NUCL SCI TECH (2016) 27:31
DOI 10.1007/s41365-016-0048-z

# Development of an innovative detection system for pebble bed kinematic studies

Ying Zhao[1,2] · Shi-Xiang Qu[1] · Xing-Wang Zhu[1] · Shi-Wei Shao[1] · Zhao-Zhong He[1] · Kun Chen[1]

Received: 29 April 2015 / Revised: 25 August 2015 / Accepted: 28 August 2015 / Published online: 6 April 2016


**Abstract** Pebble bed reactors enable the circulation of pebble fuel elements when the reactors are in operation. This unique design helps to optimize the burnup and power distribution, reduces the excessive reactivity of the reactor, and provides a mean to identify and segregate damaged fuel elements during operation. The movement of the pebbles in the core, or the kinematics of the pebble bed, significantly affect the above features and is not fully understood. We designed and built a detection system that can measure 3-axis acceleration, 3-axis angular velocity, 3-axis rotation angles, and vibration and temperature of multiple pebbles anywhere in the pebble bed. This system uses pebble-shaped detectors that can flow with other pebbles and does not disturb the pebble movement. We used new technologies to enable instant response, precise measurement, and simultaneous collection of data from a large number of detectors. Our tests show that the detection system has a negligible zero drift and the accuracy is better than the designed value. The residence time of the pebbles in a moving pebble bed was also measured using the system.

**Keywords** Pebble bed · Nuclear reactor · Kinematics · RFID · Detector

Supported by the "Strategic Priority Research Program" of the Chinese Academy of Sciences (Grant No. XDA02050100).

✉ Kun Chen
chenkun@sinap.ac.cn

1 Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Jiading Campus, Shanghai 201800, China

2 University of Chinese Academy of Sciences, Beijing 100049, China

## 1 Introduction

High-temperature gas-cooled reactors and fluoride salt-cooled high-temperature reactors are two types of advanced reactors [1]. These reactors, when using pebble-shaped fuel elements, may also be called pebble bed reactors. In a pebble bed reactor, a fissile material kernel is usually coated with multiple layers of carbon and silicon carbide to form tri-structural-isotropic (TRISO) fuel particles. The TRISO particle has very high failing temperature and extremely low release rate of radioactive materials from its kernel. Tens of thousands of TRISO particles are embedded in a spherical graphite matrix to form a fuel element or a pebble [2]. The pebble may be loaded and unloaded from the reactor core using a pebble circulation machine when the reactor is in operation [3]. In the fuel circulation, one can check the burnup and the integrity of each pebble and may discard unwanted pebbles or supply new pebbles to the reactor when the reactor is running at full power. This online circulation of fuel pebbles gives a pebble bed reactor several unique features. The online refueling process can optimize the burnup and power distribution of the core so that the fuel can be used more efficiently. The online refueling helps to reduce the excessive reactivity required when starting up the reactor because fresh fuel can be added continually. One can also identify a damaged fuel pebble and remove it from the core during the online refueling process.

In a pebble bed reactor, the pebbles are often randomly stacked to form the bed. Reactor coolant is pumped through voids between the pebbles to carry the fission heat out of the core. Reactivity control elements, such as control blades and rods, may be inserted into the bed to shut down the reactor. Because of the online refueling, the position of each pebble and the arrangement of the pebble bed changes gradually. The interaction between pebbles and the coolant, and between pebbles and the control blades also affects the movement of the pebble bed. Understanding pebble bed movement, or the kinematics of the pebble bed, is important, as it helps to estimate the burnup of the fuel and the core power distribution, and it can also support the design of refueling strategies.

Normally, velocity, acceleration, angular velocity, residence time distribution, radial pebble zoning and pebble mixing, and stagnant zones (if any) are relevant parameters of the kinematics of a pebble bed [2–5]. The kinematics of a pebble bed, however, are not yet fully understood. Because of the high temperature and strong radiation, it is difficult to conduct experiments in a reactor to develop a better understanding of the pebble bed. Hence, computer simulations and surrogate experiments are common options for studying a pebble bed.

