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THERMOFLUID ANALYSIS OF HOT GAS DUCT AND HELIUM BLOWER OF REAKTOR DAYA EKSPERIMENTAL USING RELAP5 VISA

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Abstract

Pebble Bed High-Temperature Gas-Cooled Reactor (HTGR) is one of the nuclear reactor types that were promoted to be built by the Indonesian National Nuclear Energy Agency through the Experimental Reactor Power (Reaktor Daya Eksperimental; RDE) development program. This reactor is considered to have a good passive safety system with a design that is resistant to cooling system failure including earthquake shocks. Design and safety analysis of the primary system of RDE, including the hot gas duct and helium blower system, is very important. The purpose of this research is to design a hot gas duct and helium blower system as a part of the RDE's primary cooling system. The design was performed by a thermofluid analysis using RELAP5 ViSA code. Main target design parameters of the RDE's primary cooling system are helium mass flow rate, temperature, and pressure in both hot and cold pipe of the hot gas duct. The results showed that the hot gas duct and helium blower system are able to achieve the target design parameter with the maximum error values of 2%. In addition, fibre insulation material (91% of Al_2O_3 and 9% of SiO_2) can reduce the heat transfer rate in a hot gas duct. We also found that pure SiO_2 material has better performance in reducing the heat transfer rate compared to pure Al_2O_3 material.

Keywords: Helium blower, Hot gas duct, HTGR, Pebble bed RELAP5 ViSA,, Primary cooling system, RDE, Thermofluid.

1. Introduction

High-Temperature Gas-Cooled Reactor (HTGR) type Pebble Bed nuclear reactor is one of Generation IV sophisticated reactors with strong passive safety features [1]. The passive safety feature of this reactor is designed to be resistant to cooling system failure due to earthquake shocks. The successful resistant is due to its good safety system. Safety characteristics of the Pebble Bed HTGR is a natural exhaust flow mechanism that makes the Pebble Bed HTGR design simple. The huge and distributed energy demand of Indonesia is suitable for the applications of a small and medium nuclear reactor nuclear [1, 2]. In addition, the capability of the design to perform cogeneration is very interesting to be utilized for processes using natural resources.

Indonesia is an area prone to natural disasters, especially earthquakes and tsunamis. Safety, security and efficiency factors are considered to determine the type of nuclear reactor to be built. Pebble Bed HTGR is one type of nuclear reactor that is promoted to be built by the National Nuclear Energy Agency (BATAN) through the planning of an Experimental Power Reactor (Reaktor Daya Eksperimental; RDE) development program. The reactor design used in the construction of RDE refers to the design of the 10 MW High-Temperature Gas-cooled Test Reactor (HTR-10), which is a modular type of pebble bed HTGR built by China [1].

The researches about coupling system of HTGR and the hydrogen production installation have been conducted previously. The HTGR type reactor with 900-1000 °C outlet coolant temperature is a potential nuclear power plant (NPP) type to use for cogeneration purpose. This can be used either for electricity generation plant or heat source in non-electricity applications, such as hydrogen production. Thus, it can simultaneously produce electricity and hydrogen gas [3, 4].

Setiadipura et al. [1] conducted a safety analysis simulation on the Experimental Power Reactor (RDE) type Pebble Bed when an accident occurred Depressurized Loss of Forced Cooling (DLOFC) using PEBBED code to complete neutronic and thermal-hydraulic analysis. The analysis results showed that in steady-state equilibrium condition, the average and maximum fuel temperature were 511.9 °C and 819 °C, respectively. When the DLOFC accident is initiated, the core temperature increases. Then, after 8.2 hours reach its maximum at 974.9 °C, the core temperature decreases. The results showed the cooling passive mechanism of RDE [1].

