

INTERACTION OF MOLTEN URANIUM WITH ELECTRICAL TUBE OF A BWR DURING SEVERE ACCIDENT

INTERAKSI LELEHAN URANIUM DENGAN KANAL PENETRASI KABEL LISTRIK PADA BWR SAAT TERJADI KECELAKAAN PARAH

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ABSTRACT

INTERACTION OF MOLTEN URANIUM WITH ELECTRICAL TUBE OF A BWR DURING SEVERE ACCIDENT. Fukushima accident was the first severe accident of a BWR type which the core was melted leading to RPV failure at the bottom head. Regarding its complex structures of the bottom head, the scheme of failure is different from that of previous reactor severe accidents that ever happened (i.e. TMI-2 and Chernobyl accidents). There are a lot of penetration tubes through the bottom head leading to a complex interaction between corium and the structures. Eutectic reaction is possible to happen due to high temperature leading to a rapid failure of the RPV. Therefore, it is important to understand the phenomenon of interaction between corium and the structures. In this study, an interaction between molten uranium and structure of electrical tube, one of the penetration tubes, was analyzed by using MPS-LER method. Fluid dynamics of the MPS-LER simulation was validated by experiments of fluid flow by using water and oil. Calculation results of the fluid flow showed a good agreement with that of experiments. The MPS-LER was applied to calculate the penetration rate of molten uranium which flowed through the wall of the electrical tube at the bottom head of a BWR. The penetration rate was high due to eutectic reaction. The rate achieved 555.56 $\mu\text{m/s}$. Conservatively, it took less than 1 minute of time for the molten uranium to melt the tube wall with a thickness of 1.232 cm.

Keywords: Molten uranium, electrical tube, penetration rate.

ABSTRAK

INTERAKSI LELEHAN URANIUM DENGAN KANAL PENETRASI KABEL LISTRIK PADA BWR SAAT TERJADI KECELAKAAN PARAH. Kecelakaan reaktor Fukushima merupakan kecelakaan parah pertama pada reaktor tipe BWR, dimana teras reaktor meleleh dan menyebabkan kegagalan struktur bejana reaktor bagian bawah. Struktur bejana reaktor BWR yang kompleks menyebabkan skema kegagalan tersebut berbeda dengan skema kegagalan-kegagalan bejana reaktor reaktor tipe lain saat terjadi kecelakaan parah (seperti kecelakaan reaktor TMI-2 dan Chernobyl). Ada banyak pipa-pipa penetrasi pada bagian bawah bejana reaktor BWR yang menyebabkan interaksi antara lelehan teras reaktor (korium) dengan dinding bejana menjadi kompleks. Reaksi eutektik mungkin terjadi pada kasus tersebut terkait suhu yang tinggi yang dapat mempercepat kegagalan bejana reaktor. Oleh karena itu, analisis perilaku interaksi antara korium dengan dinding bejana reaktor penting untuk dilakukan. Pada penelitian ini, analisis tersebut dilakukan dengan menggunakan metode MPS-LER. Dinamika perhitungan pada MPS-LER divalidasi berdasarkan data eksperimen aliran fluida air dan minyak (oli). Hasil validasi menunjukkan kemiripan data yang baik. Kemudian metode MPS-LER diaplikasikan untuk menghitung laju penetrasi lelehan korium (uranium) yang mengalir pada jalur pipa-pipa penetrasi pada bejana reaktor bagian bawah. Hasil perhitungan menunjukkan laju penetrasi kurang dari 1 menit, dengan ketebalan dinding bejana 1,232 cm.

Kata kunci: Lelehan uranium, kanal penetrasi kabel listrik, laju penetrasi lelehan.

INTRODUCTION

Since its first operation, nuclear reactors experienced some severe accidents, like TMI-2 accident in 1979, Chernobyl accident in 1986, and Fukushima accident in 2011. TMI-2 accident had been analyzed and it gives an important lesson on molten fuel progression in the PWR [1-3]. The accident was mitigated by cooling the molten fuel [3]. Meanwhile, the accident of Chernobyl took on catastrophic proportion as the result of undesirable reactor design features [4]. It is a type of graphite-moderated nuclear power reactor.

