Estimation on Pressure and Velocity Parameter in the Fuel Handling Pneumatic Design of RDE

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Abstract. The RDE is small size of High Temperature Gas-Cooled Reactor type. It’s being designed that have a power of 10 MW thermal, which is intended to produce the electricity and heat utilization. The reactor uses helium gas as a system of coolant at the pressure of 3.0 MPa. The fuel pebble of spherical shape are transported by the pneumatic system in the pipes and recharged from the reactor core continuously without shut-down the reactor. During the process of transportation, the fuel pebble is lifted perpendicularly along the pipe into the reactor core. Therefore, fuel pebble transportation in the pneumatic system is an important effect to stability the fuel handling operation. This paper to estimate the fuel pebble velocity through a vertical pipe with respect to the pressure of pneumatic system in the design of RDE. The pneumatic vertical pipe has 23 m length, 65 mm inner diameter and fuel pebble of 60 mm diameter, weight of one fuel pebble is 200 gr and contains an uranium kernel coated in matrix graphite. The pneumatic system of carrier gas compressed as the conveying medium must be able to transport the fuel pebble through the pneumatic pipe one by one continuously, so that it could be loaded into the reactor core safely. In the pneumatic conveying, the general equation for the velocity of an object movement, drag force of flow and Bernoulli principle were used in the analysis. An initial velocity in range of 20 to 23 m/s was analysed, meanwhile, the fuel pebble discharged from the pneumatic pipe was determined at low velocity around of 0.1 to 5.0 m/s. In this case a collision at high velocity with the reactor core that causes pebble damage can be avoided. Result shows that the pneumatic transportation for the operational requirements of the fuel handling system when the carrier gas pressure in the range of 0.09 to 0.11 MPa higher than the reactor pressure system. In order to perfectly calculation in the future, it will consider the drag coefficient on the fuel pebble with a pipe wall.

1. Introduction

Nuclear Power Plant (NPP) is one of the most widely used energy sources in the world for electricity generation and industry. The HTGR (High Temperature Gas Cooled Reactor) is one of the reactors in the generation IV of NPP which has inherent safety features and high efficiency [1, 2]. It has been developed in the world with various power capacities to produce the electricity as well as for the heat applications. The HTR-10 is an example of small modular of HTGR type reactor that was successfully operated in China [3]. The currently, a small size reactor called RDE (Reaktor Daya Eksperimental) is being designed by Batan that have a power of 10 MW thermal. The design of RDE is based on the HTGR reactor technology (High Temperature Gas-Cooled Reactor) and the reactor core is loaded with TRISO fuel [4].
The reactor uses helium gas as a coolant system. In normal power operation of HTGR reactor, the spherical fuel pebble could be loaded, unloaded and reloaded continuously without shut down the operating reactor. All these processes are performed by system called the Fuel Handling System (FHS).

The FHS is one of the sub-systems in the reactor, in which consists of new fuel supplies, fuel circulation, fuel storage and spent fuel.

The FHS is one of the sub-systems in the reactor, in which consists of new fuel supplies, fuel circulation, fuel storage and spent fuel. The fresh fuel pebble through a pipe, pebble counter and lifted perpendicularly into pneumatic pipe by helium gas to the reactor core and discharged from the reactor by gravity. The fuel pebble diameter is smaller than internal diameter of the pneumatic pipe. So that, the fuel pebble transportation in the pneumatic system is important effects to stability of the fuel handling operation.

The studies about fuel pebble handling system has been conducted in the past. Peng Huang et al. (2010) have described the HTR-10 of FHS and features of equipments. The pneumatic gas container vessel store amount of pressurized helium temporarily and could the storing pressure of 0.25 MPa higher than the pressure system of the reactor [5]. Hongbing Liu et al. have carried out the analysis on dynamic and application of fuel pebble pneumatic system in a pebble bed reactor using kinetic analysis [6].

In the developing design of RDE, an important operating parameters of FHS especially related to pneumatic systems are required. A parameter such as pneumatic pressure and fuel pebble velocity to provide the design of FHS that related to the compressed vessel and pneumatic valves. The fuel pebble transportation could be calculated by the general equation for the velocity of an object with respect to the movement from the bottom as starting point. It consider the forces operating conditions of the system.

