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New concept for ADS spallation target: Gravity-driven dense granular flow target

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For the Chinese-ADS project, to provide enough neutrons to drive the subcritical system, tens of MW spallation targets for the C-ADS are necessary. This is not an easy task. Here we propose a new concept for a gravity-driven dense granular flow target, in which heavy metal grains are chosen as the spallation target material. Compared with currently widely used targets, this conceptual design has advantages with regard to heat removal, thermal shock protection, neutron yield, radiotoxicity reduction, and convenient operation. The gravity-driven dense granular flow target has the potential to easily deal with these issues and to form a foundation for tens of MW spallation targets for cost-effective facilities. Preliminary simulations and experiments have been completed to support this conceptual design.

accelerator driven system, spallation target, dense granular flow

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1 Introduction

An accelerator driven system (ADS) is a subcritical blanket driven by neutrons produced when a high-intensity proton beam bombards a high-power spallation target. A ~1-GeV proton from a high-energy linear accelerator creates tens of neutrons when impinging on a heavy metal target because of spallation reactions. These neutrons are then injected into the subcritical blanket to activate the fissionable material. The hybrid system can be used for 1) incinerating long-term radioactive nuclei into stable or short-term nuclei, which is usually called “waste transmutation” [1–3]; 2) transforming nonfissile nuclei U^{238} and Th^{232} into highly valuable fissile nuclei Pu^{239} and U^{233}, respectively (there is an additional use: to produce tritium); and 3) generating energy mainly through fission in the subcritical core [4]. For “waste transmutation,” the ADS is suitable for minor actinide (MA) destruction. For an industrial-scale ADS MA burner, tens of MW spallation targets are needed [5] in order to generate enough neutrons to drive the subcritical cores.

The fundamental physical and technological research on the ADS in the National Basic Research Program of China (“973” Project) has been implemented since 1999 by a collaboration of China National Nuclear Corporation and the Chinese Academy of Sciences. Based on several rounds of high-level expert consultations and assessments from 2009 to 2010, a “future advanced fission energy-ADS transmutation system” was approved as a strategic leading science and technology program in January 2011 to speed up the research and development of the ADS. With regard to the rapid accumulation of nuclear waste in China, the roadmap of ADS technology in response to nuclear energy development in the future has been discussed. From the roadmap, the development of C-ADS has three phases.

Phase I. Principle verification. Solve key technological problems of ADS components, realize small-scale system

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*Corresponding author (email: wlzhan@cashq.ac.cn) integration, and develop the design of the system. The key technologies of the accelerator, spallation target, and subcritical core are to be applied to the industrial facility.

Phase II. Demonstration facility building. Implement medium-sized technological integration, build and run a ~100-MW ADS driven by tens of MW of accelerator beam power, start transmutation experiments, and verify operational reliability.

Phase III. Industrial facility and full-size technological integration. Build and run a ~1000-MW system.

The ADS must use a compact target to provide high-flux neutrons. Therefore, the first key issue of the high-power target is how to remove the heat from the high-intensity proton beam. The second key issue is the lifetime of the target, which is limited by radiation damage, heat shock, corrosion, etc. The third key issue is the integration of the complex system, stable and safe operation, and low decommissioning cost.

For industrial-scale ADS concepts, one of the most critical challenges is the completion of the tens-of-MW spallation target. Currently, MW-class spallation targets only exist in spallation neutron sources (Figure 1). In the early days of spallation target development, several solid targets at ~100-kW beam power levels were operated during the 1980s. The material of the targets was solid U, Ta, or W. In these solid targets, heat removal was limited by the heat conduction of the target material and by convection cooling. Therefore, the ability to increase the target power was limited. If the heat deposited can be dealt with offline, the upper limit of the target power will be increased significantly. Based on this concept, heavy-liquid-metal (HLM) targets with beam windows have been designed and operated in ~1-MW MEGAPIE and SNS projects [3–5]. However, some research showed problems in the MEGAPIE target, which employed a lead-bismuth eutectic (LBE) (a type of HLM) target [6]. First, the heat removal from the target window was limited by the corrosion and erosion of the LBE. As a result, the temperature and velocity of the LBE should usually be less than 550ºC and 2 m/s, respectively. Moreover, the cavitations and shock waves of an HLM can potentially damage the window structure. Last but not least, the chemistry and radiotoxicity of LBE make the target not cost effective owing to the complexity of operation, decommission, safety, gas control, intermediate circuit, etc. Consequently, the performance of HLM targets is limited because of these effects.

