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Numerical analysis of the granular flow and heat transfer in the ADS granular spallation target

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ABSTRACT

The Accelerator-Driven System (ADS) is one of the most effective tools to deal with the spent fuels by nuclear transmutation. In the ADS, the neutrons could be produced by bombarding a proper spallation target with a concentrated beam of high-energy accelerator protons. Subsequently, the produced neutrons drive the nuclear transmutation in the sub-critical reactor. Therefore, the spallation target is an essential part of the ADS. Recently researchers proposed a gravity-driven dense granular target, which has both solid and fluid target characteristics.

This study developed the FOCUS code to simulate the granular flow and heat transfer behaviors involved in the gravity-driven dense granular target. A solid sedimentation experiment was performed and simulated by FOCUS code. The simulation results were consistent with the findings in the experiment, which proved FOCUS to be an appropriate code to simulate the granular flow. Then the sensitivity analyses were performed to investigate the influence of the inlet flow rate and the target area shape on the state of the granular flow in the ADS granular spallation target. The simulation results showed that the velocity of each granular spallation target was related with the height of piled-up particles in the targets area. The geometry size of the target area obviously affected the flow state of targets. Meanwhile the inlet flow rate had a slight influence on the stable flow, unless the inlet flow was so large that targets overflow the target area. Furthermore, the study also calculated the heat transfer between each target and found that heat conduction between two contacted granular spallation targets was the main process in the targets area. The present work would be instructive for the ADS system design.

1. Introduction

In recent years, fossil fuels are principal energy sources for most countries all over the world. In China, coal is the major energy resource, accounting for about 69% of the total energy consumption (US, 2016). The single structure of energy sources leads to the fossil fuels shortages, and even energy crisis. Besides, greenhouse gases emissions is the main cause of global warming. As a clean, efficient and reliable energy, nuclear energy is a better alternative to cope with these issues.

^{235}U is a highly fissionable uranium that is often chosen as a fuel in most nuclear reactors. The ^{235}U concentration in fuel pellets will be reduced in operation, and fuels should be discharged at the end of the fuel cycle. There are still some fissile materials in spent fuels (National Research Council, 1996; DOE, 1999; Rubbia et al., 2001). For example, in a mega-kilowatt nuclear power plant, the spent fuels contain about 23.75 tons of ^{235}U and ^{238}U, 200 kg of plutonium, one-ton short-lived fission products, 20 kg of minor actinides (MA) and 30 kg long-lived fission products (LLFP) (US, 2016). The uranium and plutonium can be extracted to produce new fuel pellets, however, it is difficult to deal with MA and LLFP. They are the major risks of spent fuels, because of their high-level radioactivity and they need at least tens of thousands years to decay to the ordinary radiation level.

In the 1990s, scientists developed a new method named the Partition-transmutation (P-T) to tackle the spent fuels (Croff et al., 1980), which can transform the long-term radioactive nuclei into stable or short-term radioactive ones. The Accelerator-Driven System (ADS) is a R&D finding based on two great inventions - the particle accelerator and the nuclear reactor in the 20th century (Abderrahim et al., 2010). It is considered as one of the most effective methods to deal with the spent fuels by nuclear transmutation. In the ADS, the nuclear fission occurs as the high-energy proton beam bombards the heavy metal spallation target. The fission neutrons work as an external source that drives the nuclear transmutation in the subcritical reactor.

The spallation target is one of the most critical parts for ADS. Most targets are made out of heavy metals, such as lead (Pb), lead-bismuth alloys (LBE) (Bauer, 2010) or tungsten (W). According to different

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Nomenclature

A	radiating surface, m^2
E	elastic modulus
F	collision force, N
I	moment of inertia, kg·m^2
M	transition matrix
N	number of particles
R	thermal resistance, K/W/contact radius between two particles, m
T	moment, N·m
X	angle coefficient
X,Y,Z	local coordinates/displacement in each direction
a	acceleration, m/s^2
c	damping coefficient, N/m
d	number of dimensions/damping force, N
e	elastic force, N
$\vec{f}$	forces between particles
k	elastic coefficient, N/m
l	distance, m
m	mass, kg
n	particle number density
p	pressure, Pa
r	radius of particles, m
$\vec{r}$	position of particle
t	time, s
$\vec{u}$	particle velocity vector
w	weight function
x,y,z	global coordinate/position in each direction

heavy-metal states, spallation targets can be divided into liquid and solid targets respectively. Liquid targets are easy to reach high-power level in the sub critical system, however, it is hard to have the radioactivity of the spallation target under control, and the heat removal from the target window is limited by the corrosion and erosion. In contrast, the radioactivity of the solid target is much lower, the heat removal is limited by the heat conduction of the target material and convection cooling. As a result, the power could not get to a very high level. Under these conditions, Institute of Modern Physics, Chinese Academy of Sciences (Yang and Zhan, 2015), put forward the gravity-driven DGT (Dense Granular Target), a new concept for an ADS high-power target.

