Chapter 4

Dense Granular Flow as Heat Transfer Media: A New Type of High Power Target Design

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Additional information is available at the end of the chapter

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Abstract

High power target systems require reliable high-temperature heat transfer media. Dense granular flow materials have potential to work as heat transfer media, especially at high temperature. In this chapter, a brief review of dense granular and their heat transfer properties is introduced, including basic concepts of heat transfer, thermal behavior of these materials, and factors that affect this behavior. The implementation of these materials as targets is addressed, where two targets were designed, constructed, and tested based on the concept of dense granular flow. The results of the application of a hopper flow-type target in 2.5 MW accelerator-driven system (ADS) and a chute flow-type target in the material irradiation facility will be presented.

Keywords: dense granular flow, high power target, prototype facility

1. Introduction

In nuclear area, an accelerator is always helpful to generate particles uncommon or indiscrete in the natural world. Target materials are exposed to certain projectiles; as a result, secondary particles in the form of neutrons, photons, neutrino, and so on are generated.

For most cases, the higher particle flux outcome is more helpful. To achieve this, the target systems are designed to stand high beam intensity. Most of beam power deposits in the target material. The kinetic energy of the beam converts into internal energy and increase the temperature of target. This process also leads to radiation damage of target material and even target failure.

Lots of effort has been made to achieve high power target. But not until the 1990s, a specific megawatt target never came up. As examples, Weapons Neutron Research project in Los Alamos Neutron Science Center achieved 70 kW target with tungsten material, while Rutherford Appleton Laboratory reached 160 kW using 800 MeV protons and tungsten with tantalum cladding [1].

As mentioned above, cooling is essential to the high power target. Conventional cooling channels take too much space inside the target body and gradually get close to the limit. The MarkIII target of Swiss Spallation Neutron Source project in Paul Scherrer Institute (PSI) reaches 1.2 MW beam power based on such concept. Some projects adopt rotating target to even and lower the power density within the target body, such as European Spallation Source and China Spallation Neutron Source [1–4].

For solid target, radiation material damage also causes swelling and creep, which might damage the cooling channel and cause cooling deterioration, as the displacement per atom (DPA) increases. One way to bypass the damage is using liquid metal as target material. Meanwhile, the flow of liquid metal removes the power deposit and dumps the heat in the heat exchanger. These properties make liquid metal target a promising solution of high power target. In PSI, MEGAwatt PIlot Experiment (MEGAPIE) achieved 0.8 MW with lead bismuth eutectic (LBE). Spallation Neutron Source in US and Japan Spallation Neutron Source also achieved 1.4 and 1 MW beam power with mercury [1].

Here we are going to present a third option of target cooling, which is based on the dense granular flow [5]. Granular system makes solid materials flow like fluid and perform heat removing. Meanwhile, the candidate target materials are more various, which give better feasibility depending on the purpose of the facility.

2. Heat transfer media and heat transfer in granular material

2.1. Conventional heat transfer media

The continuous research of the thermal properties of materials is explained both by practical needs and fundamental science. Heat removal is always a crucial issue for energy conversion in the energy industry owing to increased levels of power requirement and energy efficiency. The search for materials that transfer heat well under high temperature and energy flux has covered all the industry area and never ends, and it is especially essential for design of the next generation of reactors and neutron facilities.

A medium's transfer heat ability follows three basic heat transfer ways, conduction, radiation, and convection. Conduction dominates solids' heat transfer behavior, while convection makes fluids absorb heat from a source and dump heat to a sink very efficiently. In field of nuclear energy, water is still the most important heat transfer material for cost and reliability reasons, while liquid metal such as sodium and gases such as helium take the rest portion. These fluid heat transfer media are capable of removing 10^2–10^5W/m^{2}K from surface of power component and reaching up to the order of ~10^6W/m^{2}K while boiling [6]. At high temperature, some particular situations differ because of radiation. Radiation transfers heat from one surface to another through void following the Stephan-Boltzmann law, which indicates the radiation heat transfer rate is proportional to the cubic of temperature. Hence, if radiation happens effectively in the media, heat transfer can be more efficient at high temperature.

At high temperature, thermodynamics principles allow fluid's thermal energy transfers more efficiently. But most practical heat transfer media failed under such temperature: Liquid water transforms to supercritical state over 385°C [7, 8]; steam reacts with common structural materials over 900°C [9], and about one-third of the zircaloy in the core create a sizable hydrogen bubble from the Zr-steam interactions [10]; liquid sodium or lithium, Na-K alloy, and mercury are all vaporized under 900°C; lead-bismuth eutectic, liquid lead's corrosion-erosion effect grows significant at 480–550°C [11, 12]. What's more, for nuclear usage, liquid metal loop needs multiple conditioning systems, which makes the system complicated and expensive, such as International Fusion Materials Irradiation Facility (IFMIF) [13] and eXperimental Accelerator-Driven System (XT-ADS) device [14]. Gases seem to be another good choice, which has been testified in high-temperature gas-cooled reactors. But they have to be pressurized due to their low volume heat capacity [15].

