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Dense granular Flows: a conceptual design of high-power neutron source

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Abstract. A high-power neutron source system is very useful for multifunctional applications, such as material facilities for advanced nuclear power, space radiation studies, radiography and tomography. Here the idea of inclined dense granular flow is utilized and developed in a new conceptual design of a compact high-power target to produce a high-energy and high-flux neutron irradiation (the flux is up to 10^{15} n/cm^2/s or even 10^{16}). Comparing to the traditional solid and liquid heavy metal targets, this design has advantages in material choice, fluid stability, heat removal, etc. In this paper the natures of the granular flows in an inclined chute are investigated and preliminary experimental and numerical results are reported. Then the feasibility of this design is discussed.

1 Background

In many areas of physics, chemistry, biology, materials, and nuclear engineering, to study the structure and functionality of materials, it is very valuable for a very intense source of neutrons. In complement to X-ray or synchrotron sources, neutron source has several unique advantages [1]. Spallation neutron source is an accelerator-driven facility to produce high intensity neutrons based on spallation reactions. After the successful first spallation neutron sources, several high-power neutron sources are built, constructed and planned, such as SNS [2], J-PARC [3] and ESS [4].

For engineering of spallation target, there are many design options such as plate targets, rod targets, heavy metal targets or rotation targets [5]. Recently, the new concept of gravity-driven Dense Granular Target (DGT) was proposed [6]. This new concept will contribute to the design of MW spallation target for CIADS project [7] (see details in Figure 1).

Compared to currently wide used targets, the attractions for DGT include:
1) The flowing behaviors of grains in DGT are analogous to the fluids [8] and the deposited high power will be removed off-line.
2) In DGT, heat shocks induced by proton beam are dispersed since granular materials usually show an excellent buffering performance [9].
3) Grains in DGT are renewed continuously off line. There are benefits in selecting proper materials to reduce the corrosion, chemistry-toxicity and radio-toxicity.
4) There are mature technologies in industry capable for conveying, filtering and cooling grains.

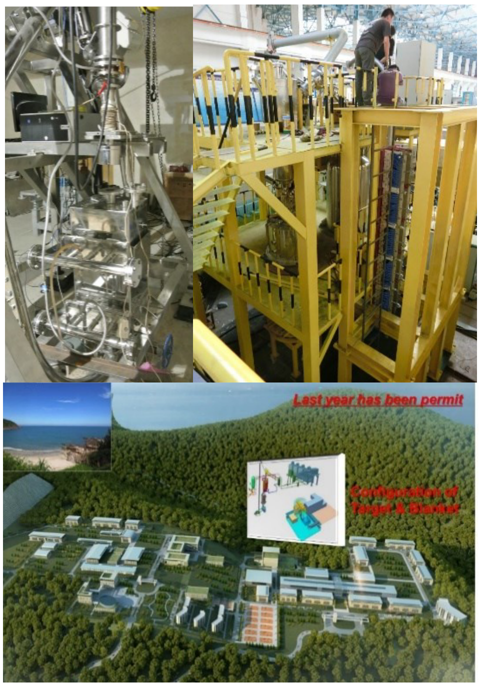

Fig. 1. Engineering application of granular target was put into practice during the target research of ADS project, which is supported by the "Strategic Priority Research Program" of the Chinese Academy of Sciences. Top-left: A principle testing facility coupled with 1.2MeV electron beam was operated in 2013. Top-right: Later in 2015, a large scale facility started its construction. Bottom: Supported by these preliminary work, the next stage namely CIADS project will setup a prototype of ADS system applying granular target, in Huizhou, Guangdong.

For the nuclear and space engineering, a strong and rapid testing facility is much needed. Here a conceptual design of a high-energy and high-flux neutron source is

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proposed which is able to offer a neutron flux up to 10^{15} n/cm^2/s. Due to a hopper was used as the container of DGT in [6], the placement of specimens is limited. For the new inclined granular flow target, the flow can be easily controlled and modified [10], which will be shown below. The dynamics and heat transfer in this target are plotted after a series of large-scale simulations.

