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New reactor cavity cooling system (RCCS) with passive safety features: A comparative methodology between a real RCCS and a scaled-down heat-removal test facility

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ABSTRACT

A new, highly efficient reactor cavity cooling system (RCCS) with passive safety features and without electrical or mechanical driving requirement is proposed. The RCCS design consists of two continuous closed regions: an ex-reactor pressure vessel region (RPV region) and a cooling region with a heat-transfer surface to ambient air assumed to be 40 (°C). The RCCS uses a novel shape to efficiently remove the heat released from the RPV through radiation and natural convection. Employing air as the working fluid and ambient air as the ultimate heat sink, the new RCCS design strongly reduces the possibility of losing the heat sink for decay-heat-removal. In the paper, we address a comparative methodology between a real RCCS (REAL) and a scaled-down heat-removal test facility (SCALE). As an example, the heat flux by radiation of (SCALE) can be the same as that of (REAL) because the two have the same temperatures of the RPV and the RCCS, $T_{RPV(REAL)} = T_{RPV(SCALE)}$, $T_{RCCS(REAL)} = T_{RCCS(SCALE)}$, and the same view and configuration factors. Next, we also conduct comparisons on natural convection using the Grashof number, $Gr_{r_{RCCS}-r_{RPV}}$. Here, the ratio of (SCALE) to (REAL) in terms of characteristic length is defined as $\frac{(r_{RCCS}-r_{RPV})(SCALE)}{(r_{RCCS}-r_{RPV})(REAL)} = \frac{1}{x}$. When the working fluid in (SCALE) can be pressurized up to $x^{\frac{3}{2}}$ times that of (REAL), (SCALE)'s Grashof number, $Gr_{r_{RCCS}-r_{RPV}}$, can be the same as that of (REAL). Moreover, (SCALE)'s heat flux on the RPV surface as the experimental conditions for obtaining the same Grashof number as that of (REAL) can be determined. The difference between (SCALE) and (REAL) in terms of the heat flux on the RPV surface is $(x-1)$ times (REAL)'s heat flux by natural convection. Thus, (SCALE) will obtain valuable experimental data for demonstrating the new RCCS's performance.

1. Introduction

The 2011 Great East Japan Earthquake occurred at 14:46 on Friday, 11 March 2011 (Japan Meteorological Agency, 2011). The earthquake triggered a tsunami with a maximum height of 13–15 (m), which arrived approximately 50 min later. The waves overtopped the Fukushima Daiichi nuclear power plant's 10-m-high seawall, flooding the basements of the turbine buildings and disabling the emergency power (diesel) generators. The heat released from the core or the RPV could not be actively removed. Some reports noted that the RPV had been damaged during the disaster and that "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 Report, 2012; Independent Investigation Commission on the Fukushima Nuclear Accident, 2012). Therefore, we 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.

On the other hand, conventional RCCSs for high-temperature gas-cooled reactors (HTGRs), such as the High Temperature engineering Test Reactor (HTTR) of the Japan Atomic Energy Agency (JAEA), have adopted forced convection of water with electrical pumps. However, when the RCCS pipes are cracked during accidental conditions, water leaks from the cracks due to the pump discharge pressure and the amount of heat-removal decreases. Moreover, forced convection by electrical pumps cannot remove heat during a loss of power, and natural convection cannot occur due to the existence of impellers in the pumps. Needless to say, an HTGR, such as the HTTR, has emergency power generators to avoid station blackout; however, the heat released from the core

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or the RPV in the Fukushima Daiichi nuclear power plant could not be actively removed.

Conversely, the new RCCS designs for HTGRs or very-high-temperature reactors (VHTR), such as JAEA's GTHTR300 (Katanishi et al., 2004), are planned to adopt natural convection of ambient air inhaled into ducts (Figs. 1(a) and (b)) (Katanishi et al., 2004; Williams et al., 1994; Lomperski et al., 2011). The air absorbs the heat released from the RPV and flows upward in the ducts due to the chimney (stack) effect, ultimately flowing into ambient air from the ducts. The RCCS requires ducts longer than 60 (m) to enhance the chimney (stack) effect and increase the air velocity in the RCCS to promote natural convection until strong winds appear; however, ambient air always flows into the ducts, and dusts, including plants and insects, accumulate inside the ducts every day. The ducts may soon rust and erode due to the humidity and salty air. Moreover, since the RCCS surface, (γ) in Fig. 1(a), is heated directly by radiation and natural convection from the RPV, the structure temperature of the RCCS increases and the dusts are burned on the surface. Therefore, large amounts of capital may need to be budgeted for maintenance and replacement of the ducts. In case of fire, the chimney (stack) effect due to the use of ducts may need to be controlled to prevent the spread of smoke and fire and to guard against damage and maintain conditions for firefighters (Daniel and Stephen, 2009).

