Annals of Nuclear Energy 122 (2018) 118–124

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

The packing factor of the pebble bed in molten salt reactor

Xingwei Chen [a,b,c], Yang Zou [a,b,c,*], Rui Yan [a,b], Fengrui Liu [a,b], Jie Zhang [a,b,c], Mudan Mei [a,b], Xiangzhou Cai [a,b,c,*]

[a] Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[b] CAS Innovative Academies in TMSR Energy System, Shanghai 201800, China
[c] University of Chinese Academy of Sciences, Beijing 101408, China

ARTICLE INFO

Article history:
Received 19 April 2018
Received in revised form 4 August 2018
Accepted 6 August 2018

Keywords:
Molten salt
Pebble bed reactor
Packing factor

ABSTRACT

Many concepts of molten salt cooled pebble bed reactor have been developed in recent decades. The packing factor (PF) of the pebble bed in the molten salt reactor should be investigated because it is of great importance for reactor design. Model experiments based on the solid fuel thorium-based molten salt reactor (TMSR-SF) were performed. Experimental results show that the PF of the pebble bed in TMSR-SF (D = 21d, H = 18d, d is pebble diameter) is about 0.57 ± 0.02. The pebble bed in liquid environment is looser than that in dry condition. The PF increases with the diameter of the reactor core and the height of the pebble bed. The geometry of the lower cone reflector may induce large variety of packing factor if the angle of reflector is smaller than the angle of repose of the pebble bed. The loading rate and flow velocity in TMSR-SF are considered to be of little influence on PF. Results from the experiments will be of reference value for the design of reactors.

1. Introduction

The manifestation of climate change is being increasingly addressed on the global stage. Nuclear power may satisfy an increasing world energy demand while conserving the climate and natural resources. The Generation IV International Forum (Pioro, 2016) has selected six reactors from 130 reactor concepts as next generation nuclear energy systems. Generation IV designs will use fuel more efficiently, reduce waste production, be economically competitive, and meet stringent standards of safety and proliferation resistance.

Molten salt reactor (MSR) is one of the six reactor technologies and solid fueled molten salt reactors are a nearer term molten salt reactor option (Serp et al., 2014). Solid fueled molten salt reactors feature low-pressure liquid fluoride salt cooling, coated particle fuel, a high-temperature power cycle, and fully passive decay heat rejection (Aufiero and Fratoni, 2016). Several designs have been proposed during the past decades (Clarno et al., 2007; Zweibaum et al., 2014; Qualls and Betzler, 2016). Chinese Academy of Science (Cai et al., 2017) launched the "Thorium Molten Salt Reactor Nuclear Energy System" project in 2011, the solid fuel thorium-based molten salt reactor (TMSR-SF) is one of the reactor types that being proposed for realizing effective Thorium energy utilization and hydrogen production by nuclear energy within 20–30 years.

The pebble bed in TMSR-SFs is a unique reactor design that utilizes spherical fuel elements that are not fixed in-core (Chen et al., 2018). In TMSR-SFs (Lin et al., 2017), fuel pebbles are 6 cm or 3 cm diameter in diameter. Fuel pebbles are loaded from the bottom of the reactor cavity and float in molten salt, and finally settle at the top part of the core. Thousands of fuel pebbles packing randomly in a cylindrical reactor cavity to form a pebble bed. The molten salt goes through the gaps between pebbles and takes the heat away. Therefore, the heat transfer is sensitive to the placement of pebbles.

Knowledge of the packing's characteristics and the fuel pebble's behavior is important for reactor design. The packing factor (PF), which is one of the key parameters for describing packing structure of pebble bed, has great effects on the design of core neutronics (Gong et al., 2017; Auwerda, 2010). It also influences the effective thermal conductivity of pebble bed, the burnup of the fuel pebbles, the heat transfer throughout packed pebble bed and the flow characteristics of molten salt. In reactor design and operation even small variations of the PF could be of strong influence. Therefore the PF is an important design parameter that must be known.

Over the years several studies have been performed to measure the PF (or void fraction) in cylindrical packed beds of small monosize spheres (Golovanevskiy et al., 2011). Experiments show that the PF is influenced by many factors, such as the column-to-particle diameter (D/d) ratio, the height of a packing bed, filling

* Corresponding authors at: Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China.
E-mail addresses: zouyang@sinap.ac.cn (Y. Zou), caixz@sinap.ac.cn (X. Cai).

https://doi.org/10.1016/j.anucene.2018.08.011
0306-4549/

process and so on (Benenati and Brosilow, 1962; Chen et al., 2006). Scott and Kilgour (2002) point out that the PF of an infinite cylinder could be 0.6366. In addition, there are also some studies for the gas cooled pebble bed reactor by means of numerical simulation or experiments (Keppler, 2013; Yang et al., 2012; Von Der Decken, 1972). The PF of the gas cooled pebble bed reactor is generally considered to be 0.60 or 0.61 (Kadak and Bazant, 2004; Jing et al., 1994; Li and Ji, 2015). The coolant and pebble interactions were usually being neglected since the pebble bed is barely changed by the coolant.

However, the results cannot be applied to TMSR-SFs directly. Because there is molten salt filled the gaps between fuel pebbles. Moreover, the way pebbles load is unique. Thus studies that used Magnetic resonance imaging (MRI) techniques to probe structure-flow correlations of a packed bed of ballotini also are not applicable to TMSR-SFs (Sederman 1997). Related studies (Laufer, 2013) based on fluoride-salt-cooled high-temperature reactors (FHRs) are published in recent years. Bardet (2007) poured the polypropylene spheres inside a dry cylindrical tank. The tank was then filled with water, and the pebbles floated against a flat perforated reflector. The PF is measured to be 60 ± 1% at D/d = 16. While simulation of the experiment that performed by Li and Ji (2011) showed that the actual PF in the cylindrical middle core region is 62%; owing to the densification effect of buoyancy.

