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Improvement of heat-removal capability using heat conduction on a novel reactor cavity cooling system (RCCS) design with passive safety features through radiation and natural convection

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ABSTRACT

A previously-reported concept of reactor cavity cooling system (RCCS) with passive safety features consists of two continuous closed regions: an ex-reactor pressure vessel region and a cooling region with a heat-transfer surface to ambient air. The RCCS uses a novel shape to efficiently remove the heat released from the reactor pressure vessel (RPV) through thermal radiation and natural convection. Employing air as a working fluid and ambient air as an ultimate heat sink, the novel RCCS design strongly reduces the possibility of losing the heat sink for decay-heat-removal during nuclear accidents including a station blackout. The RCCS could stably and passively remove the heat released from the RPV and the decay heat after reactor shutdown. The previously-reported heat-removal rate of the RCCS was approximately 3 (kW/m^2). The heat flux from the RPV surface of the High Temperature engineering Test Reactor (HTTR) is almost in the same range; 1.23–2.46 (kW/m^2). In this paper, the authors address an improvement of heat-removal capability by considering potential of heat leakage due to heat conduction through the RCCS wall aimed at increasing a thermal reactor power level. Under the assumption of doubling the RCCS wall heat transfer area, a heat-flux removed by the RCCS could be doubled, such as approximately 6.2 (kW/m^2).

1. Introduction

The 2011 Great East Japan Earthquake occurred on 11 March 2011 (Japan Meteorological Agency, 2011). The earthquake triggered a tsunami with a maximum height of 13–15 (m). At the Fukushima Daiichi nuclear power plants, the heat released from the core or the RPV could not be actively removed despite the existence of emergency power generators. The RPV had been damaged and "significant amounts" of molten fuel had fallen into the bottom of the primary containment vessel (PCV); after core meltdown, the molten fuel eroded the concrete of the PCV (The National Diet of Japan, 2012; Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, 2012; Independent Investigation Commission on the Fukushima Nuclear Accident, 2012). Therefore, the authors believe that a passive decay-heat-removal system is essential for avoiding the loss of a heat sink and a core meltdown at all nuclear reactors.

JAEA has been progressing research and development on high-temperature gas-cooled reactor (HTGR) having highly safety features by the HTTR. Now, the RCCS of the HTTR adopts water as a coolant; on the other hand, the authors have been studying a new RCCS adopting air as a coolant. As a result, the authors had previously reported a concept of the RCCS with passive safety features consisting of two continuous closed regions: an ex-reactor pressure vessel region and a cooling region with a heat-transfer surface to ambient air (Takamatsu and Hu, 2015; Takamatsu et al., 2016). The RCCS uses a novel shape to efficiently remove the heat released from the RPV through thermal radiation and natural convection. Employing air as a working fluid and ambient air as an ultimate heat sink, the novel RCCS design strongly reduces the possibility of losing the heat sink for decay-heat-removal during nuclear accidents including a station blackout. The RCCS could stably and passively remove the released heat from the RPV, such as approximately 3 (kW/m^2), and the decay heat after reactor shutdown. On the other hand, the heat flux from the RPV surface of the HTTR is almost the same value of 1.23–2.46 (kW/m^2).

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In this paper, the authors evaluate the RCCS's performance by analyses with a model of the HTTR. The authors address an improvement of heat-removal capability by considering potential of heat leakage due to heat conduction through the RCCS wall aimed at increasing a thermal reactor power level.

2. RCCSs for the HTTR

2.1. Main specifications of the HTTR

The HTTR was built at the JAEA's Oarai Research and Development Center and is the first HTGR in Japan (Saito, 1994). The main specifications of the HTTR are listed in Table 1. The reactor consists of a core and internal components arranged into an RPV with 13,200 mm in height and 5500 mm in diameter.

2.2. Dimensions and practical operating conditions of the RCCS for the HTTR

The dimensions and practical operating conditions of the RCCS at the HTTR are listed in Table 2. This RCCS adopts forced convection of water as a working fluid using electrical pumps, which is a conventional technology. The heat-loss-through-the RPV at the rated operation of 30 (MW) was designed to be 300–600 (kW), which is a required heat-removal capability for securing temperature and integrity of the structures and fuels after the reactor shutdown. On the other hand, the HTTR showed that the heat-loss-through-the RPV was 800 (kW); therefore, in the present study, the authors consider 800 (kW) including 200 (kW) as a safety margin.

