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Modeling of in-vessel gap cooling and its validation against LAVA, ALPHA, and LMP200 experiments

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ABSTRACT

The gap cooling phenomenon is a key issue to explain why the 19 tons of melt retained in the RPV lower head in the TMI accident did not significantly damage the vessel. This study developed the model for gap cooling phenomenon and was validated against the several gap cooling experiments with 30 kg, 50 kg, 70 kg of Al_2O_3 melt (LAVA and ALPHA experiments), and 220 kg and 360 kg of Al_2O_3 + Fe melt (LMP200 experiments). To estimate the thermal behavior of the vessel during the gap cooling, we modeled heat transfer from the melt and crust to the vessel and heat removal by water penetrating the gap. The gap size which determines the flow rate of water penetrating the gap was evaluated considering thermal interaction between the melt and water; Inverse-Leidenfrost effect, thermal fracture of the crust, thermal deformations of crust and vessel. In addition, a three-regime model widely used to analyze quenching heat transfer was applied to simplify the calculation compared to the calculation with the boiling curve of previous studies. A sensitivity study for the discretization dimension of the vessel showed that the 1D calculation can substitute the 2D calculation for analyzing the gap cooling experiments. From the sensitivity study, the node size and the time step were proposed as 3 mm and 0.1 s to obtain converged results. Through the extensive validation against the gap cooling experiments with the large-scaled melt mass to 360 kg (LMP200 experiments) as well as the small-scaled melt mass of 30, 50 kg of melt (LAVA and ALPHA experiments), we introduced the correction factors which account for the uncertainties of the degree of local contacts between the melt and reactor vessel and the effect of the solidified debris penetration in the gap on CCFL. We found out that the current model predicted the peak temperatures and the peak times with the error ranges of −15 ~ 15% and −50 ~ 70%, respectively. Finally, the current model was compared with other gap cooling calculation codes.

1. Introduction

During the last fifty years, three severe accidents of a nuclear power plant have occurred; TMI-2, Chernobyl, and Fukushima. The Fukushima accident showed the seriousness of the fuel melt released out of a reactor vessel (OECD/NEA, 2015; Pellegrini et al., 2019). On the other hand, during the TMI-2 accident, 19 tons of molten fuel were relocated to the lower head of the reactor vessel but did not rupture the reactor vessel (Wolf et al., 1994; Thomsen Kund Ladekarl, 1998). The reactor vessel was predicted to fail from the thermal analysis of the nuclear severe accident, thermal interaction between 19 tons of 2800 K molten oxide and carbon steel with a melting point of 1700 K (Stickler et al., 1994; Muller, 2006). From the observation, there was no adherence of the corium to the inner surface of the reactor vessel during the defueling (Wolf et al., 1994). From the thermal analyses (Broughton et al., 1989; Wolf et al., 1994; Suh and Henry, 1996a, 1996b; Linnemann et al, 1998; Thomsen, 2002; Reinke et al., 2006; Muller, 2006), the existence of the corium-to-vessel gap was needed to be consistent with metallurgical examination data. It was concluded that continuous heat removal by water ingression into the gap prevented the failure of the reactor vessel.

Therefore, several gap cooling experiments were performed for water penetration into the gap, heat transfer inside the gap, and comprehensive experiments. Regarding the water penetration phenomenon, counter-current flow limitation (CCFL) tests in a narrow channel were carried out to estimate the maximum water penetration rate into a narrow gap (Ueda and Suzuki, 1978; Mishima, 1984; Sudo and Kaminaga, 1989; Osakabe and Kawasaki, 1989; Ragland et al., 1989; Osakabe et al., 1994; Osakabe and Futamata, 1996; Vlachos et al., 2001; Drosos et al, 2006; Jeong, 2008; Li and Sun, 2010). The experiments of the heat transfer in a narrow gap found the heat transfer coefficients on the nucleate boiling regime (Aoki et al., 1982; Hung and Yao, 1985; Fujita et al., 1988; Xia et al, 1996; Kang, 2002; Hetsroni et al., 2007) and the critical heat flux (Chang and Yao, 1983; Herbst et al., 1999; Park et al., 2002; Kim and Suh, 2003; Uchibori et al., 2003; Seiler, 2006; Rempe et al., 2008). However, the wall heat flux was imposed in

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