Another research was done by Ekariansyah et al. [5]. They conducted a preliminary analysis of core temperature distribution of experimental power reactor using RELAP5. The results showed that the core temperature distribution under the assumed model of 4 core zones is below the limiting pebble temperature of 1620 °C with the highest pebble temperature of 1477 °C. Based on these reports, this type of reactor is interesting to build in Indonesia from the perspective of safety and flexibility in cogeneration applications.

In designing the primary cooling system in RDE, a coupling system is needed and can combine the core components of the reactor, steam generator, and helium blower to ensure the passive safety system of the reactor. The component used to connect the system is hot gas duct. Here, this study was focused on thermofluid modelling and analysis of hot gas duct components and helium blower by using RELAP5 ViSA software tools. The thermofluid analysis was carried out to determine the effect of fibre insulation material in the form of a mixture of 91% of Al_2O_3 and 9% of SiO_2 materials. The comparison of the type of materials were presented for understanding the heat transfer installed in the hot gas duct component.

1.1. Reaktor daya eksperimental (RDE)

The main components of the RDE nuclear system are the Reactor Pressure Vessel (RPV) and its internal parts, co-axial hot gas duct, helium blower and Steam Generator Pressure Vessel (SGPV). In the cooling system, RDE is designed to have cooling capabilities with natural mechanisms without any support from outside. This cooling capability is obtained due to the physical properties of thermal material from graphite used on the reactor core. High thermal conductivity of graphite makes the ability to transfer heat out of the reactor core better because it can reduce the temperature more.

The hot gas duct is a component exclusively found in this type of reactor where both the reactor core and the power conversion unit are placed into two pressure vessels, which need a connecting duct. The reactor core is located inside the Reactor Pressure Vessel (RPV), while the steam generator and the helium circulator are in the adjacent vessel or namely the Steam Generator Pressure Vessel (SGPV). The two vessels are connected together by a hot gas duct [6].

Helium blower is designed with a vertical structure installed at the top of the steam generator inside the SGPV. Helium blower is driven using an electric motor inserted by a converter outside the pressure vessel. The high-temperature helium gas flow from the reactor core to the steam generator is produced by the blower. In the primary system, the helium coolant with 3.0 MPa pressure reaches 700 °C at the core outlet and then drops to 250 °C at the steam generator exit, that is the helium blower operates at 3.0 MPa, 250 °C helium condition [7]. Figure 1 shows the layout of RDE's primary cooling system including hot gas duct.

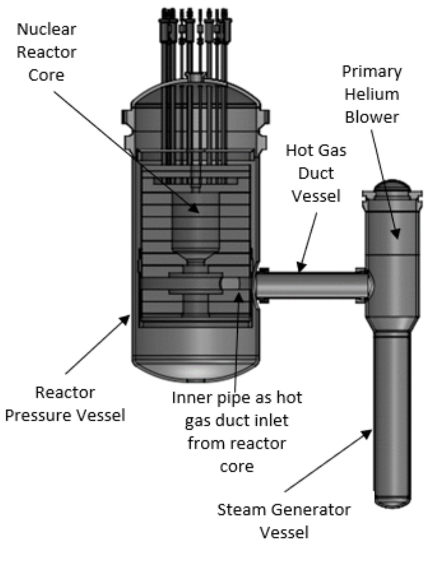

Fig. 1. Layout RDE's primary cooling system.

The primary loop pressure boundary system contains the core reactor core, the internal reactor, the steam generator, the hot gas duct, and the primary coolant (helium blower). The design of the primary loop pressure boundary system must give a guarantee. There is no unacceptable primary coolant leakage under normal and abnormal operating conditions [8].

1.2. Thermofluid analysis

Thermofluid analysis is needed in the design of primary cooling systems in nuclear reactors to predict the temperature distribution of pipes used as cooling fluid medium. Thermal fluid calculation of the RDE aims at providing heat transport capability, which can match with the heat generated by the core. Thus, it is provided with a set of thermal-hydraulic parameters of the primary loop, including the temperature distribution of the main components in the reactor, such as fuel elements, reflectors, reactor pressure vessel, etc. This report also includes the flow rate distribution and pressure losses in the primary system for initial and equilibrium core in order to meet the safety requirements under different operating conditions [9]. In this case, the hot gas duct is used as a connecting medium in the RDE primary cooling coupling system to drain helium fluid. Helium fluid is pumped by the helium blower, flowed from the steam generator towards the reactor core and vice versa in a primary cooling cycle.