2 A new concept for an ADS high-power target

Here we propose a new concept for a high-power spallation target: The gravity-driven dense granular target (DGT), which has a compact structure and the potential for high-power operation. The target material is a large collection of discrete solid particles, namely granular materials, that can show both solid and fluid behaviors. The science and technology of a dense granular flow have a long history. For example, an hourglass is a typical application of a gravity-driven dense granular flow and is believed to have originated in medieval Europe. In an hourglass, time is exactly proportional to the amount of outflowed grains if the geometry is well designed. Therefore, the application of advanced and sophisticated technologies in the field of granular industry lays a solid foundation for the implementation of the newly designed target [7,8].

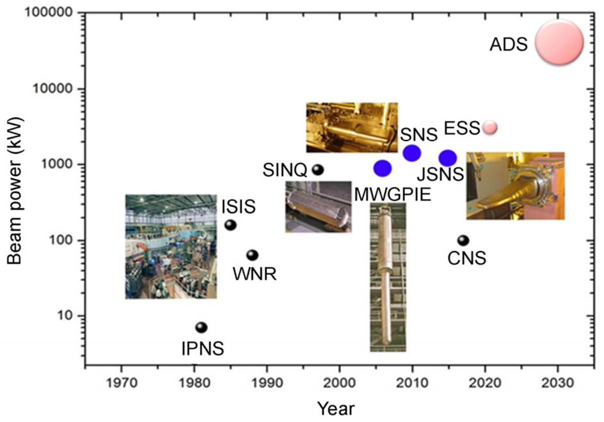

Figure 1 (Color online) The development of beam power. Black solids represent solid target, and blue solids represent HLM targets. The total beam power of the European Spallation Source (ESS) (under construction) is 5 MW, and a large-scale solid rotation target was applied. For the ADS facility, tens of MW spallation targets are needed.

Compared to HLM targets, where only a few types of heavy metals could be used, the DGT provides an opportunity to obtain benefits by grain-material selection such as high neutron yield, low radiotoxicity, high specific capacity and thermal conductivity, and low chemical toxicity and low corrosion for convenient operation. Heavy metals of non-spontaneous fission can be used in the spallation target for a high neutron yield. These heavy metals include tungsten, tantalum, lead, bismuth, mercury, osmium, and iridium. Some metals, such as osmium and iridium, will not be used in the target because there would be no economic value for the entire system. In the remaining cheaper metals, W has the highest volume heat capacity and melting point. Therefore, W grains have the greatest potential to bring the thermal power out from the beam-target interaction region. Thus, W is chosen as the target material.

In the common structural design of the ADS liquid spallation target and subcritical blanket, the spallation target usually contains a cylindrical beam tube with an optional hemispherical beam window, while a subcritical blanket surrounds the spallation target axisymmetrically [9–12]. To acquire the largest source neutron efficiency, the spallation target is usually designed axisymmetrically [6], making it compatible with the subcritical blanket. The DGT will also employ this kind of design, for the same reason.

For the DGT (Figure 2), the container for the grains is a

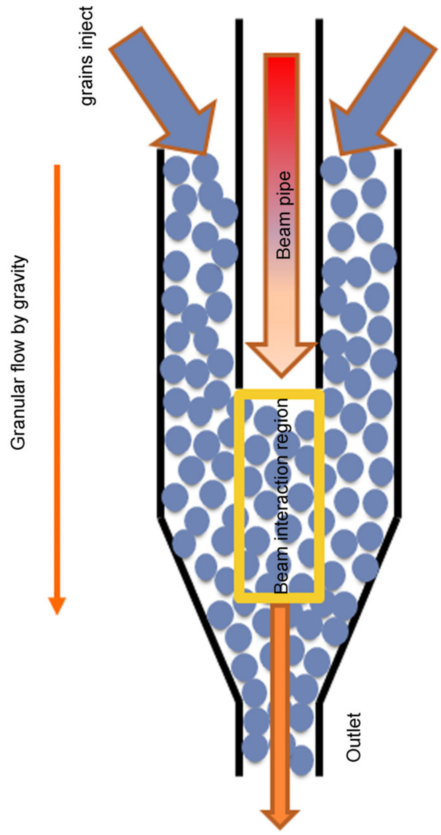

Figure 2 (Color online) Schematic of a DGT.