There are several computational approaches available, such as the discrete element method (DEM) and the coupled DEM and computational fluid dynamics (CFD) method [6–12]. In the DEM, each pebble is accurately modeled as a sphere undergoing realistic frictional interactions with other pebbles. Compared to the traditional DEM, the coupled DEM–CFD takes the coupled fluid drag forces on the pebbles into consideration.

Surrogate experiments provide useful insight into a pebble bed. In addition, experimental investigations can validate simulation methods, such as the DEM. There have been many experiments conducted to understand pebble bed kinematics using different methods, including optics-based techniques, the radioactive particle tracking method, and digital X-ray tomography [2, 3, 13–15]. The optical tracking method observes pebble behaviors through transparent experimental setups. For example, Kadak and Bazant have done scaled-down experiments with plastic beads to study the streamlines of the flow and the relative velocities of pebbles of different radii in a full three-dimensional bed and a half bed [4]. Tsinghua University has built an experimental installation to verify the feasibility of a two-region-design pebble bed reactor.

Digital X-ray tomography can image pebbles, regardless of their positions in the bed. For example, Laufer et al. [2] have completed the construction of an X-ray pebble recirculation experiment (X-PREX). Data collected by the X-PREX can be used to validate the three-dimensional DEM model. Experiments using digital X-ray tomography have also been conducted in T.U. Delft [15–17].

Though optical tracking, radioactive particle tracking and X-ray tomography are useful and have their advantages. These methods also have some limitations. For example, experiments using optical tracking can only track detailed local pebble motion at the surface of a bed. The information related to the interactions taking place deeper in the bed is lost. X-ray tomography, on the other hand, is too slow to do a real-time tracking. It usually collects data from an almost static bed. Radioactive particle tracking has been adopted to study a pebble bed, but its position reconstruction accuracy needs to be seriously improved.

In this paper, we introduce a new detection method using pebble-shaped detectors. The system contains pebble-shaped detectors, a receiver communicating with the detectors, and a control computer with advanced control software. Compared to other methods developed in the past, this system can record 3-axis angular velocity, 3-axis acceleration, posture, vibration, and temperature of each pebble in real time. Additionally, it is able to collect data in the bulk from the whole bed, regardless of the pebble position. Since the detectors are carefully designed to mimic the surrogate fuel pebbles, they do not cause distortions of the pebble bed kinematics. The detectors can be used with fluid coolants. The information of a single pebble is completely recorded and ready to be processed. Experimental data collected by this system can be used to analyze the net force, the torque, and the motion of the pebbles. The data can also be used to validate and complement results obtained from other experimental methods and simulations.

