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Research status on hydrodynamics and particle motion behavior of absorber sphere pneumatic conveying system in HTR-PM

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Abstract *–The absorber sphere pneumatic conveying system in pebble-bed high temperature gas-cooled reactor was a special application of pneumatic conveying technique. The whole conveying process was an intermittent circulation of absorber spheres between the side reflector boring and the sphere storage vessel in the reactor. The absorber spheres were designed to drop into the reflector borings by its own gravity when the sphere discharge valve was opened by the driving mechanism. The absorber spheres in the reflector boring were transported back to the sphere storage vessel when the reactor needs to be started up. The hydrodynamics and particle motion behavior characteristics of the absorber spheres were very important for the design and operation of this special pneumatic conveying system. The whole conveying process of absorber spheres was consisted of four sub-processes, i.e. the spheres discharge from the sphere storage vessel and the side reflector boring, entrainment of spheres in the feeder, conveying of spheres in the transport pipe, gas-solid separation and pile of spheres in the sphere storage vessel. The research status on hydrodynamics and particle motion behavior of the absorber spheres in the pneumatic conveying system of HTR-PM were introduced mainly from the viewpoint of granular flow and gas-solid flow. The experimental systems and apparatus constructed and numerical simulation work conducted for absorber sphere pneumatic conveying process investigation were introduced. Some typical experimental and numerical simulation results of the hydrodynamics and particle motion behavior characteristics of the absorber spheres conveying were briefly reported.*

I. INTRODUCTION

High Temperature Gas-Cooled Reactor (HTR or HTGR) is the Generation IV nuclear energy technologies [1, 2]. HTR has many advantages, e.g. the inherent safety, high efficiency, potential application for process steam, hydrogen production [3-5]. The design concept of modular HTR was firstly proposed by the Germany in the early 1980s [5, 6]. The Chinese modular high-temperature gas-cooled reactor, named as high-temperature gas-cooled reactor-pebble bed module (HTR-PM) [3] which is based on the technology and experience of the 10 MW high-temperature gas-cooled test reactor (HTR-10), is currently in the phase of demonstration plant construction.

Two independent shutdown systems, i.e. the control rod system and the absorber sphere shutdown system, were designed to shutdown the pebble-bed HTR [1, 3, 7].

The absorber sphere pneumatic conveying in HTR was a special application of pneumatic conveying technique in nuclear engineering field to control the neutron chain reaction [8]. The absorber sphere was made of B_4C in graphite. The sphere was designed to drop into the reflector borings by its own gravity when the sphere discharge valve was opened by the driving mechanism. Pneumatic conveying was adopted to transport the absorber spheres in the reflector boring back to the sphere storage vessel when the reactor needs to be started up [1, 3, 9]. The whole conveying process was an intermittent circulation of absorber spheres between the side reflector boring and the sphere storage vessel in the reactor.

The hydrodynamics and particle motion behavior characteristics of absorber sphere were very important for the design and operation of this special pneumatic conveying system in HTR-PM. The whole intermittent circulation process of absorber sphere conveying was consisted of four sub-processes, i.e. (a) spheres discharge from the storage vessel and the side reflector boring, (b) entrainment of sphere in the feeder, (c) conveying of sphere in the transport pipe, (d) gas-solid separation and pile of spheres in the storage vessel.

The absorber sphere is Geldart type-D coarse particle from the viewpoint of classical particle fluidization classification [10]. There were only a few literatures published on the absorber sphere pneumatic conveying process or on the gas-solid flow with particle diameter of above 5 mm [11].

The research status on hydrodynamics and particle motion behavior of the absorber sphere pneumatic conveying system in HTR-PM were introduced from the viewpoint of granular flow and gas-solid two phase flow. The experimental systems and apparatus constructed and numerical simulation work conducted for absorber sphere pneumatic conveying process were briefly introduced in this paper. Some typical results from the experimental and numerical simulation work were reported.

II. EXPERIMENTAL WORK

Three experimental systems and one experimental apparatus were constructed at Insititute of Nuclear and New Energy Technology (INET) to investigate the gas-solid flow and granular flow characteristics of the absorber sphere pneumatic conveying process, i. e. the partial visualization conveying system, overall visualization conveying system, full scale conveying verification test loop and the sphere discharge valve apparatus.

