The analysis of air-cooled heat exchanger for Reactor Cavity Cooling System (RCCS) on Experimental Power Reactor (RDE) design

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Abstract. The National Nuclear Energy Agency (BATAN) is designing the Experimental Power Reactor (RDE). The Reactor Cavity Cooling System (RCCS) is a new basic design in the nuclear power plant. It will be incorporated into High-Temperature Reactors (HTR), which is one proposed generation of IV reactors. While HTR has been designed and operated, the RCCS design is unique to the recent generation of gas-cooled reactors as a passive decay heat removal system. However, many aspects of the new air- or water-cooled design still need to be investigated on RCCS. The temperature, mass flow, configuration of the riser, and number of the risers on the water-cooled heat exchanger system which is used is a necessary test. The RCCS designs have not been studied for the RDE design. The heat-transfer and fluid-flow on the RCCS facility have not been investigated for the air-cooled cavity cooling system. The aim of this study is to examine the condition of the air-cooled heat exchanger of RCCS for RDE 10 MWth design. The pressure, temperature, and velocity with certain diameters of cooling pipes are computed with FLUENT 6.3 computational fluid dynamics (CFD) software package under a mass flow rate variation. The pressure, the flow velocity and delta temperature outlet were examined on the RCCS process. The air-cooled heat exchanger in RDE basic design was found to attain safe operation.

Keywords: Reactor Cavity Cooling System, High-Temperature Reactor, Experimental Power Reactor, Computation Fluid Dynamic, Air-cooled Heat Exchanger System
1. Introduction

The National Nuclear Energy Agency (BATAN) is designing the Experimental Power Reactor (RDE). The RDE design is still waiting to be approved by BAPETEN. The designs are currently under discussion. Many systems to be used in the reactor need to be investigated, especially the Reactor Cavity Cooling System (RCCS). Several RCCS basic designs are still under discussion.

The design suggested to BAPETEN is based on natural convection. The air-based cooling systems have no pumps, circulators, valves, or other active components. Those systems are designed to operate continuously in all modes of plant operation.

The configuration of the water-based cooling system that operates at low temperature and low pressure in constant flow. The water temperature stays under the permitted maximum temperature during normal operation. A high water temperature is reached only during emergency passive operation.

The air-cooled heat exchanger is one of the important systems for managing the temperature of boiling fluid in RCCS. Many aspects of water-cooled heat exchangers in cavity cooling systems, such as temperature, velocity, and pressure, must be investigated.

The reactor cavity cooling system PMR200 has scaling analyzed [1]. The RCCS for high-temperature gas coolers was analyzed by computational fluid dynamics [2]. Afterward, the thermal characteristics of the cavity cooling system were modeled with RELAP5-3D [3]. The test and modeling of thermal-hydraulic characteristics of an experimental RCCS with air was analyzed [4, 5]. The new reactor cooling system with passive safety features was computed using the novel shape for HTGRs and VHTRs [6]. GAMMA+ and Flownex have been compared for analyzing the steady-state heat transfer and natural circulation in water-cooled RCCS [7]. The methodology for new RCCS with passive safety is a comparison between a real RCCS and a scaled-down heat removal test facility [8]. Air ingress on a 200-MWe pebble bed modular high-temperature reactor has been studied [9]. Additionally, experimental analysis has been done on mixed convection in the reactor cavity cooling system of HTGR for hydrogen production [10]. The heat transfer process in the reactor cavity of a modular high-temperature gas-cooled reactor has been simulated numerically [11]. Besides that, a three-dimensional numerical investigation has been carried out on the heat transfer process in the reactor cavity of HTR-10 [12]. The design of a straight tube bundle steam generator has been studied for Experimental Power Reactor [13]. The helium purification system capability during water ingress accident in RDE was analyzed [14].

The RCCS designs have not been studied for RDE design. The fluid flow and heat transfer on the RCCS facility have not an investigation for air-cooled cavity cooling system.

The objective of this study is to investigate the water-cooled temperature in the heat exchanger of RCCS for RDE 10 MW thermal design. The variation of temperature, flow velocity, a number, and diameter cooling pipes are analyzed and simulated with FLUENT 6.3 computational fluid dynamics (CFD) software. The flow velocity and delta temperature were obtained and investigated for the RDE design.