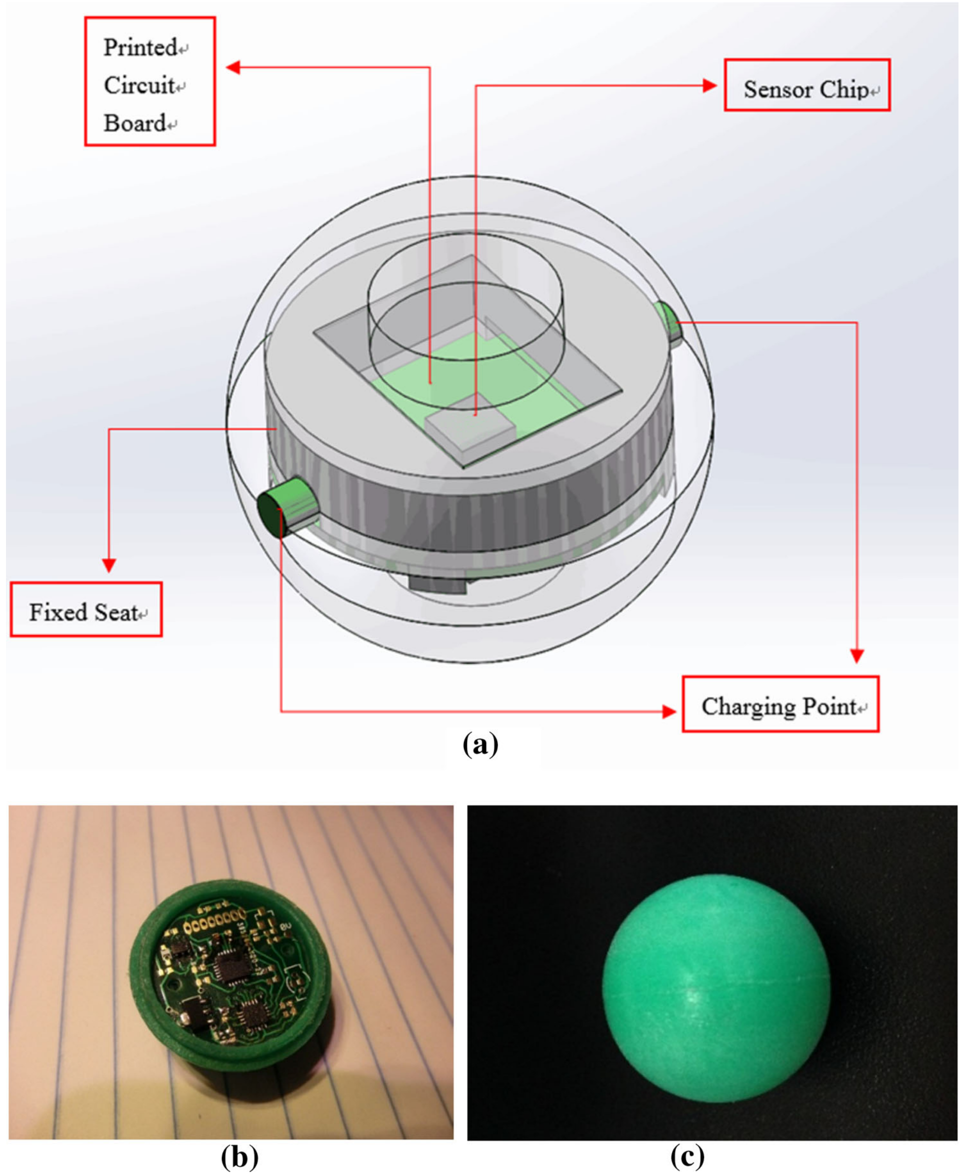
## 2 System description

Most of the experiments that study pebble beds employ plastic pebbles or glass beads instead of graphite pebbles in order to reduce the costs. The plastic pebbles and glass beads are designed based on scaling analysis so that the experiences gained from the surrogate experiments can be applied to the pebble bed reactors. We designed the pebble-shaped detectors to be the same as the plastic surrogate pebbles in terms of size, weight and shell material. The detectors can mix with other pebbles, or dummy pebbles, to form the pebble bed and to perform the experiments.

The shell of the detector is made of polypropylene, a commonly used material for surrogate pebbles. The detectors have different sizes, 6 cm and 3 cm in diameter, in order to simulate different pebble fuels. In order to ensure the weight of the detector is the same as the dummy pebble, a special internal structure is designed as shown in Fig. 1a. This structure also ensures the detector is waterproof.

The detector has a microchip that can collect 3-axis angular velocity, 3-axis acceleration, and the posture of the detector. The detector is equipped with a communication module that uses active radio frequency identification (RFID) technology [18]. Data collected by the detector can be transmitted to a receiver via radio waves and processed by software. The wireless communication module and its

Fig. 1 Sketch of assembling for the pebble-shaped detector (drawing is not to scale) (**a**) and internal and external of a detector (**b**, **c**)




antenna are carefully optimized for better performance in the pebble bed. We use 2.4 GHz and 433 MHz frequencies for different experiments. The detector also contains flash memory, a thermistor and a rechargeable battery, as shown in Fig. 1b, c.

When the receiver picks up the signals from the detectors, it sends them to a computer via a universal serial bus (USB) connection. The control software on the computer saves the data and provides basic data processing functions. The detection system is capable of handling tens or hundreds of detectors simultaneously. Figure 2a shows a working diagram of the system. Figure 2b shows a picture of the detectors. Figure 2c shows the user interface of the control software. Table 1 lists the major parameters of the system.