hopper, and W grains flow into the spallation region under gravity from the upper annular duct where the beam pipe is located. Then a proton beam from a high-energy linear particle accelerator (HELPA) will interact with the flowing W grains below the pipe. The grains will pass through the spallation region quickly and discharge from the orifice of the hopper to avoid being melted down. If the geometry is well designed, the flow rate of the hopper can be constant. Furthermore, the issues of reloading conventional fuels for the spallation target are neatly sidestepped by allowing the damaged grains to be replaced online. A circuit for continuous grain supply (including a heat exchanger, grain filter, grain elevator, grain storage, and cover gas system) will guarantee the safe, normal circulation of the working medium in the entire system (Figure 3).

The attractive features of the DGT include as follows.

(1) The behaviors of the working medium of the DGT are analogous to that of a windowless HLM target, and the high power deposited will be removed offline. In other words, like a liquid, grains in the DGT will flow away from the interaction region quickly and will be cooled externally using heat exchangers.

(2) In a DGT, heat shocks induced by the proton beam are dispersed to every part of the target materials since granular materials usually show excellent buffering performance. Consequently, there will be no splashing, cavitations, stress waves, or other hydrodynamic problems in the DGT.

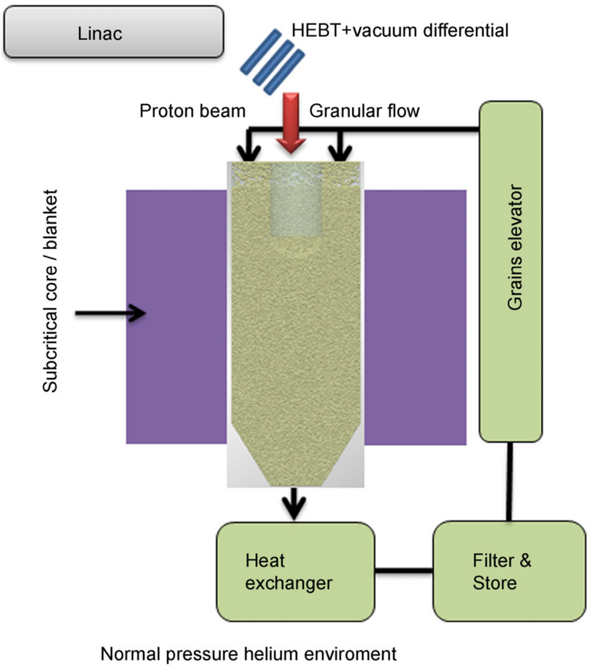

Figure 3 (Color online) Schematic outline of a DGT with grain injector and discharge outlet, heat exchanger, grain receiver vessel with filter, grain lift system, and cover gas environment.

(3) Grains in the DGT are renewed continuously offline. More importantly, there are benefits with regard to low corrosion, chemistry toxicity, and radiotoxicity when proper materials are selected.

(4) Granular engineering has mature technologies for the conveyance of grains in the chemical engineering, material engineering, food processing, and even nuclear industries. Such technologies can be easily exploited in the designs of various components of a complete target system.

3 Studies of gravity-driven dense granular target

3.1 Neutronic study

To design the gravity-driven DGT, a neutronics study has been carefully performed. First, two intranuclear models in Geant4 [13] were tested to determine the better method. Then, using the effective method, we determined the neutron yields and leaked neutron energy spectrum from the target.

In order to verify the validity and accuracy of various models used in the Geant4 code, we performed simulations of a proton beam interacting with the tungsten target. These results were compared with the experimental results obtained at Brookhaven National Laboratory (BNL) [14]. In our simulation, we applied INCL4 [15]/ABLA [16] and Bertini [17]/Dostrovsky [18] for proton and neutron transport above

2 and 150 MeV, respectively. For neutron transport below 150 MeV, the evaluated data library ENDF/B-VII.1 [19,20] was used. The obtained results are shown in Figure 4. It is noted that the results from INCL4/ABLA agree strongly with the experimental data in the range of 0.8–1.4 GeV energy.