2. Theory

The RCCS is a new passive safety system. It designed for the next generation of nuclear power plants. This is a feature of high-temperature gas-cooled reactors (HTGR) which is a Generation IV reactor.

The mechanism of heat transfer, in this case, is assumed to be free convection. There is a heat transfer between materials due to differences between hot and cold locales. Free convection is the heat transfer that occurs between a solid surface and a fluid flowing around it, using a conductive medium in the form of a fluid (liquid/gas) without the presence of a driving medium. The natural convection is a heat transfer caused by different temperatures and different densities without being driven by external forces, whereas forced convection is the heat transfer of gas or liquid flow caused by external forces.

Fluid flow can be categorized as laminar flow, turbulent flow, and transition flow. In laminar flow, fluid moves in layers or laminae with one gliding smoothly. In laminar flow, viscosity functions to reduce the tendency for relative movement between layers. Laminar flow follows Newton's law of
viscosity. Turbulent flow is a flow where the particle movements of fluid particles are very erratic because they experience mixing and particle rotation between layers, which results in a mutual exchange of momentum from one part of the fluid to another in a large scale, while the transition flow is a transition between laminar flow and turbulent flow.

The heat transfer rate \( q_c \) is calculated by equation (1).

\[
q_c = h_c A \Delta T \quad \text{or} \quad q_c / A = h_c \Delta T \quad \text{(Newton’s Law)}
\]  

(1)

\( h_c \) = specific-heat-capacity (kJ/kg), \( \Delta T = T_{in} - T_{out} \), \( T_{in}, T_{out} \) : inlet, outlet temperature

A = cross sectional area

The fluid flow rate is calculated using equation (2).

\[
\dot{m} = \rho v A
\]

(2)

\( \dot{m} \) : mass flow rate (kg/h), \( v \) : flow velocity, \( \rho \) : fluid density, which equals one.

The flow velocity is calculated by equation (3).

\[
v = \dot{m} / \rho A = \dot{m} / \rho \pi r^2 = \frac{4 \dot{m} \rho \pi}{R^2}
\]

(3)

\( R \) : diameter, \( r = R/2 \), \( r^2 = 1/4 \ R^2 \).

The volumetric flow rate is calculated using equation (4).

\[
Q = \dot{m} h \Delta T \quad \text{or} \quad Q = \dot{m} C_p \Delta T
\]

(4)

\( C_p \) : specific heat capacity (kJ/kg °C)

Measurements of flow velocity and pressure in pipes are based on Bernoulli’s law. The pressure \( p \) represents the amount of kinetic energy per unit volume \( \frac{1}{2} \rho v^2 \). The potential energy per unit volume \( \rho gh \) has a constant value at each point along a line (Eq. (5)).

The fluid flow is characterized by the unchanging mass density of the fluid along with the flow such as water, various types of oil, and emulsions. The Bernoulli equation for an incompressible stream is as given in (5).

\[
p + \rho gh + \frac{1}{2} \rho v^2 = c
\]

(5)

In (5), the meaning of the symbols is as follows: \( v \) : fluid velocity, \( g \) : gravitational, \( h \) : height relative to a reference, \( p \) : fluid pressure, \( \rho \) : fluid density. The equation is used to the uncompressed flow assuming the flow is steady (steady-state) and no friction. Flow discharge is used to calculate the flow velocity for each pipe experiment.

3. Methodology

The design of RDE is based on natural circulation and natural convection. The RDE was modeled as showing a temperature variation as expected for a 10-MWth operation. The air-based cooling system uses no pumps, circulators, valves, or other active components. Those are designed to operate continuously in all modes of plant operation. The design of the RDE is shown in Figure 1. The configuration is a constant-flow, water-based cooling system that operates at low temperature and low pressure. The RCCS design surrounds the reactor pressure vessel (RPV) as shown in Figure 1.
The air-cooled heat exchanger is an important system for maintaining the temperature of fluids in RCCS as shown in Figure 2 (in the right side).