The partial visualization conveying system was mainly used to investigate the performance of the feeder and the pressure drop characteristics of gas-solid flow. The overall visualization conveying system was mainly used to investigate the particle motion behavior during the whole conveying process. The full scale conveying verification test loop was mainly used to verify the main design functions and to obtain the operation parameters of the absorber sphere pneumatic conveying system. The sphere discharge valve apparatus was mainly used to investigate the granular flow characteristics through the sphere discharge valve which was base on the principle of angle of response.

II.A. Partial visualization conveying system

The sphere feeder was an important component of the absorber sphere pneumatic conveying system, since it may determine the absorber sphere mass flow rate conveyed. The pressure drop characteristic of gas-solid flow for absorber sphere pneumatic conveying was important for the design of conveying gas circulation blower.

Figure 1 shows the schematic diagram of the partial visualization conveying system. This experimental system used to test the feeder performance and the pressure drop characteristics of conveying process was reported in our previous work [12, 13]. The ambient air was filtrated and blown by the Roots blower to be used as the conveying gas. The gas flow rate could be adjusted by the frequency inverter or by the electric control valve and the bypass pipeline. The electric ball valve was closed before starting conveying. The spheres were separated and piled up in the storage vessel, while the conveying air was discharged to the ambient atmosphere.

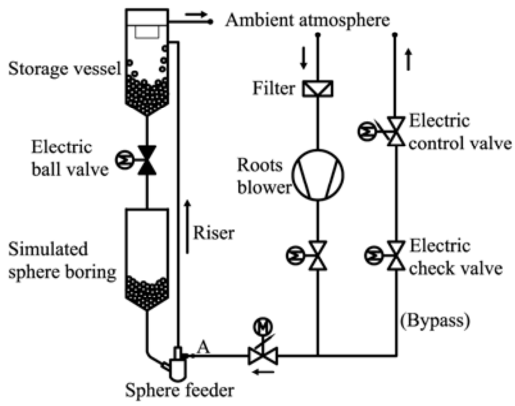

Fig. 1: Schematic diagram of the partial visualization conveying system.

The feeder and the lower section of the riser pipe were made of plexiglass. The gas-solid flow of the feeder inside and the lower section of the riser pipe were visualized. The vertical height for sphere conveying was 10.66 m. The feeder inlet gas gauge pressure, feeder inlet gas flow rate, feeder inlet gas temperature, pressure drop of the feeder and pressure drop of the riser pipe, were automatically measured and recorded in the computer by the data acquisition and measuring system.

The glass spheres with the diameter of 6 mm were used in the experiments in our previous work. The particle density of the glass sphere was 2518 kg/m^3.

Figure 2 shows the schematic of the feeder configuration used to test the performance [13]. The feeder was mainly based on the “fluidizing nozzle discharging vessel” of Matzner [14]. The spheres dropped into the feeder through the sphere inlet by its own gravity. The spheres were entrained by the conveying gas to form gas-solid flow. Two threaded connections were used to adjust the draft tube height h_1 and h_2 in the experiments to optimize the structure design of the feeder.

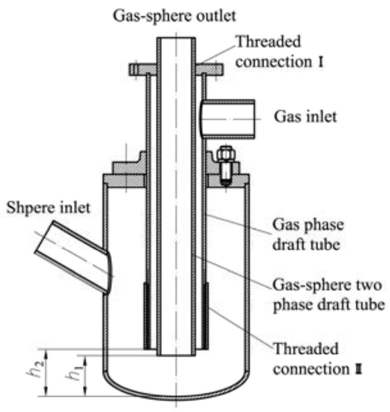

Fig. 2: Schematic of the feeder configuration.

II.B. Overall visualization conveying system

Particle motion behavior and flow patterns characteristics in the side reflector boring and in the sphere storage vessel during the absorber sphere pneumatic conveying process were important to the design for engineering application, e.g. the reactor physics design, the design of the absorber sphere position detection.

The overall visualization pneumatic conveying system has been constructed. The whole circulation loop of the spheres was made of plexiglass for particle motion and flow patterns observation.