In the calculation of the total neutron yields, the target is designed as a cylinder whose diameter is 10 cm and length is 100 cm. In Figure 5, different target materials are used in the simulations. It can be seen that the total yields of both the U and Th targets are greater than that of the W target, and that the yield of the W target is greater than that of Pb, Bi, and Sn. When the proton energy exceeds 800 MeV, the trend becomes more obvious. However, heat deposition in the Th and U targets is higher than that of the W target because of two nuclear reactions (spallation and fission). Thus, W is quite a promising candidate material for the gravity-driven DGT.

Figure 6 shows the leaked neutron spectrum for targets made of monolith metal W and W grains. The radius and length of the cylindrical target are 0.15 and 0.55 m, respectively. For the granular target, the equivalent volume fraction of the material is 0.52. The average energy of theleaked neutrons is 0.56 and 0.37 MeV for the granular target and the monolith target, respectively, as shown in Figure 6. The results clearly indicate that the granular target has a harder neutron spectrum than the monolith target.

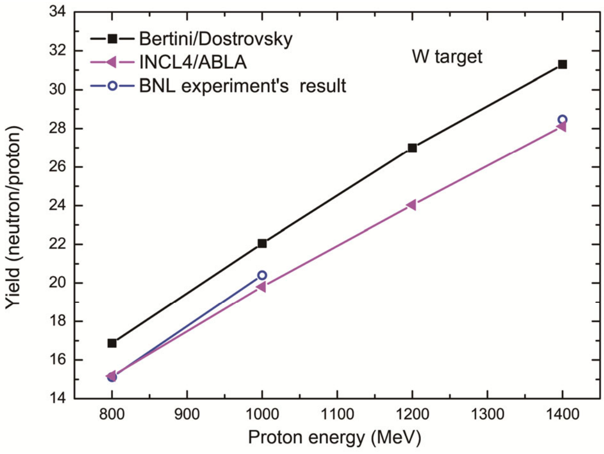

Figure 4 (Color online) Total neutron yields produced by different physics models as well as experiments at BNL.

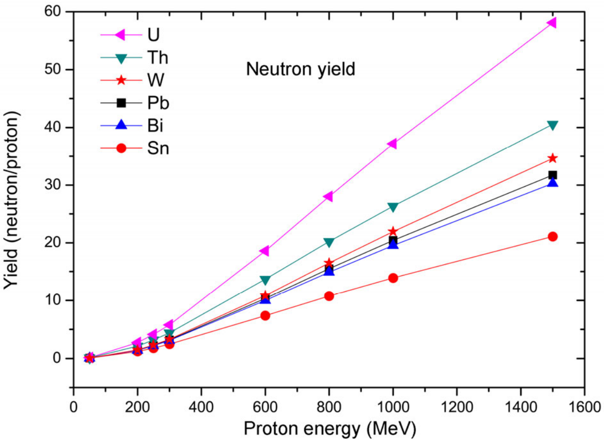

Figure 5 (Color online) Total neutron yields of protons with different energies colliding with targets made of different materials.

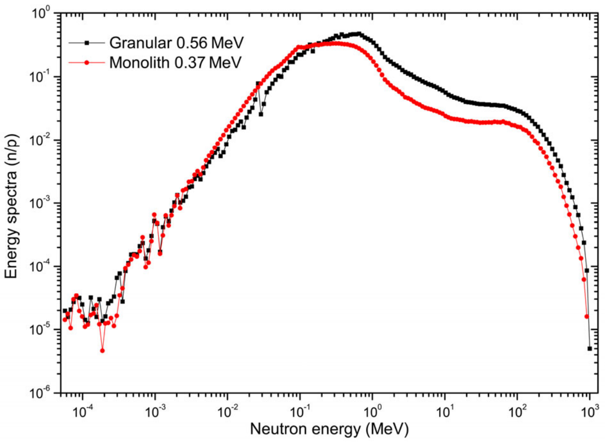

Figure 6 (Color online) Leaked neutron spectrum from sidewalls of the targets made of grains and monolith W.

Figure 7 shows the neutron flux from the sidewalls of targets made of monolith metal W and W grains. As one can see, the neutron flux for W grains is more homogeneous than that of monolith W. Since nuclear waste transmutation requires a hard neutron spectrum and homogenized neutron field, the W granular target is superior to the monolith target.