The temperature at the inlet of the air-cooled heat exchanger is 46 °C, while at the outlet from the air-cooled heat exchanger, it is 39 °C. The water temperatures from the pipeline are below 46 °C (at inlet) during normal active operation, reaching boiling point only during emergency passive operation. The delta temperature is kept in a range 7 °C wide.
The mass flow rate is 4.2778 kg/s. Natural convection with the chimney takes place at 1 atm. The material used is carbon steel. The inside diameter of the tube is 3.2 cm. The number of tubes in the air-cooled heat exchanger is 60, divided into two rows of 30 in triangular configuration.

The input parameters are velocity, temperature, and pressure. The calculation results for the temperature and pressure if the mass flow were given at 100%, 75%, 50%, and 25% of the maximum mass flow of 15 400 kg/hr or 4.2778 kg/s. Thus, the mass flow each varied at 4.2778 kg/s, 3.2084 kg/s, 2.1389 kg/s, and 1.0694 kg/s. The velocity, pressure, and temperature were obtained according to the CFD simulation using Eqs. (1) and (2). Those depended on the varying flow rate in a certain range. Afterward, velocity, pressure, and temperature were calculated using CFD.

The parameters of air cooler in RCCS RDE are presented in Table 1.

| Parameter                                               | Value       |
|---------------------------------------------------------|-------------|
| Heat exchange tube outside diameter, mm                 | 42          |
| Heat exchange tube inner diameter, mm                   | 32          |
| Heat exchange tube number                               | 60          |
| Flow path number                                        | 2           |
| Heat exchange area                                      | 13.279      |
| (outside area of base tubes) A₀, m²                      |             |
| Fin pitch b, mm, distance between pitch                 | 2.3         |
| Fin thickness, mm                                       | 0.4         |
| Fin diameter, mm                                        | 57          |
| Flow rate/area, m²                                      | 5.3         |
| Ratio of rib area to heat exchange tube                 | 23.4        |

The expansion water tank for the RCCS was also designed. There are several parameters for RDE expansion water tank, as given in Table 2.

| Parameter          | Value       |
|--------------------|-------------|
| Operation Pressure, MPa | 0.1       |
| Outside diameter, mm | 1.2        |
| Inside diameter, mm  | 1.19        |
| Height, m           | 2.7         |
| Volume, m³          | 3.0         |
| Water volume, m³    | 2.0         |
| Nitrogen volume, m³ | 1.0         |

The RDE design parameters are given in Table 3.

| Fluid       | 17.01 Cold Water | 17.02 Hot Water | 17.03 Cold Water | 17.04 Hot Water | 17.05 Cold Water | 17.06 Hot Water |
|-------------|------------------|-----------------|------------------|-----------------|------------------|-----------------|
| Design (kg/hr)| 15 400           | 15 400          | 300              | 300             | 300              | 300             |
| Operating Pressure (bar A) | 1.0   | 1.0             | 1.0              | 1.0             | 1.0              | 1.0             |
| Operating Temperature (°C)  | 39     | 46              | 39               | 46              | 39               | 46              |
4. Result and Discussion

The mass flow rate was varied as 4.2778 kg/s, 3.2084 kg/s, 2.1389 kg/s, and 1.0694 kg/s. Calculations of temperature, pressure, and velocity were performed. CFD simulations were performed on designs and on operating water-cooled RCCS facility by Fluent 6.3. The parameter design is used which has described in Table 1, 2 and 3.

The contours of the absolute pressure were obtained for mass flow rate of 1.0694 kg/s and are shown in Figure 3.

![Figure 3. Contours of absolute pressure for mass flow rate of 1.0694 kg/s](image1)

For the mass flow rate of 1.0694 kg/s, the inlet pressure was found to be 1.000 atm and the outlet pressure is obtained 0.999 atm. The difference between inlet and outlet pressures is only 0.001 atm. This pressure difference is sufficiently small. It means that the outlet pressure is still safe for RDE basic design.

For the mass flow rate of 1.0694 kg/s, the contours of the temperature are shown in Figure 4.