1.3. Reactor excursion and leak analysis program (RELAP)

The RELAP computer code is a light water reactor transient analysis code developed for the U.S. Nuclear Regulatory Commission (NRC) for use in rulemaking, licensing audit calculations, evaluating operator guidelines, and giving a basis for nuclear plant analyser. Specific applications of this capability have included simulations of transients in LWR systems, such as a loss of coolant, anticipation of transients without scram, and operational transients (such as loss feed water, loss of offsite power, station blackout, and turbine trip). RELAP is a highly generic code. In addition to calculating the behaviour of a reactor coolant system during a transient, RELAP can be used for simulating a wide variety of hydraulic and thermal transients in both nuclear and non-nuclear systems, involving mixtures of steam, water, non-condensable and solute [9].

Thermolfluid parameters for modelling the core of the Multifunctional reactor (Reaktor Serba Guna G.A. Siwabessy (RSG-GAS)) has been conducted by the RELAP5 code [10]. The simulation was performed using the thermofluid code of RELAP5/SCDAP/Mod3.4, which has the capability to model the plate-type of RSG-GAS fuel elements. Three events were simulated, which are loss of primary and secondary flow without reactor trip, blockage of core sub-channels without reactor trip during full power, and loss of primary and secondary flow followed by reactor trip and blockage of core subchannel [10].

2. Research Methods

2.1. Calculation of model geometry

The geometry calculation of the model is done using technical data of RDE. Thus, it can produce the design parameters used in designing the model with RELAP5 ViSA. The geometry calculation model is carried out on hot gas duct components, cold coolant flow regions, and helium blower. The geometrical model is developed based on the assumption that the position of the internal pipe can be maintained along with the operation.

The hot gas duct is divided into two parts consisting of several layers of material used. The first part is a co-axial gas pipe consisting of a gas pipe layer, fibre insulation, and pipe support while the second part is a gas duct pressure vessel (outer pipe), which only consists of the gas duct pressure vessel itself. Each of these layers is made of different types and physical properties of the material. Thus, it greatly affects the thermofluid phenomenon along the hot gas duct.

Then, on the helium blower, the part affected by the helium flow. This part also equipped with impeller so that the geometry calculation is done only in that part. Helium blower pumps helium cold from the steam generator to the gas duct pressure vessel to flow to the reactor core.

2.2. Model design

The design of the model is done by the RELAP5 ViSA code system using geometric calculation data of the hot gas duct model, cold coolant flow region, and helium blower. In this modelling system, there are two parts of the model made, namely thermofluid nodalization and heat structure. Then, from the two models, a program script can be made. Thus, it can be used as input to the RELAP5 ViSA program. Modelling on thermofluid nodalization begins by blocking the nodalization of the hot gas duct system, cold coolant flow region, and helium blower, in which, these are used as model parts that are directly in contact with helium flow. The hot gas duct model is made with pipe components, which are divided into two parts, namely pipe 100 for hot helium flow and pipe 200 for cold helium flow. Then, for the cold coolant flow region model pipe 400 components are used while for the helium blower model pump 930 components are used. Thermofluid nodalization model is presented in Fig. 2. In the model development, it is assumed that the mixing of the helium from the core is performed perfectly. Thus, the inlet helium has a homogeneous temperature.