2.2. Characteristic of granular flow

Granular material is a promising solution. Granular material is composed of discrete solid particles and gaseous environment where the particles immerse. Such material has been used for heating since ancient Rome by Lucretius [16]. Modern research can be trace back to Maxwell's era and got broad attentions in the twentieth century due to popularization of bed reactors [17]. Nowadays, granular heat exchanger has been widely used in many industrial areas. They perform effective heating or cooling in so many industrial processes that indicate granular materials are realistic to be a promising heat transfer media. Packed bed and powder jet solution had been came up by research groups to solve the high power density removal issues of target [18, 19]. Pebble bed fusion reactors and fission first wall breeding layers also adopt granular material using the unique advantages in the high-temperature heat transfer [20–23]. Flow of granular state enhances heat transport process, leading to better heat transfer performance and more realistic feasibility, especially for extreme internal heat source such as spallation reaction, compared to present solutions.

Its potential of heat transfer usage stems from flowability and thermal properties, which has been widely studied and practiced. The flowability allows granular materials to convey long distance by multiple methods. But granular materials' flowability is quite different from fluids'. Although granular dynamics uses many hydrodynamics concepts, granular dynamics behaves quite different from fluid. Some of granular materials' unique properties are critically helpful to be heat transfer media.

When granular materials flow out from a vessel under the action of gravity, the mass flow rate M is approximately independent of the head of material head H, just as an hourglass does. The most important research of this phenomenon was successively recorded by Beverloo et al., Aldin and Gunn, and Nedderman [24–28]. This phenomenon requires that the granular material must be not too smooth and small, while the bulk has a height not less than twice orifice diameter. A quantitative result of this flow gives a relationship of [28].

$$\dot{m} = 0.58\,\rho_s \sqrt{g}\,\left(D - 1.4\,d_p\right)^{2.5} F(\theta_\omega, \beta) \tag{1}$$

where m, ϱ_s, D, d_p, θ, and β represent mass flow rate, particle material density, orifice diameter, particle diameter, wall angle, and an angle related to friction of the material [29]. This result implies the flow rate could be controlled by local valve.

As the immerging depth increase, the normal pressure of most fluids increases linearly and is proportional to the depth. But the normal pressure of granular system gradually reaches a constant. Different from fluids, inside the granular system and between the granules and the container walls, friction exists. The upward friction force exerted by the wall neutralizes the weight of grains. An important quantitative explanation given by Janssen is in accord with the experimental stress result [30].

Other granular properties also have special effects, which stem from the friction, dissipation, and size effect of granules. These effects lead to phenomenons in granular flow, such as the jamming and dilatancy properties prevent flow channel collapse [31]; while dissipation property prevents long-range disturbance propagation [32].

2.3. Thermal properties of granular flow

Granular materials' thermal properties are decided by the components which make the effective properties vary largely. As high-temperature heat transfer media, high-melting-point metal alloy, ceramics, and other materials with good heat conductivity can be the solid particle candidate. There are relatively few gases performing heat transfer effectively, among which helium is representative. The large number of material combination makes granular media satisfy varieties of actual needs. For instance, the heat transfer media in traditional nuclear reactor need to minimize the neutron absorption and maximize the neutron moderation, while the heat transfer media had better to be the spallation material in a spallation target which needs high spallation neutron production.

Some effective thermophysical properties such as critical temperature, density, and specific heat can be estimated using simple calculations based on the properties of the initial components. But quantities such as heat transfer coefficient and effective heat conductivity are far more complicated than those. The following subsections will review critical thermal properties to get a better view of granular heat transfer media's potential.

The mainstream viewpoint of heat transfer between granular material and a panel has two stages: heat transfers from the wall surface to the first granular layer next to the wall, and heat diffuses from the first layer to the inside of granular material [33–36]. Sullivan and Sabersky [36] adopted concepts of fluid heat transfer such as Peclet and Nusselt number dealing with this process. An analytical result of temperature distribution can be derived from principles of heat transfer. This work was further extended by Spelt et al. [36, 37].

2.3.1. Mechanisms

For both two stages, whatever discrete model or continuous model is applied, one should realize that the structure of granular material leads to more heat transfer mechanisms.

As Yagi and Kunii reviewed, heat transfer in granular media happens in all three ways and their coupled effects [38]. Most concerned mechanisms of heat transfer in granular media are listed in **Table 1**.

The first stage was observed by several early researchers, depicted as a sharp temperature drop at the wall [36, 39, 40]. In this stage, the maximum heat transfer is at the order of ~10^3W/m^2K for granules' diameter at the order of millimeter in air. Such order is determined by different researchers and methods [39, 41]. When the pressure drops to 0.1 Pa, the wall heat transfer coefficient decreases to the order of ~10 W/m^2 K. Most significant heat transfer coefficient drop happens when pressure changes from ~1 kPa to 1 Pa, leading to the change of one and a half order.

In vacuum, the solid dominates the heat transfer rate, proved by the coefficient of bronze and glass, which are 30 and 5 W/m^2 K, respectively. This result agrees well with the contact heat transfer analysis, and we will discuss this effect in the effective thermal conductivity of granular material in later section. In contrast, the gas phase decides the heat transfer in atmosphere, reaching the order of ~10^3W/m^2K [35, 41]. It is believed that the porosity near the wall reaches almost 1 [42–45], which means only little solid contact at the wall leads to a minor heat transfer mechanism only significant in vacuum.

Although most researches did not evaluate the specific limit of heat transfer rate, they did observe effect of various factors. Most of them have relationship with the second stage.

	Phase	Region	Mechanism
1	Solid	In single particle	Conduction
2	Solid-Solid	Contact	Conduction
3	Solid-Solid	Surface to surface	Radiation
4	Void-Void		Radiation
5	Solid-air-Solid	Near the contact	Conduction
6	Solid-air-Solid		Convection
7	Air-Air	Long range mixing	Convection
8	Air	In the void	Conduction

Table 1. Mechanism of heat transfer in granular media.