## 3 System performance

We conducted tests to verify the performance of the system. The system contains a total of 34 detectors. When the detectors are static, the accelerations should be equal to gravity and the angular velocity should be zero. Figures 3 and 4 show the acceleration and the angular velocity measured by each detector. The results show that all the detectors have a negligible zero drift.

We also tested the system with a special rotary to verify the accuracy of the measurements. We adopted a high precision servomotor to drive the rotary and a certified tachometer to calibrate the speed of the rotary. As shown in Fig. 5, the detectors were fixed on the edge of rotary. The distance between the detectors and the center of the rotary

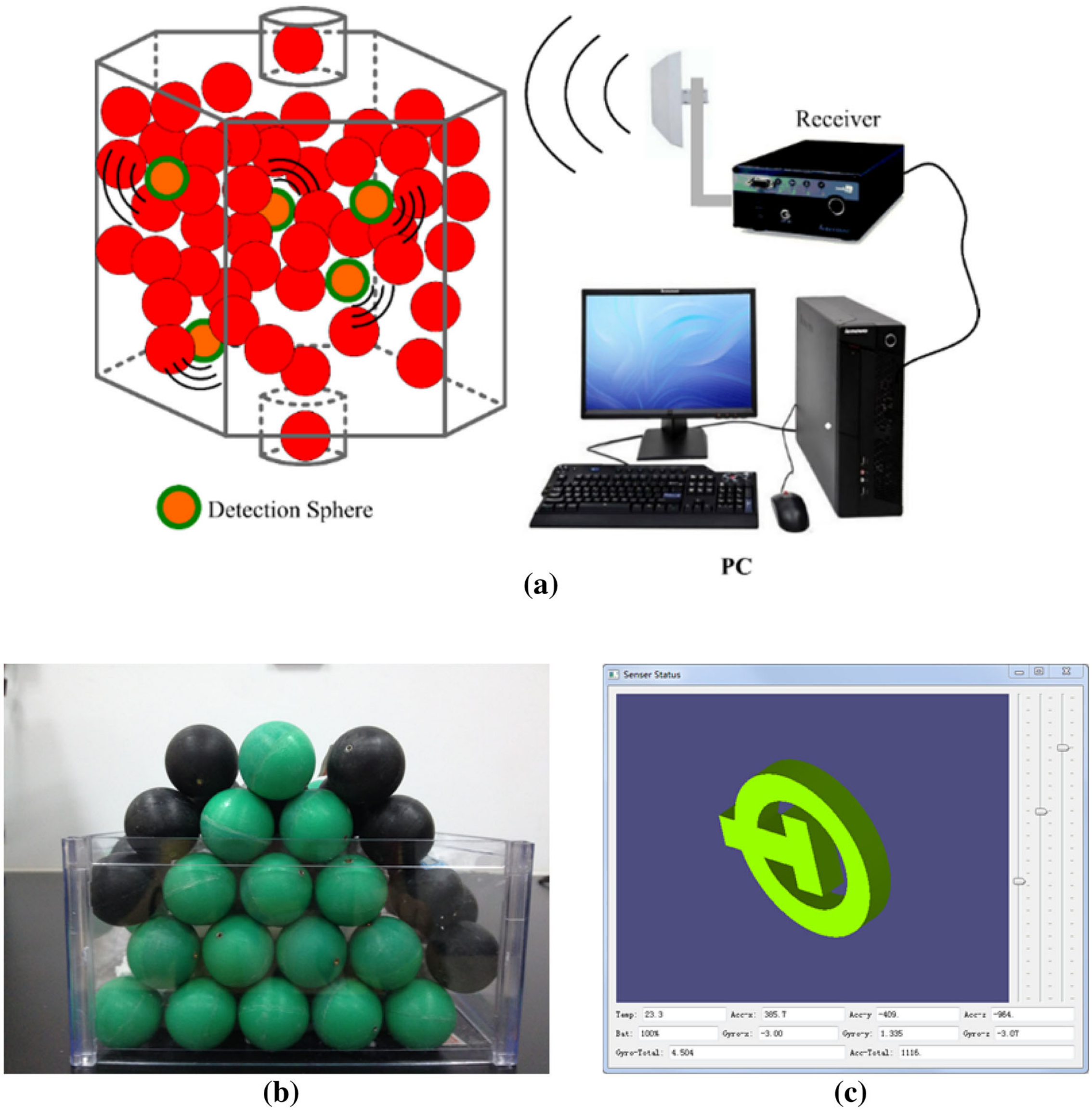



**Fig. 2** Diagram of the detection system (**a**) and detectors (**b**) and screenshot of the control software (**c**)

**Table 1** Major parameters of the detection system

| | |
|---|---|
| Waterproof | IPX7 |
| Shell material | Polypropylene |
