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# Experimental study of flow field characteristics on bed configurations in the pebble bed reactor

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ABSTRACT

The flow field characteristics are of fundamental importance in the design work of the pebble bed high temperature gas cooled reactor (HTGR). The different effects of bed configurations on the flow characteristics of pebble bed are studied through the PTV (Particle Tracking Velocimetry) experiment. Some criteria, e.g. flow uniformity ($\sigma$) and mass flow level ($\alpha$), are proposed to estimate vertical velocity field and compare the bed configurations. The distribution of the $\Delta\theta$ (angle difference between the individual particle velocity and the velocity vector sum of all particles) is also used to estimate the resultant motion consistency level. Moreover, for each bed configuration, the thickness of displacement is analyzed to measure the effect of the funnel flow zone based on the boundary layer theory. Detailed information shows the quantified characteristics of bed configuration effects on flow uniformity and other characteristics; and the sequence of levels of each estimation criterion is obtained for all bed configurations. In addition, a good design of the pebble bed configuration is suggested and these estimation criteria can be also applied and adopted in testing other geometry designs of pebble bed.



## 1. Introduction

It is generally known that the high temperature gas-cooled nuclear reactor is considered as one potential solution for the generation IV (the fourth generation) advanced reactor (Magwood IV, 1996). The Institute of Nuclear and New Energy Technology (INET) at Tsinghua University has developed the HTR-PM (High Temperature Reactor – Pebble bed Modules) (Wu et al., 2002; Zhang et al., 2002, 2004), which has been regarded as one of the National Special Grand Science-Technology Projects of China (Zhang and Yu, 2002; Zhang et al., 2006; Sui et al., 2014). The mechanisms and characteristics of the pebble-bed reactor have drawn great attention. Some countries, such as South Africa (Koster et al., 2003) and the United States (Berte, 2004), have developed their own test and demonstration reactors (PBMR, (Pebble Bed Modular Reactor), and MPBR (Modular Pebble Bed Reactor), resp.) and their prototype reactor, for example, the AVR (Arbeitsgemeinschaft Versuchsreaktor) early in Germany, and so forth (Schulten, 1978).

The basic mechanism of granular flow has not been fully understood yet, especially this specific pebble flow in the reactor core. However, the flow field characteristic is vital to the efficiency and safety of HTGR. Pebbles' behavior should be insured to fulfill thermal hydraulic rules and radiation safety requirements (Jiang et al., 2012). In the reactor core of HTR-PM (Auwerda et al., 2010), the pebbles are flowing greatly slowly which are driven by gravity, termed as a quasi-static flow regime. The particles are dumped from the outlet at the bottom, and reloaded at the top of the reactor core, forming a recirculation mode of operation. In this recirculation process, the velocities of particles throughout the bed are varied greatly, relying on the bed configurations, loading method, and etc. In common, particles flow fast in the central part and slowly near the wall. The uniformity of pebble flow is of crucial importance for the performance and safety of reactor operation, which should be focused in reactor core design work (Gui et al., 2014).

Although experimental and numerical studies (Li et al., 2005) have been done on the flowing characteristics in silo bed of different geometries, those cases mostly belong to the free outflow and focus on the prediction of outflow rate (Balevičius et al., 2011; González-Montellano et al., 2011b; Oldal et al., 2012; Albaraki and Antony, 2014). Other relating studies have also been carried out, contributing to various related aspects of them such as velocity profiles (Choi et al., 2005; Li et al., 2009; Kim et al., 2013), phenomenological analysis (Yang et al., 2012), stagnant

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zones (Jia et al., 2014), diffusion and mixing (Choi et al., 2004), as well as numerical simulations (Goda and Ebert, 2005; Gui et al., 2014), etc. However, few of them have carried out experiment investigations on the effect of bed configuration under the recirculation operation, especially with the contraction configuration at the bottom of the pebble bed, as well as the flow uniformity and the very slow region (the funnel flow regime) in such kinds of configurations.

Mass flow index (MFI) is introduced as a quantitative way to evaluate the radial flow uniformity (Johanson, 1964; González-Montellano et al., 2011a, 2012), considering a simple index to recognize the mass and funnel flow regime (Langston et al., 1995) in the silo pebble flow. The pebbles move rapidly in the mass flow regime locating in the central part of pebble bed, as while funnel flow stays nearly stagnant near the walls and corners. That is to say, the pebbles firstly loaded will be discharged firstly in the middle region, but lastly in the near-wall region. The occurrence of the two regimes is analogous with the field of boundary layer theory (Schlichting et al., 2000) in fluid mechanics, although the physics of fluids is fundamentally different from the granular media. Nevertheless, the rich body of work devoted to the analysis of the boundary layer characteristics (such as displacement thickness, momentum thickness) and the work relating to the analysis and design of contraction pipes (for instance, the wind tunnel, (Morel, 1975; Doolan and Morgans, 2007)), is similar with the base configuration of the pebble bed. These works provide a suitable framework to be applied to characterize the pebble flow regime and the near-wall flow behaviors.