Experiments will be conducted to obtain the granular flow characteristics of sphere discharge from the sphere storage vessel, sphere discharge from the side reflector boring, and sphere pile in the storage vessel during gas-solid separation. The pressure balance characteristics of the sphere circulation loop will also be investigated in this experimental system.

II.C. Full scale conveying verification test loop

The solid phase properties, gas phase properties and geometry structure of the conveying loop will affect the performance of pneumatic conveying. The design of the absorber sphere pneumatic conveying process need to be verified with high pressure helium gas and absorber sphere.

The full scale conveying verification test loop has been constructed. The design pressure of the experimental loop was 8 MPa. Helium was the working fluid for conveying. The conveying height in the test loop was same to that in HTR-PM. The absorber sphere may be preheated in the test loop to partly simulate the environment for conveying in engineering application.

The pneumatic conveying experiments of the sphere with the particle diameter of 6 mm by using different gas phase, i.e. ambient air, compressed air and high pressure helium, have been conducted. The performance test experiments of the gas circulation blower have also been conducted.

II.D. Sphere discharge valve apparatus

A new type of sphere discharge valve configuration based on the principle of angle of response of granular flow was developed. The key feature of this sphere discharge valve structure was that the sphere crushing may be avoided when closing the sphere discharge valve.

The sphere discharge valve apparatus has been manufacture which was made of steel. Experiments on granular flow characteristics of the sphere discharge valve have been conducted. Detailed information about this new type of sphere discharge valve will be reported elsewhere.

III. NUMERICAL SIMULATION WORK

III.A. Granular flow simulation

The development of Discrete Element Method (DEM) simulation provides a helpful tool for granular flow simulation [15]. The DEM simulation of granular flow has been applied to research pebble flow of fuel element [16-19] in HTR.

The DEM simulation has been applied to simulate the granular flow characteristics of absorber sphere discharge process and packing process. The parameters concerned (e.g. the sphere mass flow rate, angle of response, voidage distribution, stress distribution, particle velocity, contact force) can be obtained to optimize the structure design of the component in the absorber sphere pneumatic conveying system.

The DEM simulation of sphere discharge from the hopper, from the sphere discharge valve and from the side reflector boring through bending pipe have been conducted. The sphere packing in the side reflector boring and sphere pile in the sphere storage vessel will also be investigated.

III.B. Gas-solid flow simulation

The development of Computational Fluid Dynamics (CFD) and Discrete Element Method (CFD-DEM) coupling simulation provides a helpful tool for gas-solid flow simulation base on the individual particle scale. Detailed introduction of the CFD-DEM simulation method can be found in the review articles [20-23].

The hydrodynamic and particle motion behavior for the gas-solid flow of absorber sphere pneumatic conveying will be investigated by using the CFD-DEM simulation. Typical gas-solid flow processes will be considered, e.g. the sphere entrainment in the feeder, vertical conveying in the conveying pipe and gas-solid separation in the sphere storage vessel. Some primary work has been done recently.

IV. TYPICAL RESULTS AND DISCUSSION

IV.A. Sphere discharge

There were three types of sphere discharge structure in the absorber sphere pneumatic conveying system. They were the sphere discharge from the sphere discharge valve, sphere discharge from the hopper, sphere discharge flow from the side reflector boring through bending pipe. The classical Beverloo's law [24-26] was a good approximation for the prediction of sphere discharge flow rate through the orifice.

Experiments and DEM simulation have been conducted with these three types of sphere discharge structure. The granular flow characteristics, e.g. the discharge mass flow rate, angle of response, sphere velocity, contact force, voidage, have been obtained.

Figure 3 shows a typical result of the granular flow pattern of sphere discharge from the sphere discharge valve by DEM simulation.

Detailed experimental and DEM simulation results of the sphere discharge from the sphere discharge valve, from the hopper and from the side reflector boring through bending pipe will be reported elsewhere.

