Experimental and numerical study of granular flow characteristics of absorber sphere pneumatic conveying process

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Abstract — Absorber sphere pneumatic conveying system is the main part of absorber sphere shutdown system and closely related to granular flow. Granular flow characteristics, such as mass flow rate, angle of repose, contact forces, etc., are crucial important for the optimization of absorber sphere pneumatic conveying process. Mass flow rate of granular flow through the sphere discharge valve and the bend tube are significant for the time of ball dropping and the time of conveying back rate, respectively. Experiments and DEM simulations have been conducted to investigate the granular flow characteristics. Experimental results showed that the relation between average mass flow rate through the sphere discharge valve and the valve stroke was composed of three zones i.e. the idle stroke zone, linearly zone and orifice restriction zone. The Beverloo’s law was suitable for the granular flow through the multi-orifice during the orifice restriction zone. The variation of average mass flow rate with the valve stroke could be described by modified Beverloo’s law based on the valve stroke. DEM simulation results showed that the drained angle of repose remained 23° at different valve strokes. Mass flow rate during steady granular flow through the sphere discharge valve at different valve strokes kept stable. The variation of mass flow rate through a bend tube was different from that through a circular orifice.

I. INTRODUCTION

High Temperature Gas-cooled Reactor (HTR or HTGR) is the Generation IV advanced nuclear reactor [1-2]. HTR has many advantages, e.g. the inherent safety, high efficiency, potential application for hydrogen production and attractive economics [3-5]. A demonstration reactor, named the 10 MW high-temperature gas-cooled test reactor (HTR-10), was developed by the “Institute of Nuclear and New Energy Technology” (INET) at Tsinghua University [6]. On the basis of technology and operation experience of HTR-10, the High-Temperature Reactor Pebble-bed Module (HTR-PM) project was launched in 2001 [1]. HTR-PM was approved as one of the national special grand science-technology projects of China and is currently in construction in Shidaowan, Shandong Province [1].

Two independent systems were designed to control the neutron chain reaction and shut down the reactor both in HTR-10 and HTR-PM, i.e. the control rod system and the absorber sphere shutdown system [1, 4]. The absorber sphere shutdown system, called small absorber ball system in HTR-10, was in principle derived from the HTR-Module design [7]. Pneumatic conveying was adopted in this shutdown system [7]. The function of the shutdown system was directly realized by the absorber sphere pneumatic conveying system which mainly consisted of drive mechanism, storage vessel, reflector boring, sphere feeder, riser, roots blower and other facilities. The circuit of this system and main equipment are shown in Fig. 1.

Absorber spheres, made of B.C in graphite, were designed to drop into the reflector boring by gravity when the sphere discharge valve was opened by drive mechanism to shut down the reactor. On the other hand, during the process of reactor startup, spheres in the reflector boring were vertically conveyed back to storage vessel through riser [1, 4,
The absorber sphere pneumatic conveying process was an intermittent circulation of absorber spheres between the reflector boring and the storage vessel in the reactor [8], as described above. The whole intermittent circulation consisted of four sub-processes, i.e. (a) spheres discharge from the storage vessel and the reflector boring, (b) entrainment of sphere in the feeder, (c) conveying of sphere in the transport pipe and (d) gas-solid separation and pile of spheres in the storage vessel [8].

Granular flow characteristics, such as mass flow rate, angle of repose, stress distribution, porosity distribution, impact force between particle and wall, are significant for the optimization of absorber sphere pneumatic conveying process. Flow pattern and drained angle of repose [9] during the granular flow in storage vessel can be the design guides to indication of ball level [7]. Porosity distribution is useful for forecasting the ball level as well as the sphere quantity in devices. Mass flow rates through the sphere discharge valve and the hopper are of crucial importance for the time of ball dropping [7]. On the other hand, mass flow rates through the reflector boring and the bend tube are important to the time of ball conveying back [7]. Both the time of ball dropping and the time of ball conveying back were significant operation parameters of absorber sphere shutdown system. In addition, stress distribution and angle of repose, and impact force between sphere and wall are useful to the mechanical design of the sphere discharge valve and the absorber sphere manufacture, respectively.