In this stage the heat transport can be considered as heat diffusion in a continuous media with effective properties of granular material. The complexity of heat transfer mechanism makes multiple parameters dependence.

2.3.2. Effect of material constituent

Granular material component combination is the most principle factor of heat transfer properties. In the past century, a number of various granules' heat transfer properties have been studied. A collection of experimental data is shown in **Table 2**. It shows gas phase plays a decisive role in granular materials' heat transfer property, while the solid particle geometry plays a role as important as its inherent properties. Large surface-volume ratio makes the temperature of fluid and solid phase nearly uniform [46, 47].

In energy area, most heat transfer is performed under pressure. Pressurization enhanced heat transfer in two aspects: increase boiling temperature and volume heat capacity. High-melting-point solid granules need none of these improvements and hence may significantly reduce engineering difficulty, risk and cost. The pressure concept in granular system also has two aspects: the gas pressure and particle compress pressure.

Early stage of ETC of granular material focuses on experimental determination. Back to 1926, Aberdeen and Laby studied effective thermal conductivity (ETC) of monox powder when immersed in air, in carbon dioxide, and in hydrogen at various pressures has been determined. They found a linear relation between the conductivity of the powder and the logarithm of the pressure of the gas in which it is immersed. The result fits in

$$k = \frac{k_f}{2}\log_{10}\frac{p}{n} \tag{2}$$

where k is effective heat transfer coefficient and k_f is fluid heat transfer coefficient and n is a constant for each specific gas [48].

2.3.3. Effect of temperature

Microscope heat transfer mechanism decides most condensed matters' thermal conductivity deteriorates as temperature increases while gases are contrary. In a granular material, solid phase has more significant heat conductivity than gas phase. On the other hand, the packed solid particle structure is point contact for most cases; hence, the gas voids play an important role in the effective heat conduct which increases as temperature rises. Radiation also significantly improves effective heat conductivity of granular material under high temperature. Solid surfaces and voids allow radiation to perform efficient heat transfer, while such mechanism does not exist in bulk solid or pure gas.

Yagi and Kunii [38] determined ETC for several materials, in the temperature range of 100–800°C. The result shows an accelerated increase of ETC as the temperature increases. Most materials' ETC doubled or tripled for the test range. They proposed a model considering

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Solid	Diam./mm	Gas	Pressure/Pa	Temp./C	Effective Heat Transfer Coefficient/ W/m²K
Glass	4	Air	101k	60	0.28
Al	3.18	Air	101k	300	0.11
Iron	11	Air	101k	200	0.46
Iron	11	Air	101k	500	0.69
Iron	11	Air	101k	700	0.92
Iron	11	Air	101k	800	1.08
Glass	2.6	Air	101k	65	0.17
Steel	4.8	Air	101k	65	0.29
SiC	0.55	H_2	150		0.48
SiC	0.55	H_2	101k		1.06
SiC	0.55	CO_2	170		0.11
SiC	0.55	CO_2	101k		1.06
SiC	0.55	Air	150		0.13
SiC	0.55	Air	101k		0.23
Glass	0.32	He	76k		0.36
Glass	0.32	He	130		0.15
Glass	0.32	Air	101k		0.16
Glass	0.32	Air	430		0.12

Table 2. Some experimental result of effective heat transfer coefficient (ETC) [39, 49, 50].

the effect of radiation [38]. As Botterill published in 1989, the radiation is proportional to T^3, σ, and the character length represented by D_p; hence a radiation term of ETC falls in the form of

$$k_r = 4\sigma\chi D_p T^3 \tag{3}$$

where σ is Stefan-Boltzmann coefficient and χ is coefficient depending on the specific model. A comparative research of various radiation models and experimental results was also given by Botterill [49].

In a word, unlike traditional heat transfer material, granular material could perform better under high temperature; as previous study of gas cooling reactor, heat conductivity of graphite pebble bed exceeds pure graphite for temperature higher than 1400°C [2]. Further experimental results were reported in [38, 49, 50].

2.3.4. Effect of gas motion

As is well known, forced convection enhanced heat transfer properties. Packed bed is motionless granules with gas flows through. Researches of these systems explain the motion effect of gas phase, which also implies the same effect in granular flow.

Bunnell et al. studied a wall-heated packed bed with different superficial gas velocity, measured the inner temperature distribution, and calculated ETC through these results. They found effective thermal conductivity dependence on mass velocity of the gas, and the gas phase and solid phase temperatures are nearly uniform [51].

Solid particle motion enhanced cold and hot particles mixing, hence increasing the heat transfer rate. A lot of research about packed bed also showed that only fluid flow rate increase also leads to enhancement of ETC [46, 50, 52–55].

2.3.5. Models of ETC

To get a quick evaluation of granular materials, researchers had come up with various models, from simple to complex. Three most important models are as follows:

Maxwell (1881):

$$k = k_g \left[\frac{2\varepsilon k_g + (3 - 2\varepsilon) k_s}{(3 - \varepsilon) k_g + \varepsilon k_s} \right] \tag{4}$$

This model is probably the earliest method for granular ETC evaluation. It represents a series model that considers the system as a parallel-serial thermal resistance system [53] which got its popularity in the early age.

