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Development of Concrete Ablation Module for Molten Core-Concrete Interaction Analysis

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CONTENTS

01 Introduction

Motivation

- To prevent large amount of radioactive material release from the nuclear power plant, the containment integrity should be maintained.
- One possible way to fail the containment is base-mat through by the Molten Core-Concrete Interaction (MCCI) phenomenon.
- To evaluate this failure mode accurately, precise prediction of concrete ablation is required.
- However, the concrete ablation is analyzed with too much conservative assumptions in general system-level codes.

01 Introduction

Objective

- For this reason, the concrete ablation module is being developed for the Code of Corium-Concrete Interaction (COCCI), which is developed by KAERI based on C++ [1].

- In this research, concrete ablation model options for COCCI and analysis results are presented.

[1] Sang Ho Kim, Sang Min Kim, Jae Hyun Ham, Hwan-Yeol Kim, Rae-Joon Park, Jaehoon Jung, "Development of Computer Code for Analysis of Molten Corium and Concrete Interaction", Transactions of the Korean Nuclear Society Virtual Spring Meeting, July 9-10, 2020.

02 Concrete ablation model

Process of the concrete ablation [2]

- After the reactor vessel failure under the severe accident condition, concrete in the cavity is heated up by high temperature corium.
- During the heat-up phase, the crust layer can be formed between the corium and the concrete.
- As the crust layer grows, heat transfer from corium to concrete decreases so that corium bulk temperature rises.
- The crust layer fails in the end, then the concrete starts to melt when the boundary temperature reaches at ablation temperature of the concrete.

[2] Sang Ho Kim, Jae Hyun Ham, Hwan-Yeol Kim, Rae-Joon Park, Jaehoon Jung, "Crust Formation and Growth in Analysis of Molten Corium and Concrete Interaction", Transactions of the Korean Nuclear Society Virtual spring Meeting, May 13-14, 2021.

02 Concrete ablation model

» Representative models for concrete ablation [3]

- Quasi-steady model
  - Heat-up phase of concrete and heat conduction into concrete is ignored.
  - This model generally used for system-level code.
- Fully developed model
  - Heat-up phase of concrete is ignored same as the quasi-steady model, but heat conduction into concrete is considered.
- Transient dry-out model
  - Both heat-up phase of concrete and heat conduction into concrete are considered.

[3] M. T. Farmer, The CORQUENCH Code for Modeling of Ex-Vessel Corium Coolability under Top Flooding Conditions, ANL-18/22, Aug., 2018.

02 Concrete ablation model

Status of concrete ablation module of COCCI

- For now, the concrete ablation module of COCCI covers quasi-steady model and fully developed model so that the boundary temperature between corium and concrete is assumed as the ablation temperature from the beginning.

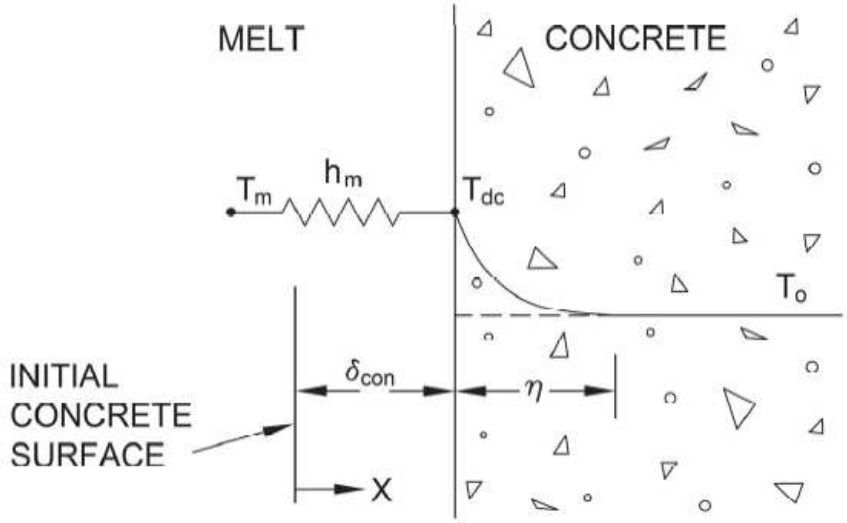


Fig. 1. Schematic of fully developed concrete ablation model [3]

[3] M. T. Farmer, The CORQUENCH Code for Modeling of Ex-Vessel Corium Coolability under Top Flooding Conditions, ANL-18/22, Aug., 2018.