Many studies have been carried out to investigate the granular flow characteristics both experimentally [10-21] and numerically [20-24]. Mass flow rate through an orifice significantly depended on particle density, orifice size, shape of orifice and particle size [12, 14]. Its dependence on different parameters was proposed by Beverloo et al. [12] with the widely accepted form as follows:

\[ W = C \rho_s \sqrt{g(D_0 - k d_p)}^{3/2} \]  (1)

Where \( W \) is the average mass flow rate through the circular orifice, \( C \) and \( k \) are empirical discharge coefficient probably depending on the friction coefficient and shape coefficient respectively [15], \( \rho_s \) is the bulk density, \( D_0 \) and \( d_p \) are diameters of orifice and particle respectively, and \( g \) is the acceleration of gravity. Equation 1 was known as the Beverloo’s law. Its validity has been tested for monosized granular samples. Its validity for granular flow through multi-orifice is unknown.

Angle of repose is the angle of the free surface of a heap of granular materials to the horizontal plane [17]. It could be defined by different methods [17-18, 20, 23] and is one of the most important macroscopic parameters in characterizing the behavior of granular materials [23]. Studies have provided evidence that material properties such as sliding friction coefficient [10, 22-24], rolling friction coefficient [10, 22-24] and surface roughness [21] as well as particle characteristics such as particle size [10, 20, 23-25] and shape [10] strongly affected the angle of repose. However, angle of repose was not obviously sensitive to density of...
particle, Poisson’s ratio, damping coefficient and Young’s modulus [23-24].

Inter-particle forces in granular medium were different from forces in continuous medium that the former organized as force network which was heterogeneous with both weak and strong networks [26]. Therefore, the stress distribution in granular medium was in contrast to what happened in liquid. According to Janssen’s model, the pressure at the bottom of a silo increased with the height of granular medium, but saturated when there were enough particles [26]. Measurements of the pressure were well described by Janssen’s model in spite of the assumptions [26]. As a result, Janssen’s model can be used for engineering design.

It is difficult to measure the microscopic properties such as velocity, contact force and impact force by experiments. Numerical method of discrete element method (DEM) is a good choice [27]. Furthermore, on the basis of the DEM results, macroscopic properties such as stress distribution and porosity distribution can be obtained by using the averaging method [28].

Although a large number of studies on granular flow characteristics have been made, few of them focused on the granular flow in high-temperature gas-cooled reactor, through multi-orifice and bend tube. In addition, since the absorber sphere pneumatic conveying system was a unique system, the fundamental studies on granular flow reported in the literature perhaps couldn’t be directly applied. Further work is still needed.

The focus of this article is on the experimental and numerical study of granular flow of absorber sphere pneumatic conveying process. Experiments of granular flow through the sphere discharge valve have been conducted to investigate the flow pattern and characteristic of mass flow rate. In addition, more detailed information such as contact forces, velocity and porosity as well as flow pattern and drained angle of repose in storage vessel were obtained by corresponding DEM simulations. DEM simulations were also carried out to study the granular flow through bend tube. However, more works need to be done on simulation post-process with the averaging method, optimizing simulation parameters and experimental validation of granular flow through bend tube.

II. EXPERIMENTAL WORK

Figure 2 is the schematic diagram of the experimental apparatus which was made of steel and fixed to iron lining. The sphere discharge valve was composed of the valve guide tray and the valve moving part, as shown in Fig. 2. The valve guide tray was connected with the protecting tube and kept stationary. The valve moving part was connected with the drive rod and moved down or up together with the drive rod to open or close the sphere discharge valve. S in Fig. 2 represented the valve stroke i.e. the stroke of the sphere discharge valve. When the valve was closed, S equaled to zero. However, S was greater than zero when the valve was open.