Yagi and Kunii [38]:

$$k = k_g \left(\frac{\beta(1 - \varepsilon)}{\gamma\left(\frac{k_g}{k_s}\right) + \frac{1}{\frac{1}{\varphi} + \left(D_p h_{rs}/k_g\right)}} + \varepsilon\beta D_p h_{rv}/k_g \right) \tag{5}$$

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in which $\beta = l_p/D_p$, $\gamma = l_s/D_p$, $\varphi = l_v/D_p$. h_{rs}, h_{rv}, l_p, l_s, and l_v represent radiation heat transfer coefficient of solid to solid, void to void, effective length of centers, thermal conduction, and fluid film at the contact point. They considered effect of fluid flow using Ranz fluid mixing equation and shows the particle size effect. The result fits temperature effect well [38].

Zehner and Schlunder's model:

$$k = k_f\left(1 - 1\sqrt{1-\varepsilon}\right)\left(1 + \frac{k_r}{k_f}\right) + k_f\sqrt{1-\varepsilon}\left\{\frac{2}{1 - \frac{k_f}{k_s}B}\left[\frac{\left(1 - \frac{k_f}{k_s}\right)B}{\left(1 - \frac{k_f}{k_s}B\right)^2} \cdot \ln\frac{k_s}{k_f B} - \frac{B+1}{2} - \frac{B-1}{1 - \frac{k_f}{k_s}B}\right] + \frac{1}{\frac{k_f}{k_r} + \frac{k_f}{k_s}}\right\} \tag{6}$$

in which B is a deformation factor. This model represents a significant improvement of contact term which applies for various material properties.

2.3.6. Total heat transfer coefficient

Schlunder gave explanation of the combination of wall heat transfer and ETC as a serial of heat resistance as follows [35]:

$$\frac{1}{\alpha} = \frac{1}{\alpha_w} + \frac{1}{\alpha_{ETC}} \tag{7}$$

Because the heat diffusive process inside the granules varies as time changes, total heat transfer coefficient also depends on time. Most measured total heat transfer coefficient is time averaged value:

$$\alpha = \frac{1}{t}\int_0^t a_t \, d\, t' \tag{8}$$

In three situations, (1) t goes to 0, (2) bed heat capacity is infinity, and (3) the bed is under perfect mixing, α_{ETC} reaches a maximum and hence derives the maximum heat transfer coefficient, i.e., the wall heat transfer coefficient. A typical time dependence of α_{ETC} based on Fourier theory is given by

$$\alpha_{ETC} = \frac{2\sqrt{(\rho c k)_{bed}}}{\sqrt{\pi t}} \tag{9}$$

The total heat transfer depends on time, hence given by.

$$\alpha = \alpha_w \frac{1}{1 + \frac{\sqrt{\pi}}{2}\sqrt{\tau}}, \quad \text{where} \quad \tau = \frac{\alpha_w^2}{(\rho c k)_{bed}} t \tag{10}$$

Through the experiments of various components' combination, Ernst showed α decreases as time increases, which is less significant for lower pressure and larger granules [39]. Such time-dependent phenomenon has been observed by other researches [36, 56]. The total heat transfer coefficient fell in the range of 50–200 $W/m^2 \cdot K$ which is also a typical range of most facility situation [57].

3. Implementation of granular flow target

With the concept of dense granular flow cooling, the target can be designed according to different demands. Two different types of granular flow target have been developed for China Initiative Accelerator-Driven System (CIADS) project and China material irradiation facility project. For both designs helium was selected as the cover gas, concerning its high thermal conductivity and safety. In principle, pressure was set lower than 1 atm to prevent leakage and help target-beam line coupling. For each case, gas pressure was variable parameter. The difference of the two targets includes structure, target material, beam energy, spectrum, and so on.

By the end of 2017, two prototype facilities were constructed and tested with electrical heating, up to about 300°C. The beam coupling experiments are planned to be performed later, depending on the progress of radiation shielding hall.

3.1. ADS target

For CIADS, the target needs to prove high neutron yield inside a subcritical reactor core. To replenish the neutrons in a subcritical power reactor, the target-beam power is very high. The primary design chose proton beam of 500 MeV @ 5 mA and beam power of 2.5 MW.

Meanwhile, the space for the target installation is very limited to lower the neutron leakage and increase the effective neutron multiplication factor (k_{eff}) of the reactor. Usually the installation space is in vacancy of several removed fuel components. In CIADS, the diameter of the target tube needs to be under 30 cm. To fit this space, a thin and long vertical tube was applied as target tube. The dense granular flow went downward within. The beam line installed coaxially in the target tube sent protons deep into the target granules and reacted at the same level of the core center. **Figure 1** shows a schematic view of CIADS, which adopts a loop target section.

Tungsten was selected as the target material. Minor iron was added to optimize the mechanical properties. The alloy was made into 1 mm sphere. Tungsten generates abundant neutrons in spallation reaction which is widely adopted in neutron resources. With the basic idea of dense granular flow, the tungsten also plays a role as coolant. Considering the beam heat load and material's temperature endurance, the circulation mass flow is required about 200 kg/s. Compared to the fluidized dilute granular flow developed in the Rutherford Appleton Laboratory, we believed that the dense flow is more stable and lowers the requirement of gas system, for this specific case.

