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 nature 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
proposed which is able to offer a neutron flux up to $10^{15}$ n/cm²/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 ($^\circ$) | $\theta_c$ | 25 |
| Length/width of the reservoir ($d$) | $D$ | 40 |
| Elastic modulus (GPa)      | $E$    | 287   |
| Poisson’s ratio            | $\nu$  | 0.032 |
| Particle-particle and particle-wall friction coefficients | $\mu$ | 0.2 |
| Density (kg/m³)            | $\rho$ | 1850  |
| Particle-particle and particle-wall coefficient of restitution | $\varepsilon$ | 0.9 |
| Thermal conductivity of particles (W/m/K) | $\lambda_p$ | 200 |
| Coefficient of linear thermal expansion ($10^{-6}$/K) | $\alpha$ | 11.3 |
| Heat capacity (J/K/kg)     | $C_p$  | 1825  |
| Hardness (GPa)             | $H$    | 1.67  |
| Thermal conductivity of gas (W/m/K) | $\lambda_g$ | 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].
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.

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°C. 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°C is small (less than 5%). The average temperature rise of particles is less than 180°C and the maximum temperature rise is no more than 400°C. 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°C (can be used as a maximum estimate of maximum temperature rise).

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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 $5 \times 10^{15}$ n/cm$^2$/s and the temperature rise in the material is acceptable.

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References

1. Wei, J., et al., China Spallation Neutron Source - an overview of application prospects. Chinese Physics C, 2009. 33(11): p. 1033-1042.
2. Gabriel, T.A., J.R. Haines, and T.J. McManamy, Overview of the Spallation Neutron Source (SNS) with emphasis on target systems. Journal of Nuclear Materials, 2003. 318: p. 1-13.
3. Oyama, Y., J-PARC and new era of science. Nuclear Instruments & Methods in Physics Research Section a-Accelerators Spectrometers Detectors and Associated Equipment, 2006. 562(2): p. 548-552.
4. Lindroos, M., et al., The European Spallation Source. Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms, 2011. 269(24): p. 3258-3260.
5. Bauer, G.S., Overview on spallation target design concepts and related materials issues. Journal of Nuclear Materials, 2010. 398(1-3): p. 19-27.
6. Yang, L. and W. Zhan, New concept for ADS spallation target: Gravity-driven dense granular flow target. Science China Technological Sciences, 2015: p. 1-7.
7. Zhan, W. ADS Programme and Key Technology R&D in China. in Proc. 2013 International Particle Accelerator Conference, Shanghai. 2013.
8. Massoudi, M. and T.X. Phuoc, Conduction and dissipation in the shearing flow of granular materials modeled as non-Newtonian fluids. Powder Technology, 2007. 175(3): p. 146-162.
9. Grujicic, M., et al., Shock-Wave Attenuation and Energy-Dissipation Potential of Granular Materials. Journal of Materials Engineering and Performance, 2012. 21(2): p. 167-179.
10. Silbert, L.E., et al., Granular flow down an inclined plane: Bagnold scaling and rheology. Physical Review E, 2001. 64(5).
11. Tian, Y., et al. A heterogeneous CPU-GPU implementation for discrete elements simulation with multiple GPUs. in Awareness Science and Technology and Ubi-Media Computing (iCAST-UMEDIA), 2013 International Joint Conference on. 2013. IEEE.
12. Qi, J., et al., GPU-accelerated DEM implementation with CUDA. International Journal of Computer Science and Engineering, Inderscience, 2015. 11(3): p. 330-337.
13. Zhang, S., et al., Investigating the influence of wall frictions on hopper flows. Granular Matter, 2014. 16(6): p. 857-866.
14. Lin, P., et al., Numerical study of free-fall arches in hopper flows. Physica a-Statistical Mechanics and Its Applications, 2015. 417: p. 29-40.
15. Borzsonyi, T. and R.E. Ecke, Rapid granular flows on a rough incline: Phase diagram, gas transition, and effects of air drag. Physical Review E, 2006. 74(6).
16. Cai, H., et al., Code development and target station design study for Chinese Accelerator-Driven System Project. Nuclear Science and Engineering, accept.
17. Agostinelli, S., et al., GEANT4-a simulation toolkit. Nuclear Instruments & Methods in Physics Research Section a-Accelerators Spectrometers Detectors and Associated Equipment, 2003. 506(3): p. 250-303.
18. Vargas-Escobar, W.L., Discrete modelling of heat conduction in granular media. 2002, University of Pittsburgh.