| Density | 0.843 (g/cm$^3$) |
| Range of angular velocity | −2000–2000°/s |
| Range of acceleration | −4–4 g ($g$ = 9.8 m/s$^2$) |
| Range of temperature | 0–40 °C |
| Wireless communication range (30 mm detector) | >3 m in air<br>>1 m in water |
| Wireless communication range (60 mm detector) | >10 m in air<br>>3 m in water |

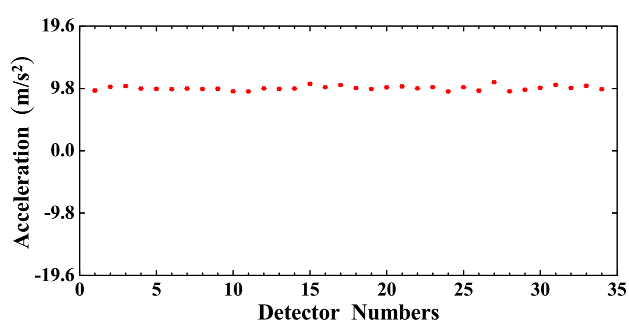



**Fig. 3** Accelerations measured by static detectors

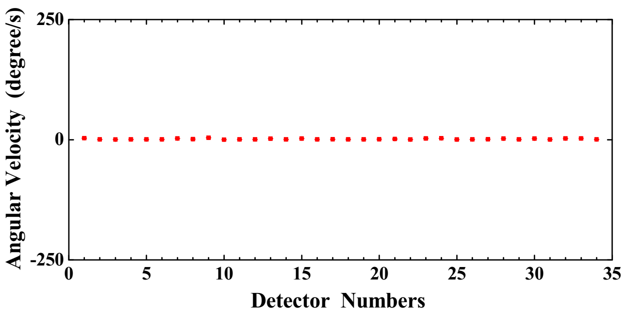



**Fig. 4** Angular velocities measured by static detectors

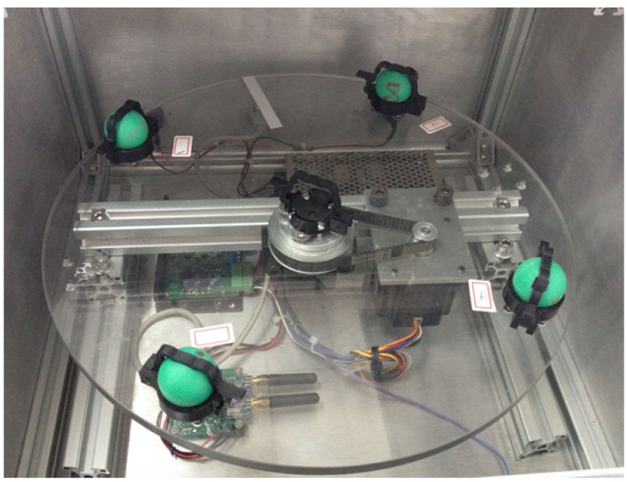


**Fig. 5** Rotary used to test the detectors

is 0.15 m. The speed of the rotary is 30 rpm. It can be calculated that the centripetal acceleration applied to the detector is 1.48 m/s$^2$ and the sum of the centripetal acceleration and the gravity is 9.91 m/s$^2$. Figures 6 and 7 show the acceleration and angular velocity of a detector. The results show that the detector is accurate in measuring acceleration and angular velocity when the detector is in motion.

