Semi-Analytical Methods and Simulation for Temperature Distribution of Helium Purification System for Reaktor Daya Eksperimental

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Abstract. Reaktor Daya Eksperimental (RDE) or Indonesian Experimental Power Reactor has been started from 2014 in term of conceptual design. The reactor design as modified of HTR-10, it’s a High Temperature Gas-cooled Reactor. RDE using Pebble bed fuel type and will be built to 10 MWh and 3 MWe. In future usage, RDE would be uses as reactor model in Indonesia. It can be scale up to generate more power or it’s can be modified as small modular reactor to supply electricity for home consumption. In the end of 2018, the project targeted to be finish all detail engineering design. One of the system that design is helium purification system. The helium purification was important to reactor because it’s affect directly to cooling mechanism of the reactors. This research aim to simulate the temperature distribution on this system to make sure that there is no overheating in some part of system. The research will considering heat from system and environment. This research using analytical methods and matlab software to simulate the problem. Visualization of temperature change and distribution can be shown in function of time. The temperature set as factor to decide which material the best to uses in the future infrastructure of RDE.

Keywords: RDE, HTR-10, helium purification system, temperature distribution

1. Introduction
Reaktor Daya Eksperimental (RDE) or Indonesian Experimental Power Reactor will be built as first power reactor in Indonesia, however RDE also can be used to be a research reactor purpose too. BATAN have responsibility as the only research institution for nuclear usage in Indonesia to create a safety design for RDE. BATAN is responsible for the development of RDE from the conceptual design stage in 2015 until a scale as planned in 2027. In 2017 BATAN has been finish a basic design and in 2018 the detail engineering design (DED) will be done completely. In a further stage, the RDE will be used as a model that can be used as a reference in the construction of the power reactor to be built in Indonesia. In addition, RDE can be used in a many of other ways such as to be used as a modular reactor to meet electricity needs in remote areas. This is supported by a design that can extinguish itself even without electricity from outside. In other hand it can also be used as a bigger power plant for large-scale electricity by scaling it up.

DED finishing work is carried out as a follow-up and improvement of the basic design that has been done. At this stage it is necessary to add some special details that can provide additional information. RDE
is made based on the basic design of htr-10, DED completion to provide any information that gives the difference between the design of HTR-10 and RDE. One that needs special attention is how the cooling system will be used by RDE. RDE is built based on the fourth generation reactor model as a high temperature gas-cooled reactor. The gas used as a coolant is helium gas. In the use of helium gas, it is necessary to have a purification step to get the appropriate level.

![Diagram of RDE](image.png)

**Figure 1.** The general scheme of RDE

**Table 1.** General data of RDE

| Parameter                        | Value              |
|----------------------------------|--------------------|
| **Core design**                  |                    |
| Fuel type                        | Pebble             |
| Core height (active)             | ~2 m               |
| Core diameter                    | ~1.8 m             |
| Core heat transfer area          | 305.4 m²           |
| Electrical power (gross)         | ~3 MWe             |
| Electrical power (net)           | ~2.9 MWe           |
| Core thermal power output        | ~10 MW             |
| **Primary cooling system**       |                    |
| Primary coolant                  | Helium             |
| Primary coolant mass flow rate   | 4.4 kg/s           |
| Primary coolant pressure         | 30 bar             |
| Core inlet temperature           | 250 °C             |
| Core outlet temperature          | 700 °C             |
| Average core temperature         | 450 °C             |
| **Primary gas blower**           |                    |
| Total static head                | Approx. 1.5 bar    |
| Nominal delivery                 | Approx. 4.3 kg/s   |
| Outlet pressure                  | Approx. 30.3 bar   |
| Outlet temperature               | 250 °C             |
| **Secondary cooling system**     |                    |
| Nominal steam mass flow rate     | ~4.0 kg/s          |
| Nominal helium mass flow rate    | ~4.4 kg/s          |
| Nominal feed mass flow rate      | ~4.0 kg/s          |
| Steam temperature                | ~530 °C            |
| Steam pressure                   | ~60 bar            |
To achieve a certain degree of purity, the helium gas that will be used will make a helium purification system. In HTR-10 the main part of the HPS consists of a cartridge filter, a molecular sieve adsorber, a copper oxide bed, a low temperature adsorber and two diaphragm compressors also contains an additional post accident cooler with a moisture separator \[2\]. In other hand, for HTGR helium coolant impurities removal is based on dust removal by mechanical filters and oxidation of CO and H\textsubscript{2} on catalyst (such as CuO and Cr\textsubscript{2}O\textsubscript{3}) at temperature around 400-600\textdegree K. then followed by removing CO\textsubscript{2} and H\textsubscript{2}O on room temperature and removing CH\textsubscript{4} and other residual in lower adsorber cooled by liquid nitrogen from -170\textdegree C to -160\textdegree C \[3\]. Helium loop is become one of important part because the activities are released and transport to primary system from the core carried by cooling gas and the graphite dust in HTGR \[4\]. One of the things that need to be considered in the purification process is the phenomenon of heat transfer. Heat transfer occurs because of different temperature differences in the system that are quite high. In this study a simple simulation of the phenomenon of heat transfer is possible in this system. This needs to be able to provide an illustration of how the phenomenon of heat transfer can occur in the system. To facilitate the experiment a selection of case studies was limited to a small part of the helium purification system. Some additional assumptions are carried out which aim to simplify and simplify cases. In its implementation, the research reviews how the physical properties occur and performs simple simulations using computational modeling.

