Evaluation of FCI with the pre-flooded cavity through simple models

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1. Introduction

A fuel-coolant interaction (FCI) is an intermediate stage for the falling corium from the reactor vessel to the bottom of the reactor cavity, where a molten core concrete interaction (MCCI) occurs. In FCI, large-scale corium experiments (FARO) showed that the large amount of heat is transferred to the surrounding water, approximately 40~50% of the initial corium energy in a few seconds even without the steam explosion [1]. Although the importance of the FCI during the falling stage without steam explosion does not get much attention, the fraction of the heat transfer is dominant before the beginning of the MCCI. The accurate prediction or analysis for this FCI results in the realistic initial temperature for the MCCI. Previously, using a series of 1-D models, we developed the lumped tool to estimate the thermal-hydraulic behavior of the FCI [2]. In this paper, we roughly analyze the energy and pressure behaviors in the falling stage during the FCI with the change of related input parameters.

2. Brief explanation for using models

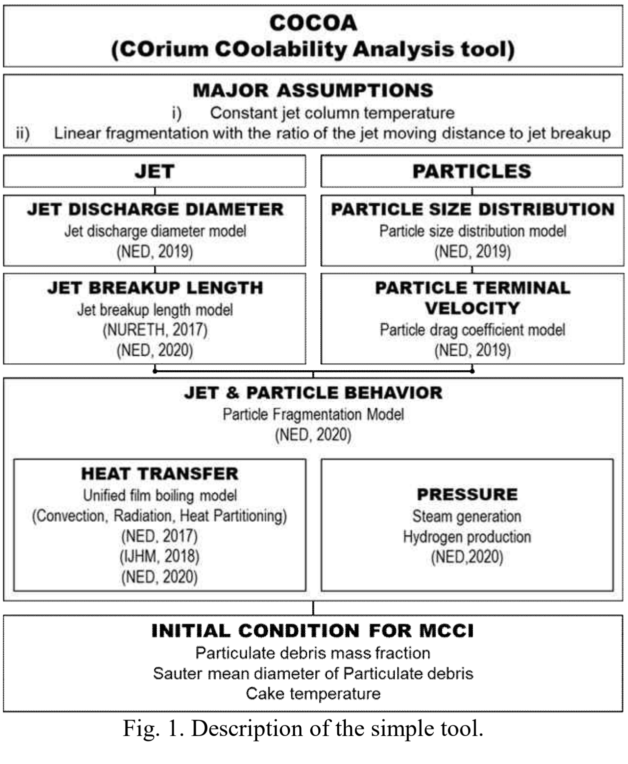

Fig. 1. Description of the simple tool.

The developed 1-D tool was named as COCOA (Corium COolability Analysis tool) [2]. The structure of the code is shown in Fig. 1. This tool was developed as a lumped code based on the 1-D correlations and relations to pursue the better prediction for the FCI without the large computational effort and the complexity. Simple mass and energy conservations are solved with the explicit time discretization. The momentum equations are replaced with the drag coefficient. The water and steam are considered as lumped volume. The corium jet and particles are treated as Lagrangian method.

Almost all of implemented models describing behaviors of the corium jet and particles were newly developed or improved, comparing to conventionally used models.

For the jet discharge diameter of the corium from the reactor vessel, Song and NO [3] developed the procedure reflecting the formation of the crust and the meltingness of the vessel wall. They showed the better agreement with the validating experiment as the average deviation of 9.5% than Pilch model implemented in MELCOR as the average deviation of 36.1 %.

For the length of the jet breakup, Kim and NO [4] suggested the correlation based on the corium experimental results. They also showed the improvement as the normalized root mean square deviation (NRMSD) of 24.7%, compared to Epstein-Fauske model as the NRMSD of 50.1~57.7%.

For the heat transfer of the corium particles, Yoon et al. [5] developed the model compensating the radiation effect at the vapor-water interface in the film boiling. This model also showed the better agreement as the NRMSD of 10.99% than Epstein-Hauser model implemented in most of severe accident codes as that of 61.92%.

As a result, limiting in the falling stage during the FCI, this tool was validated the large-scale corium experiment known as FARO [2] including ISP-39 benchmark problem. It showed better prediction capability in terms of NRMSDs (26.5% for the energy transfer, 16.9% for the pressure difference, 27.2% for the particulate debris formation) than COMETA code (36.0% for the energy transfer, 42.2% for the pressure difference, 39.3% for the particulate debris formation) which was developed by JRC Ispra.

With this validated tool, we calculate and analyze the results for the falling stage during the FCI with the change of related parameters in the next section.

3. Results

The applied input parameters for the simulation is described in Table I. The released corium mass was varied with simulations from 20 tons to 200 tons, which 20 tons is from TMI-2 accident and 200 tons is the total mass of the fuel and the surrounding materials in the reactor vessel. According to the released corium mass and the pre-flooded water temperature, the index of the parameter was named. For example, 20ton_sat means the releasing corium mass is 20 tons and the water is saturated. The water depth is from the final water level in the reactor cavity of APR1400. The initial diameter of the corium jet from the reactor vessel is determined as 0.0762 m, which is the diameter of ICI nozzle. The coefficient for the hydrogen generation (C_{H2}) by the corium fragmentation was set from the FARO results.