![Fig. 2 Schematic diagram of the experimental apparatus](image)

The sphere discharge valve was a new-type ball drop valve which was designed based the principle of angle of repose [29]. To investigate the characteristics of the valve and the granular flow characteristics, both critical valve stroke experiment and experiment of granular flow through the sphere discharge valve as well as the sampling experiments were carried out. The three kinds of experiments were conducted with the same experimental apparatus shown in Fig. 2, but without the hopper at the bottom to storage vessel. Glass sphere was used and the total mass was 50 kg for all experiments. The diameter and density were 6 mm and 2518 kg/m$^3$ respectively. Experiments were carried out in atmospheric environment.

II.A. Critical Valve Stroke Experiment

Spheres were in the equilibrium state of forces and static in storage vessel before the valve opened. It has been found that the spheres were also in equilibrium state of forces when the valve stroke, $S$ was within a range, which indicated that there was a critical valve stroke after which sphere began to flow. Therefore, experiments were carried out to measure the critical valve stroke. During the experiments, the valve was opened slowly. $S$ was measured when spheres started to fall down continuously. Then move up control rod slowly and measure $S$ when the continuous falling stopped. Repeat the processes for extra five times and average $S$ to get the critical valve stroke, $S_c$.

II.B. Experiment of Granular Flow through the Sphere Discharge Valve

The bottom of storage vessel was a multi-orifice structure, with eight circular orifices distributed in circular. Diameter of the circular orifices were 40 mm. Research on mass flow rate through multi-
orifice was not reported. Experiments of granular flow through the sphere discharge valve were conducted to investigate the characteristic of mass flow rate through the multi-orifice during the entire flow. Measuring apparatuses included stopwatch, vernier caliper and electronic balance with precision of 0.5 g and measuring range of 5 kg.

Experimental process was as follows: (1) Move the control rod down manually for a certain distance. Start stopwatch when the spheres began to fall down and stop stopwatch when the falling ended. Record the entire falling time, \( t \). (2) Weigh the spheres on the valve guide tray by electronic balance. Record the mass and get the falling spheres mass, \( M \). \( M/t \) was the average mass flow rate, \( W_{av} \). (3) Measure \( S \) by vernier caliper. (4) Repeat steps (1) ~ (3) for another \( S \) to obtain the relation between \( W_{av} \) and \( S \).

**II.C. Sampling Experiment**

Sampling experiments were conducted to investigate the characteristic of mass flow rate during the steady granular flow through the sphere discharge valve. Samples were done during steady granular flow by using plastic basins. Sampling times were measured by stopwatch. Four samples were done for each experiment, each sampling time was 5~8 s. Experiments were carried out at valve strokes of 32.42 mm and 34.72 mm respectively.

**III. NUMERICAL DESCRIPTION**

**III.A. Discrete Element Method**

Discrete element method (DEM) was originally proposed by Cundall and Strack [30] and is widely used in the simulation of granular flow [20-23, 27, 31-37]. Particle motions were described by Newton second law. The translational and rotational motions of particle \( i \) were respectively expressed by translational equation (Eq. 2) and rotational equation (Eq. 3) as follows [38]:

\[
\frac{dv_i}{dt} = \sum_j F_{ij}^c + \sum_k F_{ik}^{nc} + F_{ij}^f + F_{ij}^w
\]

\[
I_i \frac{d\omega_i}{dt} = \sum_j M_{ij}
\]

Where \( m_i \), \( v_i \), \( I_i \) and \( \omega_i \) are mass, translational velocity, moment of inertia and angular velocity of particle \( i \), respectively. \( F_{ij}^c \) is the contact force acting on particle \( i \) by particle \( j \) or wall. \( F_{ik}^{nc} \) is the noncontact force acting on particle \( i \) by particle \( k \) or other sources. \( F_{ij}^f \) is the particle-fluid interaction force on particle \( i \). \( F_{ij}^w \) is the gravitational force and \( M_{ij} \) is the torque that acts on particle \( i \) by particle \( j \) or wall. Since the fluid effect on granular flow was negligible in the experiments, \( F_{ij}^f \) in Eq. 2 was set to zero in DEM simulations.