| Water feed temperature   | ~160\textdegree C |
|--------------------------|------------------|
| Secondary pump power     | 223 lt/min       |

Figure 2. HPS HTR10\[2\]
2. Methodology
Heat transfer and distribution can be done by making some simplifications in the case to be reviewed. The research was conducted focused on objects that have a pipe shape, at this stage it can be seen that research will be carried out in the form of a straight pipe cylinder. The numerical methods in practical application can be used to determine the temperature distribution and heat transfer for solid geometries by describe geometries, temperature dependent properties, initial condition and boundary values [6].
In the work of this research it was assumed that heat only moved towards the radial direction. The assumption that heat transfer to the upright axis and displacement at each angle is the same because on the same medium. This makes the heat propagation and heat distribution that will occur in the pipe will be in the form of a temperature function that is radial or visually can be described as several concentric circles with the temperature of each circle boundary will show a different temperature. In the case where the center of the circle has a higher temperature than the outermost temperature in the circle, the distribution that occurs is linear. Identification of suitable assumptions can simplify the mathematical firm without loss of relevant detail, also it can reduce the computation time, thereby allowing close to real-time allowed the model run then make limits for error in acceptable condition [5].

Physically heat transfer can occur in the way of radiation, convection and conduction. In this case, the heat transfer by conduction and convection were the most dominant. When the fluid in the pipe has not been flowed then the heat transfer that occurs is considered to have no heat transfer rate. This assumption is needed to describe the steady conditions of heat distribution that are owned by the circular section of the cylinder. The heat transfer equation is generally written in the following form:

\[ \rho_m c_m \frac{\partial T}{\partial t} = k_m \nabla^2 T + \dot{q} \]  

(1)

with \( \dot{q} \) is the heat rate per unit volume produced by the system. Whereas for the case to be examined involves a flow of fluid in it and consider the influence of the environment. The equation used changes to

\[ \rho_m c_m \frac{\partial T}{\partial t} = k_m \nabla^2 T + \dot{q} - \dot{q_f} + \dot{q_o} \]

(2)

with \( \dot{q_f} \) is the rate per unit volume that is affected by the fluid flowing while \( \dot{q_o} \) is the influence given by the environment to the system. The value of \( \dot{q_f} \) it can be described as a conduction and advection phenomenon in the medium through which the equation given becomes

\[ \dot{q_f} = \rho_f c_f v_f \left( T_s - T_i \right) - \rho_f c_f v_f \nabla T + k_f \nabla^2 T \]

(3)
is a perfusion phenomenon that occurs between fluid and the layer where it flows, while the velocity of fluid flow in the medium. The value of \( \dot{q}_o \) described as convection between media and the system, here is seen a convection phenomenon between the system and the surrounding air

In full term the equation can be written as

\[
\rho_m c_m \frac{\partial T}{\partial t} = k_m \nabla^2 T + \dot{g} - \left( \rho_f c_f w_f \left( T_{rf} - T_{ri} \right) - \rho_f c_f v \nabla T + k_f \nabla^2 T \right) + \frac{n(T_{r2} - T_{r1})}{r_2 - (n-1)\Delta r} \tag{5}
\]