Table I. Simulating input parameters

Parameters	20ton sat	20ton sub	100ton sat	100ton sub	200ton sat	200ton sub
Corium mass (ton)	20	20	100	100	200	200
Corium temperature (K)	3000					
Initial Pressure (MPa)	0.1					
Water depth (m)	6.4					
Initial ΔT_{sub} (K)	0	50	0	50	0	50
Initial $D_{release}$ (m)	0.0762					
Mean $D_{particle}$ (mm)	3.7*					
C_{H2} (1e-3)	2.5**	0.6***	2.5**	0.6***	2.5**	0.6***

* We applied the average value of 6 available data from FARO tests, same as L-27 in Table 3-1.
** Average value of the FARO results with the initially saturated water.
*** Value of the FARO test with the initially subcooled water.

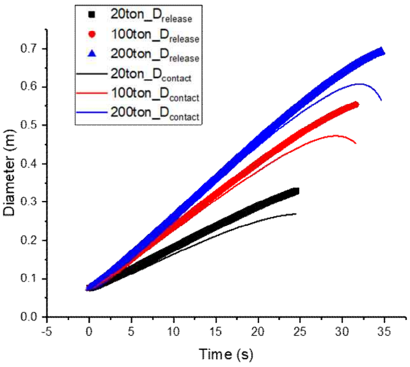

Fig. 1. Release and contact diameter during the FCI.

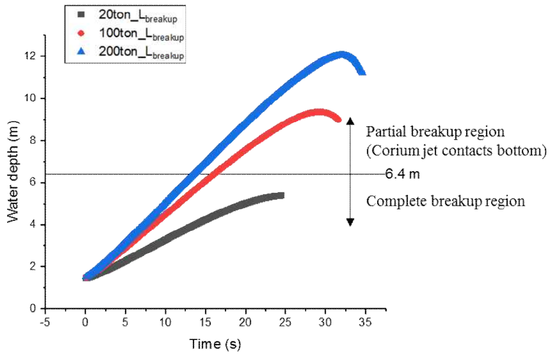

Fig. 2. Jet breakup length increase during the FCI.

As shown in Fig. 1, the releases of the corium were completed at about 25 s with 20 tons, 32 s with 100 tons, and 35s with 200 tons. As the corium continuously escapes from the reactor vessel, the hole of the diameter is increased from the initial diameter (0.762 m) to 0.33m for 20 tons, 0.55 m for 100 tons, 0.69 m for 200 tons of the corium. Since the velocity of the corium jet increases with the gravity until the corium contact with the water surface, the corium jet diameter at the water surface was smaller than the release diameter.

The jet breakup length in the pre-flooded cavity corresponds with the corium jet diameter at the contact of the water, as illustrated in Fig. 2. For 20 tons of the corium, the corium completely breaks up before the jet reaches to the cavity bottom. For 100 tons of the corium, the released corium before 15 s achieved the complete breakup. After 15 s, the corium jet partially breaks and contributes the cake formation rather than the particulate debris.

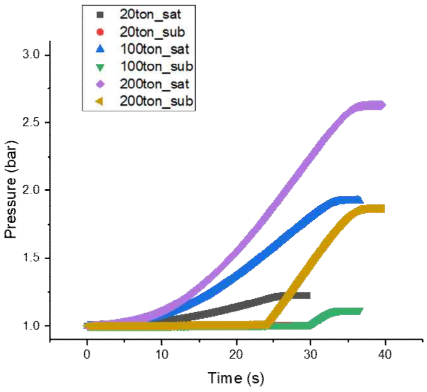

Fig. 3. Pressure increase during the FCI.

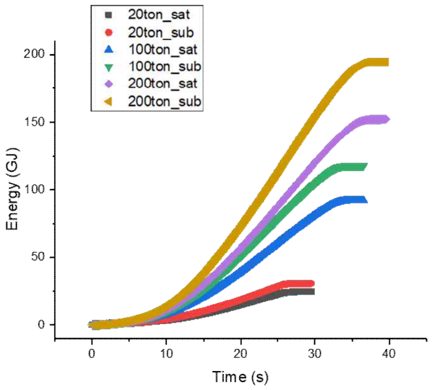

Fig. 4. Energy transfer from corium to environment during the FCI.

As shown in Fig. 3 and Fig. 4, the pressure and energy transfer were calculated for each input parameters. The integrity of the containment is kept as the maximum pressure reached 2.6 bar for 200ton_sat case. The final pressure, transferred energy and average corium temperature at the end of the falling stage in FCI is stated in Table II. The average corium temperature was calculated as the equation (1), considering the enthalpy property of the corium.

$$T_{corium} = f\left(\frac{E_{total}}{m_{corium}}\right) \qquad (1)$$

Table II. The final pressure, released energy and average corium temperature at the end of the falling stage in FCI

	20ton_sat	20ton_sub	100ton_sat	100ton_sub	200ton_sat	200ton_sub
Pressure (bar)	1.2	1.0	1.9	1.1	2.6	1.9
Released energy (GJ)	24.7	30.7	92.3	117.8	152.0	194.5
Average corium temperature (K)	1062	382	1761	1187	2126	1648

From these results, we can notice that the initial temperatures of the MCCI is quite lower than the typical values of the severe accident analysis.

For further investigation, the additional sensitivity studies are required for the corium temperature, the water depth and so on. In terms of the expansion of the capability for the tool, the continuous evaluation for the MCCI phase after FCI or the implementation of the steam explosion model would be favorable.

4. Conclusions

The evaluation of FCI during the falling stage was presented with a combination of simple 1-D models. This tool was validated its prediction capability with the large-scale corium experiment known as FARO. With the variation of input parameters, the behaviors of the releasing diameter, the jet breakup length, the containment pressure, and the energy transfer were obtained. The containment kept its integrity with the change for amounts of the corium mass and degrees of the water subcooling. The average corium temperatures after the FCI showed quite small values. The effort to improve the accuracy and the capability of the tool will be pursued furtherly.

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