Assessment of Performing Experimental Investigation on a Pebble Bed Modular Reactor (PBMR) as a Static Packed Bed Approximation

Vaibhav Khane, Ibrahim A. Said, and Muthanna H. Al-Dahhan *

^[1]Department of Chemical and Biochemical Engineering, Missouri University of Science and Technology, 110 Bertelsmeyer Hall, 1101 N. State Street, Rolla, 65409, MO, United States

* Corresponding Author (aldahhanm@mst.edu)

Abstract

Moving bed reactors have a wide range of applications in the chemical, petrochemical, and alternative energy industries in a special situation where there is a need to either continuously recirculate or replace solid particles catalysts. They are also under consideration as one of the 4th generation nuclear reactors known as Pebble Bed Modular Reactor (PBMR). In this work a continuous cold flow pebble recirculation experimental set-up, mimicking the flow of pebbles in a PBMR, is designed, developed, and tested at Missouri S&T. A unique experimental work has been performed on assessment of the possibility of using Pebble Bed Modular Reactor (PBMR) as static packed bed approximation for the needed experimental investigation. For this purpose, a radioactive particle tracking (RPT) technique is implemented around the continuous pebble recirculation experimental set-up, to compare the packing characteristics of static and moving pebble beds. The photopeak counts during RPT calibration were collected by placing radioactive particle (tracer) at different positions in the test reactor under different operating conditions of moving and static conditions. The photopeak counts between moving and static conditions show that attenuation characteristics of the medium in between tracer and detectors are not changing significantly due to movement of pebbles. This confirms that PBMR could be well approximated

by static packed beds for experimental investigation which simplify the needed experimentation to advance PBMR technology and commercialization. Obtained results are serving as a unique benchmark data for an evaluation of the contact force model that used in the Discrete Element Method (DEM) based simulations.

Keywords

Pebble bed modular reactor (PBMR), radioactive particle tracking (RPT) technique, static packed bed.

1- Introduction

The very high temperature reactor (VHTR), or high temperature gas-cooled reactor (HTGR), is one of the Generation IV reactor types that is graphite-moderated and helium cooled, using TRISO (Tri-isotropic) nuclear fuel particles. The VHTR can have a design outlet temperature of 900 °C -1000°C. The high outlet temperatures of VHTR find numerous applications in process heating and hydrogen production via the thermochemical sulfur-iodine cycle beside higher thermal efficiency of electrical power generation. There are two main versions of VHTR, which are prismatic modular reactor (PMR) and pebble bed modular reactor (PBMR). In a pebble bed modular reactor (PBMR), the nuclear fuel is in the form of spherical pebble, which moves slowly downward in the reactor core under the influence of gravity. These pebbles are made of pyrolytic graphite, and they contain micro-fuel uranium particle called TRISO (Tri-isotropic) ¹. A helium gas as a coolant moves downward through the voids formed between the pebbles and remove the heat generated from the fuel in the core. The nuclear fuel pebbles are continuously recirculated through the core and are monitored for burn-up. The flow of pebbles under the influence of gravity in a pebble bed reactor is an example of slow and dense type granular flow. The moving core of a PBMR is a cause of concern from safety and performance evaluation point of view,

which demands basic understanding about the physics governing dense granular flow. Experimental benchmarking investigation of such flows to validate models and simulations using conventional optics based techniques has certain limitations and hence radio-isotopes based flow visualization techniques such as radioactive particle tracking (RPT) technique are suitable for such investigation. It is impractical to carry out an experimental investigation in an actual scale PBMR due to the large scale and safety issues. However, an experimental benchmarking study in a scaled design set-up mimicking cold flow operation of a PBMR is possible and feasible. There are some studies **that** have been investigated the granular flow in a PBMR, but a few number of studies focused on the slow and dense type granular flow. There are some of the structural characterization studies **that** were carried out on static sphere packings ²⁻⁶. The slow and dense granular flow encountered in a PBMR is currently approximated by the study of static packed bed ⁶⁻¹⁰. In the case of slow flow regime, the solids fraction is high (dense) and contact forces between neighboring particles last over a long time (slow) ¹¹. However, there are no such experimental studies that were carried out to support the conclusions of the published research. Hence, there is a need to compare packing characteristics between static packed beds and the moving beds encountered in PBMR (packed beds with slow and dense granular flow). This aspect is investigated in this current work using calibration method of RPT technique. To compare the packing characteristics of static and moving pebble beds, it is essential to mimic slow granular flow. Vaibhav et al. ¹² have designed and developed a unique continuous pebble recirculation cold flow experimental set-up, in which the pebble trajectories, velocity, flow patterns, etc. was investigated experimentally for the first time by using non-invasive radioactive particle tracking (RPT) technique. It is clear from the above review of previous experimental studies and measure methods that there is a need to carry out an experimental investigation on a