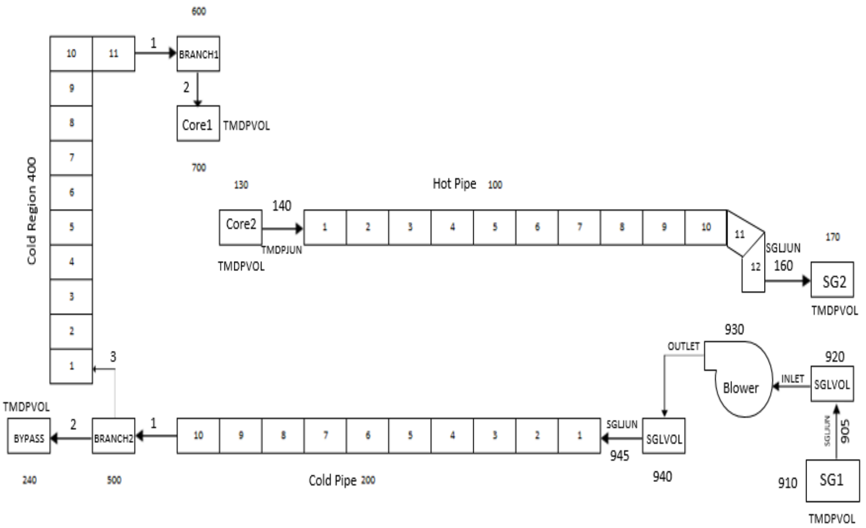

Fig. 2. Thermofluid nodalization model.

Then, the heat structure modelling is carried out only on hot gas duct wherein the pipe 100 part. The pipe makes the flow of hot helium. The pipe 200-part flows cold helium. This heat structure is used as a heat transfer medium from helium to the material used in the hot gas duct. Data on the material physical properties of each layer of liner-taper tube, thermal insulating fibre, inner tube, and gas duct pressure vessel are used in designing the heat structure model in the hot gas duct component. The cross-section of the hot gas duct and heat structure model can be seen in Figs. 3 and 4.

The program flow chart is presented in Fig. 5. The program flow chart begins with the initialization of the program model script. Then, the program script inputs data on the program. The program running process is carried out on RELAP5 ViSA. In the running process, epsilon (έ) is used as a threshold value where the value is an error value <2%. The error value is technical data minus result of RELAP5, divided by technical data, and multiplied 100%. If the differences that are between the model parameters and technical data have not yet reached the epsilon value, the program Script is re-designed to obtain the same value as epsilon. If the difference between the model parameter value and technical data has reached the epsilon value, the model that has been made can be used for simulation in steady-state conditions. The results of the simulation obtain output data in the form of parameter values in the form of mass flow rate, temperature, and helium pressure.

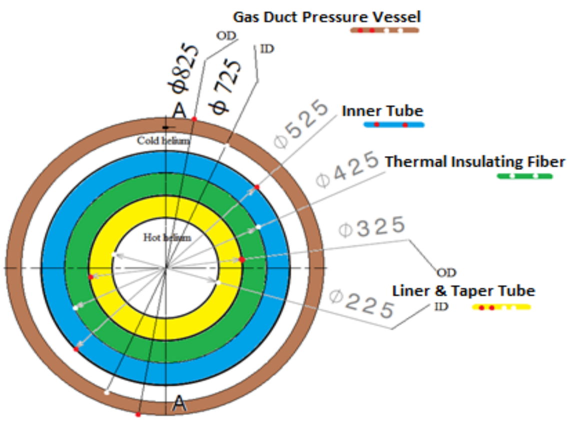

Fig. 3. Cross section of hot gas duct.

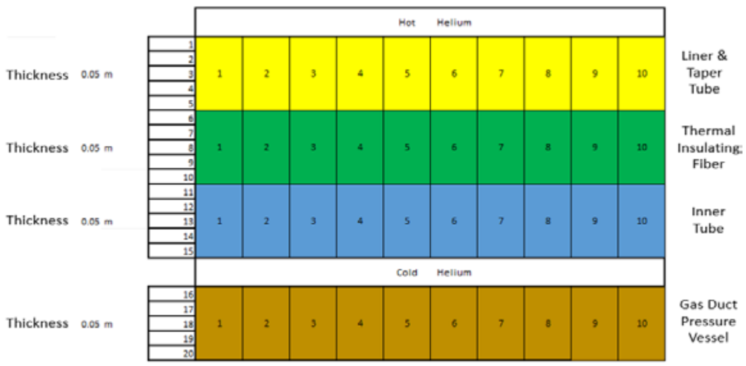

Fig. 4. Heat structure model.

