A Review on Pneumatic Transportation in The Design of Fuel Handling System in RDE-HTGR

K Widiyati\textsuperscript{1}, Sukmanto Dibyo\textsuperscript{2}

\textsuperscript{1}Mechanical Engineering Department, Faculty of Industrial Technology, Universitas Pertamina
\textsuperscript{2}Center for Nuclear Reactor Technology and Safety, National Nuclear Energy Agency of Indonesia (BATAN), Kawasan PUSPIPTEK Gd. 80 Serpong, Tangerang Selatan.

E-mail: khusnun.widiyati@universitaspertamina.ac.id

Abstract. A stable and reliable pneumatic transportation plays an important role in the operation of a pebble bed HTGR. The challenge in pneumatic transportation system is it produce side product in the form of graphite dust. The existence of the graphite dust at certain point might have the possibilities to disturb the performance and functionality of several component within the reactor. Due to this reason extensive researches to improve its performance have been conducted. In this paper, a review is presented on the operational characteristic of pneumatic transportation. This paper also presents recent researches on the improvement method of pneumatic transportation, that include the determination of optimum transportation pattern in pneumatic transportation, the study on gas transportation velocity, the effect of bend/arc pipeline on the graphite pebble velocity and the impact; dynamic analysis on wear behavior which occurred during pneumatic transportation and the estimation on the number of graphite dust produce in the pneumatic transportation cycle. On basic principle and configuration of each technique, performance and limitation of the techniques are analyzed and compared from different views to demonstrate the recent development in the field and the possible approaches which may provide solution to the pneumatic transportation design.

1. Introduction

The demand of energy is increasing with the increase of population number and economic growth globally. With the average rate of 3.4\% per year of economic growth and more than 9 billion population by the year of 2040, the demand of global energy is expected to expand about 30\% up to the year of 2040. With the decreasing amount of fossil fuel, many countries are currently seeking for non-fossil energy alternatives. Among different kinds of non-fossil energy, nuclear power offers benefits such as environmentally friendly because it emits less pollution, and lower cost. Because of this reason, nuclear energy has been seen as the economic solution in generating electricity during energy crisis.

From 1942 up to today there are several types of nuclear power plant that has been developed and being developed all around the world. Among the many types of nuclear power plant, pebble bed High Temperature Gas-Cooled Reactor (HTGR) offers benefits more than other nuclear power plant. The benefits among other are higher inherent safety, high efficiency, potential application for process steam and hydrogen production [1].
National Nuclear Energy Agency of Indonesia (BATAN) has been given the task to conduct a national program to develop and construct a pebble bed type high temperature reactor called Reaktor Daya Eksperimental (RDE) [2]. Because of the character of having strong passive safety features and flexibility to be utilized for industrial heat co-generation application, pebble bed type nuclear reactor was chosen as the model. In order to filling the enormous electrical and power demand, RDE is expected to be the master for the next Indonesia commercial nuclear reactor [3]. The pebble bed type is also flexible in term of different fuel cycle including the standard uranium, thorium, or plutonium cycle [4]. Figure 1 shows RDE for generating the electricity and superheated steam for the research. The total power generated by RDE is 10 MWth. The heat produced from RDE will be used for generating electricity maximum of 3MWe and/or heat application unit maximum 10 MWth. The electricity is generated by the steam turbine and electrical generator. The steam discharged from steam turbine will be condensed and recycled in to the steam generation system [5, 6].

The pebble bed reactor uses spherical fuel elements and adopts continuous fueling and refueling. Fuel elements are discharged from the bottom of the core one by one, after the same cycle, the burn-up of the fuel element is examined. If the fuel element has reached target burnt-up, it will be transported to the spent fuel storage, otherwise, it will be transported back to the top of the core with another new fuel elements into the core.

The fuel element used in the pebble bed reactor is tristructural-isotropic (TRISO) coated particle embedded in matrix graphite material, in a sphere shape. Helium is used as the transportation gas in the fuel handling system, as well as the coolant of the reactor. The spherical fuel is transported to the top of the core through stainless steel elevating pipe by means of pneumatic. The pressure and velocity of the transportation fluid are controlled through several sensors and valves through a programmable logic computer (PLC) running in the fuel handling system. If the fuel elements are failed to be transported to the core, it will lead to reactor shutdown and even worse it also can lead to safety accident. Due to that reason, the operation of the reactor is very much depending on the reliability of the fuel handling system, more specifically the pneumatic transportation.

