Numerical simulation of flow patterns of disks in the symmetric moving granular filter bed

C. S. Chou(1), C. Y. Tseng(1), J. Smid(2), J. T. Kuo(2) and S. S. Hsiau(3)

(1) Department of Mechanical Engineering, National Pingtung University of Science and Technology, Pingtung, Taiwan 912, R.O.C.
Email: cschou@mail.npust.edu.tw

(2) Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan 10617, R.O.C.
Email: smid@w3.me.ntu.edu.tw
Email: jtkuo@w3.me.ntu.edu.tw

(3) Department of Mechanical Engineering, National Central University Chung-Li, Pingtung, Taiwan 32054, R.O.C.
Email: sshsiau@cc.ncu.edu.tw

Abstract

By extending the stack disk theory in the asymmetrical hopper by Chou et al., the initial coordinates of the disks' center and the boundary of the filter are defined. By making use of the DEM model of Cundall & Strack, the flow pattern histories of disks and the development of quasi-stagnant zones close to the louvered walls of the 2-D symmetrical moving granular filter bed were studied numerically. Three kinds of symmetrical moving granular filter bed (i) LA=30°, RA=30°; (ii) LA=40°, RA=40°; (iii) LA=50°, RA=50°) were used, respectively. LA is the angle between the left louver and vertical line, and RA is the angle between the right louver and vertical line. On the other hand, the flow pattern of disks in the 2-D Dorfan Impingo filter bed was studied numerically, too. The results of computer simulations of the louvered walls granular filter bed show that the angle of the louver affects the flow behavior of the disks, and are compared with those of Dorfan Impingo filter bed. The numerical results reported here and the experimental results by Kuo et al.
provide fundamental and important information for designing moving granular bed high-temperature flue gas cleanup filters.

1 Introduction

Hot gas particulate filtration is a key component of current combined cycle power generation systems based on the combustion and gasification of coal. Effective particulate removal protects downstream heat exchanger and gas turbine components from fouling and erosion while cleaning the gas stream to meet environmental emission requirements. Ceramic barrier filters (Seville) are the most advanced hot gas particulate control technology. However, problems encountered during recent pilot- and demonstration-scale tests have led to concerns over the commercial exploitation of this technology. For these reasons, alternative means of particulate removal, such as granular bed filters, especially moving bed filters continue to be developed. Moving bed filters provide a method for continuous operation when combined with circulation and regeneration of the filter media. Granular bed filtration can be operated in four modes: fixed bed, intermittently moving bed, continuously moving bed and fluidized bed (Saxena et al.; Zevenhoven; Seville and Clift). The possibility of (semi-) continuous regeneration in moving bed systems makes granular bed filtration an attractive option for continuous high temperature gas cleaning purpose. Basically the designs of granular bed filters can be categorized in two groups. One group is screenless filters (see, e.g., Nykanen et al.). The other group contains the moving bed filters with lover-like walls (Dorfan; Jordan and Lindner; Ishikawa et al.). A number of granular moving bed filters have used cross-flow designs where the filter granules move downwards guided by louvered walls whilst the gas passes the moving granules horizontally, see Fig. 1. Plugging problems were encountered in some of these moving bed filters at both low and high temperatures. By extending the theory of stacks of disks in the asymmetrical hopper by Chou et al., initial coordinates of the disks’ center and the boundary of the filter are defined. By making use of DEM model of Cundall & Strak, we numerically study the flow patterns in 2-D cross flow symmetric moving beds of noncohesive granular solids driven by gravity flowing between two vertical louvered walls with no interstitial fluid flow relative to the solids. The two-dimensional computer code based upon the soft particle approach, FILTER-2D, is employed to analyze the velocity fields and flow patterns of granules in a moving granular filter bed.

2 Discrete Element Method (DEM)

The Discrete Element Method is a numerical model capable of describing the mechanical behavior of granular assemblies. The calculations performed in the Discrete Element Method alternate between the application of Newton’s second law to the particles and a force-displacement law at the contacts advocated by
Cundall & Strack\textsuperscript{2}. The calculation cycle may be summarized as in Figure 2. The DEM numerical simulation essentially consists of three major steps: (1) Contact Detection; (2) Contact Processing; (3) Particle Motion.

### 2.1 Detection of Contacts

When particles move downwards, particles probably collide with neighboring particles and (or) collide with the wall of the granular filter bed. Two identical disk-shaped particles in Figure 3 are in contact if

\[
S = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2} \leq 2R ,
\]

where \(X_1, Y_1, X_2,\) and \(Y_2\) are the center coordinates of disk 1 and disk 2, respectively, and \(R\) is the radius of the disk.

The contact between a disk and a straight wall is shown in Figure 4. The contact is detected if

\[
h_1 \leq S_h \leq h_2 \text{ and } 0 \leq S_v \leq R ,
\]

where \(S_h\) and \(S_v\) are given by

\[
S_h = (X_a - X_w)\cos \theta_w + (Y_a - Y_w)\sin \theta_w ,
\]

\[
S_v = -(X_a - X_w)\sin \theta_w + (Y_a - Y_w)\cos \theta_w ,
\]

where \((X_a, Y_a)\) are the coordinates of the center of the disk. The straight wall is defined by the coordinates of the wall reference point \((X_w, Y_w)\) and angle \(\theta_w\) with respect to the X-axis.