Forces and torques caused by interactions with neighboring particles and walls were expressed by the contact model. The Hertz-Mindlin (no slip) contact model was adopted in the simulations.

**III.B. Simulation of Granular Flow through the Sphere Discharge Valve**

Experiments of granular flow through the sphere discharge valve were simulated by DEM. The geometrical structure and size were same with the experimental apparatus. The opening processes of the valve were simulated by initialing downward uniform translational motions. Downward distances were corresponding same to valve strokes and the motion times were set to 0.5 s according to experimental videos. Density, Poisson’s ratio, and Young’s modulus were set to 7850 kg/m³, 0.31 and 1×10⁸ Pa for steel, and 2518 kg/m³, 0.25 and 9.2×10⁷ Pa for glass sphere, respectively. Total mass of glass spheres was 50 kg, i.e. 175329 particles. Time step was set to 1×10⁻³ s. Contact parameters for DEM simulations, obtained both according to the reported literature [39] and comparisons between experiments and simulations, are shown as Table 1. The subscript pp and pw represent the inter-particle contacts and particle-wall contacts respectively.

**Table 1 Contact parameters for DEM simulations of granular flow through the sphere discharge valve**

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Variable symbol</th>
<th>Variable value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliding friction coefficient</td>
<td>( \mu_{s,pp} )</td>
<td>0.25</td>
</tr>
<tr>
<td>Rolling friction coefficient</td>
<td>( \mu_{s,pw} )</td>
<td>0.25</td>
</tr>
<tr>
<td>Restitution coefficient</td>
<td>( e_{pp} )</td>
<td>0.83</td>
</tr>
<tr>
<td>Restitution coefficient</td>
<td>( e_{pw} )</td>
<td>0.83</td>
</tr>
</tbody>
</table>

**III.C. Simulation of Granular Flow through Bend Tube**

Mass flow rate through the bend tube was crucial importance for the conveying rate. However, principle of granular flow through bend tube is not reported. DEM simulations of granular flow through bend tube have been done. The geometric model of bend tube used in simulations is shown as Fig. 3. The height of vertical tube was 1900 mm. \( H \), defined as
the height of accumulated spheres in vertical tube, was 500 ~ 1900 mm. The centerline radius, \( R \), was 120 mm and degree of bend, \( \alpha \), was 45°.

![Fig. 3 Geometric model of bend tube used in DEM simulations](image)

The materials of geometric model and sphere were same with those in the simulation of granular flow through the sphere discharge valve. Contact parameters for DEM simulations are shown in Table 2.

Table 2 Contact parameters for DEM simulations of granular flow through bend tube

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Variable symbol</th>
<th>Variable value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliding friction</td>
<td>( \mu_{s,pp} )</td>
<td>0.25</td>
</tr>
<tr>
<td>Rolling friction</td>
<td>( \mu_{r,pp} )</td>
<td>0.02 mm</td>
</tr>
<tr>
<td>Rolling friction</td>
<td>( \mu_{r,pw} )</td>
<td>0.02 mm</td>
</tr>
<tr>
<td>Coefficient of</td>
<td>( e_{pp} )</td>
<td>0.9</td>
</tr>
<tr>
<td>restitutiion</td>
<td>( e_{pw} )</td>
<td>0.9</td>
</tr>
</tbody>
</table>

### IV. RESULTS AND DISCUSSION

#### IV.A. Critical Stroke of the Sphere Discharge Valve

The critical valve stroke was obtained by critical experiment, i.e. \( S_c = 29.74 \) mm. Glass spheres would not flow, since forces acting on spheres were in equilibrium when \( S \) was smaller than \( S_c \).