![Figure 4. Contours of temperature under mass flow rate of 1.0694 kg/s](image2)
For the mass flow rate of 1.0694 kg/s, the inlet temperature is 44.093 °C (colored orange with arrow line in Figure 4). The outlet temperature is 36.944 °C (sky blue with arrow line). The delta temperature is 7.149 °C. The recommended delta between inlet and outlet temperatures is around 7-9 °C. It means that the temperature outlet is still safe for the RDE basic design.

The same case for the mass flow rate of 1.0694 kg/s, the velocity vector colored by velocity magnitude is shown in Figure 5.

![Velocity Vector for the Mass Flow Rate of 1.0694 kg/s](image)

**Figure 5.** Velocity vector for the mass flow rate of 1.0694 kg/s

For the mass flow rate of 1.0694 kg/s, the inlet velocity is 0.061 m/s (light green, Figure 5) and the outlet velocity is 0.066 m/s (yellow). The delta velocity is very small at 0.005 m/s. The velocity of the mass flow is almost constant. It means that velocity that RDE basic design is still safe.

For the mass flow rate of 2.1389 kg/s, the contours of the absolute pressure are shown in Figure 6.

![Contours of Absolute Pressure in Mass Flow Rate of 2.1389 kg/s](image)

**Figure 6.** Contours of Absolute Pressure in mass flow rate of 2.1389 kg/s
For the mass flow rate of 2.1389 kg/s, the absolute inlet pressure is 1.000 atm. The absolute pressure of outlet is 0.998 atm. The different of the inlet pressure and the outlet pressure is only 0.002 atm. It means that the outlet pressure is still safe for RDE basic design.

For the mass flow rate of 2.1389 kg/s, the contours of the temperature are shown in Figure 7.

![Figure 7. Contours of temperature for the mass flow rate of 2.1389 kg/s](image)

For the mass flow rate of 2.1389 kg/s, the inlet temperature is 45.543 °C (orange, Figure 7) and the outlet temperature is 37.236 °C (blue). The delta temperature is 8.307 °C. For this mass flow rate, the recommended delta between inlet and outlet temperatures is still around 7-9 °C.

For the mass flow rate of 2.1389 kg/s, the velocity vectors are shown in Figure 8.

![Figure 8. The velocity magnitudes for the mass flow rate of 2.1389 kg/s](image)
For the mass flow rate of 2.1389 kg/s, the inlet velocity magnitude is 0.123 m/s (light green, Figure 8) and the outlet velocity magnitude is 0.133 m/s (the green to yellow). The delta velocity magnitude is 0.01 m/s. Since the delta velocity magnitude is small, the velocity magnitude for the mass flow rate of 2.1389 kg/s can be considered constant. It means that velocity magnitude for RDE basic design is still safe.

For the mass flow rate of 3.2084 kg/s, the contours of absolute pressure are shown in Figure 9.

![Figure 9. Contours of pressure absolute for the mass flow rate of 3.2084 kg/s](image)

For the mass flow rate of 3.2084 kg/s, the inlet absolute pressure is 1 atm. The absolute pressure of outlet is 0.996 atm. Those are shown in Figure 9. The difference between inlet and outlet absolute pressures is only 0.004 atm. It means that the outlet pressure, in the mass flow 3.2084 kg/s, is still safe for RDE basic design.

For the mass flow rate of 3.2084 kg/s, the contours of the temperature are shown in Figure 10.

![Figure 10. Contours of temperature for the mass flow rate of 3.2084 kg/s](image)
For the mass flow rate of 3.2084 kg/s, the inlet temperature is 46.263 °C (red, Figure 10). The outlet temperature is 38.229 °C (blue color). The delta of temperature is around 8.034 °C. The recommended delta of inlet temperature and the total outlet temperature for the mass flow rate of 3.2084 kg/s is still around 7-9 °C.

For the mass flow rate of 3.2084 kg/s, the velocity magnitude is shown in Figure 11.