3.2 Granular simulation

Granular material is one of the most common forms in existence. However, until now, there has been no comprehensive theory on granular materials that reliably predicts the behavior of such materials in technical devices [21,22]. Experiments with engineering devices are frequently expensive, time consuming, and sometimes even dangerous. The discrete element method (DEM) is now the most acceptable

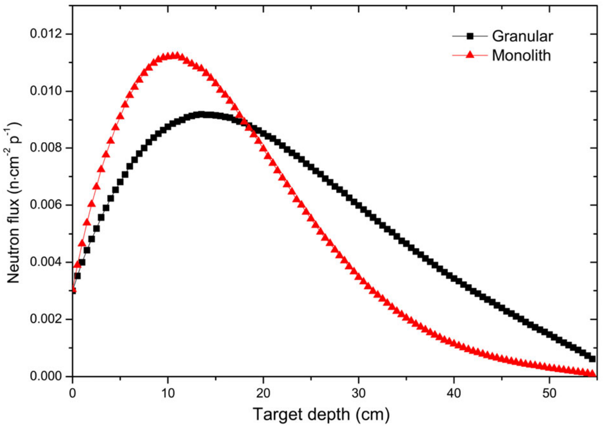

Figure 7 (Color online) Neutron flux from sidewalls of targets made of grains and monolith W.

method of simulating granular material [23–26]. DEM, closely related to MD, is a widely accepted method for simulating contact dynamics in many-body systems consisting of particles such as powders, bubbles, grains, and colloidal particles. In the most conventional formulation of DEM, the Voigt model is applied at each contact point in both the normal and tangential directions. Various contact models are employed to describe the microscopic mechanical details for a pair of touching particles. For a gravity-driven DGT, the dense granular flow can be simulated by DEM to model each of the particles and their interactions, in which a macroscopic understanding of the DGT is studied through the direct simulations of millions of particles [27,28].

To solve the problem of computing a large number of particles in a DEM simulation, a heterogeneous CPU-GPU algorithm with a message passing interface (MPI) and CUDA have been developed to simulate hundreds of millions of particles in a DGT [27,28] (See details in our previous work [29] and the flowchart in Figure 8(a). In Figure 8(b), we present the efficient applicability of GPUs to simulate the dense granular flow in the DGT. In such simulations, each W particle is accurately modeled as a monosized sphere undergoing realistic frictional interactions with neighboring particles. The parallel efficiency can be 38% when there are 512 GPUs used in the simulation. The parameters of the simulations are listed in Table 1. In other simulations with the random packing of two million grains and DGT geometry, the pressure of W grains in the spallation region shows a clear Janssen effect (Figure 9).

For an industrial-scale transmutation ADS, the proton beam seems to have at least 1 GeV of energy and a 10-mA beam intensity. In a 10-MW DGT, the proton beam interacts with the flowing W grains on the diameter of a 100-mm beam spot, and neutrons will leak out of the container. The neutron absorption must be minimized by optimizing the DGT geometry that has been used to design the granular target. The number of neutrons generated per incoming proton (n/p) is approximately 25 for the DGT. The neutron distribution is axisymmetric and as uniform as possible over all space of the core. This is only the first pass on a cylindrical DGT, and this neutron production efficiency is a good starting point.

As the particle transport model is coupled with dense granular flow codes, heat deposition and removal can be conveniently investigated by numerical simulations. In the numerical simulations of a 10-MW DGT, the temperature distributions of stable states are shown in Figure 10, and key parameters as well as results are shown in Table 2.

Distribution of the volume fraction of the target material varies with time, and the average volume fraction in the DGT oscillates around 0.52. Solid W with an approximate depth of 32 cm is required to stop a 1-GeV proton beam. Based on a volume fraction of 0.52, the range of a proton in the target is approximately 40 to 45 cm.

A small-scale experiment of the DGT, with a scale ratio of 1:10, was set up with glass beads having a diameter of 0.8 mm. The beads are conveyed by a pipe chain lift from the bottom of a hopper to the top of the system through a vertical pipe whose height and diameter are 1.8 m and 0.05 m, respectively. Then the beads are refilled into the hopper from the top, where a pipe runs along the direction of the central axis. The granular flow driven by gravity is formed in the upper coaxial annular space, and the grains flow to the outlet at the bottom. A continuously running test

