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Experimental investigation of the bed structure in liquid salt cooled pebble bed reactor

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A B S T R A C T

Based on the advanced high temperature reactor (AHTR), which is an advanced concept combining attractive attributes by adopting liquid salt and coated particle fuel, more and more reactor designs that use fuel pebbles are developed. The bed structure in liquid salt cooled pebble bed reactor is important for reactor design. To investigate the bed structure in the reactor, the Pebble Recirculation Experiment Device (PRED) and the Pebble Bed Dense Experiment facility (PBDE), which were mock-ups for TMSR-SF (Thorium-based Molten Salt Reactor with Solid Fuel) were developed. Packing experiments were performed under different conditions. The results show that, the packing factor of TMSR-SF is supposed to be about 0.574, which is much less than 0.60 in gaseous environment; the loading rate of pebbles and the velocity of inlet flow has great effect on the bottom shape of the pebble bed; the structure of the pebble bed remains stable during normal operation and changes under accident conditions; loss of the coolant in the core may cause rearrangement of pebble bed; increase in packing factor that caused by strong vibration may induce reactivity in reactor core. The pebble bed behavior under different conditions that investigated in this paper provides the basis phenomenological analysis for reactor design. Moreover, the running of PRED demonstrates the feasibility of the methods for pebble loading and defueling in liquid salted cooled pebble bed reactors.

1. Introduction

The molten salt cooled reactor is one of the six candidates for the next generation nuclear power plants. The advanced high temperature reactor (AHTR) which combine attractive attributes by adopting low pressure liquid salt, high temperature coated particle fuel from previously developed reactor was put forward (Peterson, 2003), the concept developed in recent years and several designs which adopt fuel pebbles such as PB-AHTR (pebble bed advanced high temperature reactor), FHR (Fluoride-salt-cooled High temperature Reactor) have been formed. The Shanghai Institute of Applied Physics (SINAP) has focused its efforts to develop TMSR-SF (Thorium-based Molten Salt Reactor with Solid Fuel), which is also designed to be a liquid salt cooled pebble bed reactor. Low pressure, liquid coolant and large fuel thermal margins are significant advantages of the technology.

There are usually thousands of fuel pebbles packing randomly in a reactor core, with liquid salt flows through the gaps between pebbles to take heat away. The structure of pebble bed in liquid salt is not well defined as it changes with reactor operating conditions due to the stochastic nature of the pebble bed. The uncertainty of pebble bed brings uncertainty of fuel burnup history and power distribution, which leads a great deal of uncertainty to the generation of decay heat, and the distribution of coolant. These uncertainties have great influence on the reactor physical parameter including the highest temperature of fuel pebbles. The packing structure of the pebble bed is the basis of a reactor design, such as neutron physics, thermal hydraulic and fuel management. If we don't have adequate acknowledge of the pebble bed structure, there may be some unexpected situation that affects security and economy of the reactor core. Thus, it is necessary to investigate the pebble bed under different situations including normal condition and accident conditions.

Several studies have been conducted on the packing behavior of the pebble bed in gaseous environments since the 1950s (Benenati and Brosilow, 1962; Yang et al., 2012; Decken, 1972), the pebble flow experiments mainly based on gas cooled pebble bed reactor, such as AVR, PBMR and HTR-10. The interaction between pebbles and gas flow is

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seldom considered since the interaction force is relatively small. While in the liquid salt cooled pebble bed reactor, fuel pebbles float in the reactor core due to the positive buoyancy of the pebble bed in molten salt, fluid should be considered because it flows through the pebble bed and has great influence on the structure of the pebble bed. Experiments (Bardet et al., 2007; Laufer, 2013) based on AHTR are conducted with plastic spheres and water as fuel pebbles and molten salt respectively, and provide a preliminary analysis of the structure and the packing factor of a pebble bed. But so far there is little information on the stability of the pebble bed in process of reactor operation since there is no integrated model of pebble recirculation system.

Noticed and motivated by the needs of the design of molten salt cooled pebble bed reactor, this study aims to show and demonstrate the pebble bed behavior in process of operation including pebble loading, normal condition, accident condition. To accomplish this, scaled models based on TMSR-SF are constructed to simulate the pebble bed under different conditions, the stability of pebble bed and the influence factors are analyzed in this paper, which provides a theoretical basis for reactor design. In addition, we will introduce a successful method for pebble recirculation in liquid that has never been presented before.

2. Experimental facilities

2.1. Scaling of hydrodynamic phenomena in the bed

Scaled experiments are usually conducted to study the behavior of pebble bed under various operational or accidental conditions, because it is difficult to carry out experiments in the core full of molten salt. As mentioned in Alain Griveau's report (Griveau, 2007), in order to reproduce the hydrodynamic behavior of pebbles in liquid flows, the drag and buoyancy force on the pebbles must be matched. Hence, for pebbles dynamics scaling, the Reynolds number, Froude number and pebbles to fluid densities ratio must be matched. This study is fully adequate to investigate the physics of pebbles during refueling/defueling, but lacks some elements to understand fully the dynamics of the pebble bed motion as the friction of pebbles in the molten salt is unknown.