Fukushima accident is categorized as a severe accident due to core meltdown. However, the melt-behavior is not well known because there is no severe accident of a BWR type before Fukushima. Features of BWR is unique and different from that of TMI-2 and Chernobyl reactors. Control rods are mounted into the core through the bottom part. There is a lot of penetrations through the bottom head, like an electrical tube for control systems and the control rods guide tube structures. During the severe accident, gravity will take the molten fuel and core debris into the lower plenum/head causing interaction with the penetration materials. The eutectic reaction is possible to exist during the interaction due to high temperature, leading to a decrease of materials' melting point significantly. In turn, it might lead to further rapid failure of the bottom head of the reactor pressure vessel (RPV). Therefore, it is important to understand clearly the phenomenon of interaction between corium and structures of bottom head of a BWR.

A method called a Moving Particle Semi-implicit (MPS) was developed for analyses of the interaction between incompressible media such as water and metal which are extensively used for industrial application [5, 6]. During its development, it was used for interaction analyses between materials in nuclear field [7-15]. Regarding the eutectic reaction the MPS was developed to study the eutectic reaction between metals, i.e. iron-alloy, Pb-Sn [9-11]. The developed MPS code is called as MPS method with Liquefaction of Eutectic Reaction (MPS-LER). It was validated with TREAT experiments and the simulation showed a good agreement with experimental results [12]. The study, however, does not discuss specifically the interaction between molten fuel and structure materials in the lower head of a BWR during severe accident. Dimensions of penetration components in the lower head are not considered yet. The geometry of penetration components might influence the way of interaction between corium and the component. Regarding the eutectic reaction, it might accelerate the failure of the RPV. Mechanisms of eutectic reaction between the materials which accelerates the RPV failure is important to understand. In the past, study on eutectic reaction between fuel debris and reactor structure using simulant material was carried out [16]. The objective of this study is to analyze the interaction between molten fuel and electrical tube at the bottom head of a BWR, by using MPS-LER. Eutectic reaction is considered to be significant in influencing the rate of interaction.

METHODOLOGY

MPS-LER Method

MPS is a modified particle method. Computer simulation using MPS method has the capability of analyzing complex geometry and physics [5]. Properties of a material are described in a particle which interacts with its surrounding particles based on kernel function $w(r)$ as shown in Eq. (1), where r is the distance between two particles. Fig. 1 shows the concept of MPS method.

$$w(r) = \begin{cases} \frac{r_e}{r_0} - 1 & (0 < r < r_e) \\ 0 & (r \geq r_e) \end{cases} \quad (1)$$

The number of surrounding particles which influence a particle's properties is covered by the parameter r_e .

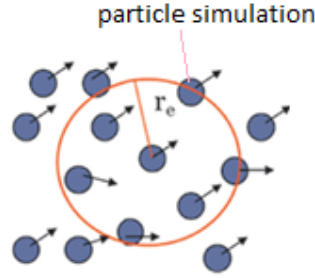


Figure. 1. Concept of MPS method [10].

A model of eutectic reaction was included into the MPS called as MPS with liquefaction of eutectic reaction (MPS-LER). Experiments of TREAT and Pb-Sn interaction were used for validation of the MPS-LER [9-12]. Calculation of the eutectic reaction includes two steps. The first step is a calculation of the mass transfer of particle which is solved by mass diffusion equation (Fick's second law). The second step of eutectic reaction modeling is consideration of chemical reaction which may delay or accelerate the melting process during the interaction. Eq. (2) shows the Fick's second law.

$$\frac{\partial m}{\partial t} = D \nabla^2 m \quad (2)$$

m is mass and D is a coefficient of diffusion. MPS Laplacian model is used to solve the right-hand side of the Eq. (2). The model is shown by Eqs. (3) and (4),

$$m_i^{t+1} = m_i^t + D \Delta t \cdot \frac{2d}{n^0 \lambda} \sum_j (m_j^t - m_i^t) w_{ij} \quad (3)$$

$$\lambda = \frac{\sum_{j \neq i} |\vec{r}_j - \vec{r}_i|^2 w(|\vec{r}_j - \vec{r}_i|)}{\sum_{j \neq i} w(|\vec{r}_j - \vec{r}_i|)} \quad (4)$$

m_i^{t+1} is mass of i particle at time step $t+1$, m_i^t is mass of i particle at the time step t , m_j^t is mass of j particle at the time step t , r_i is position vector of i particle, r_j is position vector of j particle, d is the number of space dimension, and n^0 is initial particle number density of inner particle. In this study, the MPS-LER is modified to simulate the interaction between molten uranium and penetration component of the electrical tube at the bottom head of a BWR during the severe accident. Geometry and dimension of the electrical tube were considered.