Figure 11. The velocity magnitude for the mass flow rate of 3.2804 kg/s

For the mass flow rate of 3.2804 kg/s, the inlet velocity magnitude is 0.170 m/s (light green, Figure 11) and the outlet velocity magnitude is 0.201 m/s (yellow). The delta velocity magnitude is 0.031 m/s. The delta velocity magnitude is still sufficiently small. The velocity magnitude for the mass flow rate of 3.2804 kg/s is therefore almost constant. It means that velocity magnitude for RDE basic design is still safe.

For the mass flow rate of 4.2778 kg/s, the contours of absolute pressure are shown in Figure 12.

Figure 12. Contours of Absolute Pressure for the mass flow rate of 4.2778 kg/s
For the mass flow 4.2778 kg/s, the inlet absolute pressure is 1 atm (red, Figure 12). The outlet absolute pressure is 0.993 atm (blue). While the difference between the inlet and outlet pressures is larger than in previous cases, it is merely 0.007 atm which is sufficiently small. It means that the outlet pressure, under the mass flow rate of 4.2778 kg/s, is still safe for RDE basic design.

For the mass flow rate of 4.2778 kg/s, the temperature is shown in Figure 13.

**Figure 13.** Contours of Temperature for the mass flow rate of 4.2778 kg / sec

For the mass flow 4.2778 kg/s, the contours of the Inlet temperature are 45.999 °C. The outlet of Temperature is 38.956 °C (Figure 13). The delta temperature is around 7.044 °C. The recommended delta of the total inlet temperature and the total outlet temperature for the mass flow rate of 4.2778 kg/s is still around 7-9 °C.

For the mass flow rate of 4.2778 kg/s, the velocity magnitude is shown in Figure 14.

**Figure 14.** Velocity magnitude for the mass flow rate of 4.2778 kg/s
For the mass flow rate of 4.278 kg/s, the velocity magnitude inlet is 0.249 m/s (green, Figure 14) and the velocity magnitude outlet is 0.270 m/s (yellow). The delta velocity magnitude is 0.21 m/s. Therefore, the velocity magnitude for the mass flow rate of 4.278 kg/s can be considered constant. It means that velocity magnitude for RDE basic design is still safe.

The chart of delta temperature for mass flow rate variation of 4.2778 kg/s, 3.2084 kg/s, 2.1389 kg/s, and 1.0694 kg/s is shown in Figure 15. The delta temperature are 7.149 °C, 8.307 °C, 8.034 °C, and 7.044 °C, respectively. The recommended delta temperature is still around 7-9 °C.

The chart of velocity magnitude outlet for mass flow rate variation of 4.2778 kg/s, 3.2084 kg/s, 2.1389 kg/s, and 1.0694 kg/s shown in Figure 16. The inlet velocity magnitudes are 0.061, 0.123, 0.170, and 0.249 m/s. The outlet velocity magnitudes each are 0.066, 0.133, 0.201 and 0.270 m/s. The delta of velocity magnitude each are 0.005, 0.010, 0.301 and 0.021 m/s. Those numbers indicate that there is relatively little difference between velocity magnitudes at inlet and outlet. It means that the velocity magnitude in RDE basic design is still safe.
The chart of outlet pressure for mass flow rate variation 4.2778 kg/s, 3.2084 kg/s, 2.1389 kg/s, and 1.0694 kg/s is shown in Figure 17. For the inlet pressure 1 bar, the outlet pressures are 0.999, 0.998, 0.996 and 0.993 atm. The outlet pressure are still almost near the same with inlet pressure. It means that the outlet pressure for RDE basic design is still safe.

![Pressure Chart](image)

**Figure 17. Outlet pressure in mass flow variation**

5. Conclusion
The variation of absolute pressure, temperature, and velocity magnitude was analyzed and computed with FLUENT 6.3 computational fluid dynamics software package. The pressure, magnitude velocity, and delta temperature of air-cooled heat exchangers were obtained and investigated for the RDE design. For the mass flow rate variation of 1.0694, 2.1389, 3.2084, and 4.2778 kg/s, the outlet pressure, the outlet velocity magnitude, and the outlet temperature exhibit little difference with the inlet pressure, inlet velocity magnitude, and inlet temperature, respectively, so that the air-cooled heat exchanger of the RDE basic design is safe condition.

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