For the case reviewed, it is assumed that the radial direction is considered to have the same heat distribution for each angle and the distribution of the fluid flow is neglected, so that the phenomenon of heat transfer is considered as a displacement in one dimension, assum ed before the fluid flow and the influence of the outside can still be distributed so the system is considered to be in a steady state with a temperature distribution profile. To solve this, the equation used changes to

\[
\frac{k_m}{\rho_m c_m} \frac{\partial^2 T}{\partial r^2} + \frac{\dot{g}}{\rho_m c_m} - \frac{1}{\rho_m c_m} \left( \rho_f c_f w_f \left( T_{rf} - T_{ri} \right) - \rho_f c_f v \frac{\partial T}{\partial r} + k_f \frac{\partial^2 T}{\partial r^2} \right) \frac{\partial T}{\partial r} + \frac{\dot{q}_o}{\rho_m c_m} = 0 \tag{6}
\]

The equation becomes a temperature differential equation with two variables (position and time), computationally can be solved using the finite difference method. The known initial state is for temperature at \( r_2 \) have \( T_{r2} \) and the temperature value at < \( r_1 \) have an equal value with \( T_{r1} \). By using the finite difference method, you can replace the second-order differential equation and one as the form of the Taylor series

\[
\frac{k_m}{\rho_m c_m} \frac{\partial^2 T}{\partial r^2} - \frac{1}{\rho_m c_m} \left( \rho_f c_f w_f \left( T_{rf} - T_{ri} \right) - \rho_f c_f v \frac{\partial T}{\partial r} + k_f \frac{\partial^2 T}{\partial r^2} \right) \frac{\partial T}{\partial r} + \frac{\dot{g}}{\rho_m c_m} + \frac{\dot{q}_o}{\rho_m c_m} = 0 \tag{8}
\]

To simply the equation use simple substitute term \( \frac{k_m}{\rho_m c_m} = E ; \frac{\rho_f c_f w_f}{\rho_m c_m} = F ; \frac{\rho_f c_f v}{\rho_m c_m} = F ; \frac{k_f}{\rho_m c_m} = G \) for initial condition when there is no heat from outer system, G can be negligible.

\[
E \frac{\partial^2 T}{\partial r^2} + F \frac{\partial T}{\partial r} + Fw_f \left( T_{rf} - T_{ri} \right) + G = 0
\]

Add other substitute \( Fw_f \left( T_{rf} - T_{ri} \right) + G = H \)

\[
E \left( \frac{T_{ri} - T_{rf}}{\Delta r^2} \right) + Fv \left( \frac{T_{rf} - T_{ri}}{2\Delta r} \right) + H = 0 \tag{9}
\]

Add other substitute \( \frac{E}{\Delta r^2} = J ; \frac{Fv}{2\Delta r} = K \)
\[ J(T_{i-1} - 2T_i + T_{i+1}) + K(T_{i+1} - T_{i-1}) + H = 0 \]

\[ (J - K)T_{i-1}^j - 2T_i + (J + K)T_{i+1}^j + H = 0 \]  

(10)

When \( i = 1 \)
\[ (J - K)T_0^j - 2T_1^j + (J + K)T_2^j + H = 0 \]
\[ -2T_1^j + (J + K)T_2^j = -H - (J - K)T_0^j \]

When \( i = n - 2 \)
\[ (J - K)T_{n-3}^j - 2T_{n-2}^j + (J + K)T_{n-1}^j = -H \]
\[ (J - K)T_{n-2}^j - 2T_{n-1}^j + (J + K)T_n^j = -H \]

When \( i = n - 1 \)
\[ (J - K)T_{n-1}^j - 2T_n^j + (J + K)T_{n+1}^j = -H \]
\[ (J - K)T_n^j - 2T_{n+1}^j = -H - (J + K)T_{n+1}^j \]

This pattern can be written in the form of a matrix

\[
\begin{bmatrix}
-2J & J + K & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
J - K & -2J & J + K & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & J - K & -2J & J + K & 0 & 0 & 0 & 0 & 0 \\
& \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & J - K & -2J & J + K & 0 & T_{n-2}^0 & -H \\
0 & 0 & 0 & 0 & J - K & -2J & J + K & T_n^0 & -H \\
0 & 0 & 0 & 0 & 0 & J - K & -2J & T_{n-1}^0 & -H \\
0 & 0 & 0 & 0 & 0 & 0 & J - K & -2J & T_n^0 & -H \\
\end{bmatrix}
= 
\begin{bmatrix}
T_1^0 \\
T_2^0 \\
T_3^0 \\
\vdots \\
T_{n-2}^0 \\
T_n^0 \\
\end{bmatrix}
\]