To sustain the operation, the system also included conveying, cooling, conditioning, monitoring, cleaning, and other affiliate systems. To lift the spheres back into the target, a chain conveyor is employed. The spheres inside flow vertically under gravity. When the spheres

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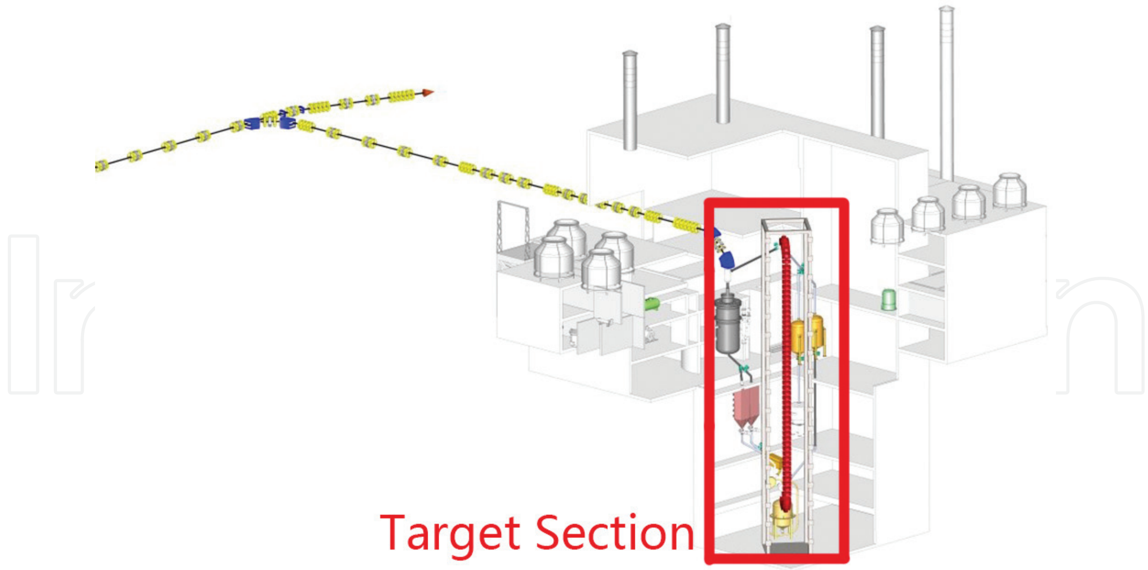

Figure 1. Schematic diagram of CIADS.