### 2.2 Contact Processing

The contact force model (force-displacement law) currently implemented in the present model is same as the one used by Cundall and Strack\textsuperscript{2}. The schematic representation in a contact force model for two identical disks and the contact force model for a disk and a wall in a straight line are shown in Figures 5 and 6, respectively. The normal direction of the force is modeled as viscoelastic. It consists of elastic contributions (spring) and viscous damping contributions (dashpot). The force in a tangential direction is modeled as viscoelastic below the friction limit, and the friction limit is assumed to be given by the Mohr-Coulomb law.

The linear spring force employed in this research work is proportional to the relative displacement between the two disks and the contact stiffness. The current spring forces in the normal and tangential directions, \(F_n^N\) and \(F_s^N\), can be expressed as

\[
F_n^N = F_n^{N-1} + K_n (n\Delta t) ,
\]

\[
F_s^N = F_s^{N-1} + K_s (s\Delta t) ,
\]
where $K_n$ and $K_s$ are the normal and tangential spring stiffness, $\Delta t$ is the time step, $n$ and $s$ are relative velocity at the contact in the normal and tangential direction respectively, and the superscript N refers to the $N^{th}$ time step. The damping force employed in this research work is proportional to the rate of relative displacement and the damping coefficient. The damping force in the normal and tangential directions, $D_n$ and $D_s$ are given by

$$D_n = C_n n \quad \text{and} \quad D_s = C_s s,$$

where $C_n$ and $C_s$ are the normal and tangential damping coefficients.

Consequently, for the $N^{th}$ time step, the total normal force $F_{cn}^N$ and the total tangential force $F_{cs}^N$ acting on particle i by particle j can be expressed as

$$F_{cn}^N = F_n^N + D_n,$$

$$F_{cs}^N = F_s^N + D_s.$$

The total tangential force for the $N^{th}$ time step is limited by the friction condition

$$F_{cs}^N = \frac{F_{cs}^N}{|F_{cs}^N|} (\mu F_{cn}^N),$$

where $\mu$ is the coefficient of interparticle friction. The moment acting on particle i by particle j is obtained by calculating as

$$T_{ij} = -F_{cs}^N R.$$

The counterpart for contact processing between a disk a straight wall can be obtained if particle j is replaced by a wall.

2.3 Particle Motion

Once all of the resultant forces and moments acting on each disk are obtained, new velocities and positions for all disks are obtained by numerical integration of Newton's second law. Equations of the linear and angular motion are

$$m \frac{d^2 \bar{r}}{dt^2} = \bar{F}_c + m \bar{g},$$

$$\frac{d \bar{\omega}}{dt} = \frac{\bar{T}_c}{I}.$$

Where $m$ is the disk mass, $\bar{r}$ is the position vector of the disk, $\bar{F}_c$ is the total contact force acting on the disk, $\bar{T}_c$ is the total moment due to the tangential contact force, $I$ is the disk moment of inertia, and $\bar{\omega}$ is the angular velocity. By employing the indicial notation, the component of Eq. (12) can be expressed as
\[ \dot{r}_k = \frac{(F_c)_k}{m} + g_k, \]  
where \( k \) is the free index, and "." is the derivative with respect to time. By making use of the half-step "Leap-Frog" finite difference method of Potter\(^{13}\), and assuming that the acceleration of a disk over a time step \( \Delta t \) is constant, the integration of Eq.(14) leads to an expression for translational velocity

\[ \left( \dot{r}_k \right)_{t+\frac{\Delta t}{2}} = \left( \dot{r}_k \right)_{t-\frac{\Delta t}{2}} + \left[ \frac{(F_c)_k}{m} + g_k \right]_t \Delta t. \]  
This new value for velocity is used to update the position of the disk using a further numerical integration

\[ \left( r_k \right)_{t+\Delta t} = \left( r_k \right)_t + \left[ \dot{r} \right]_{t+\frac{\Delta t}{2}} \Delta t. \]  
By the same token, the disk angular velocity at time \( t + \frac{\Delta t}{2} \) and rotation at time \( t + \Delta t \) can be determined.

3 Results and Discussions

Table 1 lists the input for computer simulation. Figures 7 (30°/30°), 8 (40°/40°), 9 (50°/50°) and 10 (Dorfan Impingo) demonstrate the flow history of the colored granules and each figure has four frames. Frame A show the flow history of the colored granules at time \( t=0.06 \) sec., and the time intervals for frames A to D is 0.06 sec.

