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Effects of New Model for Particle Bed Dry-out Heat Flux Implemented in MAAP 5.06 on MCCI

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1. Introduction

In the event of a severe accident at a nuclear power plant where the core is damaged and the reactor vessel is failed, extensive core melt material is released into the reactor cavity. This release involves complex phenomena related to the heat transfer from the molten core to the coolant. The core melt material released into the reactor cavity deposits on the concrete floor of the reactor cavity.

The high-temperature melt reacts with the concrete, leading to concrete erosion, a process known as the Molten Core-Concrete Interaction (MCCI). If this interaction progresses to the embedded steel liner plates of the containment building, it can compromise the final safety barrier of the nuclear power plant, threatening the public's safety by potentially leading to the release of fission products.

The cooling characteristics of the melt in the MCCI phenomenon are closely related to determining the depth of concrete erosion. Upon release into the reactor cavity, the core melt material initially reacts with the coolant, causing some to jet breakup fragment while the remainder spreads and deposits in the reactor cavity. The particle size distribution of the fragments generated at the early phase of the core melt ejection into the water has been the subject of various studies due to the complexity and uncertainty surrounding the behavior of the corium.

This paper compares a new model for calculating the dry-out heat flux according to the particle size of the fragmented melt with existing models. Additionally, the new model is analyzed for application to the APR 1400 NPP.

2. Characteristics of Particle Bed from the jet breakup

2.1. Particle Size from the Jet Breakup

Several experimental investigations have been conducted to determine the characteristics of particle beds which are intended to be representative of the ex-vessel particle beds produced during severe accidents in nuclear reactors. The two main mechanisms which produce ex-vessel particle beds are jet breakup during relocation of corium from the reactor vessel through a water pool in the reactor cavity and melt eruption which entrains corium and concrete containing particles into the overlying pool of water due to the flow of off-gas produced by molten core-concrete interaction. The study in this paper focuses on the MCCI effect of particle size on jet breakup among two main mechanisms.

Jet breakup occurs when a hot corium jet enters a pre-flooded cavity, as illustrated in Figure 1. Corium particles can be stripped off from the corium jet due to violent corium and water interactions. Some of the jet may reach the bottom of the reactor cavity and form a continuous corium bed. The particles that are stripped from the jet by the water are expected to come to rest on the top of the continuous corium bed forming a particle bed.

A similar jet breakup process can occur in the reactor vessel lower plenum when material relocates out of the core. Because of this, numerous investigations into jet breakup have been conducted. The experiments chosen for discussion here are those which have characterized the particle bed formed by jet breakup.

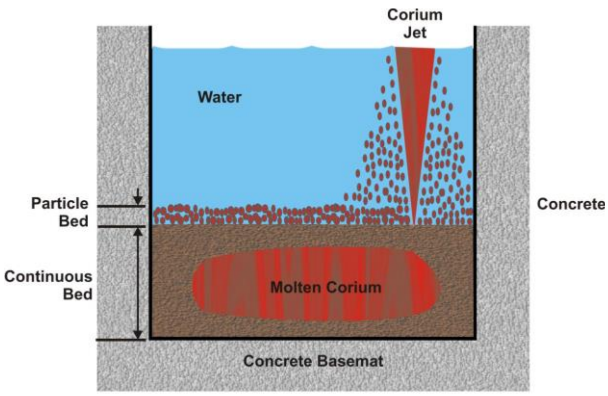

Fig. 1. Illustration of particle bed generation through jet breakup [1]

2.2. Particle Size and Porosity from the Jet Breakup

The TROI experiments were performed by KAERI to investigate the behavior for real corium material interactions with water for conditions similar to those in the APR1400 [2]. The experiment used particle beds