Experiment and Simulation Conditions

In this study, experiments of flowing fluids as shown in Fig. 2 were carried out to validate the fluid dynamics of the MPS-LER simulation. Two different fluids were used. The first experiment used water and the second experiment used oil. The bottleneck was filled with the fluid and then started flowing the fluid when the bottle tip was opened. Fluid dynamics of flow rate was used for comparison with that of the simulation. The fluid dynamics are different due to different properties of density and kinematic viscosity of the both fluids. It is also expected to happen in the simulation. Meanwhile, the simulation was made by using MPS-LER with particle size of the simulation is 0.0001 m. Properties of fluids in the simulation were set the same as those of water and oil.

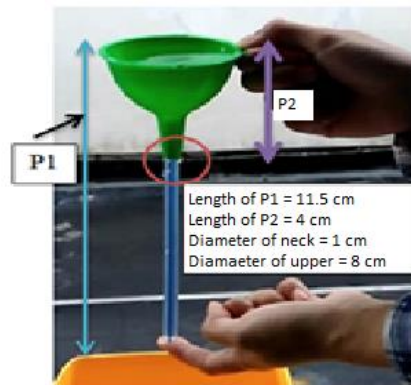


Figure. 2. Experiment of flowing fluid through a bottle neck.

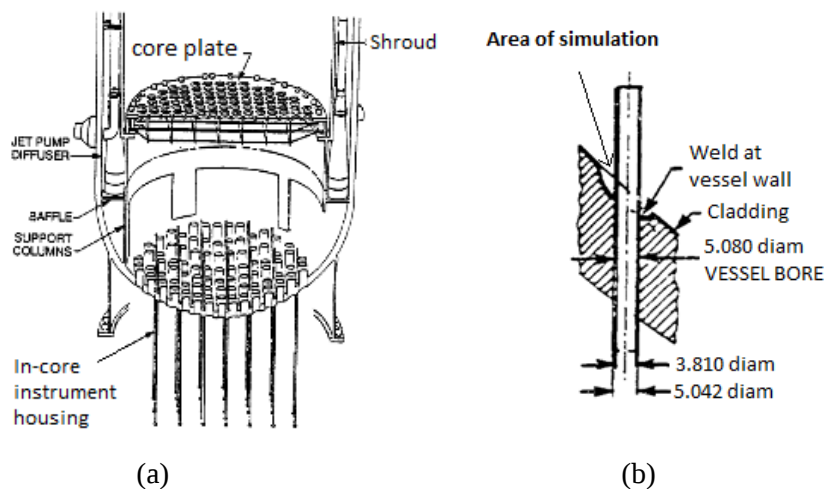


Figure. 3 (a) Bottom head structures of a BWR, **(b)** Penetration tube through the bottom head.

The same simulation condition was applied to simulate the molten uranium which flowed through the wall of an electrical tube of a BWR. The structure of a BWR bottom head is shown in Fig. 3(a) [17]. The high kinematic viscosity of corium will lead to a slow flow. The part analyzed here is at the joint of the electrical tube and the wall of RPV. Fig. 3(b) shows the thickness of the electrical tube which is 1.232 cm, while the thickness of RPV wall is much thicker than that of the penetration tube wall. Fig. 4 shows the simulation of selected area. Purple color means liquid phase, while blue color means solid phase. It was assumed that the tube was purely made of stainless steel (SS) 304 and thickness of 1.1 mm on all sides were taken as the sample of the whole thickness of the tube wall. The diffusion coefficient of the SS304 and uranium were used the same as previous study [9]. During the severe accident, molten uranium was relocated into this part and interacted with the electrical tube wall. The number of particles to simulate the object was 17532 particles consisting of 13650 particles for simulating molten uranium, 3646 particles for simulating the tube and bottom head walls, and 236 particles as dummy wall. The initial temperature of molten uranium was assumed to be 1600 K and the initial temperature of the wall was 1000 K.

