Containment Model Enhancements for MCCI in MAAP 5.04

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1. Introduction

Molten Core-Concrete Interaction (MCCI) is one of the most important phenomena on severe accidents in nuclear power plants (NPPs) since it can threaten the integrity of the reactor containment building in NPPs. In order to investigate MCCI in NPP applications, Modular Accident Analysis Program (MAAP) developed by Electric Power Research Institute (EPRI) has been used widely in the utility fields. MAAP 5.04, the latest code revision released in 2016 [1], has some containment model enhancements related to MCCI including: i) bulk cooling model in the early phase of water and top of corium interaction, ii) MCCI heat transfer model improvements, and iii) corium pool stratification model. This paper introduces the three models above and examines the impact of those models on a large dry Pressurized Water Reactor (PWR) with a wet cavity.

2. MCCI Model Enhancements in MAAP 5.04

MAAP 5.04 has many improvements over previous versions, and there are about eleven improvements in the containment model in particular [1]. This chapter introduces three items that can affect MCCI analysis among the enhanced container models.

2.1 Bulk cooling model

When a MCCI occurs, the concrete slag melted and mixed with the corium can lower the melting temperature of the corium pool. As a result, the temperature at the upper surface of the corium pool can be higher than the melting temperature, and there is no crust covering the upper surface of the pool. This condition most likely occurs if there is no water in the reactor cavity. If water is added later as a measure to stabilize the corium in the reactor cavity, the upper surface of the corium can be cooled by water and crust can form. However, the corium pool is agitated by non-condensable gases from concrete ablation at the bottom. In certain conditions, the non-condensable gas velocity is sufficiently large, and it can prevent the formation of a stable upper crust. If this occurs, the upper surface of corium pool stays at a crust-free condition, until the gas velocity drops below a critical velocity to allow stable crust to be formed. The crust free heat transfer between corium and water is also termed as "bulk cooling" [1].

MAAP 5.04 introduces a new model for bulk cooling of corium. This model accounts for rapid heat transfer that can occur during initial phases of corium-water contact, when corium is submerged beneath a pool of water. The bulk cooling model evaluates whether a stable upper crust can be formed between the corium pool and water. If the stable upper crust cannot be formed because of the agitation of off-gases, it assesses heat transfer from the crust-free corium surface to water, assuming: i) the heat transfer regime at the top surface is film boiling; and ii) the heat transfer area is larger than the flat surface area because of the area deformation at the interface when off-gases bubble through the interface. Combination of the crust-free corium surface and area expansion leads to much larger heat flux from the corium to water than the heat flux if such a cooling mechanism is ignored. Fig. 1 shows the comparison of heat flux to water in CCI-2 experiment data [2]. As shown, if the bulk cooling model is not activated, the maximum heat flux calculated by MAAP5 is close to 1 MW/m^2, which is significantly lower than the experiment data. If the bulk cooling model is activated, the maximum heat flux is about 2.1 MW/m^2, which is much closer to the experiment data.

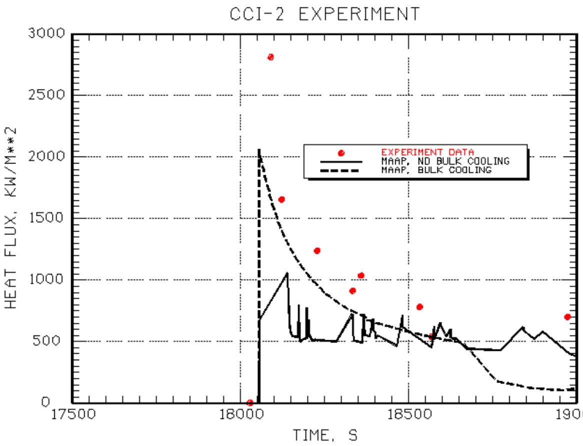

Fig. 1. Comparison between MAAP Calculated Heat Flux with Bulk Cooling Model On/Off and CCI-2 Data [1]

As the corium pool temperature decreases, concrete ablation rate decreases and off-gases flow also decreases. It eventually leads to a stable crust formed at the top of the corium pool. Once the stable crust is formed, the bulk cooling stops and the heat transfer between corium and water is calculated through water ingression and melt eruption models. Activating the bulk cooling model may lead to rapid corium quenching, especially when corium ablates high gas content concrete such as limestone common sand concrete (LCS) and limestone concrete.

2.2 MCCI heat transfer model improvements

When corium relocates from the reactor pressure vessel (RPV) into the reactor cavity, it can accumulate on top of the cavity floor to form a corium pool. Heat from the corium pool can ablate concrete, damaging the containment and potentially leading to containment failure. Therefore, accurate simulation of concrete ablation and corium properties requires appropriate heat transfer coefficients.