02 Concrete ablation model

Derivation of decomposition heat

- If the concept of a thermal boundary layer thickness in the concrete wall behind the ablation front is employed, then the thermal response in this layer satisfies the transient one-dimensional heat conduction equation as below:

$$1)\ \rho_{con} C_{con} \frac{dT}{dt} = k_{con} \frac{d^2T}{dx^2}$$

- The linear temperature profile (steady state) was assumed in the concrete in this research.

$$2)\ T(x) = ax + b$$

02 Concrete ablation model

Derivation of decomposition heat

- Boundary conditions including thermal boundary layer thickness can be expressed as below:

$$3)\ T(x=0) = T_{con,ab}$$

$$4)\ T(x=\xi_{con}) = T_{con,o}$$

$$5)\ \frac{dT}{dx}|_{x=\xi_{con}} = 0$$

- The ablation rate based on the energy balance equation between corium and concrete can be expressed as below:

$$6)\ \rho_{con}\Delta h_{con}\eta' = HTC\left(T_{bk,m} - T_{con,ab}\right) + k_{con}\frac{dT}{dx}|_{x=0}$$

$$= HTC\left(T_{bk,m} - T_{con,ab}\right) + k_{con}\frac{(T_{con,o} - T_{con,ab})}{\xi_{con}}$$

02 Concrete ablation model

Derivation of decomposition heat

- It is assumed that materials in the concrete except gas are merged to the corium by ablation so that decomposition heat can be expressed as below:

$$7)\ Q_{dc} = (1-\chi_{g,con})\cdot A\cdot \rho_{con}\Delta h_{con}\eta'$$

$$= \left(1-\chi_{g,con}\right)\cdot A\cdot \left(HTC\left(T_{bk,m}-T_{con,ab}\right)+\ k_{con}\frac{\left(T_{con,o}-T_{con,ab}\right)}{\xi_{con}}\right)$$

$$= \left(1-\chi_{g,con}\right)\cdot \left(Q-A\frac{k_{con}\left(T_{con,ab}-T_{con,o}\right)}{\xi_{con}}\right)$$

- In the quasi-steady model, heat conduction into concrete is ignored because the thermal boundary layer thickness is infinite.

$$8)\ Q_{dc} = \left(1-\chi_{g,con}\right)\cdot Q$$

02 Concrete ablation model

Nomenclature

- ρ_{con} = density of concrete [kg/m^3]
- C_{con} = heat capacity of concrete [J/kg-K]
- k_{con} = conductivity of concrete [W/m-K]
- $T_{con,ab}$ = ablation temperature of concrete [K]
- ξ_{con} = thermal boundary layer thickness [m]
- $T_{con,o}$ = internal temperature of concrete [K]
- Δh_{con} = amount of change of concrete enthalpy [J/kg]
- η' = ablation rate [m/s]
- HTC = heat transfer coefficient from corium to concrete [J/m^2-sec]
- $T_{bk,m}$ = bulk melt temperature [K]
- Q_{dc} = decomposition heat [W]
- $\chi_{g,con}$ = mass fraction of gas in concrete
- Q = heat transfer from corium to concrete [W]
- A = heat transfer area [m^2]

03 Analysis results

» CCI-2 test analysis

- To confirm the effect of the concrete ablation model on the results, CCI-2 test [4] was analyzed using COCCI.
  - Concrete decomposition temperature : 1800 K
  - Initial corium temperature : 2150 K
  - Weight percent of gases in concrete : 0.275 %
  - Total simulation time : 360 minutes
  - Beginning of water injection to the top of the corium : 300 minutes

[4] Jaehyun Ham, Sang-Ho Kim, Sangmin Kim, Jaehoon Jung, "Sensitivity analysis for CCI-2 test using CORQUENCH", Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, July 9-10, 2020

03 Analysis results

CCI-2 test analysis

- The comparison of bulk melt temperature and the ablation depth are shown in Fig. 2 and Fig. 3.
- In this analysis, 1.0 and 0.1 were assumed as the thermal boundary layer thickness.
- As shown in figures, there are not much difference between the results of CCI-2 test and COCCI analysis.