Previous studies have been done on different topics on pneumatic transportation. This paper provides a comprehensive review on pneumatic transporatation, from its operational characteristics; method to improve method of pneumatic transportation system, which includes the determination of optimum transportation pattern in pneumatic transportation, the study on gas transportation velocity, the effect of bend/ arc pipe on the graphite velocity and the impact, dynamic analysis on wear behavior which occured during pneumatic transportation; and the estimation on the number of graphite dust produced in the pneumatic transportation cycle. On basic principle and configuration of each technique, performance and limitation of the techniques are analyzed and compared from different
views to demonstrate the recent development in the field and the possible approaches which may provide solution to the pneumatic transportation design.

2. Pneumatic Transportation

Pneumatic transportation is an important method used to transport granular materials from one level to another in several industrial processes. In comparison to hydraulic transportation method, pneumatic offers advantages, such as being hygene, practical, flexibility of routing and economical whilst providing transportation capacities [8]. Nevertheless, several drawbacks and challenges have been reported in pneumatic transportation that may affects the performance, such as pipe abrasion, granular material deposition and wear/attrition during transportation process. Another problem in pneumatic transportation are bending and elbows are widely applied. Due to this reason, extensive research in order to study and to minimize the drawbacks have been performed, such as the research in the area to determine the optimum transportation pattern, research to study the wear mechanism and its parameter in the granular material inside the transportation pipeline, the research of the byproduct of the wear mechanism in the pneumatic transportation system, etc.

Wear property of the granular material in the industrial context can lead to undesirable output, such as an increase in dust generation that can increase the possibility of dust explosion, and hazards on the operators, as well as loss in functionality and product performance. Kotzur et. al [9] have devided the category of pneumatic transportation, i.e.: lean phase, which characterized with high gas transportation velocity and low material concentration within the pipeline; and dense phase, which characterized with low gas transportation velocity and high material density concentration in the pipeline.

Wear property of the granular material in lean phase pneumatic transportation may occurred due to impact. The previous study [9] reported that material velocity within the pipeline played the most influential factor, and yet it is affected by the presence of other solid particles within the pipeline. The investigation on the effect of graphite fuel pebble force as the function of velocity in pebble bed reactor was reported by Liu et. al [10].

The pipeline geometry, which includes internal diameter, alignment, length of the straight section, is also another thing to consider for pneumatic transportation design, yet, the research in the field of HTGR is still limited. The previous studies on the internal diameter of the pipeline was mainly focused on industrial application, which is considered small diameter ranging from 0.75 to 2 inches [11,12]. Eventhough scale-up procedure to accomodate larger pipe diameter has been provided by Wypych and Arnold [13], but this work was limited to application of small material diameter in the air environment. Investigation on the influence of bend/ arc pipeline geometry on wear property of the granular material behaviour have been conducted [14,15]. They found that the short bend r/D ratio (radius of the centerline of the bend devided by the diameter of the pipe), i.e.: r/D ≈3 to 5, was reported to possess higher impact angles and therefore produced more attrition [14]. Meanwhile greater radius ratio, i.e.: r/D = 9 to 12, was reported to reduce the attrition with the increase of r/D. In addition to that, material attrition increases with the increasing number of transportation pipe bend [15].

3. Fuel Handling System

Fuel handling is the process to transport and circulating the fresh graphite fuel and used graphite fuel from its storage into the reactor, then discharging from the reactor until the fuel is stated to be failed or has already reached the burnup level. The operational of the reactor to produce electricity depends highly on the functionality of fuel handling system. Due to that reason, the stability and the reliability of the fuel handling system is very important in the operation of pebble bed HTGR.

Beck et. al [16] have identified possible issues occurred in 7 (seven) high temperature gas cooled reactors (HTGR) established around the world, including the issue in graphite dust and fuel handling system. The occurence of graphite dust in HTGR is associated with the handling of fuel pebbles. The sources of dust production is reportedly occured in AVR in the form of notching, spalling, pitting, fuel
sphere fracturing and peeling because of air ingress [16]. The existence of the graphite dust is a problem for causing decontamination on heat exchanging surface. The graphite dust also occurred in HTTR, however, many information on the wear of the fuel pebbles, its generation and the correlation to fuel transportation method were still in question for further research [16]. Furthermore, dust accumulation has caused carbonaceous in the primary helium circulator [16]. Deposition of graphite dust at the bottom of the core or as a result of a carried off and collected onto the surface in the primary circuit, including the heat exchanger, could decrease its efficiency.