DGT has integrated a series of discrete solid particles, thus it has both solid and fluid target characteristics. Theoretically, the DGT can handle with a higher beam power, the high power deposited will be removed offline. In other words, like a liquid, granular spallation targets in the DGT will flow away from the interaction region quickly and will be cooled externally using heat exchangers and can generate more neutrons. Besides, benefits to the solid phase characteristics, and granular spallation targets in DGT are renewed continuously offline. The radiotoxicity and chemical toxicity of the target are lower.

Granular materials are one of the most common forms in engineering. This study focused on movements of the granular target in ADS. The flow behaviors of granular targets in the DGT system are similar to those achieved by many researchers in the hopper discharging process studies. Fickie et al. (1989) adopted gamma-ray radiation to observe the flow process in the two-dimension case, and found that during the flow process of the non-viscous coulomb powder, there was a “free falling arch” above the outlet with the distance of twice width of the outlet. Gentzler and Tardos (2009) measured the concentration and velocity distribution of millimeter particles in different half-angles with Nuclear Magnetic Resonance (NMR) imaging and believed that particles accelerated at a certain height above the outlet in the large half-angle case. And Sielamowicz et al. (2006) employed the Digital Particle Image Velocimetry (DPIV) technique to study millimeter particles, the axis velocity distribution was slightly asymmetrical. Donsì et al. (1997) measured the pressure distribution in different outlet diameters case with pressure sensors, and found that the outlet's diameter had certain influences on pressure distribution in the hopper.

It has been quite costly and sometimes even dangerous to do experiments with engineering devices. Thus it would be a great alternative to do numerical simulation and study granular targets' mass and heat transfer. Now, the discrete element method (DEM) is considered as the most appropriate method to simulate such materials.

In recent years, with the rapid development of numerical simulation, a lot of detailed information that can't be measured by experiment has been obtained. The DEM, which was initially proposed by Cundall in 1971(Cundall, 1971),is a way that has been mostly recognized in simulating granular materials (Burman, 1980; Cundall and Strack, 1979; Johnson and Johnson, 1987). Weir (2004) used DEM to simulate the behavior of millimeter particles in hopper and proved the conclusion of Fickie who found particles started expansion at the top of the outlet. And Hirshfeld and Rapaport (2001) adopted the same method to study the impacts of the outlet diameter, and believed that the outlet particles' velocity was associated with the root of the effective diameter of the outlet. Ketterhagen et al. (2009) found that with the increase of half angle, the flow type in hopper was changed through simulating the flow of 2 mm particles in hopper with different half angles.

The studies of the hopper discharging process have laid the foundation for the research of granular targets in the DGT system. But there are still some differences between these two processes. Few studies about the hopper discharging process have ever calculated heat transfer which was an important issue for ADS. The DGT system was newly developed, and the flow behavior and heat transfer in the targets area should be investigated effectively. Considering the characteristics of the granular target, the discrete element method model in the FOCUS (Guo et al., 2017) code is employed to study the flowing behavior of the granular target. The influence of the inlet mass flow rate and the shape of target area on outlet flow rate and the outlet velocity of the granular target will be analyzed. Furthermore, the heat transfer model was incorporated into the FOCUS code to study the effect of the heat removal of the granular target.

2. Theoretical method

2.1. The FOCUS code

The FOCUS code is capable of handling the fluid-solid mixture flow (Guo et al., 2017). In this study, the fluid flow is not involved. Only the DEM model is employed to simulate the solid movement.

According to the different study objects, there are different kinds of DEM elements, including block element, disk element and sphere element, etc. But for each kind of element, the process of calculation is the same. In this study, the sphere element is chosen as the study object.

When the distance between two solid bodies is less than the sum of their diameters, the two solid bodies are considered to be contact. The equations of motion by Newton's second law for each body are as follows:

$$\vec{a}_i^{\,k} = \partial \vec{u}_i^{\,k}/\partial t = \vec{F}_{col}^{\,k}/m_i \tag{1}$$

$$\vec{\alpha}_i^{\,k} = \partial \vec{\omega}_i^{\,k}/\partial t = \vec{T}_{col}^{\,k}/I_i \tag{2}$$

In these two equations, $\vec{a}_i^{\,k}$, $\vec{\alpha}_i^{\,k}$ are acceleration and angular acceleration, respectively, $\vec{F}_{col}^{\,k}$ and $\vec{T}_{col}^{\,k}$ refer to the joint force and moment, respectively, k stands for the number of time steps in the DEM