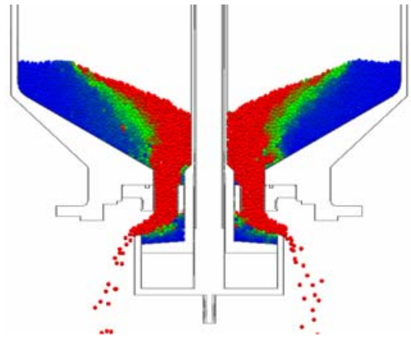

Fig. 3: DEM simulation typical result of the granular flow pattern of sphere discharge from the sphere discharge valve.

IV.B. Sphere Feeder

Experimental results from the partial visualization conveying system with ambient air as source gas showed that the start performance of the sphere conveying was reliable with the feeder designed [12]. The restart of the sphere conveying after the blower trip was also reliable [27, 28]. The sphere feeding rate in average [12] was determined by gas-sphere entrainment at low superficial gas velocity and by sphere discharge through the bending pipe at high superficial gas velocity, respectively (Fig. 4).

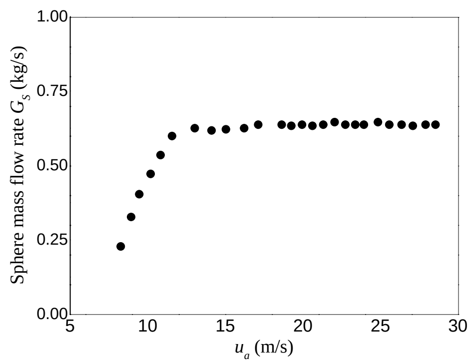

Fig. 4: Effect of superficial gas velocity u_a on sphere mass flow rate conveyed.

Figure 5 shows the typical photograph of flow pattern of the feeder and the bottom of the riser pipe for steady conveying at high u_a in the partial visualization conveying system [29]. The feeder performance was affected by the combination of draft tube height h_1 and h_2 in Fig. 2 [13].

Fig. 5: Typical photograph of flow pattern of the feeder and the bottom of the riser for steady conveying at high u_a.

The mechanism of sphere entrainment in the feeder by the conveying gas will be further investigated by experimental study and CFD-DEM simulation.

IV.C. Sphere Vertical Conveying

Experimental results from the full scale conveying verification test loop with high pressure helium as conveying gas showed that the sphere conveying was successful with the feeder designed.

The pressure drop characteristics for sphere vertical conveying were obtained from the partial visualization conveying system with air as conveying gas and from the full scale conveying verification test loop with high pressure helium as conveying gas. The performance of the gas circulating blower was obtained.

The gas-solid flow features, e.g. the pressure drop model, sphere velocity distribution and voidage distribution along the vertical conveying pipe, will be investigated in the future.

IV.D. Gas-solid Separation

Experimental results from the partial visualization conveying system with ambient air as source gas showed that the pressure drop of the gas-solid separation in the storage vessel was much lower than that of gas-solid flow in the riser. Similar result was also observed in the full scale conveying verification test loop with high pressure helium as conveying gas.

The separation of gas-solid flow and pile of sphere in the sphere storage vessel are important for the design of the sphere storage vessel with cyclone and the sphere position detection. The experiments and numeric simulation are being undertaken.

V. CONCLUSIONS

The absorber sphere pneumatic conveying in HTR was a special application of pneumatic conveying technique in nuclear engineering field. There were some special requirements for the design of the absorber sphere pneumatic conveying process which are different from the common application of pneumatic conveying technique. The hydrodynamics and particle motion behavior of the absorber sphere pneumatic conveying system in HTR-PM were introduced from the viewpoint of granular flow and gas-solid two phase flow. The experimental platform has been constructed for investigation and verification. The numerical simulation platform has been developed to optimize the design of granular flow and gas-solid flow of component configuration and conveying system. The sphere discharge flow characteristics were obtained by experiments and DEM simulation. Experimental results from the full scale pneumatic conveying verification test loop with high pressure helium as conveying gas showed that the start and restart for sphere conveying was reliable with the feeder designed. The mass flow rate characteristics for sphere conveying were obtained. The pressure drop characteristics of gas-solid flow were obtained in the experiments.

Further work on the granular flow and gas-solid flow characteristics of the absorber sphere pneumatic conveying system are needed to make a comprehensive understanding and to optimize the design of the system.

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