Zhipeng et. al [17] investigated the wear behaviour of graphite fuel pebble under different transportation gases, i.e.: helium, nitrogen and oxygen. They found that transportation gas affected to the wear property of graphite fuel pebble. It highlighted that there were linear correlation between wear rate and gas transportation velocity. Friction between graphite fuel pebble and stainless steel pipe caused graphite ball wear due to the cutting action of the peak of surface characteristic in pipeline material (abrasive wear type). Furthermore, gas flow also contributed to the wear of graphite ball. In addition to that, wear rate under helium environment is greater than the one affected by oxygen and nitrogen. This research however did not specifically address the formation of the dust as the product of friction. Xiaowei et. al [18] stated in their research that graphite dust is generated from the wear property of graphite fuel pebble and the cycling movement of the fuel element. The main source of graphite dust was graphite reflectors, charge and discharge pipes and the surrounding fuel elements. Shen et. al [19] also stated that the sources of graphite dust were the mechanisms of pebble-pebble contact, pebble-wall (structural graphite) contact, and fuel handling (pebble-metal abrasion), more specifically is in the lifting pipe in the fuel handling system. During the graphite fuel pebble transportation mechanism, the graphite fuel pebble experienced multiple collision with the lifting pipe which cause abrasion on the pebble and thus generating graphite dust [20].

4. Experiment and Numerical Analysis on Graphite Dust Formation
As stated in Section 3, the formation of graphite dust was mainly due to the wear property of the graphite component. Graphite dust is produced by the relative movement of graphite fuel towards graphite reflectors, transportation pipes, and the surrounding of fuel elements inside the reactor. The later mechanism is difficult to analyze the production of graphite dust inside the core. A research by Xiaowei et. al [18] further stated that chemical process of graphite material also contributed to the production of graphite dust in HTGR.

Zhipeng et. al [17] and Shen et. al [19] conducted an experiment to measure the wear property of graphite fuel due to abrasion. Shen et. al [19] stated that there were two factors that affecting abrasion rate of the graphite fuel, i.e.: tribology and dynamic behaviour. In term of tribology behavior, they found that the abrasion rate of graphite fuel is larger when located in helium environment in comparison with nitrogen and oxygen environment. In addition to that, in term of dynamic behavior, oscillation under helium environment occurred due to intensive collision of graphite fuel pebble and lifting pipe, which lead to abrasion of graphite fuel pebble and produce graphite dust was agreed both by Zhipeng et. al [17] and Shen et. al [19]. Greater abrasion rate greatly occurred in helium. Abrasion under air and nitrogen environment occurred in the bend pipe, while abrasion in helium environment occurred in straight vertical pipe, which increase significantly due to oscillation.

Numerical studies on dynamic analysis of graphite’s wear properties also have been carried out by several researchers [18, 21, 22]. Liu et. al [21] investigated the dynamic and kinetic of graphite fuel using a combination of straight and bend lifting pipe. The research objective was to understand the effect of axis velocity and lateral velocity of the graphite fuel inside the pipe when the gas (helium) velocity was varied. The key to highlight from this research was that pneumatic transportation has a good efficiency which proven by the axis velocity during transportation in bend pipe is almost equal to the gas velocity during transportation in straight pipe. Increasing gas velocity was shown to increase transportation efficiency. Nevertheless, gas velocity should be maintain to be in the range of 2.4 m/s to 10 m/s for a successful transportation. In addition to that, axis velocity decreased as graphite fuel flow in the bend pipe, due to collision to the pipe which increase the frictional resistance. On the contrary,
axis velocity increased as graphite fuel flow in the straight pipe. Liu et al. [22] performed an investigation on the pneumatic transportation pattern of the graphite fuel. Their objective were to determine the optimum lifting time between pebbles in the lifting pipe. They proposed two fuel pebbles lifting together (TFPB) method in comparison to single lifting method. It was found that the distance between two pebbles influenced the pebble force condition, specifically the force of the upper pebble. The distance of the pebbles is affected by the gas transportation velocity. In summary, the velocity component determine the pebble force condition. By setting the right interval lifting time between two fuel pebbles into the pipe line, the collision between the two fuel pebbles could be avoided. The key finding of their research was the velocities of the fuel pebbles changed when the fuel entered the lifting pipe and when the distance between the fuel pebbles is very short. The optimum difference between interval lifting time of the two fuel pebbles was greater than 5 second to avoid collision. By controlling the interval time between fuel pebbles, the distance of the pebbles can be maintained as well as the force acting on the upper pebble, and thus avoiding collision between the two pebbles. Xiaowei et. al [18] calculated the pressure of pebble on wall using equation provided by Janssen [23] and validation using Descreet Element Method (DEM). They found that the distribution of the normal pressure on the wall using numerical simulation confirmed the calculation method, in which the hopper junction of the core experienced the largest pressure, and thus severe wear of graphite fuel is expected to happen in this area compare to the other part of the reactor. Furthermore, the graphite dust produced in this area is approximately 100μg per cycle, which was accepted by the design. Rustamian et. al [24] conducted analysis on graphite wear using an equation provided by Archard [25] to estimate the the number of graphite dust production, which validated using finite element simulation in ABAQUS. Linear velocity of pebble movement in response to the distance traveled did not affect significantly to the wear mass. It was expected that an estimation of 0.094 mg average dust was produced per pebble pass, making an average graphite dust of 3.5 gram per year. Rustamian et. al [24] considered contact points between pebble to pebble, while Xiaowei et. al [18] used the consideration not only pebble to pebble contact, but also pebble to wall contact in their analysis.

