fluid turbulent diffusivity, \( v \). The following expression from Johansen\(^9\) was used for estimating the fluid turbulent diffusivity:

\[ \frac{\nu_1}{v} = \begin{cases} \left( \frac{y^+}{11.15} \right)^3, \text{when } y^+ < 3; \\ \left( \frac{y^+}{11.4} \right)^2 - 0.049774, \text{when } 3 < y^+ < 52.108; \\ 0.4 y^+, \text{when } y^+ > 52.108. \end{cases} \] ........................ (A8)

The particle momentum equation in the y direction (perpendicular to the wall surface) can be normalised as follows:

\[ \left( 1 + \frac{\rho_f}{2 \rho_p} \right) \frac{\partial V_{py}}{\partial y} + \frac{\partial \nu_{de}}{\partial y} = - \frac{\partial V_{py}^2}{\partial y} - \left( 1 - \frac{\rho_f}{\rho_p} \right) g^* \] ........................ (A9)

where \( g^* = \frac{v}{u_e} g \) is the normalized gravity acceleration rate (\( g = 9.81 \text{ m/s}^2 \)), \( \nu_{de} \) is the normalized form of the Cunningham corrected particle relaxation time, which is estimated as \( \nu_{de} = \tau^*_C C_v \), \( C_v \) is the Cunningham correction factor and it can be calculated as:

\[ C_v = 1 + \frac{2 \lambda}{d_p \rho_p} \left( 1.257 + 0.4e^{-1.0d_p/2\lambda} \right) \] ........................ (A10)

where \( \lambda \) represents the molecular mean free path in the gas. Here, \( \lambda \) is equal to 66 nm and referred to the air under standard temperature and pressure (STP) condition.\(^9\)

The lower and upper boundary conditions may be expressed as following:

Upper boundary: \( y^+ = 60 \quad \overline{V_{py}} = 0 \quad C_p^* = 1 \)

Lower boundary: \( y^+ = 0.45 \lambda + \frac{r^*}{v} \quad C_p^* = 0 \) ........................ (A11)

where \( k_i^* = \frac{u_e}{v} k_i \) is the normalized form of the roughness height.\(^{10} k_i \).

The numerical procedure can be found in.\(^{11}\) By writing \( \frac{\partial}{\partial y} \) (Eq. A7) = 0, a single-pass marching FDM (finite difference method) is used to solve the particle mass concentration in the boundary layer with the boundary conditions of Eq. (A11). Thereafter, the \( V_{py} \) distribution within the boundary layer is solved from Eq. (A9) with the boundary conditions of Eq. (A11). Lastly, the deposition velocity was estimated by using Eq. (A7) with the solved the particle mass concentration and the particle convective velocity.

**Drift-flux Model**

A simplified drift-flux model which considers gravitational separation and diffusion was adopted to simulate the particle transport and concentration in this study. The governing equation for particle transport in turbulent flow field can be expressed as follows:

\[ \frac{\partial C_i}{\partial t} + \frac{\partial \left[ (u + v_i) C_i \right]}{\partial x} = \frac{\partial}{\partial y} \left[ (D_B + \epsilon) \frac{\partial C_i}{\partial y} \right] + S_i \] ........................ (A12)

where \( C_i \) is the particle mass concentration, \( \text{kg/m}^3 \), \( u \) is the fluid velocity and \( v_i \) is the particle settling velocity with respect to different diameters, \( \epsilon \), is the particle eddy diffusivity (assumed to equal to the carrier fluid turbulent diffusivity, \( v \), due to small relaxation time of particles. The magnitude of particle relaxation time is a function of the square of the particle diameter. The relaxation time is found to be of the order of \( 10^{-4} \), for particles with an aerodynamic diameter of 10 \( \mu \text{m} \) in air). Also, \( D_B \) is the Brownian diffusion coefficient and it can be estimated as follows:

\[ v_{de} = \frac{C_v \rho_p g d_p^2}{18 \mu} \] ........................ (A13)

\[ D_B = \frac{k_B T C_v}{3 \pi \mu d_p} \] ........................ (A14)

where \( k_B \) is the Boltzmann constant (\( 1.38 \times 10^{-23} \text{ J/K} \)), \( T \) is the absolute temperature (\( T = 273 + T_r \), and \( T_r \) is room temperature, 20°C).

For particles of micron size, the Brownian diffusion coefficient could be generally neglected as a result of its small magnitude. From Eqs. (A10) and (A14) one could estimate that the value of 2.72 \( \times 10^{-11} \text{ m}^2/\text{s} \) is for 1 \( \mu \text{m} \) particles, if the carrier phase is air.

The particle flux towards the wall due to the deposition is taken into account as a sink term (\( S_i \)) in the area adjacent to corresponding walls. The deposition particle flux at each unit area (\( dA \)) of the walls could be estimated by the following relationship:

\[ J_d = v_i C_v \rho_p dA \] ........................ (A15)

where \( v_i \) is the particle deposition velocity close to each cell and calculated from the above deposition model, \( C_v \) is the particle mass concentration at the cells adjacent to the walls and \( dA \) is the area of the walls.