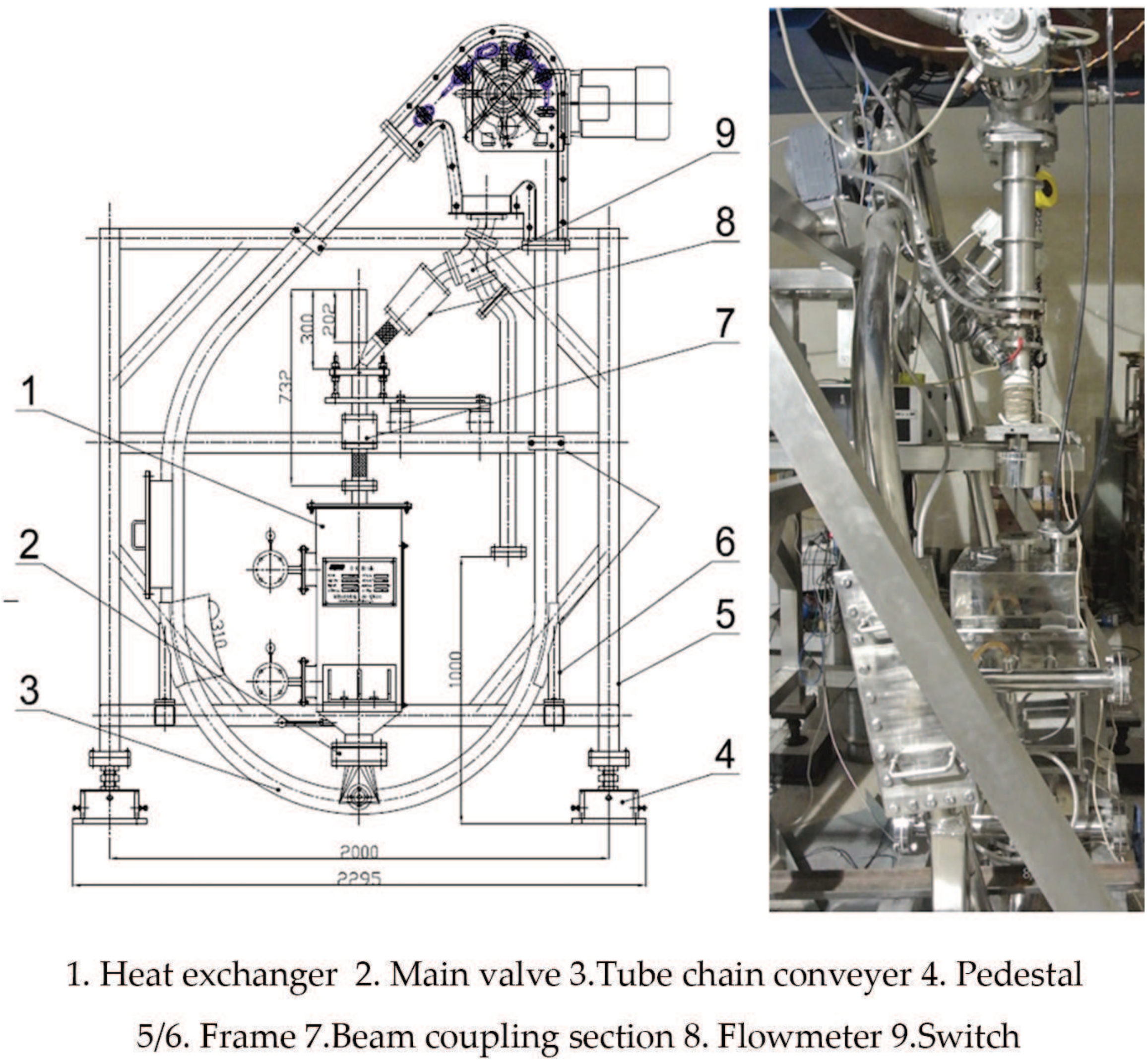

Figure 2. Electron beam coupling test facility.

flow to the bottom of the loop, the elevator lifts them back to the top, and the spheres reenter into the target. The elevator actively supplies the energy to sustain the circulation; hence the reliability and feasibility should be carefully considered. Other confines came from the ADS application, such as airtight and compact. Due to the grain size and density, pneumatic system does not fit the system well. Both conventional mechanical conveyer and a new developed magnetic conveyer are chosen as potential candidate. The heat of spheres will be removed in a panel heat exchanger. Through the steel shell of the heat transfer panel, the heat is transferred to the counter water flow. The width of parallel flow channel formed by the panels is large enough to avoid arching and clogging. **Figure 2** shows an electron beam coupling test facility constructed in 2015. Without conditioning and some other minor systems, the facility is simplified to test the circulation and heat loading effect. As shown in **Figure 3**, the coupling section is about 1:5 to the full scale.

The full-scale testing was setup later in 2017, as shown in **Figure 4**. The model facilities were put into practice as a preliminary design verification by Institute of Modern Physics, Lanzhou. Other than the components of previous system, sieving and cover gas systems were installed. Conveying system was updated to a magnet conveyer, and heat exchange test was elevated to about 250°C.

3.2. Target for material irradiation facility

Material irradiation facility also requires intensive neutron source to test material tolerance of radiation damage. The China material irradiation facility aims at a small-scale and low-cost facility. To maximize the radiation effect, the facility design took the advantage of forward neutrons. The system adopted deuterium beam of 20 MeV@5 mA and beryllium as the target material. Due to 20 MeV deuterium only has a very low penetration at the order of millimeter; there is hardly effective neutrons leak out, with the previous configuration. Hence, a new structure based on chute flow was adopted.

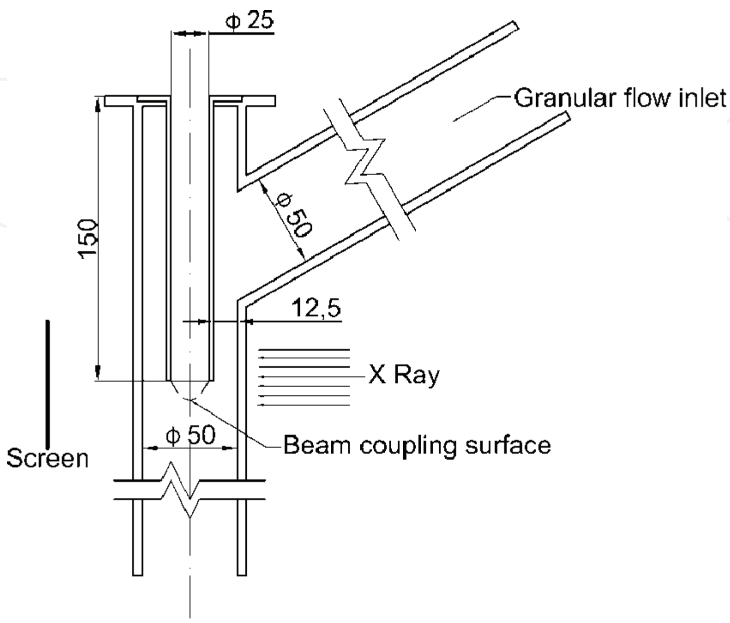

Figure 3. Profile of coupling section.