5. Conclusion
Pneumatic transportation of graphite pebble fuel plays an important role to ensure the availability of fuel in the pebbel bed HTGR. It is reported that pneumatic transportation of graphite fuel pebbles produces graphite dust during the cycle. The existence of graphite dust not only decrease the efficiency of the other component in the reactor, but it also could cause fission product decontamination which can lead to safety issue. Optimizing the performance of the pneumatic transportation as well as minimizing the production of graphite dust have been the challenges in the research of pneumatic transportation in HTGR.

Most of existing research works regarding pneumatic transportation design, such as gas transportation velocity, the pipeline geometry, and the impact on the granular material, has been focusing on the industrial context which mainly work in small diameter, ranges from 0.75 to 2 inches. Although scale-up procedure has already provided, yet, the design of pneumatic transportation still not covering the working field in nuclear industry. A massive work still need to be done in this area in order to fill this gap. This paper encourages other researchers to pursue investigation on pipeline geometry in birdenon environment of pneumatic transportation.

It is important to highlight that the gas transportation velocity has reported to influence the force of graphite fuel within the pipeline. The force is a function of velocity which dependent to the time of lifting and distance between graphite fuel pebbles. As a result, regulating the velocity not only will maintain the force of the graphite fuel, but also controlling the pebbles from collision. gas velocity should be keep within the range of 2.4 to 10 m/s, while the time interval between two pebble lifting process should be greater than 5 second for successful transportation.

The pipeline geometry is as important as the transportation gas velocity in the attempt to improve the performance of pneumatic transportation. An arc pipeline can work as a axis velocity reducer,
which means that the axis velocity decrease rapidly when the fuel element is transported in an arc pipeline. On the other hand, the ratio of radius of the centerline of the bend to the diameter of the pipe (r/D) also affecting the occurrence of attrition. Therefore, it is important to design properly the pipeline which incorporate arcs/bends.

6. Acknowledgements
This work was financially supported by the Ministry of Research, Technology and Higher Education of the Republic of Indonesia (Flagship INSINAS for BATAN 2018).