Table 1. Geometrical and material parameters in this paper.

Quantity(Units)	Symbol	Value
Diameter of particles (mm)	d	5
Width of the chute (d)	W	40
Length of the chute (d)	L	600
Height of the gate (d)	G	25
Inclination angle of the chute (°)	θ_c	25
Length/width of the reservoir (d)	D	40
Elastic modulus (GPa)	E	287
Poisson's ratio	ν	0.032
Particle-particle and particle-wall friction coefficients	μ	0.2
Density (kg/m^3)	ρ	1850
Particle-particle and particle-wall coefficient of restitution	ε	0.9
Thermal conductivity of particles (W/m/K)	λ_p	200
Coefficient of linear thermal expansion (10^{-6}/K)	α	11.3
Heat capacity(J/K/kg)	C_p	1825
Hardness (GPa)	H	1.67
Thermal conductivity of gas (W/m/K)	λ_g	0.1517

2 Flow behaviors

DEM (Discrete Element Method), closely related to MD (Molecular Dynamics), is a widely-accepted method for simulating contact dynamics in many-body systems consisting of particles, such as powders, bubbles, grains and colloids. To simulate the granular flows in the proposed target, a DEM code containing heat-transfer module was run on GPUs (Graphic Processing Units) [11-14].

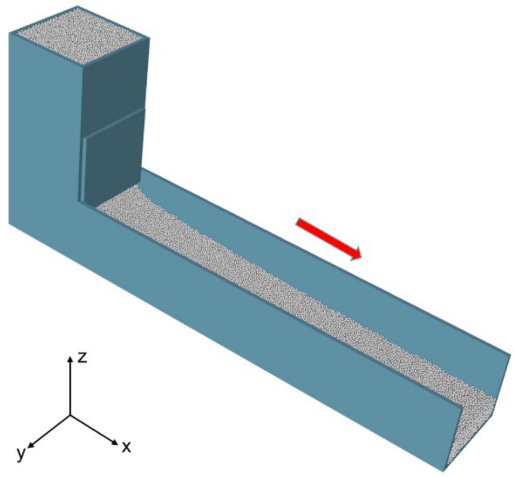

Fig. 2. Configuration of the simple model of chute flows. The red arrow denotes the flowing direction.

