Revaluation of a Coolability of a Packed Debris Bed with a Single Phase Flow

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1. Introduction

Preliminary safety analyses of the KALIMER-600 design have shown that the design has inherent safety characteristics and is capable of accommodating double-fault initiators such as ATWS events without coolant boiling or fuel melting. However, for the future design of sodium cooled fast reactor, the evaluation of the safety performance and the determination of containment requirements may be worth due consideration of triple-fault accident sequences of extremely low probability of occurrence that leads to core melting. For any postulated accident sequence which leads to core melting, in-vessel retention of the core debris will be required as a design requirement for the future design of sodium cooled fast reactor. Also, proof of the capacity of the debris bed cooling is an essential condition to solve the problem of in-vessel retention of the core debris.

Accordingly, evaluation of coolability of a packed debris bed with single phase flow was carried out for proof of the in-vessel retention of the core debris.

2. Revaluation of Coolability of a Packed Debris bed

2.1 Cooling with Conduction alone

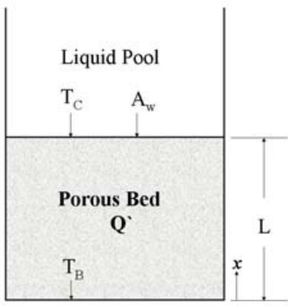

Fig. 1. Schematic diagram of a packed debris bed

If the heat flow through the packed debris bed of Fig. 1 is by a conduction alone, the amount of heat transferred by a conduction through upper surface was the same as the amount of heat generation of the packed debris bed. In this case, the temperature difference between the top and bottom of the packed debris bed can be expressed as follows.

$$T_B - T_C = \Delta T = \frac{Q_p'(1-\varepsilon)L^2}{2k} \quad (1)$$

where k is the conductivity of the sodium and debris particles mixed bed, Q_p' is the heat generation rate per unit volume of the solid particle in the packed debris bed, and ε is the porosity of the packed debris bed.

We predicted the coolable thickness of a packed debris bed based on Eq. (1) and results was shown in Fig. 2. In this case, we assumed that the debris was accumulated on the core catcher uniformly. Also, the porosity and decay heat generation were 0.9 and 2% of norminal power density respectively. In Fig. 2, coolable thicknesses of packed debris bed with inner, inner+middle, and whole core meltdown case were 35.5cm, 33.2cm, and 35.2cm respectively. Especially, in case of the whole core meltdown, coolable thickness was about 24% of that of the packed debris bed. This is far less than the 148.5 cm bed thickness so that it is concluded that the packed debris bed is not coolable by conduction alone.

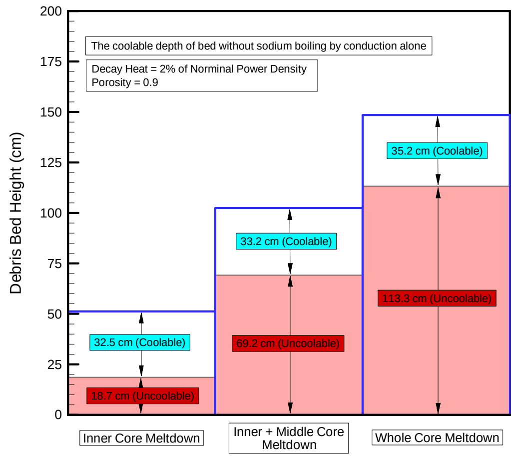

Fig. 2. Coolable thickness with variation of core meltdown type

2.2 Cooling with Single Phase Flow

Hardee and Nilson[1] was derived an analytical model of a single phase convective roll cell using a first order approximate technique. They have shown that the temperature difference driving convection in the layer is respectively 1/4 and 1/2 of the actual temperature difference between the sodium above the bed and the bottom surface of the packed debris bed for balance on the forces and heat. So, the temperature difference between top of bed and bottom of the bed was expressed as follow.

$$T_B - T_C = \Delta T = \frac{4Q_p'(1-\varepsilon)L}{v\rho C} \qquad (2)$$

where v is velocity, ρ is density, C is specific heat.