Four different flow regions were observed: (1) a quasi-stagnant zone adjacent to the louvered wall; (2) a transition region between the quasi-stagnant zone and a central flowing core; (3) a central flow core plugged region; (4) left and right free surface regions. Generally speaking, the velocity profiles are symmetrical due to the symmetric louver configurations. The quasi-stagnant zone area becomes larger as the angle of louver increases, and these results from Figures 7 to 9 explain the effect of louver angles upon the development of quasi-stagnant zones. For Dorfan Impingo filter bed, the convergence section is in the middle of each stage (see Fig. 10) and the exit of the filter bed is widest among the illustrated filters. Consequently, the development of quasi-stagnant zones in the Dorfan Impingo filter bed is not obvious.

In the transition region (i.e. shear zone), granules move from one layer to another and the velocity gradient is significant. There is a cascading granular transport in the transition region at different stages in the granular bed, and consequently granules flow from the shear zone of the upper stage into the underneath transition region. However, granules will not flow from convergence section of the Dorfan Impingo filter bed into the area close to the wall of the underneath vertical section (i.e. bin). Therefore, the porosity is formed gradually at the
area close to the wall of the vertical section. The velocity fluctuation about the average plug velocity in the central flow core plug region is small. Because of the existence of free surfaces between two louver-walled systems, the granular flows expand when the granules are just leaving the exit of the upper louvered section. A convergent granular bed ensues due to the louver-walled. Unlike the granular flows in the bin-hopper system, the granular flows in the current granular moving bed are affected by the upper and lower louvered-wall systems.

4 Conclusions

Four kinds of 2-D symmetrical moving granular bed filters were studied numerically. Granular bed flow in the filter channel is influenced by the angle of the louver and four different flow regions were observed in the symmetrical granular moving filter bed. The quasi-stagnant zone area becomes larger as the angle of the louver increases and the development of quasi-stagnant zones in the Dorfan Impingo filter bed is not obvious. The louvered walls as well as the free surface of the filter granules affect the velocity field of the granules.

Acknowledgement

The authors gratefully acknowledge the financial support from the National Science Council of the R.O.C. for this work through project NSC 87-2211-E-020-007.

Reference


2. Cundall, P.A. & Strack, O., A discrete numerical model for granular assemblies, Geotechnique, 29 (1979) 47.


---

**Figure 1: Illustration of the granular filter bed.**
Air Pollution

Figure 2: The calculation cycle of DEM.

Figure 3: Disk pair in contact.

Figure 4: Contact between a particle and a straight wall.

Figure 5: Contact force model for two identical disks.
Air Pollution

Figure 6: Contact force model for a disk and a straight wall.

Table 1: Input for Computer Simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Particle-Particle</th>
<th>Particle-wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness $K_n$ (KN/m)</td>
<td>15000</td>
<td>75000</td>
</tr>
<tr>
<td>Stiffness $K_s$ (KN/m)</td>
<td>12000</td>
<td>6000</td>
</tr>
<tr>
<td>Damping Coefficient $C_n$ (KN-s/m)</td>
<td>0.025</td>
<td>0.27</td>
</tr>
<tr>
<td>Damping Coefficient $C_s$ (KN-s/m)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Coefficient of friction $\mu$</td>
<td>0.57735</td>
<td>0.267949</td>
</tr>
<tr>
<td>Radius of Disk</td>
<td>0.005m</td>
<td></td>
</tr>
<tr>
<td>Mass of Disk</td>
<td>0.077123kg</td>
<td></td>
</tr>
<tr>
<td>Time Step</td>
<td>$6 \times 10^{-6}$sec</td>
<td></td>
</tr>
<tr>
<td>Gravity</td>
<td>9.81 m/s</td>
<td></td>
</tr>
<tr>
<td>Number of Disk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$30^\circ / 30^\circ$</td>
<td>3236</td>
<td></td>
</tr>
<tr>
<td>$40^\circ / 40^\circ$</td>
<td>2816</td>
<td></td>
</tr>
<tr>
<td>$50^\circ / 50^\circ$</td>
<td>2596</td>
<td></td>
</tr>
<tr>
<td>Dorfan</td>
<td>2064</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7: The flow pattern of the moving granular filter bed ($30^\circ/30^\circ$). (A) The flow pattern at time $t=0.06$. (B) The flow pattern at time $t=0.12$. (C) The flow pattern at time $t=0.18$. (D) The flow pattern at time $t=0.24$. 
Figure 8: The flow pattern of the moving granular filter bed ($40^\circ/40^\circ$). (A) The flow pattern at time $t=0.06$. (B) The flow pattern at time $t=0.12$. (C) The flow pattern at time $t=0.18$. (D) The flow pattern at time $t=0.24$.

Figure 9: The flow pattern of the moving granular filter bed ($50^\circ/50^\circ$). (A) The flow pattern at time $t=0.06$. (B) The flow pattern at time $t=0.12$. (C) The flow pattern at time $t=0.18$. (D) The flow pattern at time $t=0.24$.

Figure 10: The flow pattern of the moving granular filter bed (Dorfan Impingo). (A) The flow pattern at time $t=0.06$. (B) The flow pattern at time $t=0.12$. (C) The flow pattern at time $t=0.18$. (D) The flow pattern at time $t=0.24$. 

Air Pollution