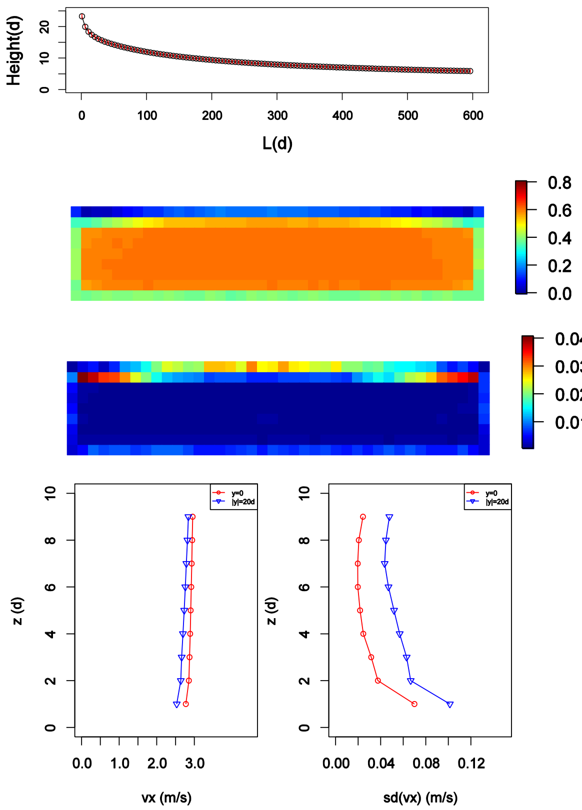

Fig. 3. The simulation results of granular flows in a chute with gate height of 25d, chute width of 40d and inclination angle of 25°. Top: the variation of the shape of the flow. Middle-top: spatial profile of volume fraction in the cross section which is perpendicular to x direction at x = 1500 mm. Middle-bottom: Spatial profile of standard deviation of volume fraction in the cross section which is perpendicular to x direction at x = 1,500 mm. Bottom-left: spatial profile of v_x with different depths at x=1,500 mm. Bottom-right: spatial profile of standard deviation of v_x with different depths at x = 1,500 mm. Red circles represent v_x of the central particles and blue inverse triangles represent v_x of the particles near the sidewalls.

To simplify the model, monosized beryllium particles (diameter d is 5 mm) are simulated. The material of the reservoir and chute is the same as particles and their roughness is assumed as nil. The configuration of the 'the basic' case is schematically shown in Figure 2. The geometrical and material parameters in the basic case are shown in Table 1. The inclination angle is set as 25° to avoid potential stagnant or gaseous state in the downstream flow [15]. Initially the particles are packed in the reservoir and then are discharged through an opening gate. The time-averaged velocity and volume fraction fields along the chute flow are plotted and the stability of the flow is analyzed.

For this design, the stability of the flow is very important. The morphology of the flow is stable over time (see in Figure 3). To evaluate the stability of the flow, temporal profiles of velocity and volume fraction fields are analyzed and their standard error is calculated. Here it is showed that the standard errors of volume fraction are very small except at the free surface. For v_x, the standard error on the bottom is more than the standard error at the free surface and although both are relatively small.

3 Neutronics study

The results of deuterium beams hitting a monolithic beryllium target are calculated by using GMT (GPU-based Monte Carlo Transport program) [16] and checked by Geant4 [17]. The power density distributions along beam direction for different beam energies are plotted in Figure 4. When the beam energy rises from 10 MeV to 80 MeV, the maximum penetration depth grows from 0.1 cm to 2.0 cm and the maximum power density in the target decreases slightly. This profile is used for the following simulations of heat transfer.

A beryllium target bombarded by an 80MeV, 20mA deuterium beam is simulated and the energy spectrum of neutrons is shown in Figure 5. It is showed that this target will provide sufficient high-energy neutrons to replicate the radiation environment inside fission and fusion reactors. The higher energy neutrons can be produced to satisfy the DEMO 14 MeV peak by increasing the energy of the beam. On the other side, the low-energy neutrons can be produced by utilizing moderators.

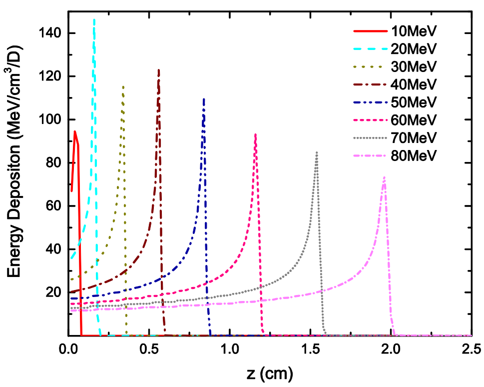

Fig. 4. The profiles of power density distributions along beam direction with different energy deuterium beams.

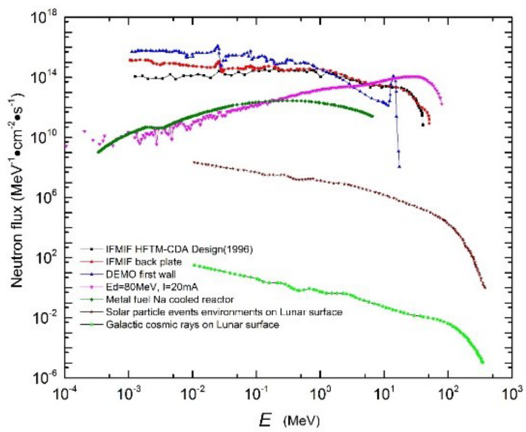

Fig. 5. The energy spectrum of neutrons in different situations. Pink inverse triangles denote the spectrum in the current design.