7. References
[1] Li T, Zhang H, Huang Z, Qi W and Bo H 2014 Research Status on Hydrodynamics and Particle Motion Behavior of Absorber Sphere Pneumatic Transportation System in HTR-PM Proceeding of the HTR 2014, Paper HTR2014-7-1287, Weihai, China, October 27-31, 2014.
[2] Terms of reference of Procurement Services Consulting for Preliminary Engineering Design Document Preparation of Power Reactor Experimental, Center of Assessment of Energy Nuclear System, national Nuclear Energy Agency (BATAN), 2014.
[3] Setiadipura T, Irwanto D and Zuhair 2015 Preliminary Neutronic Design of High Burnup Cycle Pebble Bed Reactor Atom Indonesia 41 (1) pp 7-15.
[4] Setiadipura T, Irwanto D and Zuhair 2017 Preliminary Neutronic Study on Pu-based OTTO Cycle Pebble Bed Reactor Kerntechnik 82(6) pp 643-647.
[5] Subekti M, Bakhri S and Sunaryo GR 2018 The Simulator Development for RDE Reactor J. Phys. Conf. Ser. 962 pp 012054-012062.
[6] Sriyono, Kusmastuti R, Bakhri S and Sunaryo GR 2018 Analysis of Helium Purification System capability during water ingress accident in RDE J. Phys. Conf. Ser. 962 pp 012034-012042.
[7] Pancoko M, Nugroho A, Priambodo D and Setiadipura T 2018 Design Study of A Straight Tube Bundle Steam Generation for Reactor Daya Eksperimental International Journal of Mechanical Engineering and Technology (IJMET) Vol 9 Issue 5, 531-540. Article ID: IJMET_09_05_058.
[8] Middha P, Balakin B V, Leirvaag L, Hoffman AC and Kosinski P 2013 PEPT – A Novel Tool for Investigatin of Pneumatic Conveying Powder Technology 237 pp 87-96.
[9] Kotzur B A, Berry R J, Zigan Stefan, Pablo G T and Bradley Michael SA 2018 Particle Attrition Mechanism, Their Characterisation, and Application to Horizontal Lean Phase Pneumatic Transportation System: A Review Powder Technology, Elsevier. doi: 10.1016/j.powtec.2018.04.047.
[10] Liu H, Du Dong, Han Z, Zou Y and Pan J 2015 Dynamic Analysis and Application of Fuel Elements Pneumatic Transportation in A Pebble Bed Reactor Energy 79 pp 33-39.
[11] Hanley K J, Byrne E P, Cronin K, Oliveira J C, O’Mahony J A and Fenelon M A 2011 Effect of Pneumatic Transportation Parameters on Physical Quality Characteristics of Infant Formula J. Food Eng. 106 pp 236-244. Doi: 10.1016/j.jfoodeng.2011.04.029.
[12] Kalman H 1999 Attrition Control By Pneumatic Transportation Powder Technology 104 pp 214-220. Doi: 10.106/0032-5910(99)00097-2.
[13] Wypych P W and Arnold P C 1987 On Improving Scale-up Procedures For Pneumatic Transportation Design Powder Technology 50 pp 281-294.
[14] Aarseth K A 2004 Attrition of Food Pellet During Pneumatic Transportation: The Influence of Velocity and Bend Radius Biosys. Engineering 89 pp 197-213. doi: 10.106/j.biosystemseng.2004.06.008.
[15] Alman H 2000 Attrition of Powders and Granules at Various Bends During Pneumatic Transportation Powder Technology 112 pp 244-250. Doi: 10.1016/S0032-5910(00)00298-9.
[16] Beck J K, Garcia C B and Pincock L F 2010 High Temperature Gas-Cooled Reactors Lessons Learned Applicable to the Next generation Nuclear Plant INL Idaho National Laboratory, US Department of Energy Office of Nuclear Energy.

[17] Zhipeng C, Yanhua Z, Lei S and Suyuan Y 2014 Investigation on Wear Behavior of Graphite Ball Under Different Pneumatic Transportation Environment Proceeding of the HTR 2014, paper HTR2014-41275, Weihai, China, October 27-31, 2014.

[18] Xiaowei L, Xiaoxin W, Li S, Xiaoyuy Y and Suyuan Y 2017 Nuclear Graphite Wear Properties and Estimation of Graphite Dust Production in HTR-10 Nuclear Engineering and Design 315, pp 35-41.

[19] Shen K, Su J, Zhou H, Peng W, Liu B and Yu S 2015 Abrasion Behavior of Graphite Pebble in Lifting Pipe of Pebble-Bed HTR Nuclear Engineering and Design 293 pp 395-402.

[20] Rostamian M, Potirniche G, Cogliati J J, Ougouag A and Tokuhiro A 2012 Computational Prediction of Dust Production in Pebble Bed Reactors Nuclear Engineering and Design 243 pp 33-40.

[21] Liu H, Du Dong, Han Z, Zou Y and Pan J 2015 Dynamic Analysis and Application of Fuel Elements Pneumatic Transportation in A Pebble Bed Reactor Energy 79 pp 33-39.

[22] Liu H, Du D, Han Z, Chang B, Pen J and Shen P 201. Pneumatic Transportation Pattern of Fuel Pebbles in A Pebble-Bed Reactor Annals of Nuclear Energy 99 pp 434-443.

[23] Janssen H A 1982 Z. Ver. Dtsch. Ing. pp 1045.

[24] Rostamian M, Potirniche G P, Cogliati J J, Ougouag A B and Tokuhiro A 2012 Computational Prediction of Dust Production in Pebble Bed Reactors Nuclear Engineering and Design 243 pp 33-40.

[25] Archard J F 1953 Contact and Rubbing on Flat Surface Journal of Applied Physics 24 (8) pp 981-988.