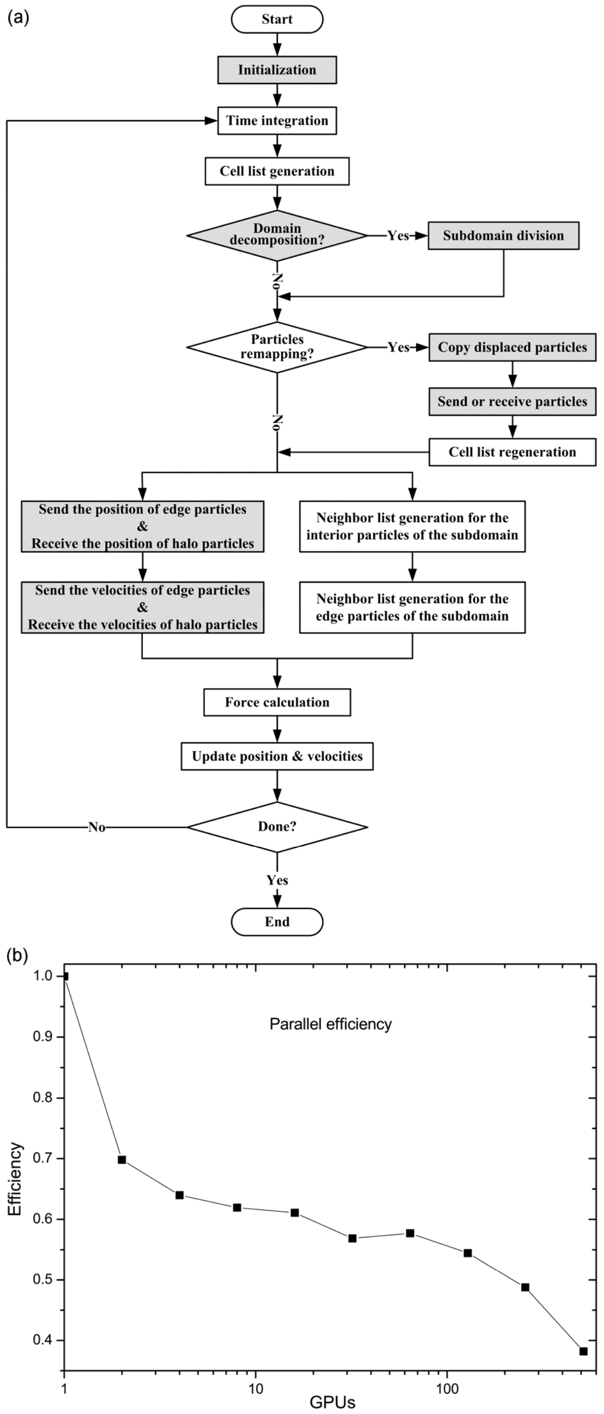

Figure 8 (a) Flowchart of multi-GPU DEM algorithm; (b) parallel efficiency vs. number of GPUs at ~250 million W grains.

Table 1 Simulation parameters for GPU code efficiency test

Parameters	Value
Density of grains	19250 kg/m^3
Diameter of grains	0.005 m
Young's modulus	411 GPa
Poisson's ratio	0.28
Diameter of container	0.28 m
Diameter of outlet of container	0.18 m
Diameter of beam pipe	0.15 m
Number of particles	250 000 000
Number of GPUs	512
Number of CUDA cores	229376

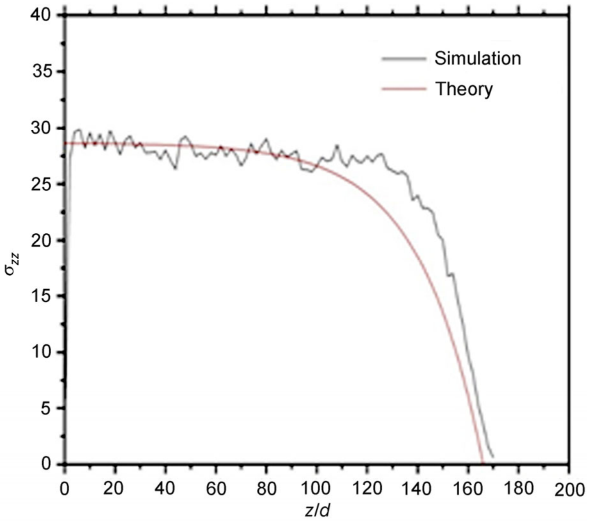

Figure 9 Curves of theoretical and simulated Janssen effect.

of 24 h was performed, during which the mass flow rate was measured and the fluctuations were less than 10% (Figure 11). Test results with outlet diameters of 13, 15, and 18 mm show that the mass flow rates are consistent with those from numerical simulations (Figure 12).

