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CFD-Assisted model development for estimation of hole-ablation diameter of a pressure vessel during severe accidents

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ABSTRACT

To evaluate the released radioactive materials to an environment under a nuclear severe accident, it is necessary to analyze the ex-vessel phenomena. The releasing diameter is one of the most essential parameters to estimate the ex-vessel phenomena. The diameter is enlarged because the wall of a reactor vessel melts due to the high temperature of corium flow. In this study, a hole-ablation model was developed based on the one-dimensional heat balance equations for molten corium flow, crust layer, and molten layer of the reactor vessel, respectively. Moreover, the heat transfer coefficient for the situation of discharging flow was obtained using computational-fluid-dynamics. As a result, we proposed the enhancement factor, 1.57, to be multiplied by the heat transfer coefficient for an external turbulent flow. We found out that the strong effect of the critical thickness of the molten wall layer on the thicknesses of the crust layer and the molten wall layer. We suggested the relationship between the critical thickness of the molten wall layer and the ratio of the superficial velocity of the molten wall layer to that of the corium discharging flow. The proposed model was compared with the Pilch model: the mean averaged error (MAE) of the present model was 9.51%, whereas that of the Pilch model was 36.13%. In the case of the low superheat of the corium where the crust can be produced, the Pilch model without the crust formation model predicts the much larger final-hole diameter than the present model does.

1. Introduction

The phenomena of nuclear severe accidents has attracted attention by researchers in the field of nuclear engineering. The nuclear severe accident is called “core melt accident” in the definition of IAEA (IAEA, 2006). For a core melt accident that occurred in a light water reactor, the reactor vessel may fail by the thermal attack of the molten corium. There are two types of failure modes for a reactor vessel: failure of the in-core instrumentation penetration and thermal creep of the reactor vessel. The penetration failure results in a rupture of about 7.5 cm in diameter due to a failure of the weldment. The length of rupture in the penetration failure was determined as the thickness of a reactor vessel. Its length affects the total heat transfer rate from discharging corium flow to a reactor vessel contacting it. Thermal creep is a failure that occurs due to deformation caused by thermal loading of the reactor vessel.

The thermal–hydraulic analysis for molten corium released from the reactor vessel is required to evaluate the amount of radioactive material released to an environment. The molten corium flow, which is released in the form of jet, has a jet break-up length in the water pool of the cavity. The jet break-up length is one of the most important initial conditions used to analyze the ex-vessel phenomena. However, in most codes simulating fuel–coolant-interactions (FCI), the nozzle diameter is used as a crucial input parameter to govern the jet break-up length (Berthoud and Valette, 1994; Meyer et al., 1998; Annunziato et al., 1999; Davis and Young, 1994; Moriyama et al., 2006; Young, 1982; Chu et al., 1995; Melikhov et al., 2011). The models of the jet break-up length proposed by Epstein and Fauske (2001), Saito et al. (1988) and other researchers are expressed in the form of L/D (L: jet break-up length, D: nozzle diameter).

The jet break-up length L is a key factor in terms of steam explosion and thermal behavior of the molten corium at the cavity-flooded condition. If the jet break-up length exceeds the flooded water level, the leading edge of a molten jet may impinge the bottom of a cavity. The impinging may cause the steam explosion. In terms of thermal behavior of the molten corium, the jet break-up length determines the fraction of hard debris of the molten corium. The difference of cooling rates between a hard debris and a loose debris is large due to the water ingression (Yeo and No, 2019). Therefore, the nozzle diameter releasing the jet plays an important role in the assessment of a severe accident. In

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