Water and PP (polypropylene) spheres are used in the scaled experiment to simulate molten salt and fuel pebbles, with the viscosities and densities of Flibe molten salt at 650 °C and of water at 20 °C. We can obtain that the experimental setup has a reduced length scale of 44.1%, and a coolant velocity reduced to 66.4%. For salt temperatures ranging from 600 °C to 850 °C, the density ratio of pebble to salt ranges from 0.846 to 0.971. Both high- density PP with the density of 0.910 and low-density PP with the density of 0.845 are used in the experiment respectively to match with the density ratio in TMSR-SF.

2.2. PRED

The Pebble Recirculation Experiment Device (PRED), shown schematically in Fig. 1, is 46.6% scaled model of the TMSR-SF, it consists of reactor core model, two storage tanks, two loading devices, defueling device, conveyer device, and pebble distribution device and water loop. The PRED is constructed to confirm the feasibility of the pebble recirculation in liquid salted cooled beds at the beginning of the project and conduct pebble flow experiments.

The reactor core model (see Fig. 2(a)) is a 63 cm diameter, 84 cm high cylindrical, clear acrylic tank, two pebble loading tubes from the loading devices insert into the bottom center of the tank. A cone reflector, shown in Fig. 2(b), is fixed in the tank to form 84 cm high active core area which can be filled with pebbles. The cone reflector with 45° angle is perforated with 1 cm diameter holes to allow water flow to pass through while blocking the pebbles, the total open area is 35%.

The rotary defueling tube is located right above the active core, the lower portion of the defueling tube goes through the hole at the center of reflector and inserts into the pebble bed, there is an elbow at the end of the tube to guide pebbles in, and a discharge hole at the top of the tube to eject pebbles (see Fig. 2(c)). The upper portion of the defueling tube inserts into the discharge chute which connects to an inclined tube for pebble discharge. The length of the defueling tube was designed according to the density ratio in order to empty the tank. At equilibrium, it can be observed that the buoyancy forces of pebbles in the defueling tube are strong enough to push 3–4 pebbles above the liquid free surface. When the electric motor at the top end of the defueling tube starts running, pebbles enter into the rotating defueling tube, move upward and then exit from the tank one by one.

The pebble recirculation process is as follows: The liquid level was controlled at a certain height with the variable frequency pump and the pressure sensor in the water loop. Then pebbles stored in the tank fell down the loading tube when the loading device started running. Once the gravity of pebbles in the tube became larger than the buoyancy of the pebbles immersed in water, pebbles injected one by one into the bottom chamber of the reactor core, and then moved upward by buoyancy. When the defueling device started running, pebbles get out of the core through the rotating defueling tube, and then the pebbles will be transferred to the storage tanks at the top via adjustable speed conveyor. The PRED can meet the requirements of both online refueling and shutdown refueling, with a controlled defueling rate of up to 900 per hour, and an adjustable loading rate of 0–2400 per hour. Table 1 shows the parameter of PRED, the diameter of PP spheres is 3% larger than required by the scaling, and the pebble size distortion results in mismatch of the Froude and Reynolds numbers on the order of 3%.

The experiments conducted on PRED include: Packing behavior in process of loading as described in Section 3.1; Pebble bed during normal condition as described in Section 3.2; pebble bed during drops of liquid level caused by an accident as described in Section 3.3.1.

2.3. PBDE

The PRED does not apply to run experiments under the seismic condition or at large flow velocity. Therefore, Pebble Bed Dense Experiment facility (PBDE) which is 1:4 scaled model with vibration table is built for seismic simulation tests and experiments with large velocity. The Schematic representation of PBDE is shown in Fig. 3(a). The facility comprises: reactor core model, loading tube, vibration table, water loop, and pressure instrument, as shown in Fig. 3(b). The parameters are shown in Table 1.

The experiments conducted on PBDE are mainly focused on the pebble bed under accident conditions, such as flow velocity change as described in Section 3.3.2; earthquake accident as described in Section 3.3.3. In addition, the packing factor of a randomly packed bed which is defined to be the ratio of pebbles volume to total volume was also measured in PBDE, since the cone reflector above the tank is adjustable and it is easier to get the packing factors with different loading methods, the result is shown in Section 3.2.

3. Experimental results

3.1. Pebble bed during pebble loading process

When pebbles were loaded into the tank, they rose up by buoyancy and then landed on the bottom of the bed. The flow path and the position where pebbles landed on presented certain randomness, but also had certain regularity. The figure gives a clear graphical representation of the streamline trajectory by recording the positions of pebbles at different times, as shown in the Fig. 4. The streamlines do not vary from a straight line by more than 3d (pebble diameter).

The water flow has influence on the bed structure. When there is no water flow, it is clear that pebbles float up with a lateral diffusion within 3d distance at speed of 0.19 m/s. Hence the bed geometry tends to be a cone-shape with angle of repose from 20° to 28° since the pebbles are injected from the center of the bottom of the reactor. However, when there is water flow, especially when the flow in the