slow and dense granular flow encountered in a PBMR. In this work, the same setup which is developed in investigation of pebble flow dynamics using radioactive particle tracking in a pebble bed modular reactor (PBMR) by Vaibhav et al.¹² is used during this current investigation as a part of RPT calibrations to compare packing characteristics between packed beds and moving beds encountered in PBMR, to find out the effect of pebble movement on the packing characteristics. Also, a unique experimental data on the slow and dense granular flow in a PBMR are presented. The obtained information will help in the investigation the effects of dense and slow flow on the pebble dynamics, gas coolant dispersion and mixing⁹, and a heat transfer⁸ in the PBMR.

2- Experimental Setup

A cold flow continuous pebble recirculation experimental set-up has been designed, developed, and tested (Figure 1) by vaibhav et al.¹² at Multiphase Reactors Engineering and Applications (mReal) laboratory to experimentally investigate the flow of pebbles in a mimicked test reactor by using non-invasive RPT technique to measure the pebble trajectory, velocity, flow patterns, etc. The developed set-up was developed in a novel features of i) a continuous moving belt is used to carry the exit pebbles, ii) the pebbles return at various locations at the top of bed by developing a unique design of returning and connecting in a non-violent manner, iii) a unique mechanical design has been designed and developed at the bottom of cone of bed to adjust the flow of pebbles without jamming. The pebble bed modular test reactor made of acrylic (1foot outer diameter with 11.95 inches inside diameter and 1foot in height) is filled with glass marbles of 1/2" diameter having density ~2.5g/cm³ and is mounted on a stand. The residence time of pebble in the core is an important parameter from various **neutronic** and safety related **considerations**; this can be controlled by controlling the exit flow rate of a pebble. An exit

controller has been designed and developed at the bottom opening of the cone of bed in a unique design to prevent the Pebble- jamming without affecting the flowing downward pebble. The glass marbles are coming out of opening in extractor tube, which is operated by a solenoid operated slider, falls into a conveyor bin just below the reactor. From there, the glass marble is transferred to the hopper at the top via adjustable speed conveyor. Conveyor bin releases the glass marbles to the hopper. Marbles are then transferred to the top of the reactor via inlet control mechanism which consists of straight and elbow sections of one pebble diameter tube. This inlet control mechanism also has three swivel joints. The inlet control mechanism is connected to a top plate (diameter matching with the reactor) having 17 holes. These holes are provided to return the pebble at 17 different radial positions. Further details regarding the experimental set-up can be found elsewhere ^{12,13}.

Figure 1. Scaled down cold flow continuous pebble recirculation experimental set-up.

3- Radioactive particle tracking (RPT) technique based study of granular flow in a PBMR.

Radioisotopes based measurement techniques are found in a variety of applications in the multiphase flow systems used in many practical applications. Various velocimetry visualization techniques such as Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV) are of limited use in the multiphase flow systems, as these systems are opaque and contain a large volume fraction of the dispersed phase. Among different velocimetry techniques available, a versatile and non-invasive radioisotopes based flow mapping technique, known as RPT technique is not only accurate but provides data in a non-invasive manner without any limitations from system opacity due to high penetration capability of gamma rays. Radioactive particle tracking (RPT) technique is being used in this experimental study, in which the RPT technique is being implemented on the continuous pebble recirculation experimental module at mReal (Figure 2). RPT technique can be used to provide extensive information about the flow field,

instantaneous and time-averaged velocities, stagnant zone, trajectories and other parameters in 3-D^{12,14-17}. The executed experiments in this study are a part of RPT calibration. **A strong source of radioactivity is required for the study of granular flow in PBMR due to the presence of highly attenuating glass marbles. So, a Coblat-60 (~600µm in diameter) source of 500µCi strength tracer was selected in this study. Also, Co-60 based tracer particle was used in the current study due to its prolonged half-life (~ 5.2 years) and its lesser irradiation time requirement in nuclear systems as a part of the preparation of radioactive tracer. In the current set of experiments, a radioactive Co-60, dynamically similar to the pebble, was placed inside a 1 mm hollow Teflon sphere particle of ½” diameter. This tracer particle, which is similar in shape, size (1/2’ dia.) and density to the other pebbles (glass marbles), has been used to carry out RPT experiments in this study.**

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156 Figure 2. RPT technique implementation around continuous pebble recirculation experimental
157 set-up.