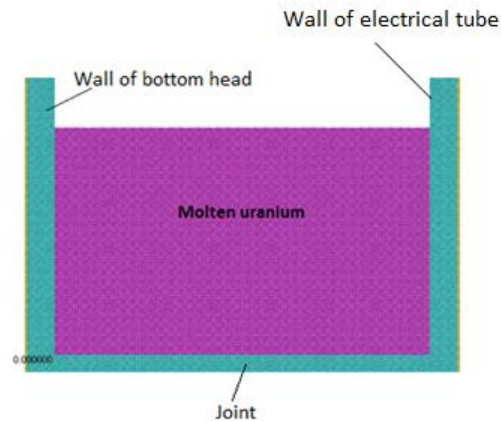


Figure 4. Simulation of interaction between molten uranium and penetration tube.

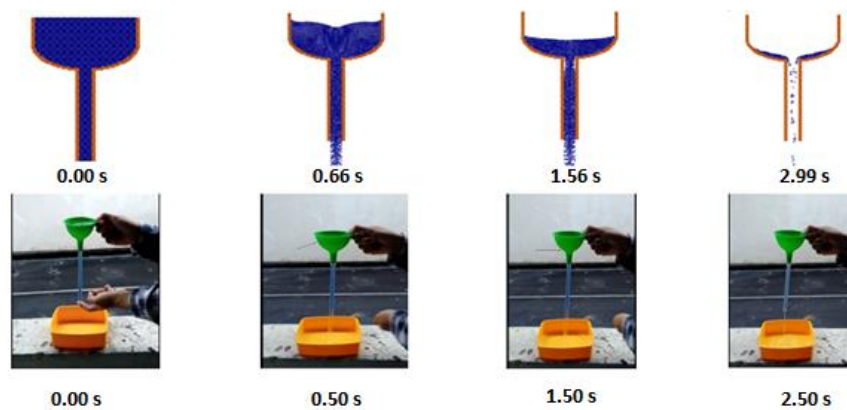


Figure 5. Comparison of time of water flow between simulation and experiment.

Table 1. Time of water flow.

Height of static fluid (cm)	Time (s)	
	Experiment (s)	Simulation (s)
11.50	0.00	0.00
5.75	0.50	0.66
2.88	1.50	1.56
0	2.50	2.99

RESULTS AND DISCUSSION

Figs. 5 and 6 show comparisons between calculations by simulation and experiments. Tables 1 and 2 show the time flow. The comparisons show that the calculations agreed with that of the experiments. A short time period of flowing water is due to its low kinematic viscosity, while fluid of oil took more time to flow due to its higher kinematic viscosity. The behavior should be consistent for other fluids, as well as molten uranium.



Figure. 6. Comparison of time of oil flow between simulation and experiment.

Table 2. Time of oil flow.

Height of rest water (cm)	Time (s)	
	Experiment (s)	Simulation (s)
11.50	0,00	0,00
10.35	3,00	2,99
0	25,0	26,22

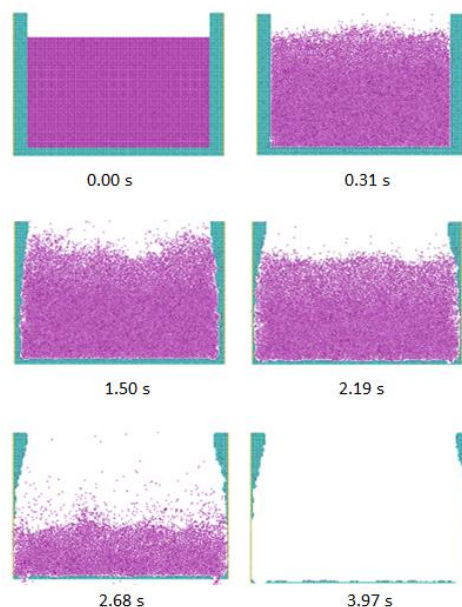


Figure. 7. Diffusion pattern of molten uranium into the wall of penetration tube.