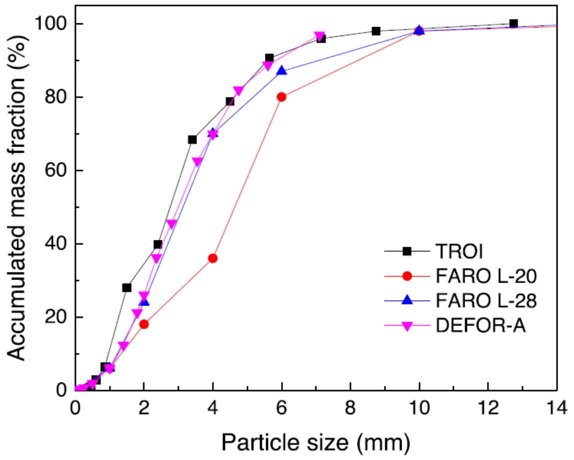

Fig. 2. TROI Particle Size Distribution [2]

comprised of 70% UO_2 and 30% ZrO_2 which were produced by jet breakup in water. The particle size distribution was given graphically as shown in Fig 2 and was characterized in terms of various representative diameters as shown in Table I.

The porosity of the particle bed was measured to be 47%. Single-phase pressure drop tests were performed on the particle bed and were found with compare well against the Ergun equation [3] using a representative particle diameter of approximately 1 mm.

Table I: Representative Particle Sizes in the TROI Experiment [2]

Method	Reported for Experiment
Mass Median (mm)	3.580
Sauter Mean (mm)	2.321
Length Weighted Mean (mm)	1.326
Particle Number Weighted Mean (mm)	0.726
Effective Size based on Ergun Equation Pressure Drop (mm)	1.0

3. Calculation Results

3.1. Compare Calculation Results of Lipinski 0-D 1980 and 1982 Models

Lipinski developed two models which are Lipinski 0-D 1980[4] and 1982[5] to predict the dry-out heat flux for uniform beds of spherical particles. His model combined the extended Ergun equation with mass and energy conservation relationships to determine the limit for heat removal from a particle bed. For a bed resting on an impermeable plate, the solution of these equations produces two expressions, one for the dry-out heat flux in the laminar limit and one for the dry-out heat flux in the turbulent limit.

As shown in Fig 3, The dry-out heat flux predicted the same results in turbulent conditions, but in laminar conditions the 1982 model is typically about 30% lower than that predicted by the 1980 model.

Lipinski's model is a very strong function of porosity, a strong function of particle diameter, and a moderate function of pressure over the range of values expected in typical LWR applications.

Figure 4 shows example results for a deep particle bed at various pressures. As the pressure increases, the dry-out heat flux increases. Also, as the particle size increases, the difference of dry-out heat flux becomes larger.

