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Numerical study on cooling characteristics in granular and liquid spallation targets

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ABSTRACT

Accelerator Driven System (ADS) has been developed to provide external neutron source for transmutation and multiplication to handle issues of short nuclear fuel supply and increased nuclear waste. With heavy nuclides bombarded by high-energy proton beam, neutron yields in spallation material which is accompanied by formidable energy deposition. Due to little survival of solid target from high power density and many unresolved issues in liquid target, granular target is motivated with higher sustainable power density. Although many investigations into cooling capability in spallation targets have been conducted, little literature is available on granular target which merits further study.

In the present study, investigation is focused on cooling characteristics of granular target compared with liquid target based on the same target model. Due to combination of granules and fluid, coupled CFD-DEM method is employed to simulate movement and heat exchange for granular target, but only CFD technique for liquid target. Directed against same studied domain, comparison and analysis are carried out for two types of targets in the present study. Our research indicates that the granular target owns higher safety margin to withstand severe conditions especially under high energy deposition. The present findings may help to clarify and confirm the safe and reliable spallation target for some specific applications.

1. Introduction

Accelerator Driven System (ADS), one of favorable innovative technologies has been developed to handle these issues of short nuclear fuel supply and increased nuclear waste (Shetty, 2013; IAEA, 1997; OECD/NEA, 2002). Under the bombardment of proton beam with high energy accelerated by accelerator, the yielded neutron can be applied to interact with long-lived highly radioactive nuclear waste for transmutation and to induce nuclear fuel for breeding. The increased focus on ADS in China can be attributed to many inherent superiorities and wide applications (Wu et al., 2016).

The accelerated protons with desired energy are extracted from accelerator to interact with the material of spallation target which refers to neutron creation and energy deposition. The efficiency and productivity are sensitive to the materials, dimensions and proton energy. For proton beam with given energy, there exists an optimal depth and radius of target to gain maximum neutron source by decreasing leakage and absorption and increasing interaction with target material. In the reported literature, spallation target is heated by about 70% beam energy with proton energy of 600 MeV and over 80% energy source of target comes from proton beam. Therefore sufficient cooling is urgent to remove the surgent to remove the Shetty, 2013

Many investigations into spallation targets have been carried out, related to liquid and various forms of solid targets, in which neutron production, angular distribution, energy deposition and radiation effect are dominantly concerned (Bauer, 2005, 2010; Ghorbanpour and Ghasemizad, 2015; Liu et al., 2014). Energy deposition is the critical issue in solid spallation target due to poor cooling of monolithic tungsten target. The monolith targets may be subjected to breakup and degradation under high power (Efthymiopoulos, 2011). Additionally thermal-hydraulic characteristics of tungsten target have been analyzed in (Ammerman et al., 2009). The concept of tungsten target with multiple segments is proposed by (Russell et al., 1995, 1997) which can decrease neutron absorption. Furthermore much work has been also conducted on liquid spallation target including window and windowless spallation target. Liquid lead bismuth alloy (LBE) is mainly selected as spallation material and coolant to study thermal-hydraulic characteristics (Mantha et al., 2006, 2007; Nelson et al., 2012; Wang et al., 2017). Transient heat transfer with different heat position yielded by different proton beam energy is calculated and analyzed in (Liu et al.,

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Table 1
Description of spallation targets.

Classification	Spallation material	Configuration	Coolant	Features/Issue
Solid Target	Lead, Tungsten, Uranium, Tantalum	Monolith/Segments	Heavy water/LBE	Stable configuration; Multiple spallation material; Lower sustainable power density; Higher thermal shock and stress, radiation swelling and rupture
Fluidized Target	Tungsten powder Stationary tungsten spheres Rotating tungsten cylinders Stationary tantalum spheres Moving tungsten spheres	Fluidized powder Pebble bed Granular flow	Tungsten powder He-gas stream Tungsten spheres	Multiple spallation material; Higher neutron production; Higher sustainable power density; Porous structure, power flattening; Lower thermal shock and stresses; No cavitation and phase change
Liquid Target	Liquid lead Mercury LBE	Heavy liquid metal	Liquid lead Mercury LBE	Higher sustainable power density; On-line purification and reloading; Remarkable corrosion, cavitation, shock waves and liquid leakage; Material compatibility, activation; Higher sealing requirement

2016). The flow pattern and free surface of ADS windowless target have been widely researched through experimental and numerical methods (Batta et al., 2014; Xiong et al., 2015). Recently, much attention has been focused on fluidized spallation target (Shetty, 2013; Zhang, 2016). Densham et al. have reviewed the requirements of fluidized powder target and suggested that tungsten powder could be used for fluidized powder target in MW-class application (Densham et al., 2009). Pugnat et al. have proposed a conceptual design in which stationary tantalum spheres with diameter of 2 mm are used for spallation target and efficiently cooled by helium-gas stream with high mass flow (Pugnat and Sievers, 2003). The essential parameters affecting cooling are analyzed for stationary target of tungsten spheres and rotating target of densely packed tungsten cylinders cooled by helium flowing with CFD porous model (Szabo, 2010). Besides, Table 1 presents some kinds of spallation targets distinguished by its configurations.

