Preliminary Study of Temperature Homogenisation in Experimental Power Reactor Hot Gas Chamber

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Abstract. BATAN’s proposed Experimental Power Reactor (RDE) has an issue concerning severe temperature deviation in hot coolant gas channel. To ensure longevity of downward component such as heat exchanger, temperature deviation must be kept as low as possible. Simulation of gas mixing in a full-scale hot gas chamber was performed to study the temperature homogenisation of hot and cold coolant gas, using simplified design. The simulation showed that temperature homogenisation of the coolant was around 99.63%, translated into temperature difference of 0.74°C. This preliminary result shows that the proposed hot gas chamber design is potentially suitable for use in RDE. Pressure drop is also discussed.

Keywords: RDE, HTGR, hot gas chamber, temperature homogeneity

1. Introduction
BATAN’s proposed Experimental Power Reactor (Reaktor Daya Eksperimental/RDE) is a modular High-Temperature Gas-cooled Reactor (HTGR), a Generation IV nuclear reactor design. It employs helium as coolant instead of water as with light water reactors (LWRs). Therefore, HTGR is able to operate at higher temperature than LWRs. The cold helium gas moves downward from the top reactor vessel plenum into the pebble bed core, heated to an average temperature of 700°C and then flows into steam generator [1,2].

The coolant gas temperature, however, is not evenly distributed. Neutron flux is higher in the centre region of the core than in the outer region. This means that the core is hotter in the centre, subsequently causing deviation in the heated coolant gas temperature. Previous researches estimated that temperature deviation can reach 120-210°C [3,4]. Such large deviation can lead to damage to heat exchanger and steam generator due to alternating thermal loads, thus compromising plant safety.

To keep the power plant operation safe and ensure longer operational age of the components, the coolant gas must be homogenized enough before entering hot gas duct. It is done by mixing the coolant gas inside a hot gas chamber that is located on the bottom of reactor vessel [3]. The coolant gas, after heated in the core, will enter into numerous holes on the bottom reflector and flow into the hot gas chamber, where it will be subsequently mixed.
A preliminary study on hot gas chamber for HTGR is carried out to figure out its behaviour in mixing the coolant gas into acceptable homogeneity. The study is conducted using FLUENT software to analyse temperature distribution of the modelled hot gas chamber.

2. Theory

HTGR’s hot gas chamber is located at the bottom of reactor vessel. Helium enters the chamber via numerous holes into several chambers, where it is subsequently mixed owing to chamber configuration. The mixed gas then flows through the outlet of hot gas chamber into the hot gas duct, further mixed in it, and then flows into the heat exchanger.

In this study, homogeneity of the coolant gas is described by dimensionless unit called Temperature Homogeneity Degree (THD). It is described using the following equation,

\[ THD = 1 - \frac{\Delta T_{out}}{\Delta T_{in}} \] (1)

where \( \Delta T_{in} \) denotes temperature difference between hot and cold gas in inlet channels, and \( \Delta T_{out} \) denotes temperature difference between hot and cold gas in the hot gas duct, after mixing. Range of THD is from 0% to 100%, where 0% implies that there is no gas temperature homogeneity whilst 100% implies perfect temperature homogeneity.

To ensure longevity of heat exchanger components, temperature deviation must not exceed 15°C [4]. Translation into THD depends on how large temperature deviation in inlet coolant is.

Besides the hot gas chamber, gas flow rate also contributes in determining THD. Fluid flow is a factor of Reynolds number [3], which is expressed by the following equation,

\[ Re = \frac{\rho v R_h}{\mu} \] (2)

where \( v \) is mean fluid velocity and \( R_h \) is hydraulic radius of the fluid channel. As a rule of thumb, \( Re < 500 \) is categorised as laminar flow, \( Re > 12500 \) is a turbulent flow, and between them is transition flow [5-6].

Early experiments [3,4,7] concluded that Reynolds number makes little significance to temperature homogenization. However, more recent simulation [8] showed larger impact of different Reynolds number on temperature homogeneity. It should be noted that earlier experiments was conducted using scaled-down models and air as coolant instead of helium.

There is yet any CFD simulation for hot gas chamber in small-power HTR. Previous simulation was performed for a HTR-PM design, a much larger version of HTGR compared to RDE [8].

3. Methodology

The simulation was carried out using computational fluid dynamics (CFD) FLUENT software. CFD solves fluid dynamics problem by simulating fluid flow using Navier-Stokes equation [9,10].

\[
\frac{Dv_i}{Dt} = \frac{\partial v_i}{\partial t} + V_j \frac{\partial v_i}{\partial x_j} = - \frac{\partial \phi_i}{\partial x_i} - \alpha \frac{\partial p}{\partial x_i} + \alpha \frac{\partial}{\partial x_j} \left\{ \left[ 2 \mu \left( e_{ij} - \frac{1}{3} \nabla.V \right) \right] \delta_{ij} \right\} \\
= \frac{\partial \phi}{\partial x_j} - \alpha \frac{\partial p}{\partial x_i} + \alpha \frac{\partial}{\partial x_j} \left\{ \left[ \mu \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \right] - \frac{2}{3} \mu \frac{\partial v_k}{\partial x_k} \right\} 
\] (3)

To perform a CFD simulation, a geometrical model of the fluid flow must be designed, followed by creating mesh and lastly defining parameters. The geometrical model of fluid flow inside the hot gas chamber was designed using Gambit software.
Solving the problem was completed using FLUENT software. Working fluid used is helium. Viscosity, operational conditions and input parameters were also determined. Convergence criteria were also defined in FLUENT, as well as initial value of iteration to start the calculation.