Furthermore, the Relaxation Method (RM) PTV is based on the use of iterative relaxation process technique and it is widely applicable to complex flows with local rotating and shear motions (Ohmi and Li, 2000). In RM, as the reference particle selected by the quasi-rigidity radius finds many neighbors flowing similarly, the positive estimate of such movement is increased. The most important advantage of this relaxation method is that the examination is on the basis of the probability of particle matching between the first and the second frames, defined for every possible pair of particles inclusive of the probability of those being no-matched (or the probability of the loss of partners). Fortunately, it is suitable to measure the 2-D flow regime of very slow and dense granular flow here since there exist particles which will disappear when they are flowing towards the outlet.

Since the frictional and hard-core inelastic interactions between particles in the near-wall pebble flow have common characteristics with the molecular interactions in a fluid (Radjai and Roux, 2002). Motivated this consideration, this study aims to analyze the particle motion in the near-wall region with analogy to the boundary layer theory, and demonstrate some typical results on the bed configuration effect. Besides, the snapshots of the flow regimes and velocity profiles with different bed configurations will be shown. In addition, the whole velocity uniformity will be analyzed with different estimation criteria.

## 2. Methodology

### 2.1. Experimental Set-up

In this study, a 2-D test facility is designed based on a real pebble-bed reactor at Tsinghua university with the scale of 1:5 (Fig. 1a). The experimental setup consists of several main parts. Firstly, the vessel is made up of Plexiglas which has the dimensions of 800 * 1000 * 120 mm in width, height, and thickness, respectively. About 70000 black glass pebbles with the diameter 12 mm

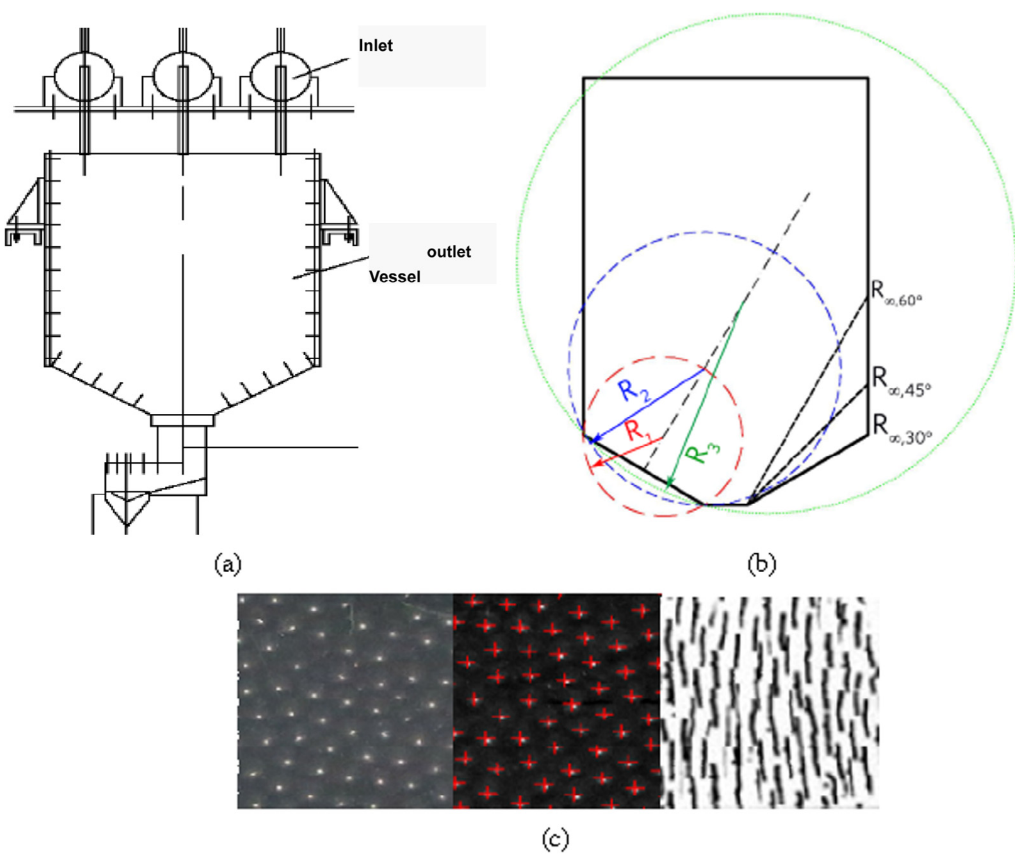


**Fig. 1.** Sketch of experiment setup and images. (a) The experiment setup; (b) Different bed base configurations. (c)The experimental images of particles (left inset), the locations of the particles marked by the red crosses (middle inset), and the trajectories of individual particles (right inset).