Fig. 7 shows diffusion pattern of molten uranium into the walls of the electrical tube and bottom head. Its heat transfer is shown in Fig. 8. The eutectic reaction is shown by the change of the steel wall (blue) into a liquid phase (purple). The temperature of the wall which interacts with the uranium increases rapidly, while the temperature of the molten uranium decreases slowly. The first layer of the wall started melting at 0.31 s. It takes short time of about 3.97 s to melt the 1.1 mm of the simulated wall, showing high penetration rate due to the high temperature which causes a high diffusion coefficient. The eutectic reaction decreases the melting point of the steel leading to the fast diffusion. It agrees with the results of the previous study which penetration rate was high at high temperature [12]. At 2.68 s a part of the bottom wall starts forming holes leading the molten uranium to flow downward due to gravity.

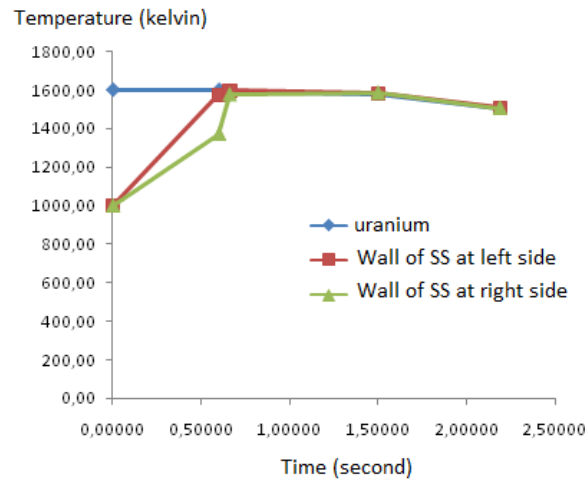


Figure. 8. Temperature during interaction.

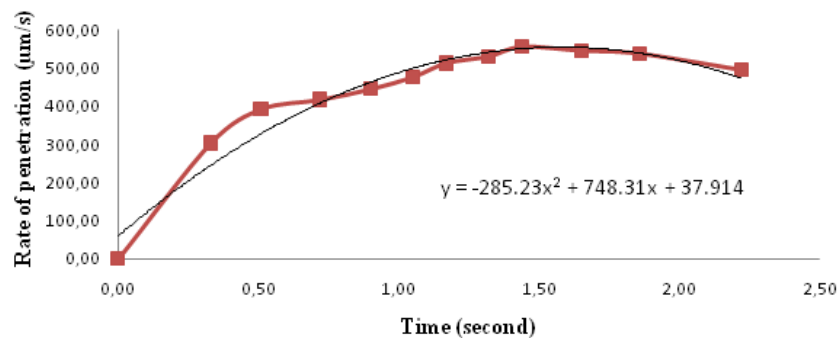


Figure. 9. Penetration rate of molten uranium into electrical tube wall.

Fig. 9 shows the rate of penetration of the molten uranium into the wall. The penetration rate is changed due to change of temperature. At the beginning, the penetration rate increases rapidly due to the rapid increase of the wall temperature as result of interacting with the molten uranium. Then the penetration rate is getting slower due to low change of temperature as shown in Fig. 8. The highest penetration rate is about 555.56 µm/s. [9] reported that positive gradient of the penetration rate with increasing temperature was due to liquefaction which the formation of a liquid particle, i.e. eutectic particle, will be determined by its temperature and mass fraction. After 1.5 s the penetration rate tends to decrease slowly due to the slow decrease of its temperature. Melting time of the actual whole wall thickness of the electrical tube (12.32 mm) was predicted conservatively by using the highest penetration rate. It took time about 22.18 s for the molten uranium to melt the tube wall.

CONCLUSION

MPS-LER was applied to analyze the interaction between molten uranium and electrical tube at the bottom head of a BWR. Two experiments of flowing fluids using water and oil were carried out by using bottleneck for validation of the fluid dynamics of the simulation. The calculation results showed a good agreement with that of experiments. Hence, it would be consistent for the fluid of corium which flowed through the wall of the electrical tube during the severe accident of a BWR. Penetration rate during its interaction was calculated and high penetration rate was resulted due to eutectic reaction. The highest penetration rate could reach about 555.56 µm/s. Conservatively, it took less than 1 minute to melt the whole wall thickness of the electrical tube.

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