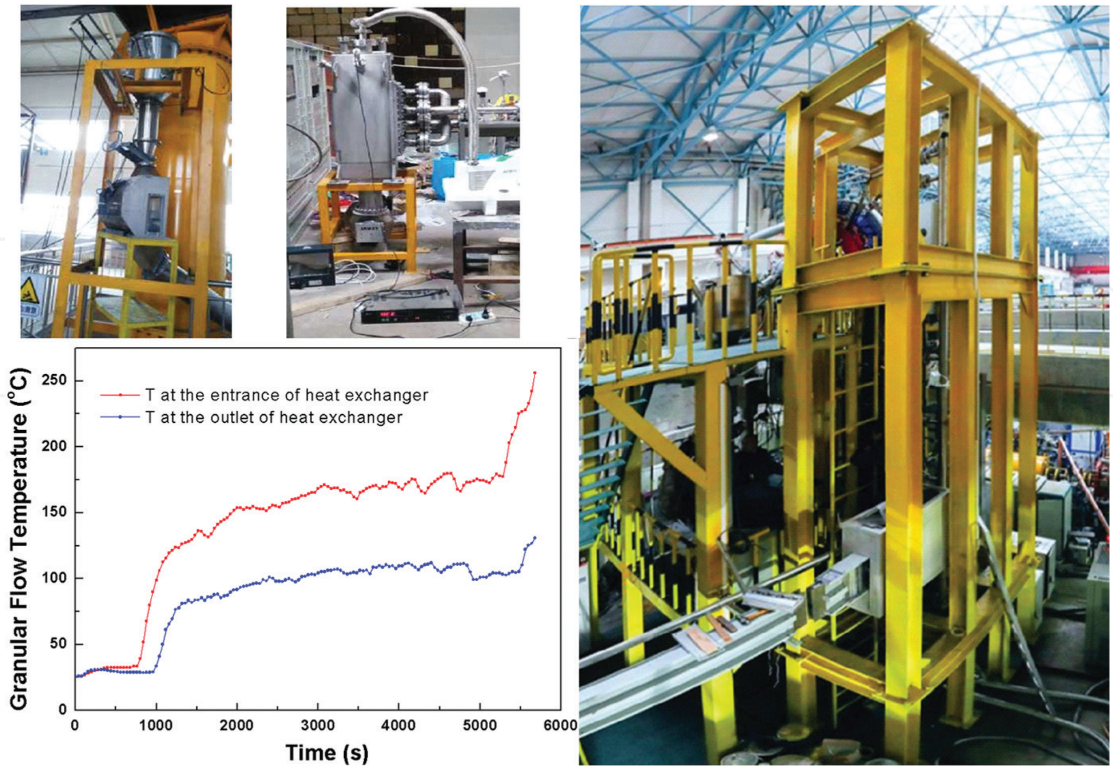

Figure 4. Prototype facility and heating test.

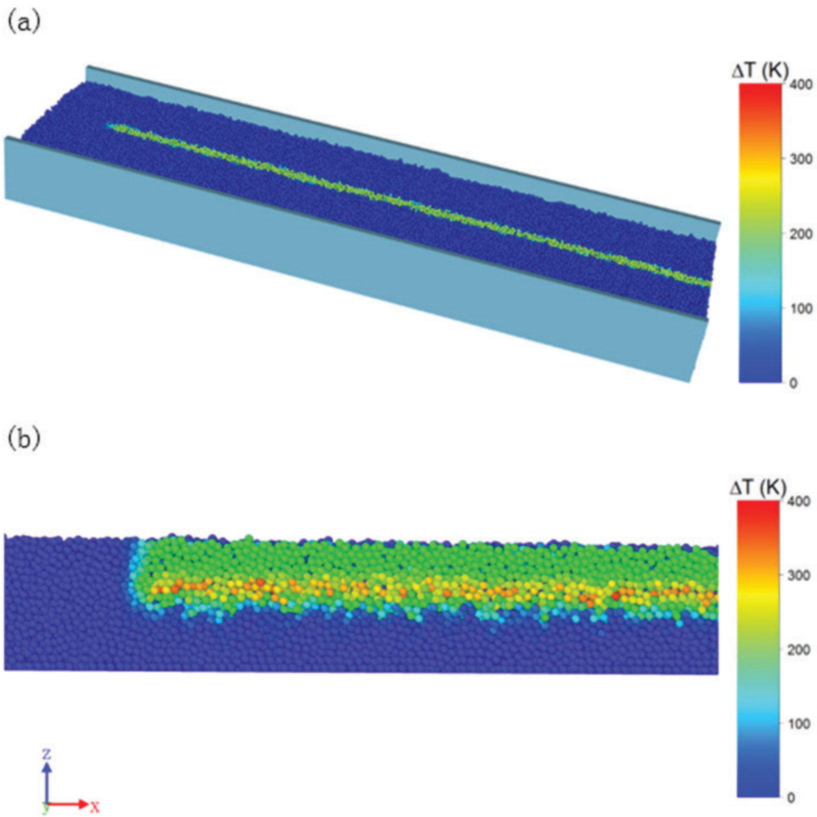

Figure 5. Simulation of beam heat load.

To demonstrate the heat load effect of this chute flow target, this progress is simulated by our GPU code [58]. **Figure 5** showed one of the simulation results of heat deposition in a chute flow. The result showed the 20 MeV beam particles only penetrate several millimeters into the flow. According to the design and simulation, mass flow at about 2–3 m/s is sufficient to remove the heat. The parameters of feeding rate, chute slope, beam spot position, and flow channel width system could be well adjusted to required reaction region. After its first test, target section of the facility in **Figure 2** was replaced by a slope chute. **Figure 6** showed the test loop facility and targets applied in the system. An acrylic chute was chosen to observe the flow status, and a stainless steel chute was installed for beam coupling effect of the facility. The experimental result is showed lower right.

Figure 6. Electron beam coupling of chute flow target.