Previous versions of MAAP used user-defined constant heat transfer coefficients for sideward and downward core-concrete heat transfer. MAAP 5.04 has the option to calculate convective heat transfer coefficients from molten pool to crusts to determine downward and sideward heat transfer and ablation rates at each time step. This option accounts for both natural convection and gas sparging induced circulation in the corium pool. This model assumes that: i) the corium-concrete pool is always surrounded by an oxidic refractory crust, and ii) the heat transfer coefficients can be evaluated assuming an equivalent radius and height of a cylinder. In order to calculate gas sparging and natural convection induced circulation heat transfer correlations, new subroutines have been added to calculate the thermal expansion coefficient and two-phase viscosity correlation for a corium pool in containment.

2.3 Corium pool stratification model

The oxidic and metallic phases of a corium pool may be immiscible and have the potential to separate into stratified layers under certain conditions, as shown in Fig. 2.

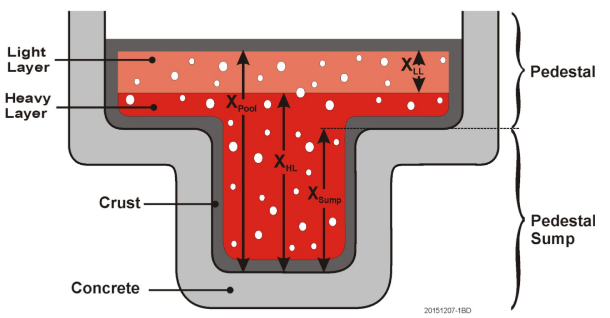

Fig. 2. Stratified Ex-Vessel Corium Pool [1]

MAAP 5.04 can quantify the impact a stratified pool has on the heat transfer coefficients between the corium pool and concrete and the resulting effects on ablation. A corium pool in the containment can be modeled as a three fluid system composed of a metallic liquid, an oxidic liquid, and gas sparging through the liquids. The liquids are considered immiscible but can be treated as a homogeneous layer if the sparging gas flow rate is large enough. As the gas flow rate decreases, the homogeneous system will stratify into distinct layers once the gas flow rate falls below a critical value due to gravity-induced separation. In some MCCI experiments, stratification between the metallic phase and oxidic phase was observed. This stratification is more probable for basaltic concrete than other concrete types due to lower carbon dioxide concentrations. If stratification occurs, it may affect concrete ablation, water ingression and corium properties in the containment.

3. Impact of New MCCI Models in NPP Application

The impacts of bulk cooling, gas sparging and natural convection induced circulation heat transfer correlations, and ex-vessel corium pool stratification are investigated by calculating the heat flux, heat transfer coefficients, and the erosion depth of concrete in NPP applications. The target plant is assumed to have the scale of 1400MWe NPP, the pre-flooding strategy for wet-cavity, and the siliceous type of concrete. The accident scenario is Large Break Loss of Coolant Accident (LBLOCA) and the extensive vessel failure, which means the whole corium in the vessel moved to the cavity at once, is assumed to maximize MCCI. Under this case, RPV failure is predicted at 4,131 second.

3.1 Bulk cooling effect

Fig. 3 shows the comparison of heat flux from the corium to water between MAAP calculation using bulk cooling model or not. The data with bulk cooling model shows the heat flux jumps to about 5 MW/m^2 immediately after the water-corium contact. It then decreases to lower than 600 kW/m^2 in a few hundred seconds. If the bulk cooling model is not activated, the maximum heat flux calculated by MAAP5 is close to 1.1 MW/m^2, which is much lower than the case with activating the bulk cooling model.

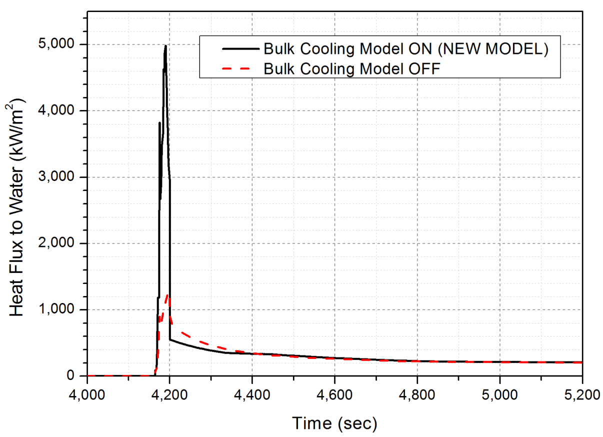

Fig. 3. Comparison of Heat Flux to Water according to Bulk Cooling Effect

The downward concrete ablation depth according to the bulk cooling model effect is shown in Fig. 4. Activating the bulk cooling model leads to rapid corium quenching and the lower concrete erosion depth than the case without bulk cooling model despite there were little off-gases flow and small melt eruptions due to the siliceous concrete. In this case, the user specified constant coefficient for the nominal downward heat transfer is assumed to be 1,000 W/m^2 K which is the default value for the siliceous concrete in MAAP 5.04.