The attitude and the rotation angle of the detector were calculated using a quaternion algorithm [19]. Attitude,

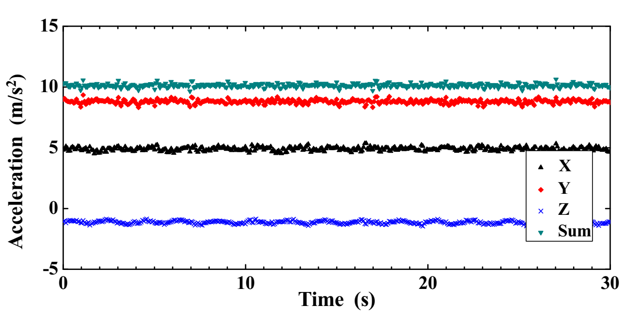



**Fig. 6** Accelerations measured in the rotary test

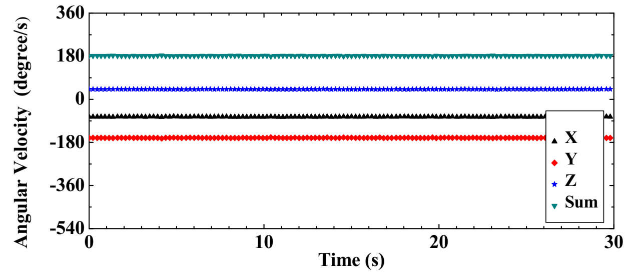



**Fig. 7** Angular velocities measured in the rotary test

including roll, pitch, and yaw, describes the angular position of the detector relative to the gravity direction [20]. In the rotary test, the detector rotates around the $z$-axis at a constant speed. Thus, the rotation angle around the $z$-axis should increase linearly and the yaw, which describes the angular position, should change periodically. Figure 8 shows that the period of the yaw is 2 s. Figure 9 shows the measured rotation angle. The measurements agree with the expectations.

## 4 Preliminary applications

The residence time distribution of the pebbles is of great interest in studying the pebble bed kinematics. Conventionally, it is obtained by means such as radioactive particle

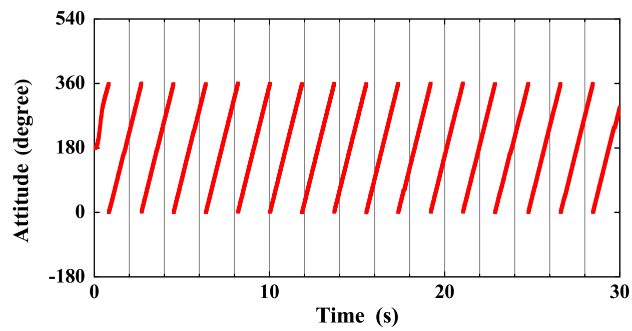



**Fig. 8** Yaw of the detector in the rotary test

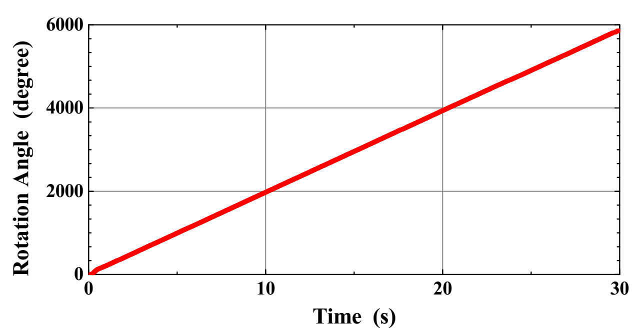



**Fig. 9** Rotation angle of the detector in the rotary test

tracking. We applied our detection system to measure the residence time of the pebbles in a transparent silo without using any radioactive material.

The silo consists of a cylinder and a hopper bottom with a baffle, as shown in Fig. 10. The inner diameter and the total height of the cylinder are 30 and 90 cm, respectively. The conical base has a slope angle of 30° and the diameter of the orifice is 15 cm. The silo is filled with mono-sized plastic pebbles. The pebble detectors are placed at the top of the pebble bed with radial distances of 0, 4, 8, and 13.5 cm. The total height of the bed is approximately 88 cm. The test was done by opening the orifice and allowing the pebbles to flow down freely.