We can determine v using the Eq (3) derived by Macdonald et al.[2] which relates the friction factor for the packed bed to the Reynolds number.

$$v^3 + \frac{180\mu(1-\varepsilon)}{R\rho D_e} v^2 - \frac{Q_p' L \beta g D_e \varepsilon^3}{R\rho C} = 0 \qquad (3)$$

where L is the debris bed thickness, μ is dynamic viscosity, D_e is the equivalent particle diameter, R is the roughness of particle surface, g is the acceleration of gravity, and β is the thermal expansion coefficient.

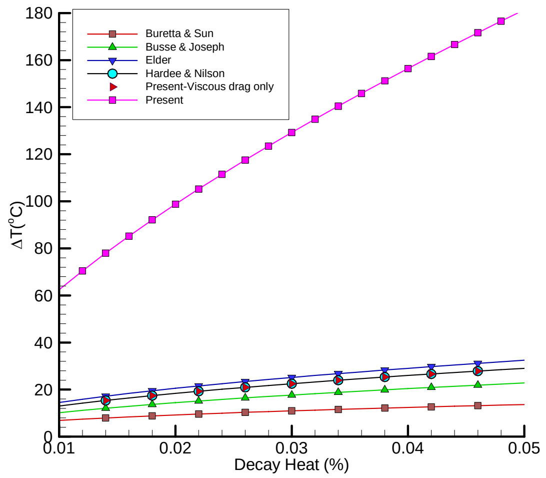

Fig. 3. Comparison with other model

Fig. 3 show the results of comparison with other models which was developed to estimate the temperature difference between top and bottom of the porous media. In Fig. 3, the present model (right triangular symbol) that was disregarded of inertia resistance term good agreed with Hardee and Nilson model. But, calculation result of Eq (2) that involved the inertia resistance term was different from other models.

Eq. (3) is modified Ergun equation which was considered satisfactory for calculating the resistance to flow through a packed bed of particles. So, Ergun equation was consisted of the sum of the viscous resistance and the inertia resistance. From a view point of fluid dynamics, the present model was more reasonable then other model.

For revaluation of the ability of post accident heat removal with KALIMER-600, the sensitivity studies were performed with porosity, equivalent diameter, and roughness.

Calculation results show that 15 sets among 450 sets were uncoolable with single phase flow which the sodium temperature above the bed exceed the boiling point. Table 1 shows uncoolable parameter sets.

Table 1. Uncoolable parameter sets

	D_e (cm)	ε	R	ΔT (℃)
Inner + Mid. Core Meltdown	0.09	0.500	1.800	447.774
	0.09	0.500	2.275	459.902
	0.09	0.500	2.750	471.240
	0.09	0.500	3.375	485.158
	0.09	0.500	4.000	498.126
Whole Core Meltdown	0.09	0.500	1.800	515.574
	0.09	0.500	2.275	530.597
	0.09	0.500	2.750	544.585
	0.09	0.500	3.375	561.691
	0.09	0.500	4.000	577.574
	0.09	0.600	2.750	374.255
	0.09	0.600	3.375	389.897
	0.09	0.600	4.000	404.172
	0.18	0.500	3.375	372.374
	0.18	0.500	4.000	388.397

3. Conclusions

In a previous study[3], there were some errors in a heat generation rate per unit volume of a packed debris bed. In a nuclear reactor problem, a heat generation term is not based on a total volume of a debris bed but based on a volume of a solid particle in a debris bed.

We performed a coolability analysis of a particulate debris bed, which is accumulated on a core catcher, with a single phase flow when an HCDA occurs and obtained improved results.

Results of the sensitivity studies showed that the coolability of the packed debris bed depended on how large the debris diameter and porosity were

Post accident heat removal of KALIMER-600 with a single phase flow was possible except for special parameter sets.

REFERENCES

[1] H. C. Hardee and F. H. Nilson, Natural Convection in Porous Media with Heat Generation, Nuclear Science and Engineering, Vol. 63, pp 119-132, 1977.

[2] I. F. Macdonald et al., Flow Through Porous Media – the Ergun Equation Revisited, Industrial and Chemical Engineering Vol. 18, 1979.

[3] Jewhan Lee et al., Numerical Analysis of Characteristics of a Particulate Debris Bed Coolability with Single Phase flow, Korea Nuclear Society Spring Meeting, Gyeongju, Korea, May 29-30, 2008.