The PF is a well understood in gaseous environments; however, the PF in a molten salt cooled pebble bed reactor still needs to be exploited. The basic objective of this study is to analyze the PFs and its variation range in pebble bed reactor. Therefore, experimental facilities that simulate pebble bed reactor have been constructed, and experiments are performed with different influence factors, such as the geometry of a reactor core, flow velocity, loading rate. The experiment results obtained from this work will provide data support for the reactor design.

2. Experimental facilities and method

2.1. Scaling analysis

Large numbers of investigations are required to obtain sufficient data of the PF of the pebble bed. It is quite clear that the investigations cannot be done by utilizing full-scaled experiments with molten salt and graphite pebbles. In order to be able to extrapolate from the results of model experiments to reactor conditions, similarity laws should be considered in the design of model experiments. To transit from a granular system to a scaled system (Pöschel et al., 2001), the necessary scaling parameters are as follows: all length, acceleration, friction coefficient, elastic constant.

In the model experiments, Water and polypropylene spheres were used to simulate the molten salt and fuel pebbles. To keep the same gravitational field, the density ratio of the pebble to the water is equivalent to that of fueled TRISO pebbles and molten salt. The diameters of pebbles are scaled in accordance with the facility. In addition, similar loading patterns were applied in the experiment, in which pebbles were injected from the bottom of the reactor core.

Frictional forces are the main force between pebbles. The static coefficient of friction between fuel spheres lubricated by a molten salt is approximate to be 0.25, while the coefficient of friction between dry polypropylene is approximately 0.29 (Buster et al., 2016). It may be smaller because the fluid provides lubricity. But experiments conducted in a column with water showed that there is no obvious difference between pebble beds with grinding ball and smooth ball. The elastic constant of graphite fuel spheres in an actual reactor system is unknown. It is considered that the distortion caused by elastic constant are deemed to be acceptable. Results from the model experiments can be of reference value for the design of reactor.

Moreover, the hydrodynamic behavior of pebbles, which has influence on the formation of the pebble bed, can be reproduced by matching the drag and buoyancy force on the pebbles during loading process. In order to obtain result more equivalent with that in TMSR-SF, the Reynolds number, Froude number and pebbles to fluid densities ratio are matched and a 1:2 scaled experiment device was designed.

2.2. Experimental facilities

Several facilities based on TMSR-SF are devised for the experiments. The sketches of the facilities are presented in Fig. 1 and the parameters are listed in Table 1. The reactor core model (RCM, see in Fig. 1a) and columns are used to study the influence factors of the PFs in reactor core. While the pebble recirculation experiment device (PRED, see in Fig. 1c), which is a 1:2 scaled model of TMSR-SF, is aimed to provide the PFs for the design of reactor Table 2.

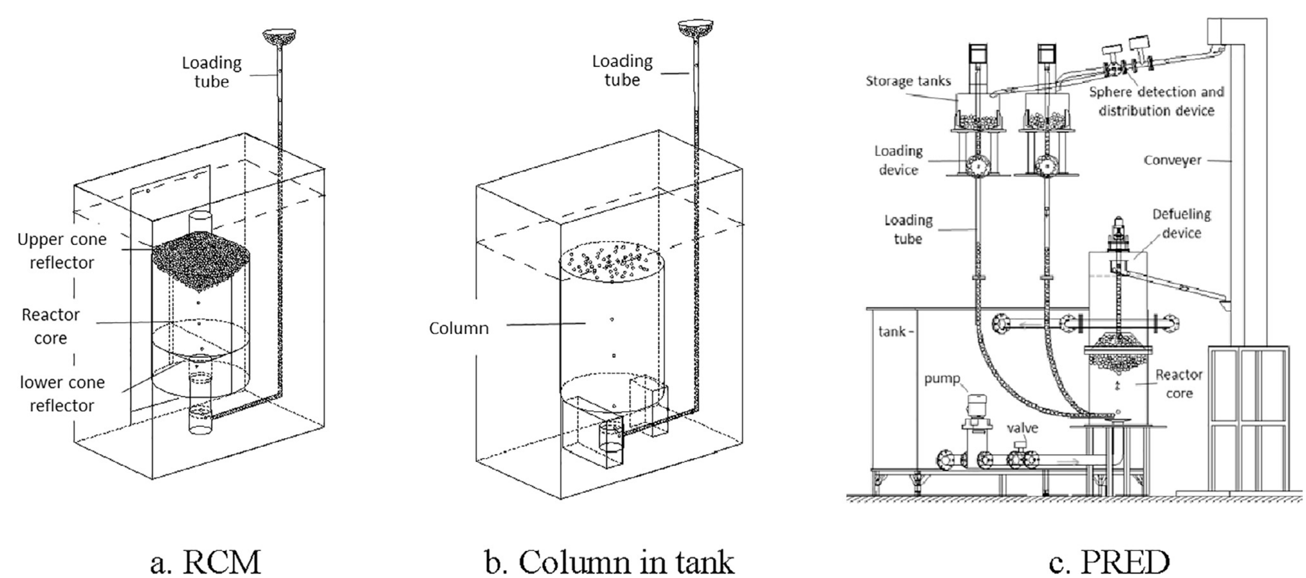

Fig. 1. Experimental facilities.