The tests were repeated 45 times. The mean residence times of the pebbles on the top of the bed are in the range of 7.0–8.0 s, as shown in Fig. 11. The preliminary result shows that the residence time increases linearly with the radial distance.

We also recorded the whole test using a high-speed camera. The camera was able to record the residence time of those pebbles that were close to the surface of the silo. As shown in Fig. 12, the differences in the residence times given by the two different methods is less than 0.08 s. This result indicates that the measurement of the residence time using our detection system has a reasonable accuracy.

Fig. 10 Test silo

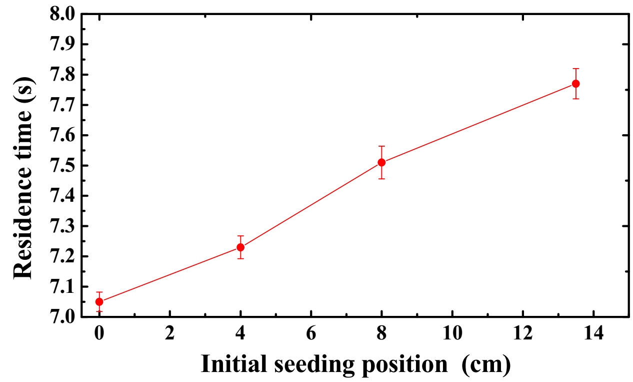



Fig. 11 Mean residence time versus the radial distance

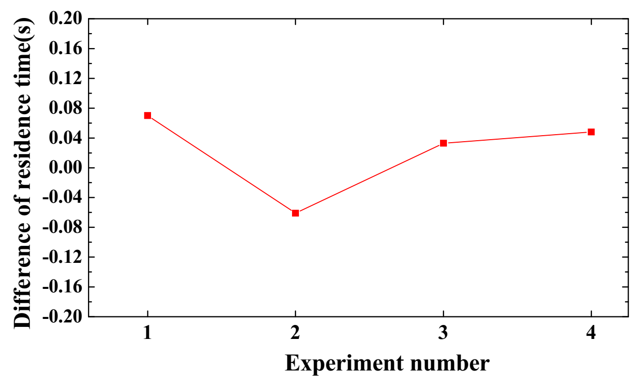



Fig. 12 The difference of the residence times measured by the pebble detectors and the high-speed camera

## 5 Conclusion and potential applications

The pebble-shaped detection system has demonstrated good performance in terms of acceleration, angular velocity, and rotation angle measurement. The residence time of the pebbles was measured, and part of the results was compared to those measured by a high-speed camera. The pebble-shaped detectors demonstrated their capabilities of measuring the residence time accurately. In fact, by using this system, one can obtain other valuable information from the surrogate pebble bed experiments. In addition, new measurement features may be added to the system as required.

This system can be used to study the kinematics of a pebble bed, and to validate and complement experiments done by other methods. For example, the acceleration can be used to estimate pebble contact forces that are typically difficult to be quantified [2]. The angular velocity, which is also difficult to obtain using other methods, plays an important role in the pebble discharging process [21]. With this system, one can study the pebbles sliding and rolling against each other and against the wall, which may generate graphite dust and cause excessive wear [22, 23].

