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Improvement of the MELCOR condensation heat transfer model for the thermal-hydraulic analysis of a PWR containment

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ABSTRACT

During a hypothetical loss-of-coolant accident or a severe accident in a light water nuclear reactor (LWR), condensation heat transfer directly affects the pressure behavior and hydrogen distribution in the containment. This work aims at the improvement of the condensation heat transfer model in the MELCOR code, which is a fully-integrated computer code that models the progression of severe accidents in a LWR. It is known that MELCOR generally under-predicts the condensation heat transfer. For the improvement of MELCOR, we have assessed the MELCOR condensation model first. Other two models developed by Liao and Dehbi were also assessed for a comparative study. The assessment range is limited to the thermal-hydraulic conditions inside the containment building during a hypothetical design basis accident or a severe accident. We selected six condensation experiments of COPAIN, CONAN, Park, Anderson, Dehbi, and Kang and, then, assessed the three models against these data. The results of calculations showed that the MELCOR condensation model generally under-predicts the condensation heat transfer by about 45% and, however, it is the most precise and consistent in comparison with the other two models. Based on these results, the MELCOR model was selected as a base for model improvement. Then, four modifications were suggested: The effect of condensing surface curvature on condensation was considered into the MELCOR model first. The effective diffusion coefficient is applied for steam-air-helium tests. A multiplier to enhance condensation was obtained from the best fit of the calculated-to-measured plot. At last, to reflect the effect of superheated steam, a degradation factor deduced from the COPAIN experiment was adopted. The results of the modified MELCOR model showed very good agreements with most of the experimental data within ±30% error.

1. Introduction

During a hypothetical accident in a light water nuclear reactor, such as loss-of-coolant accident (LOCA) or main steam line break (MSLB), liquid water or steam at high pressure and high temperature is released inside the reactor containment building. This adds huge amount of mass and energy into the containment in a short period, resulting in rapid heat up and pressurization of the containment atmosphere. Even after the initial blowdown, the energy release due to the decay heat is continued. This may threaten the integrity of the containment building, which is the last barrier to prevent the leakage of radioactive materials to environment. However, significant portion of the heat is transferred to the structures inside the containment and the containment wall by single-phase convection and condensation heat transfer. The latter is a key mechanism for heat removal from the containment atmosphere and plays a crucial role to mitigate the pressurization of the containment.

Recently, in order to secure the integrity of the containment building for an accident with long-term power outages, passive containment cooling systems (PCCSs), which do not use an external power source, have been actively developed. These PCCSs commonly use condensation heat transfer. For example, the APR + reactor (Jeon and No, 2014), an advanced PWR developed in Korea, utilizes a passive heat removal loop driven by natural circulation, in which condensation occurs on the outer wall of the heat exchanger tubes installed in the containment building. The PCCS of AP1000 (Jiang et al., 2013) also uses condensation at the inner surface of the steel containment. As a result, condensation heat transfer becomes more important in the design and safety analysis

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of advanced nuclear power plants.

Condensation in the containment occurs under the presence of noncondensable gases (NCGs). The presence of even a small quantity of NCGs largely degrades condensation rate. To investigate the effect of NCGs on condensation, numerous theoretical and experimental studies have been performed from the early 1900s. In 1929, Othmer (1929) observed that even though the mass fraction of NCGs was very small, the heat transfer coefficient (HTC) decreased by about 50% comparing with pure steam condensation. Since then, Al Diwany and Rose (1973) also experimentally obtained similar results to Othmer's work. The diffusion layer model proposed by Colburn and Hougen (1930), and the boundary layer model proposed by Minkowycz and Sparrow (1966) theoretically explained the effect of NCGs. All these models have contributed to a better prediction. However, there are still great rooms for the improvement of condensation heat transfer model.

This work aims at the improvement of the condensation heat transfer model in the MELCOR code (Gauntt et al., 2005a; 2005b). It is a fully-integrated computer code that models the progression of severe accidents in light water reactor (LWR) nuclear power plants. It can simulate the thermal-hydraulic behaviors of reactor coolant system and containment, core damage process, relocation, molten core concrete interaction, behavior of a fission product, hydrogen generation, etc. MELCOR employs the stagnant film model suggested by Colburn and Hougen (1934) to calculate the condensation heat transfer under the presence of NCGs. It is known from previous studies that MELCOR usually underestimates the condensation heat transfer. Tills et al. (2008) calculated the Dehbi experiment (Dehbi, 1991) and the Huhtiniemi experiments (Huhtiniemi and Corradini, 1993) to assess MELCOR under natural convection conditions, and they confirmed that the MELCOR condensation model underpredicts the condensation rate by about 30–50%. Hogan et al. (2010), Liao (2007), and Sevón (1993) also obtained similar results. If the condensation inside the containment is underpredicted, the pressure must be over-predicted. This is might be conservative in terms of containment integrity but not desirable for accident management. For example, considering of the presence of hydrogen generated during a severe accident, it is not conservative anymore because the concentration of hydrogen must be underestimated (Yadav et al., 2016). Thus, the realistic evaluation of condensation in the containment is essential for accident analysis and management.