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An array of sixteen non-collimated sodium iodide (NaI) scintillation detectors was arranged strategically around the continuous pebble recirculation experimental setup. Roy et al.¹⁸ recommended that better resolution and accuracy in position reconstruction can be achieved using four detectors per plane. Also, Roy et al. suggested a symmetric distribution of detectors around the experimental setup and an alternate staggering of adjacent plane detectors during the implementation of RPT experiments. Hence, four detectors per plane at 90° to in-plane neighboring detectors were used in the current study. The adjacent out-of-plane detectors on same column post were staggered at 45° to improve sensitivity¹⁸. The schematic of the detector arrangement is shown in Figure 3(a) and 3(b). Table 1 shows the position coordinate of the RPT detectors. Further details about the detector arrangement, source activity selection, and preparation of tracer can be found elsewhere^{12,13}.

a. Top view

b. Side view

Figure 3. Schematics of RPT detector arrangement.

186 Table 1 Position coordinate of the RPT detectors.

Detector	Z, cm	R, cm	$\theta, ^\circ$
1	7.62	22.86	112.5
2	15.24	22.86	67.5
3	22.86	22.86	112.5
4	30.48	22.86	67.5
5	7.62	22.86	22.5
6	15.24	22.86	337.5
7	22.86	22.86	22.5
8	30.48	22.86	337.5
9	7.62	22.86	202.5
10	15.24	22.86	157.5
11	22.86	22.86	202.5
12	30.48	22.86	157.5
13	7.62	22.86	292.5
14	15.24	22.86	247.5
15	22.86	22.86	292.5
16	30.48	22.86	247.5

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To investigate the packing characteristics of slow and dense flow inside the PBMR as a part of RPT calibration, a novel calibration methodology and apparatus which were designed and developed by Vaibhav et al.¹² for pebble bed reactor study with using RPT technique are used during this study. Figure 4 shows a schematic diagram and actual picture of calibration apparatus.

Figure 4. Calibration apparatus¹²

The calibration methodology is an analytical solution to the forward problem of RPT, i.e. finding the instantaneous tracer position based upon counts data received in the detectors, is not possible. This problem is solved by performing a set of calibration experiments at the same operating conditions as those of actual RPT experiments^{12,19}. The RPT calibration involves placing a radioactive particle at known locations inside multiphase system using calibration apparatus and recording photo-peak counts in each detector.

202 It consists of a rod (1/4" in diameter and 43" in length) having a Teflon vial (1" in length) at the
203 tip to contain the radioactive particle. With the help of a guide bush arrangement, the rod can
204 slide in/out to place a radioactive particle at any height. The exact position can be recorded with
205 the help of a scale (Range: 0 to 40") attached to the rod. This rod can be placed at selected radial
206 positions with the help of threaded holes in the top plate mounted on the test reactor. Once tracer
207 particle is placed at known positions, counts data can be recorded by running data acquisition
208 program in calibration mode. The non-collimated sodium iodide (NaI) scintillation detectors
209 (Sixteen NaI detectors) kept collecting counts continuously at a frequency of 6 Hz. A sampling
210 frequency of 6 Hz was chosen because of the slow movement of the pebbles. At smaller
211 sampling frequencies, the signal-to-noise ratio is better due to the larger sampling time.

212 Radioactive tracer particle (Cobalt-60) was used in synchronization of photo-peaks in all the
213 detector channels. The slow and dense granular flow in a PBMR is currently approximated by
214 the study of static packed beds ⁷. However, there are no such experimental studies that have been
215 carried out to support the conclusions of the published research. Hence, there is a need to
216 compare packing characteristics between static packed beds and the moving beds encountered in
217 PBMR (packed beds with slow and dense granular flow). To find out the effect of pebble
218 movement on packing characteristics, three different cases of experiments were carried out as a
219 part of RPT calibration as follow:

220 Case 1: Static packed bed case

221 In which there is no marbles come out from the bed (no exit flow), this case investigates the
222 packing characteristics for conditions of no movement of pebbles. The photo-peak counts from
223 this case will be compared with other cases (cases 2 and 3) of moving bed to reflect the impact of
224 movement on the packing characteristics.