\( \begin{bmatrix}
-H - (J - K) \\
-H \\
\vdots \\
-H \\
-H - (J + K) \\
\end{bmatrix} \)

Furthermore, the profile that has been obtained will change with the change in time and can be solved by the Euler method, which can simply be write in general as

\[ T_{i}^{t+1} = T_{i}^{t} + \Delta T_{i}^{t} \cdot *d_{t} \]  

(12)

Changes in time provide different values in heat that occurs between the environment and the system that occurs with the phenomenon of convection. The value of convection that occurs depends on the magnitude of the temperature difference between the surface and the environment and the depth of the position of a point against the surface. This case main problem was there is outer heat affect the temperature that can change the system temperature distribution profile. Temperature profile will change by time increasing, but it’s heat transfer will be decrease. After performing simple calculations and simulations, it is obtained a simulation of changes and distribution of heat that occurs in the pipe based on the position function and the transient state of time. The next step is done by doing the same thing in the direction of the flow. By doing repeated calculations in each layer in the direction of flow, the temperature distribution that occurs along the pipe can be described.

**Figure 5.** The layer of the cylinder layer from low temperature to high temperature
Simulations based on semi-analytical solutions are carried out using several parameters which include physical conditions of the system state and parts that are used as examples of research. The parameters used include the type of material used and its physical properties, the fluid material used, the desired data size includes the amount of data and the steps and iterations that will be used. The following are some of the data used as parameters in this study:

| Parameter use in experiment | value |
|-----------------------------|-------|
| The desired amount of radial position data $n_r$ | 1000 |
| The desired number of tube slices data $n_z$ | 1000 |
| The desired amount of time data $n_t$ | 1000 |
| Inner circle radius $r_1$ | 0.1 m |
| Outer circle radius $r_2$ | 0.125 m |
| Pipe length $z$ | 1 m |
| Simulation time $t$ | 10 s |
| Radial step $dr$ | $dr = \frac{r_2}{n_r + 1}$ |
| Length step $dz$ | $dz = \frac{n_z + 1}{z}$ |
| Time step $dt$ | $dt = \frac{nt}{t}$ |
| Heat conduction of steel pipe | 84 W/mK |
| Heat conduction of fluids helium | 0.1411 W/mK |
| Mass density of pipe $\rho$ | 7800 kg/m$^3$ |
| Mass density of fluids | 0.179 kg/m$^3$ |
| Specific heat of pipe $c$ | 480 J/kgK |
| Specific heat of fluids | 5139 J/kgK |
| Inner heat rate per volume | $10^6$ W/m$^3$ |
| Perfusion from fluids flow | - |
| Initial temperature of $r_1$ | 300 K |
| Initial temperature of $r_2$ | 301 K |
| Estimated fluids flow temperature | 600 K |
| Flow rate of fluids | 4 m$^3$/s |

3. Results and discussion

Figure 6. Temperature distribution for steady state of the pipe
This research uses a lot of simplification so that further research is needed to improve the research that has been done. In this study, it has not been included in the calculation of the different values of fluid flow velocities based on the radial position function, as well as the existence of an advection phenomenon where the fluid flow that occurs in the pipe also has the potential to provide changes in temperature within the pipe itself. The addition of the flowing fluid factor should also take into account that in the pipe flowed by
a certain temperature fluid will cause expansion in the pipe through which in this study the effect of thermal 
expansion has not been taken into account. When calculating thermal expansion, the value of the 
dimensions of the object to be simulated has a size that changes according to the function of time. This can 
be solved by repeating the recurring calculations over time.

4. Conclusion
Using an analytical solution to the physical phenomena can be solved using computational methods. In its 
implementation, it is necessary to take into account many factors from outside that continue to change with 
the time function. Simulations are carried out using a number of assumptions that actually keep the results 
from the actual situation. But this simplification can make it easier to do computation, besides that the 
shortcomings that occur because of differences with the actual situation can be reduced by adding repeated 
calculations iteratively or adding parameters that need to be taken into account. The simulation carried out 
in this study can be an initial description for similar research. It is necessary to add many factors that are 
taken into account in the refinement in order to fully describe the actual situation.

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