Helium gas flows into the primary helium gas tube in an annular path as a reactor inlet coolant temperature of 395 (°C) and inside the inner tube as a reactor outlet coolant temperature of 850 (°C) or 950 (°C). The reactor inlet coolant entering into the RPV flows upward vertically in an annular path between the permanent reflector blocks and the RPV. The temperature of the RPV is always approximately 395 (°C), which is always controlled by the reactor inlet coolant temperature control system at the rated operation of 30 (MW).

The HTTR experiments show that the temperature difference between the RPV (approximately 673.15 (K) = 400 (°C)) and the RCCS structure (approximately 373.15 (K) = 100 (°C)), as indicated by the HTTR experiment data, need to be approximately 300 (K) to remove 600–800 (kW) by radiation and natural convection at the rated operation of 30 (MW). The percentage of the radiation in the heat-transfer mechanisms from the RPV to the RCCS is approximately 75–80 (%) at the rated operation. On the other hand, the percentage of the natural convection in the heat-transfer mechanisms is approximately 20–25 (%) (Takamatsu, 2015).

In other words, when the temperature difference between the RPV and the structure of the RCCS is decreased, the amount of heat removed by radiation is decreased and a heat-removal rate of 600–800 (kW) can no longer be achieved. Therefore, the temperature of the RCCS structure needs to be below 100 (°C) because the RPV temperature is kept constant in normal operation, 400 (°C), affected by the reactor inlet coolant temperature.

Table 1
Main specifications of the HTTR.

Thermal reactor power	30 MW
Coolant	Helium
Reactor outlet coolant temperature	850 °C* 950 °C**
Reactor inlet coolant temperature	395 °C
Primary coolant pressure	4.0 MPa
Primary coolant flow rate	12.4 kg/s* 10.2 kg/s**
Core structures	Graphite
Core height	2900 mm
Core diameter in effective diameter	2300 mm
Fuel element type	Prismatic block
RPV	Steel (2 1/4Cr-1Mo)

*Rated operation mode: operation at a reactor outlet coolant temperature of 850 °C.
**High temperature test operation mode: operation at a reactor outlet coolant temperature of 950 °C.

Table 2
Dimensions and practical operating conditions of the RCCS using the forced convection of water with pumps at the HTTR (Takamatsu and Hu, 2015; Takamatsu et al., 2016).

Length between the core center and the RCCS surface, Radius	3.86 (m)
Diameter of the RCCS	7.72 (m)
Circumference of the RCCS surface	24.3 (m)
Height of the RCCS	16.9 (m)
Heat-transfer surface of the RCCS	409.0 (m^2)
Maximum temperature limits of the RPV affected by the reactor inlet coolant temperature, 395 (°C) (Table 1), at the rated operation of 30 (MW)	Approximately 673.15 (K) = 400 (°C)
Structure temperature of the RCCS	Approximately 373.15 (K) = 100 (°C)
Temperature difference between the RPV of 673.15 (K) = 400 (°C) and the RCCS structure 373.15 (K) = 100 (°C)	300 (K)
Heat released from the RPV or heat removed by the RCCS at the rated operation of 30 (MW)	600–800 (kW)

3. A proposed RCCS with passive safety features

3.1. Physical concept

Our proposed RCCS adopts a novel shape as shown in Fig. 2(a) for implementation in the HTTR (Takamatsu and Hu, 2015; Takamatsu et al., 2016). The RCCS uses air as its heat transport medium. The reactor cavity of the RCCS is enlarged and includes two continuous closed regions: an ex-reactor pressure vessel region and a cooling region attached on the top of it. The height of the cooling region, such as approximately 22 (m), is the same as that of the RPV region, such as approximately 19 (m), including the RPV. The cooling regions feature two or three heat-transfer surfaces: an inside surface, an outside surface, and a top surface. Moreover, the heat-transfer surface, such as the RCCS outer surface, can easily be increased in size by machining it or adding fins. In other words, the height of the cooling region can be decreased by increasing the heat-transfer surface. Major basic analytical parameters of the concept are listed in Table 3.

3.2. Analyses

To understand reactor coolant dynamics, in 2015, the JAEA purchased a large supercomputer named SGI ICE X, manufactured by Silicon Graphics International Corp., which exhibited the highest calculation performance in Japan. However, when a conventional three-dimensional, STAR-CCM+ (CD-Adapco, 2017) was used to analyze the heat removed by the RCCS at steady state, obtaining results took several weeks because of the complex natural convection and radiation phenomena between the RPV and the RCCS.

In other words, a period on the order of approximately months is necessary for obtaining results for the analysis of the heat removed by the RCCS at transient state. Moreover, it is more difficult for current supercomputers to analyze the transient heat removed by the RCCS.