The purpose of this analysis is to estimate the fuel pebble velocity through a vertical pipe with respect to the pressure of pneumatic system in the developing design of RDE.

2. The Fuel Handling Systems

In general, the design of FHS determines an optimal condition and reliable operation, therefore in the normal operation the fuel pebble could be loaded into the reactor vessel, circulation and burn-up of fuel detection perfectly. The FHS is an important part of reactor component, key equipment including charging control system, discharging control system, fuel separator, pneumatic system and burn-up measurement station. Due to the fuel pebbles could be loaded, unloaded and reloaded continuously, therefore all these processes are performed automatically by the FHS as shown in the Figure 1. The pneumatic system is one of the FHS components, in which the fuel pebbles are transferred using a helium gas compressed as the conveying medium from the bottom of pneumatic pipe to the reactor core.

The size of spherical fuel pebbles approximately of 60 mm in diameter, and each of fuel pebble contains thousands of tri-structural-isotropic (TRISO)-coated of fuel particles [7]. In the design of RDE, a height of pneumatic pipe is approximately of 23 m. The gas vessels is connected to the lower end of the pipe supplied sufficient gas up-flow to accelerate the fuel pebble. A solenoid valve is used to switch open and close the gas flow on and off. Table 1 shows the parameter data of Pneumatic FHS design of reactor RDE.
Table 1 Parameter Data of Pneumatic Fuel Handling System [8, 9,10]

| No. | Item                                                      | value                          |
|-----|-----------------------------------------------------------|--------------------------------|
| 1   | pipe material                                             | 304 stainless steel            |
| 2   | pneumatic inner diameter (I.D), mm                        | 65                             |
| 3   | length of straight pipe, mm                               | 23.000                         |
| 4   | I.D roundness tolerance, mm                              | 0.25                           |
| 5   | density of pebble, g/cm$^3$                              | 1.70                           |
| 6   | the densities of helium, kg/m$^3$                         | 0.179                          |
| 7   | fuel pebble diameter, mm                                 | 60                             |
| 8   | weight of fuel pebble, gr                                | 200                            |
| 9   | fuel pebble material                                     | coated in matrix graphite      |
| 10  | helium gas reactor pressure, MPa                         | 3.0                            |
| 11  | FHS capacity, fuel elements/day                          | up to 125                      |
| 12  | frequency of fuel element circulation in the core         | 5                              |
| 13  | quantity of fresh fuel daily added to FHS circuit, pcs/day| ~25                            |
| 14  | nominal helium carrier flow rate, kg/s                   | 0.3                            |
3. Methodology

The force and operating conditions of the pneumatic system are determined by several parameters such as the carrier gas flow velocity, pressure and density as well as the dimension of the fuel pebble and the pneumatic pipe. In the case of pneumatic system, the fuel pebble lift perpendicularly from the bottom to outlet of the pneumatic pipe. The general equation to calculate the velocity of an object with respect to displacement or movement from the starting point of pneumatic as follows:

\[ v_t = \sqrt{(2 \cdot g \cdot h + v_i^2)} \] \[ \text{(1)} \]

Where:
- \( h \): the vertical displacement (m)
- \( v \): the vertical velocity (m/s)
- \( g \): the acceleration due to the gravity (9.8m/s²)

The process of fuel pebble pneumatic system could be described as: a fuel pebble at first enters to the pneumatic pipe then transported moving upward flow by the helium gas using the carrier gas system as shown in Figure 2. In this case, during the pneumatic conveying process there are several driving forces along the movement path of pebble.

The forces acting on the pebble during pneumatic conveying process include gravitational force in the vertical direction, drag force of gas flow (equation 2) and friction to the pipe wall.

The force of the pebble can be approximately calculated as [11]:

\[ F_d = \frac{1}{2} C_d \rho A V^2 \] \[ \text{(2)} \]

Where \( C_d \) is drag coefficient of dimensionless, \( \rho \) is density, \( A \) is cross-sectional area, \( V \) is velocity of object relative to the fluid.