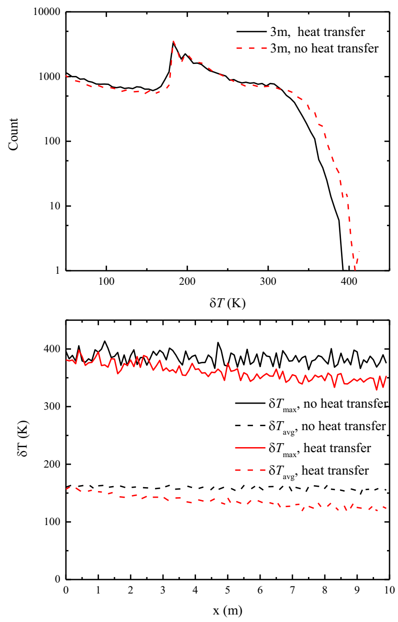

Fig. 6. Top: the distribution of temperature rises. Bottom: the distribution of temperature profile along the x direction.

4 Heat limit

The heat transfer process in chute flow with an 80 MeV, 20 mA deuterium beam (beam spot size is 20×20 mm^2) is simulated. It is supposed that the system is operated in a Helium environment (1 atm). The distances between release gate and the shooting point L varies between 2,000 and 3,000 mm. The profile of energy deposition (shown in Figure 4) is used here. In this simulation, four modes of heat transfer are considered: a) thermal conduction through the particle contacts, b) thermal conduction through the stagnant gas film, c) thermal conduction through the contact gaps between two particles, d) radiant heat transfer between surface of particles [18]. The material parameters used for the heat transfer models are listed in Table 1. In this simulation the temperature of particles released from reservoir is set around 290 ℃. Quantitative results are shown in Figure 6 (where L = 3,000 mm). For the case L = 3,000 mm, the ratio of particles whose temperature rise is more than 400℃ is small (less than 5%). The average temperature rise of particles is less than 180℃ and the maximum temperature rise is no more than 400℃. For comparison, a system without heat transfer is also simulated, where each particle is assumed to be thermally insulated. In this system, the maximum temperature rise is no more than 420℃ (can be used as a maximum estimate of maximum temperature rise).

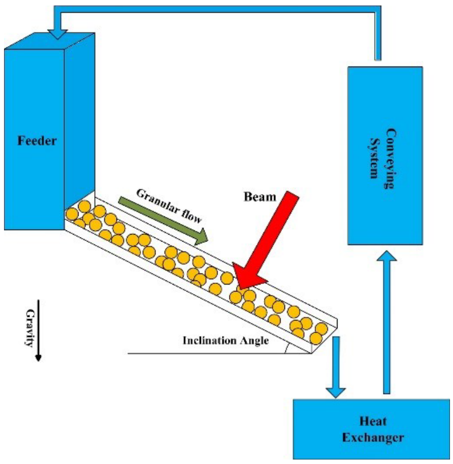

Fig. 7. Schematic diagram of the gravity-driven chute flow target system.

5 Conceptual design and Discussions

A conceptual design of the gravity-driven chute flow target is schematically shown in Figure 7. As a feeder, there is a reservoir or a hopper filled with heavy metal particles. Downstream there is an inclined chute and the particles discharging from the feeder will flow down the chute by gravity. The beam hits the flowing particles at a fixed position. At the end of the chute, the particles will flow into a heat exchanger where they are cooled. After filtering, the particles are re-injected into the feeder by a conveying system. The stability of the flows is illustrated above and can be conveniently controlled by adjusting the inclination angles of chute. The chute can be polished to avoid the surface waves mentioned above. The numerical study shows that the neutron flux can be up to 5×10^{15} n/cm^2/s and the temperature rise in the material is acceptable.

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