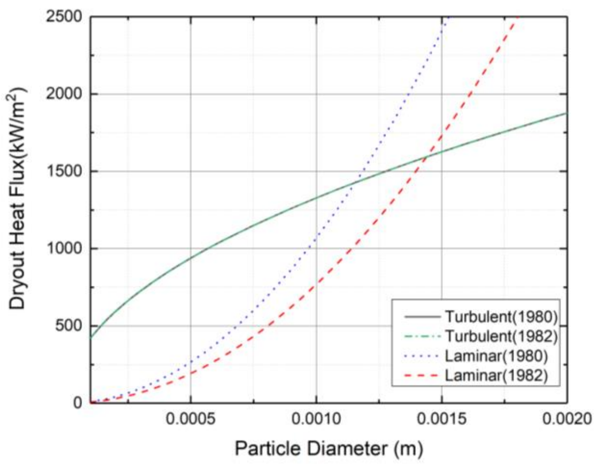

Fig. 3. Lipinski's 0-D Model 1980 vs 1982 at 1bar and ε = 0.47

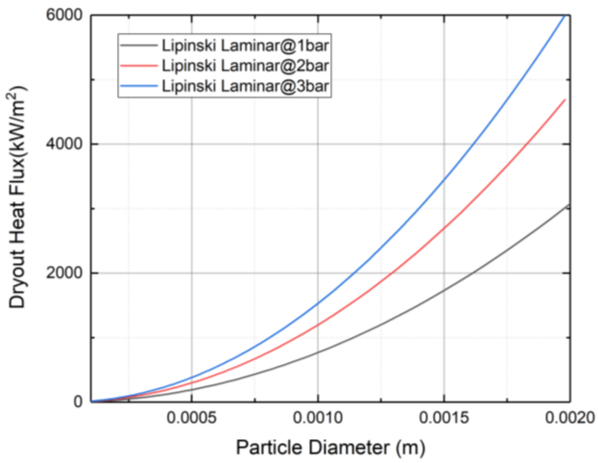

Fig. 4. Lipinski Laminar 0-D(1982) Dry-out Heat Flux at 1,2,3 bar and ε = 0.47

3.2. MAAP Evaluation Results for APR1400 NPP

The existing model applied to the MAAP code was the Lipinski 1980 model. Using the MAAP API (Application Programming Interface), a new Lipinski 1982 model was added to calculated the dry-out heat flux. For a conservative analysis, MAAP calculates the dry-out heat flux under both laminar and turbulent flow conditions and uses the smaller value.

In this chapter, preliminary calculations of concrete erosion depth due to the dry-out heat flux of the particle bed during pre-flooding were performed for the APR1400 NPP using the two models defined in the previous chapter. The accident scenario selected was the Large Break Loss of Coolant Accident (LBLOCA), in which the severe accident progresses rapidly, leading to the earliest reactor vessel failure. The analysis considered severe accident mitigation strategies and features. The assumptions for the analysis were based on the results indicated by the TROI experiments, applying an effective particle diameter of approximately 1 mm and a porosity of 0.47.

As shown in Figure 5, after the reactor vessel failure, erosion begins when corium reaches the reactor cavity floor. It can be explained that the Lipinski 1982 model is eroded about 10% more than 1980 model at about 50,000 seconds.

In conclusion, the Lipinski's 1982 model is more conservative in terms of predicting erosion depth in MCCI phenomena.

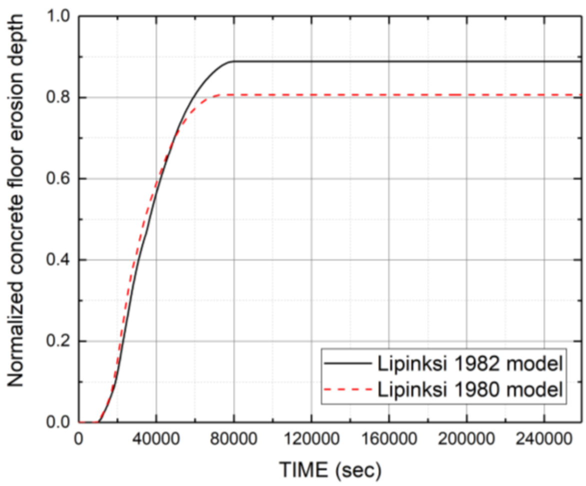

Fig. 5. Normalized concrete floor erosion depth

4. Summary

The model used to calculate dry-out heat flux in MAAP was Lipinski's 1980 model, and a new model, Lipinski's 1982 model, was added using MAAP 5.06 API. In addition, in order to confirm the influence of the two models in APR1400 NPP, the concrete erosion depth due to dry-out heat flux of the particle bed during pre-flooding was preliminarily calculated.

The dry-out heat flux predicted the 1982 model is typically about 30% lower than that predicted by the 1980 model in laminar conditions. Additionally, as the pressure and particle size increases, the dry-out heat flux becomes larger.

As a result of the analysis, the erosion depth of Lipinski 1982 model was 10% higher than the 1980 model at about 50,000 seconds. In conclusion, the Lipinski 1982 model was found to be a more conservative model in terms of erosion depth of the MCCI phenomenon.

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