Case 2: Moving bed case with maximum exit flow rate of ~ 40 marbles per minute

This case represents the condition of movement of pebbles inside the bed with a maximum exit flow rate.

Case 3: Moving bed case with controlled exit flow rate of ~ 12 marbles per minute

This case is selected to represent an intermediate condition between maximum movement inside the bed (case 2) and condition of no movement (case 1).

In each case of experiments, a radioactive tracer containing a Co-60 particle was placed at different heights (in increments of 1 cm) along the central axis of the test reactor and for each position tracer photo-peak counts were recorded in each detector channel (Figure 5).

Figure 5. Experimental set-up for comparison of packing characteristics between static packed beds and the moving beds of PBMR.

5. Results and discussion

The obtained photo-peak counts data in these three different cases (static packed bed case, moving bed case with maximum exit flow rate of ~ 40 marbles per minute, and moving bed case

249 with controlled exit flow rate of ~ 12 marbles per minute) were analyzed to check effect of
250 movement of pebbles on structural characteristics of the packed beds in terms of the counts
251 received. The structure of the bed affects the gamma rays attenuation and hence the counts
252 received by the detector. If the distribution of pebbles had changed significantly due to the
253 movement of pebbles, it would change the attenuation characteristics of the heterogeneous
254 medium in between the tracer and detectors and will be subsequently reflected in the magnitude
255 of the photo-peak counts data. The photo-peak counts data obtained for three different cases is
256 plotted on the same graph for each detector. These representative detectors from each row are
257 mounted on the same column of detector support structure. The other three detectors from the
258 same row exhibited the same trend as shown by a representative detector from that row. The
259 tracer was always placed below the horizontal plane of 1st row detectors. Hence, photo-peak
260 counts recorded in 1st row detectors are found to decrease with increase in the distance between
261 tracer placement position and the top surface of the test reactor. On the other hand, the tracer is
262 always placed above the horizontal plane of 4th row detectors. Hence, photo-peak counts
263 recorded in 4th row detectors are found to increase with the increase in the distance between
264 tracer placement position and the top surface of the test reactor. For 2nd and 3rd row detectors,
265 the tracer is initially placed above their horizontal level and afterwards below their horizontal
266 level. Hence, photo-peak counts recorded in 2nd and 3rd row detectors are found to increase
267 initially and then decrease with increase in the distance between tracer placement position and
268 the top surface of the test reactor. A peak in the photo-peak counts data is observed for 2nd and
269 3rd row detectors. The distances from the top surface of the test reactor corresponding to these
270 observed peaks are different for 2nd and 3rd row detectors and are due to the fact that 2nd and

271 3rd low **row** detectors are mounted at different horizontal levels. Figures 6-9 show a comparison
 272 of photo-peak counts data for three cases.
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Figure 6. Photo-peak counts data for first row detectors.

Figure 7. Photo-peak counts data for second row detectors.

Figure 8. Photo-peak counts data for third row detectors.

Figure 9. Photo-peak counts data for fourth row detectors.

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275 The average absolute relative error (AARE) and standard deviation (σ) for case 2 (moving bed
 276 case with exit flow rate of ~ 40 marbles per minute)/case 3 (moving bed case with controlled exit
 277 flow rate of ~ 12 marbles per minute) with respect to case 1 (static packed bed case) are
 278 calculated using Equations 1 and 2²⁰

$$AARE = \frac{1}{N} \sum_{i=1}^N \frac{Counts_{case2/case3} - Counts_{case1}}{Counts_{case1}} \quad 1$$

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$$\sigma = \sqrt{\sum_{i=1}^N \frac{(\frac{Counts_{case2/case3} - Counts_{case1}}{Counts_{case1}} - AARE)^2}{N-1}} \quad 2$$

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283 Where N= no. of measurement points

284 For 1st row detectors, average absolute relative error (AARE) and standard deviation (σ)

285 between case 3 (controlled flow rate case) and case 1 (static bed case) were found to be 8.07%