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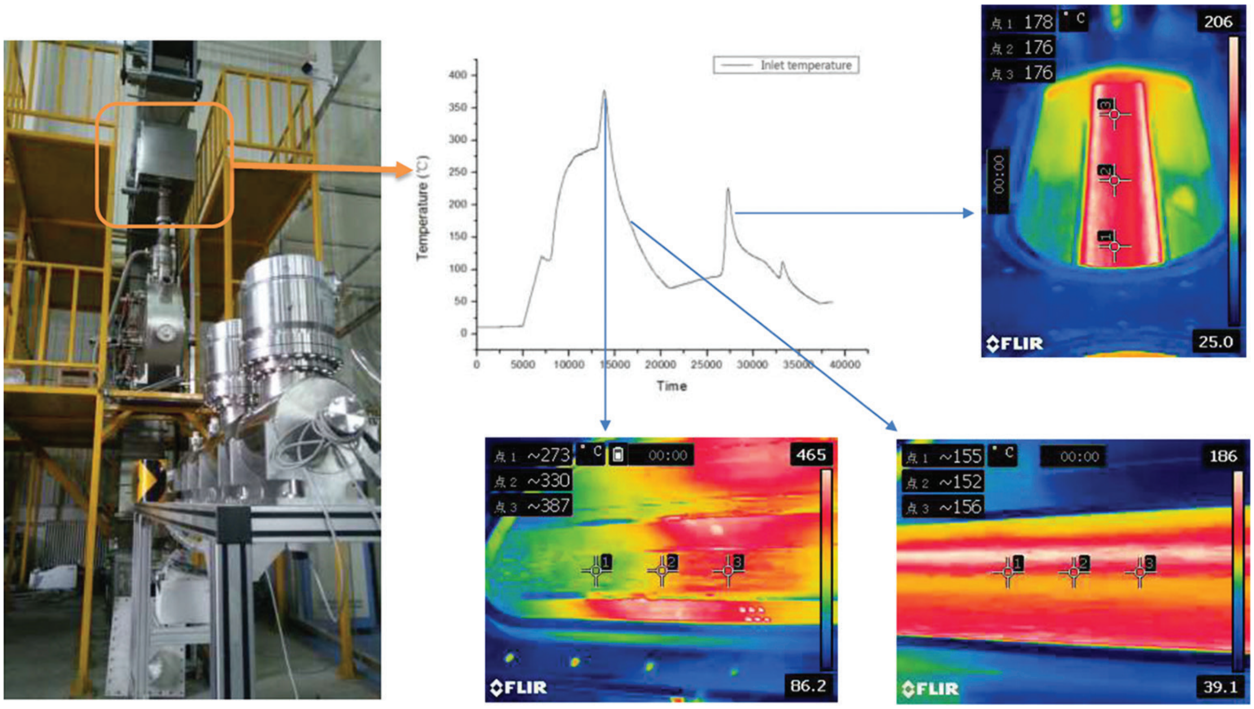

Figure 7. Prototype of material irradiation facility target and heating.

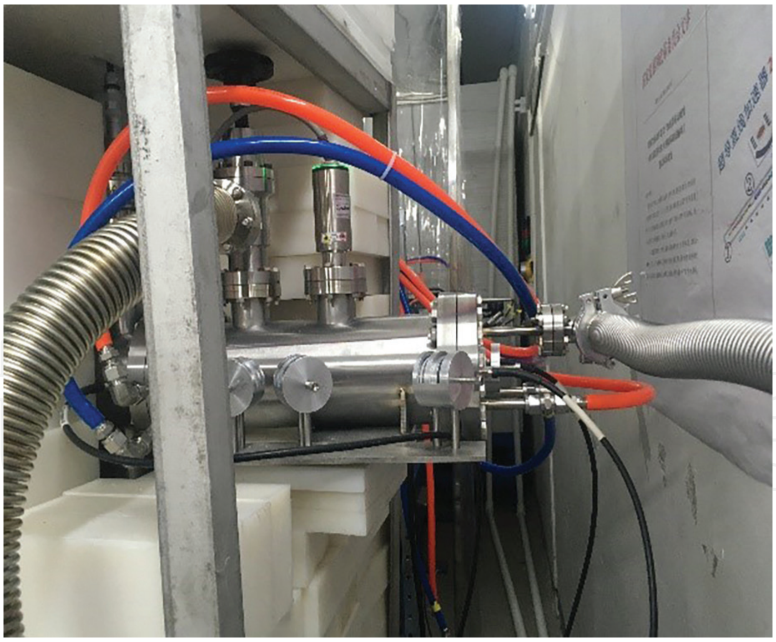

Figure 8. Static granular target.

The target design is first tested on remodeled small-scale circulation loop for ADS target in 2015. The facility is also radiated by electron beam. Temperature of the flow increased slightly, which showed that the system heat removal is workable.

Later in 2017, a full-scale prototype facility finished its major construction, as shown in **Figure 7**. Due to the radiation hazards, instead of actual beam, system used laser and electric heating to test temperature endurance and heat removal effect. 30 kW electric heating offered major overall heating power, while laser provided a high power density up to 3 MW/cm^2. Granular flow reached an average temperature more than 300°C and maximum temperature more than 500°C. High-temperature testing was performed over 200 h, among which the longest continuous run lasts more than 100 h.

To test the neutron performance of this target material, a static granular target as shown in **Figure 8** was installed in the beamline of a 20 MeV linear accelerator. The neutron yield data is tested through proton beam and the same 1 mm beryllium in static vacuum chamber. Five stacks of activated foils are located around the chamber. The measurement of the foils deduced a total neutron flux of $2.14\times10^{13}/cm^2\cdot mA\cdot s$.

4. Conclusion

The unique property of dense granular flow makes it possible to transfer heat effectively at high temperature. The major mechanism and factors of granular were reviewed. Using the granular material as heat transfer media and target material, two different configurations came up depending on the application. The prototype testing facilities were constructed. More designs and applications based on the granular heat transfer media are to be developed hopefully.

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Notation

k	effective thermal conductivity
k_g	gas phase thermal conductivity
k_s	solid phase thermal conductivity
D_p	particle diameter
ε	void fraction/porosity

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