3.1. General Design
The scope of the geometrical design is limited to gas chamber, hot gas duct and inner coolant channels without structural materials. Hot gas chamber is an annular block separated into eight unevenly distributed “chamber” sections. The gas flows from above each chamber through numerous small holes. After mixing, the gas flows out of chamber into annular alley, and then enters the hot gas duct.

Due to simplified design, some changes are done compared to other HTR’s hot gas chamber. For the chambers, simple brick-shaped columns are used instead of prismatic columns. No arc-like features used to smooth the gas flow in the chambers. Each chamber has four small channels as coolant gas entrance.

3.2. Geometrical Modelling
The geometrical design is modelled using Gambit software. Due to simplified modeling, it was only used to model the fluid flow. The fluid flow model within the hot gas chamber is shown in figure 1.

Meshing was done using tetragonal type mesh and different mesh sizing. The mesh number on this model is limited to around 500 thousand. Interpolation format is set to first order upwind.

For boundary conditions, the holes above gas chambers are treated as inlet flow channels with different temperature input from the innermost channels to the outermost channels. Meanwhile, the far end of hot gas duct is treated as outflow channel. The rest of the model is treated as wall.

It is assumed that the fluid flows entirely from vertical coolant channel located above the gas chamber. No gas enters the chamber through the pebble bed channel. Gas leakage is assumed to be 14%. Last, temperature difference is set to 200°C between innermost and outermost coolant channel. This range is within the limit of temperature deviation as mentioned in reference [3].

Input parameters for the hot gas chamber modelling are shown in the following table. Other unmentioned parameters are determined within FLUENT programme.
Table 1. Simulation parameters

| Parameter                              | Value          |
|----------------------------------------|----------------|
| Fluid type                             | Helium         |
| Pressure (MPa)                         | 3              |
| Diameter of hot gas duct (cm)          | 30             |
| Diameter of inlet gas channels (cm)    | 4              |
| Fluid flow rate (kg/s)                 | 4.27           |
| Inlet gas temperatures range (°C)      | 600-800        |
| Turbulence model                       | k-epsilon      |

4. Result and Discussions
Temperature homogeneity simulation on RDE’s hot gas chamber is performed using a standard simplified model as described above. The simulation reached its convergence at 2,371 iterations. Temperature homogeneity as well as pressure drop will be analysed based on simulation result.

Temperature profile is shown in figure 2.

Figure 2. Total temperature profile of hot gas chamber.

CFD simulation of the hot gas chamber resulted in remarkable temperature homogeneity. Cross sectional temperature profiles of hot gas chamber are shown in figure 3. From the profile shown in figure 3, gas mixing occurs mainly in each of the chambers. Despite not having arc-like features, gas mixing performs fairly well in the chamber. No significant gas holdup occurs in innermost bottom of each gas chamber, except chambers located on the opposite of the hot gas duct.

The coolant gas was mixed further in the annular alley. However, no significant mixing occurred in hot gas duct, as shown further in figure 3. The reason is that the mixing has already occurred well in chambers and alley.
Figure 3. Cross-sectional temperature profile of hot gas chamber; upper region (left), middle region (middle) and lower region (right).

THD in simulated model of hot gas chamber reached value of 99.63%. It is translated into 0.74°C temperature deviation between hot and cold gas. This is a remarkably high degree, despite of the large temperature deviation between hot and cold gas and simplified chamber modelling. Previous simulation [8] with more detailed design shows less THD value, around 91-99%. However, since it was assumed that no gas enters the chamber through pebble bed channel, the real homogeneity of this design might be lower.

Temperature profile result is provided in Table 2.

Table 2. Calculation result of temperature profile of hot gas chamber.

| Item   | Maximum temperature (°C) | Minimum temperature (°C) |
|--------|---------------------------|---------------------------|
| Inlet  | 800                       | 600                       |
| Outlet | 700.3484                  | 699.6094                  |
| THD    |                           | 99.63%                    |

Another analysed parameter is pressure drop. Pressure profile of hot gas chamber is shown in figure 4.

Figure 4. Total pressure profile of hot gas chamber.
Pressure drop mainly occurs in the base of hot gas duct, where the higher-pressure gas enters the duct. Neither significant pressure drop nor pressure deviation occurs from the base to the tip of the hot gas duct.

Cross sectional pressure profiles of the hot gas chamber are shown in figure 5.

![Figure 5](image)

**Figure 5.** Cross-sectional total pressure profile of hot gas chamber; upper region (left), middle region (middle) and lower region (right).

The pressure is highest in the chambers located on the opposite of hot gas duct due to gas holdup, gradually dropping as the gas moves into the annular alley and finally into the hot gas duct. Total pressure drop from inlet channels to outlet port of hot gas duct reaches ± 6,365 Pa. This value is relatively similar with previous experiment conducted using similar gas flow rate [8].

Total pressure profile result is provided in Table 3.

**Table 3.** Calculation result of pressure profile of hot gas chamber.

| Item            | Total pressure (Pa) |
|----------------|---------------------|
| Inlet (average) | 7,718.131           |
| Outlet         | 1,352.92            |
| Pressure drop  | 6,365.211           |

5. Conclusion
Simulation of hot gas mixing in RDE’s proposed hot gas chamber has been performed using FLUENT software. Using simplified chamber configuration, THD value reaches around 99.63%, which implies extremely well temperature homogeneity. Meanwhile, pressure drop value is around 6,365 Pa, which is comparable to previous simulation with similar gas flow rate.

The simulation result shows that simplified chamber configuration is promising to reach high THD value, reducing temperature deviation until below safe limit. Further researches with better and improved design and parameters are necessary to obtain temperature homogeneity value more credibly and reliably. Several other flow parameters must also be investigated to obtain the optimum configuration for full-scale application.

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