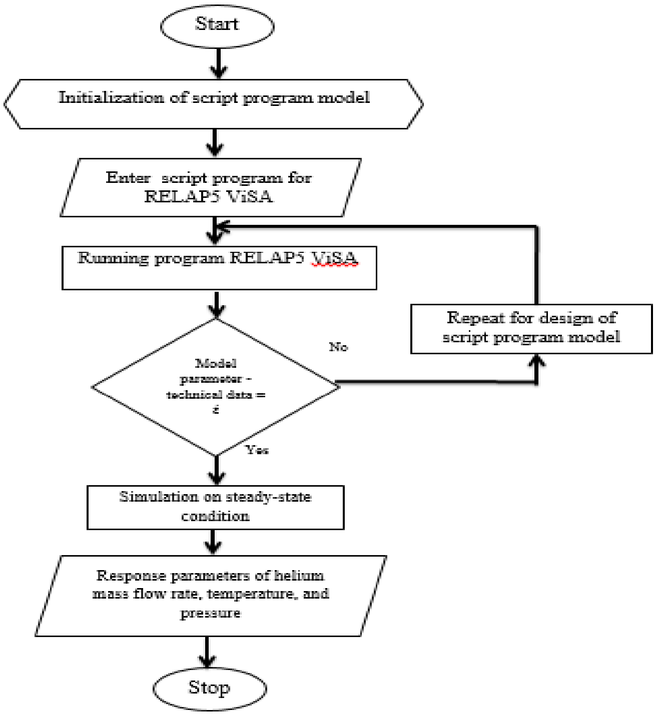

Fig. 5. Flow chart of RELAP5 ViSA program.

3. Results and Discussion

3.1. Model validation

Model validation was carried out with the aim of proving the truth of modelling by comparing the simulation results with the technical characteristics of hot gas duct and RDE helium blower data. Model validation is carried out based on two parts of the system, namely the co-axial gas pipe (inner pipe) and gas duct pressure vessel (outer pipe). The results of model validation can be obtained using specific parameters such as flow rate, temperature, and helium pressure in the pipe section. The data are shown in Tables 1 to 4. Based on the experimental results relating to error values in the mass flow rate (kg/s), temperature (K), and pressure (MPa), all error values are less than 2%. Thus, the model used in the current simulation of RDE 10 MW is valid.

Table 1. Comparison of the results of validating the co-axial gas pipe model with RDE technical data.

No	Parameter	Technical data	Result of RELAP5	Error (%)
1	Mass Flow Rate (kg/s)	4.27	4.3	0.70
2	Temperature (K)	973	972.6	0.04
3	Pressure (MPa)	3	2,99	0.12

Table 2. Comparison of the results of the helium blower model validation with RDE technical data.

No	Parameter	Technical data		Result of RELAP5		Error (%)	
		In	Out	In	Out	In	Out
1	Mass flow rate (kg/s)	4.27	4.27	4.3	4.3	0.70	0.70
2	Temperature (K)	510	523	515.8	522.6	1.13	0.07
3	Pressure (MPa)	2,98	3	2,97	2,99	0.09	0.01

Table 3. Error value from the validation of a cold pipe model.

No	Parameter	Error (%)			
		Pipe	Branch2 1	Branch2 2	Branch2 3
1	Mass flow rate (kg/s)	0.70	0.70	1.69	0.54
2	Temperature (K)	0.72	0.66	0.66	0.66
3	Pressure (MPa)	0.09	0.09	0.09	0.09

Table 4. Error value from the validation of the cold coolant flow region model.