The relationship quantitatively between pressure and velocity of fluids is described according to the Bernoulli’s equation as follows;

\[ P_1 + \frac{1}{2} \rho v_1^2 + \rho gh_1 = P_2 + \frac{1}{2} \rho v_2^2 + \rho gh_2 \] \[ \text{(3)} \]

Where \( P \) is the absolute pressure, \( v \) is velocity of fluid, \( h \) is height above some reference point. Therefore, the relationship between pressure and velocity by solving Bernoulli’s principle then we obtain;

\[ \Delta P = \frac{1}{2} \rho (v_2^2 - v_1^2) + \rho gh \] \[ \text{(4)} \]

This is a form of principle the energy conservation. The Bernoulli’s equation in fact, just a convenient statement of energy conservation for an incompressible fluid in which an absence of friction.
Following are parameter data and assumptions and simplifications used for the estimations,

- The fuel pebble and pipe wall friction coefficient equal zero is assumed.
- Various low velocities around of 0.1 to 5.0 m/s is determined, in which the pebble achieve to the outlet of pneumatic pipe.
- Carrier gas temperature is approximately of 65°C.
- Drag coefficient of fluid is 13.3 [6].
- Bending in the outlet pipe causes collision to the wall is neglected.

4. Results And Discussion

The diagram at initial and outlet velocity of pebble in Figure 3 is shown. In this graph, the initial velocity in range of 19 to 23 m/s was estimated. In this case, the velocity patterns that must be met at various different pipe heights are displayed at once. Based on this figure, to maintain the fuel pebble lift reaches the outlet pipe, then at least the minimum initial velocity is approximately of 20.5 m/s. Meanwhile, the range of outlet velocity analyzed qualitatively is slightly effect to the pebble initial velocity of the pneumatic pipe. The outlet velocity was determined by considering at low velocities (0.1 to 5.0 m/s). The pneumatic transfer system must be designed to minimize its contribution to pebble breakage. This requires careful operating design and necessitates conveying of the pebble at the lowest possible velocities.

A collisions the pebble at high velocity with the reactor core that cause damage can be avoided. The maximum velocity fuel pebble can be damaged due to collisions with the cores, there is no information about that. In this case, the damage includes changing shape, size (degree of sphericity) as well as broken. Therefore, the process of fuel pebble lifting is an important effect to the fuel handling system. Furthermore, the transportation of the fuel pebbles in pneumatic system is great significance to the reliable operation of reactor.
Fig. 3. Diagram of pebble initial and outlet velocity

The Figure 4 depicts 3 curves, namely curves of pressure due to flow friction, drag force and force according to law of motions. Therefore, all parameters that work on the system as well as dimensions and operating conditions have been included. The estimation of range operating parameter based on the design of dimension as well as fuel pebble of pneumatic system. Nevertheless, this figure shows wide range of both velocity and pressure conditions.

The Figure 5 shows the total pressure added from the 3 curves mentioned in Figure 4. As shown in Figure 5, the pneumatic transportation can meet the operational requirements of the fuel handling system when the carrier gas pressure in the range of 0.09 to 0.11 MPa is higher than a reactor coolant system at the pressure of 3.0 MPa.

Some important analysis made from these figures is that the carrier gas compressed must be minimum of 3.09 MPa so the pebble can be blown achieve to the reactor core. Furthermore, the pneumatic system of carrier gas compressed as conveying medium must be able to transport the fuel pebble through the pneumatic pipe one by one continuously without shut-down the reactor, so that it could be loaded into the reactor core safely. The pressure and the velocity of gas can be adjusted by a pressure regulator. In this case, the velocity at the pressure-reducing valves must be maintained. Pneumatic pressure that is too low can cause the pebble fuel to not successfully load into the reactor core. Therefore, the pebble which returns back down causes unstable reactor operation.

Fig. 4. Diagram of pebble velocity and pneumatic pressure
5. Conclusion

The estimation of fuel pebble velocity through the vertical pipe with respect to the pressure of pneumatic system in several ranges was conducted. The force parameters that work on the system as well as dimensions and operating conditions have been included. The range of initial velocity analyzed qualitatively is slightly effect to the fuel pebble outlet velocity of the pneumatic pipe. The pneumatic transportation can meet the operational requirements of the fuel handling system when the carrier gas pressure in the range of 0.09 to 0.11 MPa is higher than the reactor pressure system. In order to perfectly calculation in the future, it will consider the drag coefficient on the fuel pebble with a pipe wall.

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Fig. 5. Diagram of total pneumatic pressure drop and pebble velocity
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