286 and 6.15%, respectively, whereas AARE and standard deviation between case 2 (maximum flow

287 rate case) and case 1 (static bed case) were found to be 7.94% and 6.74%. Similarly for 2nd row

288 detectors, average absolute relative error (AARE) and standard deviation between (case 3)

289 controlled flow rate case and case 1 (static bed case) were found to be 9.16% and 7.25%,

290 respectively, whereas AARE between case 2 (maximum flow rate case) and case 1 (static bed

291 case) were found to be 7.85% and 6.55%. Similarly for 3rd row detectors, average absolute

292 relative error (AARE) and standard deviation between case 3 (controlled flow rate case) and case

293 1 (static bed case) were found to be 8.39% and 6.43%, respectively, whereas AARE and standard

294 deviation between case 2 (maximum flow rate case) and case 1 (static bed case) were found to be

295 7.85% and 5.55% respectively. Similarly for 4th row detectors, AARE and standard deviation

296 between case 3 (controlled flow rate case) and case 1 (static bed case) were found to be 10.18%

297 and 6.64% respectively, whereas AARE and standard deviation between case 2 (maximum flow

298 rate case) and case 1 (static bed case) were found to be 9.12% and 6.38 % respectively. These

299 values of AARE and standard deviation for different cases, considering the Poisson distribution

300 of radioactive decay process, are smaller in magnitude. This suggests that attenuation

301 characteristics of the medium in between the tracer and the detectors are not changing

significantly due to the movement of pebbles. Hence, slow and dense granular flow encountered in a PBMR could be represented by the examination of static packed beds depending on the type of measurement and the parameters to be investigated.

This is an important finding which justifies the use of packed bed geometry for simplicity in the experimental investigation of many studies that help to advance the knowledge and engineering science of PBMR such as investigation of gaseous coolant dispersion⁹, heat transfer⁸, and bed structure²¹ in terms of solids hold-up and voidage cross section distribution of the design and construction of complex experiments involving continuous pebble recirculation experimental set-up. However, additional experimental/computational work is required to investigate further and validation of methodology to check the effect of pebbles movement on the structural characteristics of the bed.

5. Remarks

A non-invasive radioisotopes based flow mapping technique, known as radioactive particle tracking (RPT) technique is implemented around the continuous pebbles re-circulation experimental set-up to assessment performing of the pebble bed modular reactor (PBMR) as a static packed bed approximation. Three sets of experiments were carried out as a part of RPT calibration as follow: case 1) static packed bed case, case 2) moving bed case with exit flow rate of 40 marbles per minute, and case 3) moving bed case with exit flow **rate** 12 marbles per minute. In each set of experiments, a radioactive tracer containing a Co-60 particle was placed at different heights (in increments of 1 cm) along the central axis of the test reactor and for each position tracer photo-peak counts were recorded in each detector channel. The obtained photo-peak counts data for different three cases indicates that attenuation characteristics of the medium in between tracer and detectors are not changing significantly due to movement of pebbles. Also, average absolute relative error (AARE) and standard deviation between counts data for static packed bed case (case 1) and moving bed cases (cases 2 and 3) are smaller in magnitude. This suggests that slow and dense granular flow encountered in PBMR can be will represent by examination of static packed bed approximation. Investigation of study PBMR as static packed bed approximation will assist in understanding the thermal hydraulics of the reactor core under specific conditions. Also, results provided benchmarking data for assessment of commercial CFD codes such as DEM based simulation results. **The current results discussed in this article needs to be extrapolated to take into account effect of unit cell structure such as BCC lattice structure and poly-disperse spheres which can be the future scope of this research.**

337 NOMECLATURE

338	Symbol	Description
339	C	counts recorded in the detector
340	N	number of measurement points.
341	σ	standard deviation

342 Abbreviations

343	AARE	average absolute relative error
344	CFD	computational fluid dynamics
345	DEM	discrete element method
346	HTGR	high temperature gas-cooled reactor
347	NGNP	next generation nuclear plant program
348	PBMR	pebble bed modular reactor
349	PMR	prismatic modular reactors
350	RPT	radioactive particle tracking
351	VHTR	very high temperature reactor

352 Acknowledgements

353 The authors acknowledge the financial support provided by Department of Energy (DOE)
354 Nuclear Energy Research Initiative (NERI) project (**NERI-08-043**).

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