No.	Parameter	Error (%)			
		Cold region	Branch2 1	Branch2 2	Branch2 3
1	Mass flow rate (kg/s)	0.54	0.54	0.54	0.54
2	Temperature (K)	0.66	0.66	0.66	0.66
3	Pressure (MPa)	0.01	0.01	0	0

3.2. Effect of fibre insulation material

In the simulation model, the effect of fibre insulation material on heat transfer on a hot gas duct was tested. The inner and outer pipes are given a fibre insulation material. Then, we compared the impact of additional fibre insulation material on the energy obtained. From the two tests (with and without additional insulation), parameters were tested based on the helium mass flow rate, temperature, and pressure data on the hot gas duct. The results are shown in Table 5.

Based on Table 5, the values of heat loss parameters, pressure drop, heat transfer rate differences between Node-1 and Node-10, and the difference in heat transfer rate between co-axial gas pipe and gas duct pressure vessel on hot gas duct given fibre material insulation is smaller than hot gas duct without being given fibre insulation material. This is because the physical properties of thermal conductivity, material density, and the specific heat capacity of materials from fibre insulation materials can reduce the rate of heat transfer that occurs along the hot gas duct. In this case, heat transfer by radiation between co-axial and gas duct vessel are not calculated.

Table 5. Results of testing models with fibre insulation materials.

Parameter	Without fibre insulation model		Fibre insulation given model	
	Co-axial	Gas duct vessel	Co-axial	Gas duct vessel
Heat loss dT(K)	6.2	5.7	5.4	4.9
Pressure drop dP (Pa)	682	100	692.3	54.2
Heat transfer rate difference between Node-1 and Node-10 Q (watt)	2.898	5.318 724.93	2.419	4.721 623.73
Heat transfer rate difference between co-axial and gas duct vessel (watt)	1,695.07		1,678.27	

3.3. Comparison of types of fibre insulation materials

Next, model testing was done by comparing the types of material Al_2O_3 and SiO_2. The results are shown in Table 6. The results of model testing given SiO_2 material with a content of 100% have the smallest parameter values compared to that of other tests. This states that SiO_2 material with a content of 100% is the best material for being used as a fibre insulation material on the hot gas duct. SiO_2 can reduce the rate of significant heat transfer that occurs along the hot gas duct. In this case, heat transfer by radiation between co-axial and gas duct vessel are not calculated. The hot gas duct design developed in this study, in general, have the same performance as the HTR-10 hot gas duct. According to Ekariansyah et al. [11], this is in a good agreement [11]. Silica is also good since this material is largely available and can be easily produced [12-14].

Table 6. Results of model testing with a comparison of fibre insulation materials.

Parameter	Without fibre insulation model		Fibre insulation given model	
	Co-axial	Gas duct vessel	Co-axial	Gas duct vessel
Heat loss dT(K)	5.5	5	1.4	1
Pressure drop dP (Pa)	673.6	54.2	603.6	0
Heat transfer rate difference between Node-1 and Node-10 Q (watt)	2,502	4,785 638.62	258	1,737,6 132.53
Heat transfer rate difference between co-axial and gas duct vessel (watt)	1,644.38		1,347.07	

4. Conclusion

Thermofluid design analysis of the hot gas duct and helium blower as part of RDE's primary cooling system is already performed using RELAP5 ViSA code. Main target design parameters of the RDE's primary cooling system are helium mass flow rate, temperature and pressure in both hot and cold pipe of the hot gas duct. The results showed that the hot gas duct and helium blower system are able to achieve the target design parameter with maximum error values of 2%. In addition, the results showed that fibre insulation material (91% Al_2O_3 and 9% SiO_2) can reduce the heat transfer rate in thea hot gas duct. Pure SiO_2 material is the best for reducing the heat transfer rate.

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