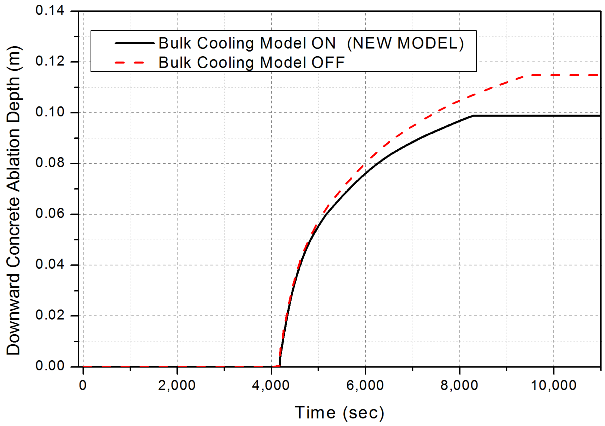

Fig. 4. Comparison of Downward Concrete Ablation Depth according to Bulk Cooling Effect

3.2 Convective heat transfer coefficients effect based on corium pool properties and conditions

In order to investigate the effect of MCCI heat transfer model improvements (Section 2.2) and corium pool stratification model (Section 2.3) in a NPP application, the comparison between MAAP calculation using the user specified nominal heat transfer coefficients and the convective heat transfer coefficients based on corium pool properties and conditions such as the gas sparging/bubble, natural convection induced circulation, and corium pool stratifications conducted. The user specified constant coefficient for the nominal downward heat transfer is assumed to be 1,000 W/m^2 K.

Fig. 5 compares the corium pool temperatures for the new heat transfer coefficient model effect. If the constant heat transfer coefficient is used, the corium pool temperature shows the higher values than the case using the constant coefficient generally. Based on this result, it can be expected that the heat transfer coefficient calculated at each time step by the new model removes heat more efficiently.

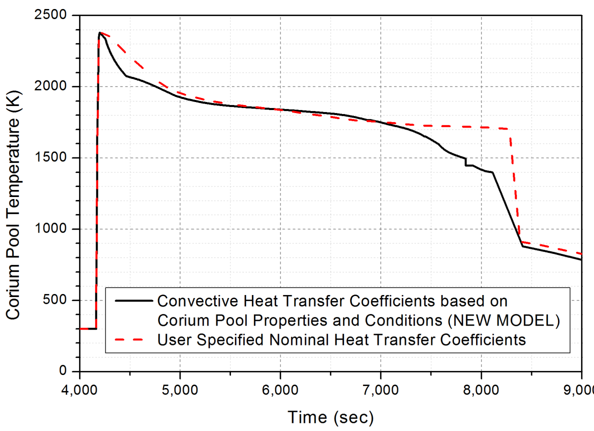

Fig. 5. Comparison of Corium Pool Temperature according to Heat Transfer Correlations Options

The downward concrete ablation depth for the new heat transfer coefficient model effect is shown in Fig. 6. If the user activates the option for the convective heat transfer coefficients based on corium pool properties and conditions, it shows the lower concrete erosion depth than the case using the constant heat transfer coefficients.

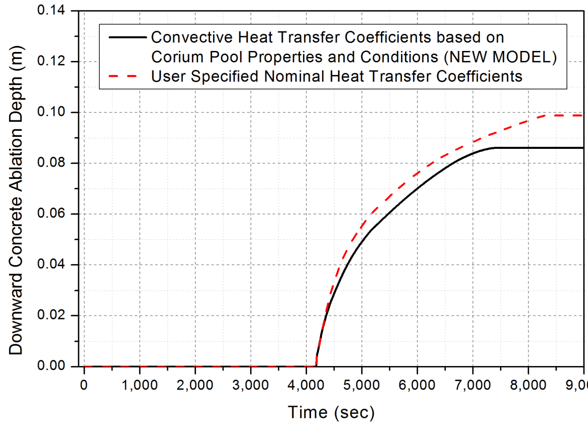

Fig. 6. Comparison of Downward Concrete Ablation Depth according to Heat Transfer Correlations Options

4. Conclusion

This paper introduces the new containment models relevant to MCCI analysis in MAAP 5.04 and examines the effect of new models on a NPP application. The new developed bulk cooling model was validated against the measured heat flux in CCI-2 experiment [2] and good agreements were observed as shown Fig. 1. In a NPP application on this paper, it is confirmed that activating the bulk cooling model leads to the rapid corium quenching. Using the heat transfer correlations instead of the nominal heat transfer coefficients in a plant application, the lower corium pool temperature and concrete ablation depth are observed.

Additionally, the effects on the other new models in MAAP 5.04 will be examined in the future.

REFERENCES

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[2] M. T. Farmer, S. Lomperski, and S. Basu, "The Results of the CCI-2 Reactor Material Experiment Investigating 2-D Core-Concrete Interaction and Debris Coolability," 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Avignon, France, October 2-6, 2005