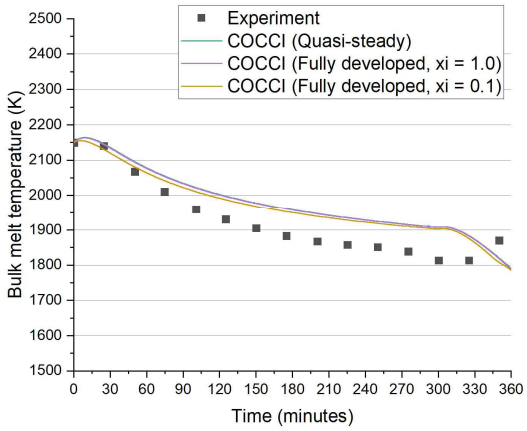


Fig. 2. Comparison of bulk melt temperature

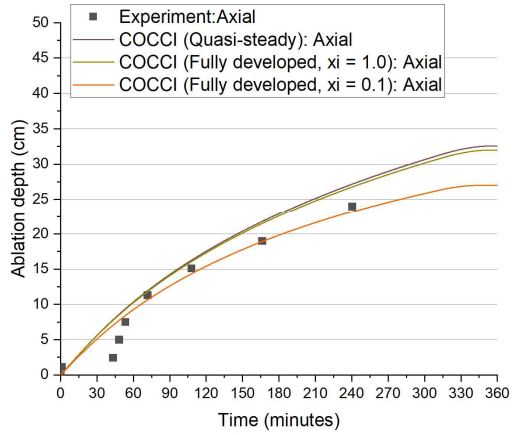


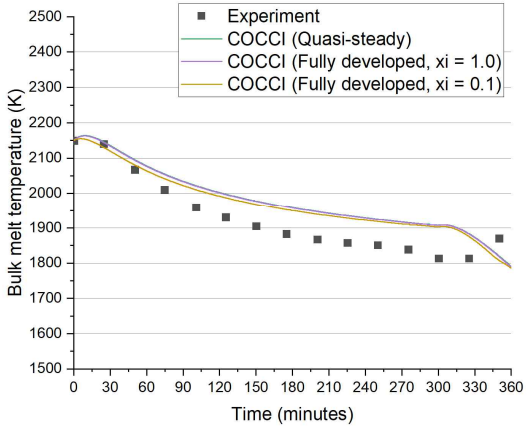
Fig. 3. Comparison of ablation depth

03 Analysis results

CCI-2 test analysis

- The bulk melt temperature results are almost same, however, the ablated depth decreases when the fully developed model is used.

- When small value of thermal boundary layer thickness is assumed, the ablated depth decreases, because decomposition heat decreases and heat conduction into concrete increases following the equation (7).



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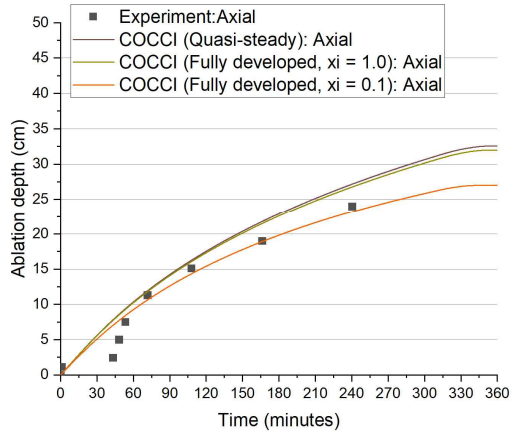

Fig. 3. Comparison of ablation depth

04 Conclusion

Summary & Further study

- The model options for the concrete ablation module of COCCI, and analysis results of CCI-2 test were presented in this research.
- For now, the quasi-steady and the fully developed model were covered in the module, the difference between these models is consideration of heat conduction into concrete.
- The effect of the heat conduction according to the thermal layer thickness was shown in the analysis results.
- For further work, the module will include transient dry-out model as an option so that the concrete heat-up phase can be considered.

THANK YOU

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