To improve the condensation heat transfer model of MELCOR, assessment has been carried out first using the MELCOR Version 1.8.6. Other condensation models developed by Liao and Vierow (2007) and Dehbi (2015, 2016) were also assessed for a comparative study. Based on the assessment results, one of these can be adopted as a base model for further improvement. The two models have their own meanings: The Liao model is one of the recent theoretical models and the Dehbi model is an advanced semi-theoretical model that has been developed for a PCCS design. It is noted that, considering the application of MELCOR, this assessment is limited to the thermal-hydraulic conditions inside a containment building during a severe accident. In this regard, we selected six condensation experiments; COPAIN (Mimouni et al., 2011), CONAN (Vyskocil et al., 2014), Park (1996), Anderson (1998), Dehbi (1991), and Kang et al. (2016) tests. These experiments involve various thermal-hydraulic conditions inside the containment from atmospheric pressure to the design pressure of a typical containment building during an accident. Using the test data sets from the six experiments, the three condensation models were assessed. From the results of the calculations, a base condensation model was selected for subsequent improvements.

The aforementioned three condensation models and six experiments are briefly described in Section 2 and 3, respectively. Section 4 presents the assessment results and model improvements. Conclusions are drawn in Section 5.

2. Condensation heat transfer models

Three condensation heat transfer models, which are to be assessed, are briefly presented in the following sub-sections.

2.1. The stagnant film model in MELCOR

MELCOR adopts the stagnant film model (also called Couette flow model) to calculate the condensa-tion heat transfer under the presence of NCGs (Gauntt et al., 2005b). When steam including NCGs cond-enses on a wall, the NCGs accumulated near the condensate film hinder condensation heat transfer. By the accumulation of NCGs, the steam partial pressure at the liquid-gas interface becomes smaller than that of the flow center, and this difference provides the driving force that allows the steam to diffuse toward the condensate film (see Fig. 1). The section, where the pressure changes, is called a diffusion layer, and it plays a role as a resistance reducing condensation rate. To simplify this phenomenon, the stagnant film model assumes that the condensate film is stagnant and heat and mass transfer occur only in the direction perpendicular to the wall. The heat from the steam-gas mixture is transferred to the condensate film interface by both condensation heat transfer and convective heat transfer. Then the heat passes through the film to the wall surface. This concept is illustrated in Fig. 1 and the energy balance is given by

$$h_f(T_i - T_w) = h_{fg} h_m \rho_v \ln\left(\frac{P_t - P_{s,i}}{P_t - P_{s,b}}\right) + h_{conv}(T_b - T_i), \tag{1}$$

where h_f, h_m, and h_{conv} denote the film HTC, the mass transfer coefficient, and the convective HTC, respectively. The first term in the right-hand side of Eq. (1) represents the condensation heat transfer, which is deduced from the molar-based Fick's law and heat and mass transfer analogy under a saturated condition. The mass transfer coefficient, h_m, is defined as $Sh \times D/L_c$, where the Sherwood number, Sh, is calculated as $NuSc^{1/3}Pr^{-1/3}$ by the heat and mass transfer analogy. The diffusion coefficient, D, varies depending on

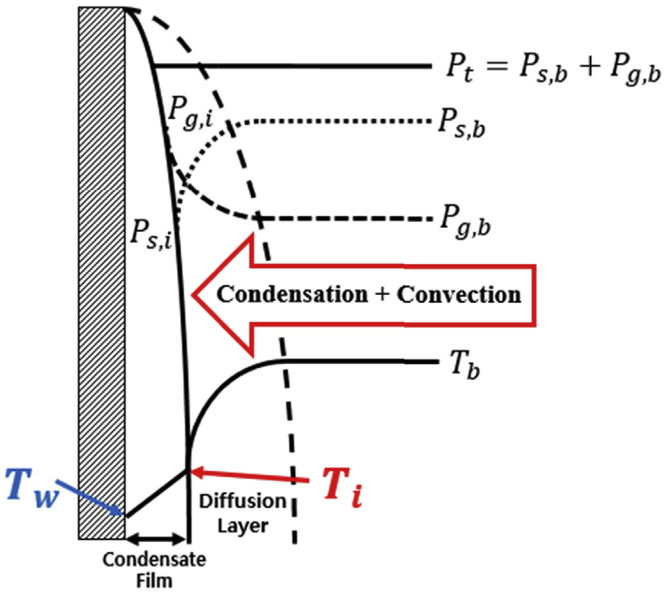

Fig. 1. Concept of the stagnant film model.

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