Study of geometric parameters for i-SMR reactor vessel auxiliary cooling system

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1. Introduction

The reactor vessel auxiliary cooling system (RVACS) is being proposed as an addition to the i-SMR defense-in-depth concept. The RVACS have a limitless inventory, unlike the other passive safety systems, which have a coolant inventory capacity limitation. The RVACS is typically defined as having a high temperature that causes a density differential between the interior and exterior of the channel, and residual heat is evacuated via convective heat transfer between the air and the containment vessel (CNV) [1]. The heat removal capability of an RVACS is not only correlated to the CNV temperature, but it is also governed by the system thermal resistance and hydraulic disturbance. Based on MARS-KS code simulations for annular and multichannel designs, this study investigates the effects of geometrical parameters such as air gap, plenum size, riser height and diameter, downcomer diameter, and surface emissivity on the cooling performance of the reactor vessel auxiliary cooling system (RVACS) in i-SMR.

2. Methods and Results

This section describes the RVACS MARS-KS model for annular and multichannel. The MARS-KS model for multichannel is developed by separating the heated section from the annular channel model into several channels. Simulated outcomes are also investigated and explained in the sections that follow.

2.1 MARS-KS model for annular channel

The geometry of RVACS is depicted in Figure 1 and consists of the following major components: a downcomer where air is drawn from the ambient, lower and upper plenums for enhancing uniform flow distribution around the heated section, a heated section formed by the outer wall of the containment vessel and the air separator wall, and a riser for increasing buoyancy force and, thus, stimulating the air flow rate. The MARS-KS annular channel model is built in order to do sensitivity analysis on key design parameters. The air flow path was represented by a heated section pipe (400), through which air was heated by convection in the CNV and SP, a downcomer pipe (200), through which air flowed under complete insulation conditions, a lower plenum (300), an upper plenum (500), and a riser pipe (600). To limit the flow induced by the pressure head effect, we placed the riser and downcomer pipes at the same height. The ASHRAE Handbook [2] and the MAR S-KS code manual guide [3] were used to determine the form loss coefficient for an abrupt change in the flow path along a system component.

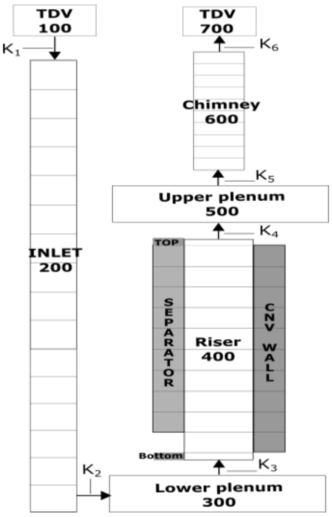

Figure 1. Nodalization of annular channel

The RVACS heat transfer mechanism is depicted in Figure 2. Due to the large temperature differential, the air in the heated section is heated by convective heat from the CNV wall, whilst the SP is heated by radiative heat from the CNV wall. Because the SP is properly insulated, this radiative heat turned into convective heat from the SP to the air under steady-state conditions. As a result, convective heat transfers from both the CNV and SP walls heated the air at the same time. The rate of heat transfer from CNV was equal to the enthalpy rise of air from the inlet to the outlet. When the total heat transferred from CNV(Q_{CNV}) was split into convective ($Q_{Conv,CNV}$) and radiative ($Q_{Rad,CNV}$) heat, and radiative heat was converted into convective heat from SP, the energy balance equation is expressed as equation (1).

$$Q_{CNV} = Q_{Conv,CNV} + Q_{Rad,CNV} = Q_{Conv,CNV} + Q_{Conv,SP} \tag{1}$$

MARS-KS automatically determines the appropriate heat transfer correlation in the convection region: Nusselt number of 4.36 for a laminar regime, Churchill and Chu correlation [4] (equation (2)).

$$Nu = \left\{ 0.825 + \frac{0.387 Ra^{1/6}}{\left[1 + \left(\frac{0.492}{\Pr} \right)^{9/16} \right]^{8/27}} \right\} \tag{2}$$

The following equation can be utilized to calculate the i-surface radiation heat flux:

$$q_i^{''} = R_i - \sum_{j=1}^{n} R_i F_{ij} = \frac{\varepsilon_i}{\rho_i}\left(\sigma T_i^4 - R_i \right) \tag{5}$$

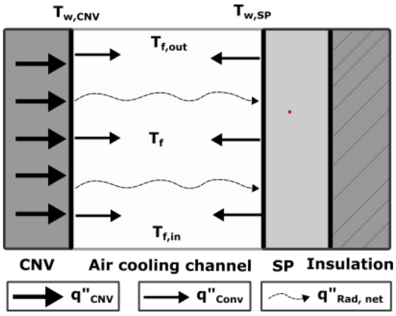

Figure 2. Heat transfer mechanism of RVACS

2.2 MARS-KS model for multichannel

The concept of separating the annular sector of annular channel into numerous smaller channels along the radius is referred to as multichannel. Figure 3 displays the multichannel model nodalization. The heated section is divided into several channels that are independently connected to the lower and upper plenums.