Thus, this work proposes a new air-cooled RCCS design that does not use the chimney (stack) effect and rely on emergency power generators (Takamatsu and Hu, 2015). The design concept and analysis results are presented in the following sections. In the future, a downsized new RCCS will be designed and built for demonstrating experiments at the scaled-down heat-removal test facility. We also address a comparative methodology between a real RCCS and a scaled-down heat-removal test facility. As an example, we define the experimental conditions for radiation and natural convection through the use of the same Grashof number, $Gr_{r_{RCCS}-r_{RPV}}$, or the same heat-transfer coefficient of natural convection.

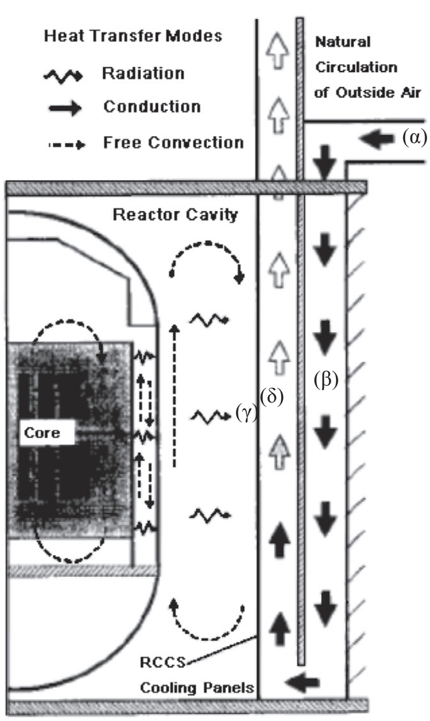

Fig. 1(a). MHTGR passive decay-heat-removal (Williams et al., 1994).

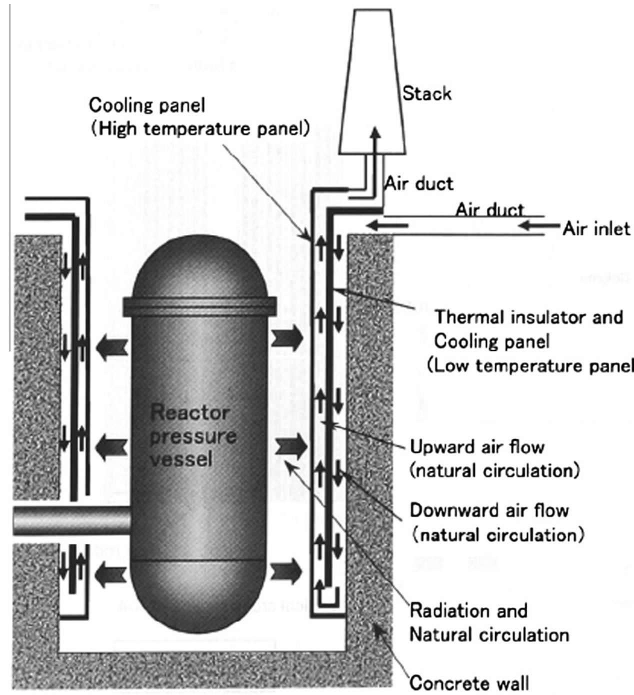

Fig. 1(b). GTHTR300 passive decay-heat-removal (Katanishi et al., 2004).

2. RCCSs for the HTTR

2.1. Dimensions and operating conditions of the RCCS at the HTTR

The dimensions and operating conditions of the RCCS at the HTTR are listed in Table 1.

This RCCS adopts forced convection of water as the working fluid using electrical pumps, which is a conventional technology. The heat-loss-through-the RPV at the rated operation of 30 (MW) is 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.

However, we employ a heat-loss-through-the RPV of 800 (kW) at the rated operation of 30 (MW), which is 200 (kW) higher than the heat loss of the RCCS described above.

Decay heat at the elapsed time of 40–100 (s) after reactor shutdown, as calculated by Wigner and Way's equation (Way and Wigner, 1948), shows approximately 3 (%) of the rated operation. On the other hand, this corresponds to about 800 (kW) of heat discharged from the RPV. It is therefore confirmed that the decay heat and stored heat (in the fuel and the large amount of graphite in the

Table 1
Dimensions and operating conditions of the RCCS using the forced convection of water with electrical pumps at the HTTR.

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	24.2531 (m)
Height of the RCCS	16.8574 (m)
Heat-transfer surface of the RCCS	408.84 (m^2)
Maximum temperature on the RPV affected by the reactor inlet coolant temperature, 395 °C (Table 2), at the rated operation of 30 (MW)	673.15 (K) = 400 (°C)
Structure temperature of the RCCS	Approximately 373.15 (K) = 100 (°C)
The released heat from the RPV or the removed heat by the RCCS at the rated operation of 30 (MW)	600–800 (kW) 800 (kW) = 600 (kW) + 200 (kW)