4 Discussion and conclusions

A gravity-driven dense granular target can avoid limitations that exist for solid targets and liquid targets. However, a gravity-driven DGT naturally poses some new challenges. For example, the wear of grains occurs almost everywhere in the system and should be considered carefully. Recently, wear tests in the atmosphere from room temperature (RT) to 1000°C show that W alloy grains exhibit excellent wear resistance against SiC and SIMP steel [30], and that the maximum wear amount is far smaller than 1 mm/year. In the international standard, the NE series hoists (with a general transport height up to 40 m) are suitable for conveying powder, grains, and small blocks of abrasive and nonabrasive materials. Since the hoist is a ring chain, it allows delivery of high-temperature materials (up to 600°C), which simplifies the design of the heat exchanger. Although some technologies have been used in similar cases, such as water-cooled beam entry windows, countercurrent water corrugated plate heat exchangers, and granular elevators, there are other subsystem components that need to be studied in detail.

It was demonstrated by numerical simulations and small-

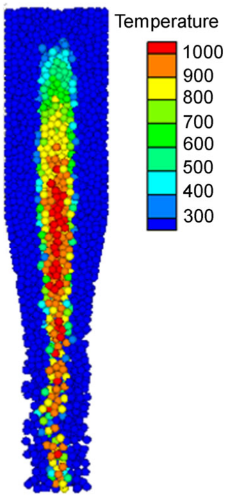

Figure 10 Temperature distributions of 10-MW gravity-driven DGT in stable status.

Table 2 Parameters and main results of temperature simulation

Parameter	Value
Diameter of container	0.28 m
Diameter of outlet of container	0.15 m
Diameter of beam spot	0.18 m
Same temperature of grains from inlet	250ºC
Average temperature of grains from outlet	500ºC
Maximum temperature of grains	950ºC
Average velocity of grains through spallation region	0.6 m/s
Stable average volume fraction	0.52

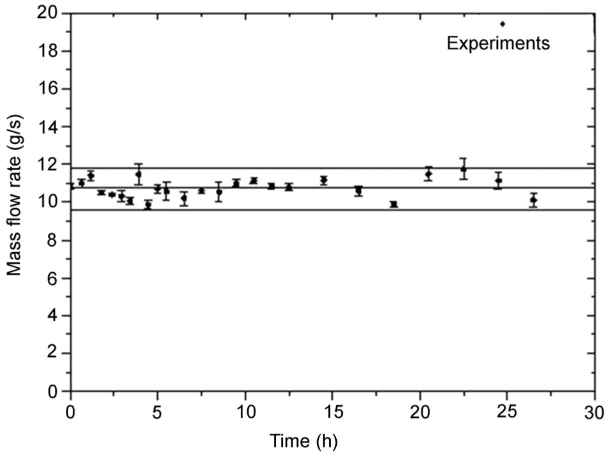

Figure 11 Mass flow rate measurements of a small-scale test loop in 24 h.

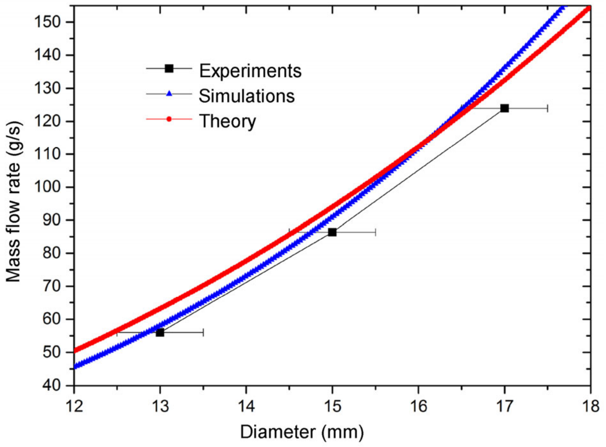

Figure 12 (Color online) Curves of mass flow rate from experimental, simulated, and theoretical data.

scale loop experiments that grains can be readily driven by gravity to form a dense and stable granular flow within a chamber. In general, advantages of a gravity-driven DGT include the possibility of very high heat removal, long operational life, low chemical toxicity and radiotoxicity, and other modest system parameters. The configuration of a DGT has great potential to form the basis of tens of MW spallation targets for cost-effective ADS facilities.

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