## References


1. US DOE, (US DOE Nuclear Energy Research Advisory Committee and Gen IV International Foru), A technology roadmap for generation IV Nuclear Energy Systems (2002)
2. M.R. Laufer, Granular dynamics in pebble bed reactor cores. Ph.D. Thesis, University of California, Berkeley (2013)
3. V.B. Khane, Experimental and computational investigation of flow of pebbles in a pebble bed nuclear reactor. Ph.D. Thesis, Missouri University of Science and Technology (2014)
4. A.C. Kadak, M.Z. Bazant, Pebble flow experiments for pebble bed reactors. In 2nd international topical meeting on high temperature reactor technology, Beijing, China, Sept. 22–24 (2004)
5. K.K. Rao, P.R. Nott, S. Sundaresan, *An introduction to granular flow* (Cambridge University Press, New York (USA), 2008)
6. Y. Li, J. Wei, A collective dynamics-based method for initial pebble packing in pebble flow simulations. Nucl. Eng. Des. **250**, 229–236 (2012). doi:10.1016/j.nucengdes.2012.05.020
7. J.J. Cogliati, A.M. Ougouag, Pebbles: a computer code for modeling packing, flow and re-circulation of pebbles in a pebble bed reactor. HTR2006: 3rd international topical meeting on high temperature reactor technology, Johannesburg, South Africa, Oct. 1–4 (2006)
8. C.H. Rycroft, G.S. Grest, J.W. Landry et al., Analysis of granular flow in a pebble-bed nuclear reactor. Phys. Rev. E **74**, 021306 (2006). doi:10.1103/PhysRevE.74.021306
9. Y. Li, Y. Xu, S. Jiang, DEM simulations and experiments of pebble flow with monosized spheres. Powder Technol. **193**, 312–318 (2009). doi:10.1016/j.powtec.2009.03.009
10. G. Liu, Y. Zhang, H. Lu et al., Numerical simulation of particle flow motion in a two-dimensional modular pebble-bed reactor with discrete element method. Science and Technology of Nuclear Installations, Article ID 458190 (2013). doi: 10.1155/2013/458190
11. Y. Li, W. Ji, Modeling of interactions between liquid coolant and pebble flow in advanced high temperature reactors. Transactions of the American Nuclear Society, Vol. 104, Hollywood, Florida, June 26–30, 201
12. L.E. Silbert, D. Ertaş, G.S. Grest et al., Granular flow down an inclined plane: Bagnold scaling and rheology. Phys. Rev. E **64**, 051302 (2001). doi:10.1103/PhysRevE.64.051302
13. X. Yang, W. Hu, S. Jiang, Experimental investigation on feasibility of two-region-designed pebble-bed high-temperature gas-cooled reactor. J. Nucl. Sci. Technol. **46**, 374–381 (2009). doi:10.1080/18811248.2007.9711543
14. S.Y. Jiang, X.T. Yang, Z.W. Tang et al., Experimental and numerical validation of a two-region-designed pebble bed reactor with dynamic core. Nucl. Eng. Des. **246**, 277–285 (2012). doi:10.1016/j.nucengdes.2012.02.005
15. G.J Auwerda, J.L Kloosterman, A J M. Winkelman et al., Comparison of experiments and calculations of void fraction distributions in randomly stacked pebble beds. PHYSOR 2010-Advances in reactor physics to power the nuclear renaissance, Pittsburgh, Pennsylvania, USA, May 9–14, (2010)
16. G.J. Auwerda, J.L. Kloosterman, D. Lathouwers et al., Macroscopic and microscopic packing properties of experimental and computational pebble beds. Nucl. Technol. **183**(3), 272–286 (2013)
17. A. Ooms, Pebble flow in a high temperature reactor. Master Thesis, Delft University of Technology, 2008
18. M.M. Radmanesh, *Radio frequency and microwave electronics illustrated* (Prentice Hall, New Jersey, 2001)
19. R.H. Zhang, H.G. Jia, T. Chen et al., Attitude solution for strapdown inertial navigation system based on quaternion algorithm. Opt Precis Eng **16**(10), 1963–1970 (2008). **(in Chinese)**
20. Y.Y. Qin, *Inertial navigation[M]* (Science Press, Beijing (China), 2014)
21. Y. Yu, H. Saxén, Discrete element method simulation of properties of a 3D conical hopper with mono-sized spheres. Adv. Powder Technol. **22**, 324–331 (2011). doi:10.1016/j.apt.2010.04.003
22. C.H. Rycroft, A. Dehbi, T. Lind et al., Granular flow in pebble-bed nuclear reactors: scaling, dust generation, and stress. Nucl. Eng. Des. **265**, 69–84 (2013). doi:10.1016/j.nucengdes.2013.07.010
23. X.W. Luo, S.Y. Yu, Z.S. Zhang et al., Estimation of graphite dust quantity and size distribution of graphite particle in HTR-10. Nucl. Power Eng. **26**(2), 203–208 (2005). **(in Chinese)**