#### IV.B. Granular Flow through the Sphere Discharge Valve

Experimental results showed that the relation between the average mass flow rate, \( W_{av} \), and the valve stroke, \( S \), were composed of three zones i.e. the idle stroke zone, linearly zone and orifice restriction zone. \( S \) were during 0 ~ 29.74 mm, 29.74 ~ 51.55 mm and 51.55 ~ 60 mm, respectively for the idle stroke zone, the linearly zone and the orifice restriction zone. The Beverloo’s law was suitable for the granular flow through multi-orifice during the orifice restriction zone. The variation of \( W_{av} \) with \( S \) could be described by modified Beverloo’s law based on the valve stroke. DEM simulation results were in good agreement with the experimental results for \( W_{av} \), defining that the entire falling in simulation began when the valve was opened and ended when there was little sphere falling. Most absolute values of relative error were smaller than 10%, the maximum was 16%.

DEM simulation results showed that the flow pattern of granular flow in storage vessel belonged to core flow and the drained angle of repose remained 23° with different valve strokes, which was useful for the design of the indication of ball level.

#### IV.C. Sampled Mass Flow Rate

The results of sampling experiments showed that sampled mass flow rates during steady granular flow were constant for the two valve strokes, i.e. 32.42 mm and 34.72 mm. Same results were obtained by DEM simulations with other valve strokes. As a result, it could be inferred that mass flow rate through the sphere discharge valve during steady granular flow kept stable for different valve strokes.

#### IV.D. Granular Flow through Bend Tube

Figure 4 shows the typical simulation result of mass flow rate of granular flow through bend tube. The variation of mass flow rate of granular flow through bend tube was different from that through a circular orifice. Variation of mass flow rate through bend tube was divided into three stages, i.e. initial variation, steady state and linear decrease. It was worth to be concerned that the initial variation and linear decrease for different \( H \) during 500 ~ 1900 mm were same. Initial variation was composed of two increase stages with different slopes. The values during steady state were also same.

![Fig. 4 Typical simulation result of mass flow rate of granular flow through bend tube](image)
It was inferred that the flow mechanism for granular flow through bend tube was different from that through a circular orifice. Further DEM simulations of granular flow through bend tube with different degrees of bend, $\alpha$, were done. According to the analyses, it could be inferred that mass flow rate through bend tube was mainly determined by centerline radius, $R$ and $\alpha$. However, further study needs to be done to deeply analyze the flow mechanism from aspects of stress distribution and mass conservation.

V. CONCLUSIONS

Experiments and DEM simulations have been conducted to investigate the granular flow characteristics of absorber sphere pneumatic conveying system. Experimental results showed that the critical valve stroke, $S_c$, for granular flow through the sphere discharge valve was 29.74 mm. Relationship between average mass flow rate, $W_{av}$, and valve stroke, $S$, were composed of three zones, i.e. the idle stroke zone, linearly zone and orifice restriction zone. The Beverloo’s law was suitable for the granular flow through multi-orifice in the orifice restriction zone. Variation of average mass flow rate with the valve stroke could be described by modified Beverloo’s law based on the valve stroke. On the other hand, DEM simulation results showed that the drained angle of repose remained 23$^\circ$ with different valve strokes. Mass flow rate during steady granular flow through the sphere discharge valve for different valve strokes kept stable. For the granular flow through bend tube, variation of mass flow rate was different from that through a circular orifice. Flow mechanism for granular flow through bend tube perhaps was mainly determined by $R$ and $\alpha$.

Studies for granular flow characteristics of absorber sphere pneumatic conveying were still not sufficient. In the following work, granular flow through the sphere discharge valve with the hopper, as well as balls blocked characteristics of the valve will be studied by DEM simulation. Furthermore, studies on other macroscopic and microscopic characteristics such as velocity distribution, stress distribution, porosity distribution and contact forces are also needed to be investigated.

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REFERENCES