Particle transport in granular target suffers from dense gas-solid flow, helium and particles denoting continuous and discrete phase respectively. Due to complexities of transport and varieties of mechanism, numerical simulation dominates in understanding, design and optimization of granular target, in which two methods are predominantly employed (Traoré et al., 2015; Saidi et al., 2015). Euler-Euler algorithm derives from continuum model, in which the discrete phase is also regarded as continuum similar to continuous phase. This approach is clearly dependent on reliable models, which may be empirical formula or Kinetic Theory of Granular Flow. The inaccurate results may be attributed to far assumptions from actual mechanisms. The other is Euler-Lagrange method, in which the motion and force of single particle are calculated with newton's second law and contact force-displacement principle based on Discrete Element Method (DEM). The continuous phase is solved by CFD technique. The two phases are coupled mainly through drag force models and coupled energy. A large number of correlations have been thoroughly reviewed in literatures (Deen et al., 2007; Du et al., 2005; Feng and Yu, 2004). Due to the correlation of results with mechanical properties, effects of particle properties on results have been reviewed and analyzed (Paulick et al., 2015). Due to agreement with actual process, DEM has been extensively used for discrete phase since proposed by Cundall and Strack (1979). The detailed dynamics of individual particle can be gained with DEM, not with experiments or Euler-Euler method. Its powerful capability directs much attention towards coupling with CFD, and many investigators have implemented this algorithm for spouted beds, fluidized beds, riverbed deposit, seeders and etc. (Behnam et al., 2012; Chen et al., 2012; Karimi et al., 2012; Li et al., 2012; Patil et al., 2015). The coupled CFD-DEM approach is recognized as one of the best and most promising techniques to examine the behavior of particle-fluid flows. Many research findings have been published on CFD-DEM coupling. Heat transfer is predominantly resulted from particle-particle collisions, particle-wall collisions and particle-fluid heat transfer. Since the porosity of target is very low, thermal conductivity may be much stronger than convection (Rickelt et al., 2013).

In the present study, CFD and CFD-DEM algorithms are applied for simulations of liquid and granular spallation targets. Based on the energy deposition calculated with Monte Carlo Method, the cooling characteristics are researched on granular and liquid targets against the same studied domain.

2. Model

2.1. CFD model

With the improvement of computer technology and numerical algorithm, CFD has been an attractive and indispensable approach, which can be applied to many industries. Based on three conservation equations, the flow field of continuum is predicted. The basic equations with porosity ε are given by:

Continuity Equation:

$$\frac{\partial}{\partial t}(\varepsilon\rho_g) + \nabla(\varepsilon\rho_g\overrightarrow{u_g}) = 0 \tag{1}$$

Momentum Conservation Equation:

$$\frac{\partial}{\partial t}(\varepsilon\rho_g\overrightarrow{u_g}) + \nabla(\varepsilon\rho_g\overrightarrow{u_g}\overrightarrow{u_g}) = -\varepsilon\nabla P + \varepsilon\rho_g\overrightarrow{g_g} + div(\mu\cdot grad\overrightarrow{u_g}) + S_u \tag{2}$$

Energy Conservation Equation:

$$\frac{\partial}{\partial t}[\varepsilon\rho_g\cdot T] + div(\varepsilon\rho_g\cdot\overrightarrow{u_g}\cdot T) = div\left(\frac{k}{c_p}\cdot gradT\right) + \frac{S_T}{c_p} \tag{3}$$

where ε, ρ_g and $\overrightarrow{u_g}$ represent porosity, density and velocity vector respectively; P, $\overrightarrow{g_g}$, μ and S_u denote pressure, gravity acceleration, dynamic viscosity and momentum source term respectively; T, k, c_p and S_T are temperature, thermal conductivity, specific heat capability and energy source term separately.

Due to little effect of helium flow on particle transport, laminar model is additionally introduced to solve continuous phase. And the relevant models and algorithm in CFD method are not shown in the present study.

2.2. DEM model

The DEM method was originally proposed by Cundall et al. and then further perfected (Tsuji et al., 2008). Every particle within computation