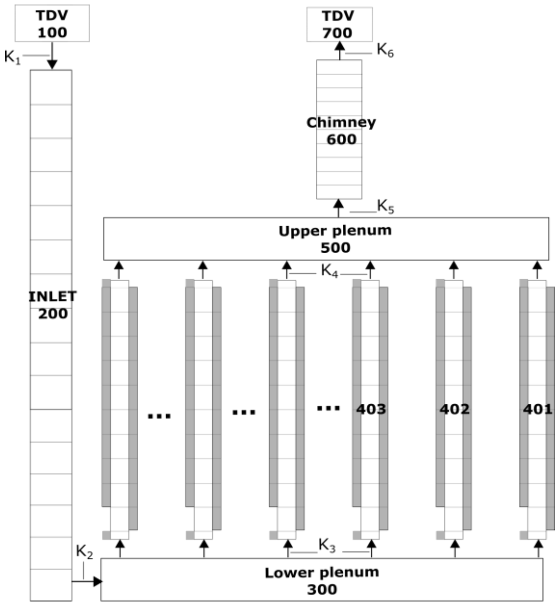

Figure 3. Nodalization of multichannel

2.3 Effect of geometrical parameters on annular channel

Figure 4 depicts the effect of the air gap. A narrower air gap enhances convection heat transfer by generating faster air flow across the CNV and SP surfaces. This, however, increases pressure loss within the gap. When the air gap is raised from 2 cm to 10 cm, the heat removal rate increases by 110%, owing mostly to a decrease in pressure. Then the heat removal rate decreases with air gap higher than 10cm.

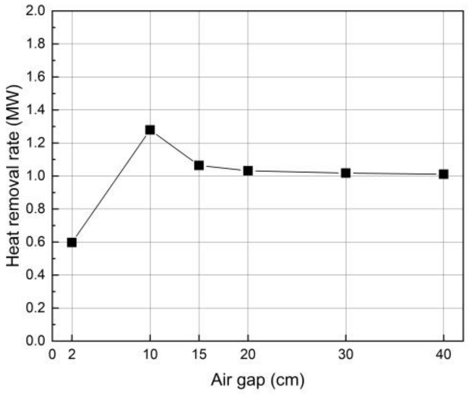

Figure 4. Effect of air gap on system performance

As plenum size increases, friction loss decreases, but form loss increases at rapid contraction and expansion zones, resulting in the optimal value of $D_p/D=4$. Moreover, the rate of heat removal increases by around 10% for every 10 meters of riser height. The reasoning is straightforward and directly related to the operating principle of natural circulation systems, where increasing the loop height and density difference between heat source and heat sink results in a higher induced driving pressure differential (buoyancy force) [5]. Similarly, increasing the riser and downcomer diameters by 0.1m increases the heat removal rate by around 30% on average, because larger diameter increases the flow area of the loop and a reduction in hydraulic resistance lessens the opposing frictional pressure gradient, resulting in a higher flow rate. Also, increasing emissivity improves heat removal performance. The increase in heat removal with every 0.1 increase in CNV emissivity is 2.2%, but the increase for separator is only 1.9%.

2.4 Effect of geometrical parameters on multichannel

Figure 5 demonstrates multichannel performance under various plenum sizes. It is worth noting that the cases of a single channel and an annular channel are identical. For a plenum size of $D_p/D=3\sim5$, the heat removal rate increases from 1 to 8, then steadily decreases as the number of channels increases further. However, when the plenum size $D_p/D=7\sim9$ was used, the peak value was reduced to 6 channels. On average, the optimal number of channels removes 6% more heat than annular channels. In compared to annular channels, multiple channels improve heat removal by uniformly dispersing flow throughout the heat transfer surface; nevertheless, friction and form loss increase pressure loss, which explains the appropriate number of channels. The dimensions of the upper and lower plenums have a significant impact on pressure drop and flow distribution between sub-channels, as well as system performance. Each D (hydraulic diameter of heated section) increase in plenum size improves system performance by 1.7% on average. This could be explained by increasing the uniformity of the flow distribution and minimizing the frictional pressure drop, which results in a larger flow rate. This influence, however, is only noticeable when the plenum size is less than $D_p/D = 7$, and it reduces as plenum size grows because no additional increase in heat removal rate is noticed. As a result, $D_p/D = 7$ is regarded as the saturation size for plenums. The decreasing effect of stimulating uniform flow distribution is most likely due to the uniform flow distribution already achieved at $D_p/D = 7$; thus, increasing plenum size has minimal effect on flow distribution.

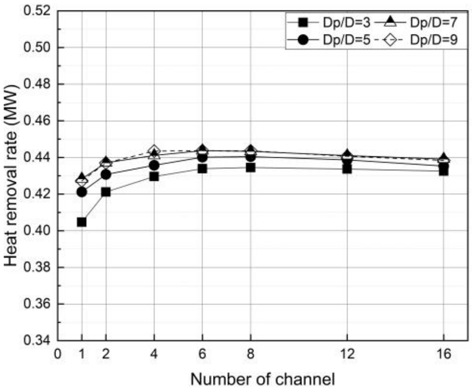

Figure 5. Heat removal rate with various number of channel

3. Conclusions

The outcomes of the annular channel design parameter show that the air gap is an effective design adjustment for improving RVACS performance. Convection heat transfer is enhanced by a shorter air gap, which results in faster airflow across the CNV and SP surfaces. This, however, increases the pressure loss in the gap. The optimal air gap was determined to be 10cm due to the contradicting impacts of increasing heat transfer by increasing flow rate and lowering air velocity on CNV as the air gap is expanded. Because of the decrease in frictional pressure loss and increase in form loss as plenum size increases, $D_p/D=4$ has been established to be the ideal size for the lower plenum. Greater riser height, larger riser and downcomer diameter, and surface emissivity are all beneficial for improving RVACS performance. RVACS performance could be enhanced by 6% by dividing annular channels into 6 or 8 channels. Plenum size influences system performance by controlling flow distribution among sub-channels. Flow is distributed more equally throughout sub-channels as the plenum size increases, approaching homogeneity at Dp/D=7. Raising the plenum size over the saturation level has little effect on system performance.

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