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Possible Hydrodynamic Fragmentation Behaviors of Molten Metallic Fuel in a SFR Fuel Assembly under Initiating Phase of Severe Accidents

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1. Introduction

Metallic fuel has inherent safety characteristics for the mitigation of the accident consequences under design extension conditions (DECs). However, the advantages of the metallic fuel in the transient state have not been enough to solve licensing issues of metal-fueled sodium-cooled fast reactors (SFRs). Although the hypothetical core disruptive accidents (HCDAs) for SFRs with the metallic fuel rarely occur due to its inherent safety and design features, it is needed to clearly evaluate the possibility of an early termination of the transient accident induced by molten metallic fuel-sodium coolant interaction under an initiating phase of the HCDAs, as a part of risk assessment for SFRs. To predict how such accidents progress, the coupled thermal-hydraulic and neutronic phenomena should be identified [1], but in this study the molten fuel-sodium interaction in terms of only thermal-hydraulics was considered. If the molten metallic fuel is well fragmented by its interaction with the sodium, passive cooling could be expected with guaranteeing effective flow paths for the natural circulation flow. That is a reason why it is should be examined whether the fragmentation of molten metallic fuel occurs inside the subchannel or not.

Figure 1 shows a configuration of the molten metallic fuel behavior during an Ex-pin, where pressurized molten metallic fuel is ejected and dispersed into the sub-channel after the fuel pin failure. It is depicted taking into account an unprotected loss-of-flow (ULOF) accident scenario.

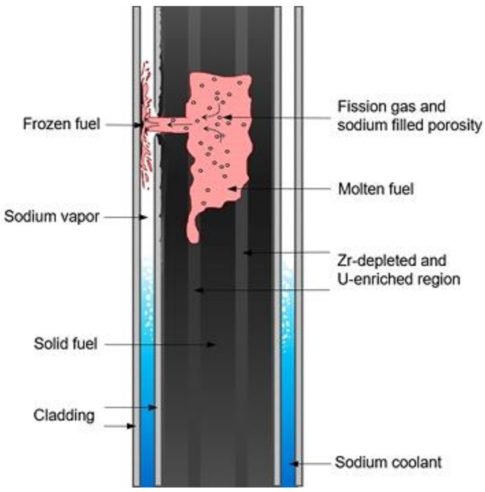


Fig. 1. Configuration of molten fuel behavior during Ex-pin

There were some safety experiments to study the transient fuel behavior during the molten fuel relocation phase. Gabor et al. [2,3] conducted several experiments where a molten uranium was poured into an open pool filled with the sodium. They revealed that highly porous debris bed was formed which means that the molten uranium was finely fragmented with filament-like fragments. On the other hand, there were other cases where characteristics of melt fragmentation were examined using simulants. Nishimura et al. [4] performed some experiments to investigate the molten fuel-sodium interaction with a copper, a silver, and an aluminum. Zhang et al. [5] also carried out simulant tests for the melt fragmentation using a stainless steel and the copper. All of them found that various fragmentation behaviors of molten metals were formed with test conditions. From previous studies, it was known that the fragmentation was mainly dominated by the hydrodynamic effect like the ambient Weber number as following:

$$We_a = \frac{\rho_s v^2 D_o}{\sigma_m} \tag{1}$$

where ρ_s is the density of sodium vapor, v and σ_m denote the velocity and surface tension for molten metallic fuel, respectively. D_o is the diameter of melt jet that is determined by the diameter of horizontal ejection nozzle. The fine fragmentation is dependent on the relatively high hydrodynamic condition. Since ambient Weber number shows force ratio of inertial force to stabilizing surface tension, it could represent a hydrodynamic deformation parameter.

Previous investigators performed these fragmentation tests within a limited range of the ambient Weber numbers. In addition, they did not consider structures of the fuel assembly because all of tests did not focus on initiating phase of severe accident. As a conservative approach, unanticipated transients leading to the fuel pin failure could occur even at the beginning of the cycle (BOC). In such a case, the molten metallic fuel may be erupted with the low ambient Weber number.

In the present study, computational fluid dynamics (CFD) simulations of the Ex-pin were carried out with a modelling of the prototype generation-IV sodium-cooled fast reactor (PGSFR) fuel assembly. The numerical simulations were performed to predict only hydrodynamic characteristics. Thus, all possible fragmentation behaviors were investigated within the low range of ambient Weber numbers, focusing on accident consequences at the BOC.

2. CFD modelling

To investigate the fragmentation behavior of molten metallic fuel, a numerical approach was used. The numerical simulation was conducted with commercial CFD code, Flow-3D that adopt numerical simplicity, and volume of fluid (VOF) method for free surface interface tracking. Thus, this simulation tool is an appropriate for qualitative analysis of the melt fragmentation during a liquid-gas interaction. There are mass and momentum conservation equations to solve complicated flow mixing in Flow-3D, as shown in equations (2)–(3).

$$v_f \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(uA_x) + \frac{\partial}{\partial y}(vA_y) + \frac{\partial}{\partial z}(wA_z) = \frac{S_o}{\rho} \qquad (2)$$

$$\begin{aligned} \frac{\partial u}{\partial t} + \frac{1}{v_f}\left(uA_x \frac{\partial u}{\partial x} + vA_y \frac{\partial u}{\partial y} + wA_z \frac{\partial u}{\partial z}\right) &= -\frac{1}{\rho}\frac{\partial P}{\partial x} + G_x + f_x \\ \frac{\partial v}{\partial t} + \frac{1}{v_f}\left(uA_x \frac{\partial v}{\partial x} + vA_y \frac{\partial v}{\partial y} + wA_z \frac{\partial v}{\partial z}\right) &= -\frac{1}{\rho}\frac{\partial P}{\partial y} + G_y + f_y \\ \frac{\partial w}{\partial t} + \frac{1}{v_f}\left(uA_x \frac{\partial w}{\partial x} + vA_y \frac{\partial w}{\partial y} + wA_z \frac{\partial w}{\partial z}\right) &= -\frac{1}{\rho}\frac{\partial P}{\partial z} + G_z + f_z \end{aligned} \qquad (3)$$

Figure 2 shows the 7-pin bundle where the design parameters of PGSFR fuel assembly were modeled such as a narrow gap between pins. Since this numerical simulation problem is symmetrical, only half of the fuel assembly was modeled. The rip size was considered to be a hole of diameter of 3.7 mm, assumed as the half of fuel pin diameter.

Molten metallic fuel (U-10wt%Zr) and sodium vapor were chosen as fluid domains. The physical properties of them are shown in Table I. As a test condition, ejection velocities of 9, 18, 36, 72, 144, 288 mm/s were simulated, where the low range of ambient Weber number was considered assuming the low burnup fuel condition. For a turbulence model, standard k-ε model was set. Inlet and outlet boundary condition were set as flow rate of 0 kg/s concerning ULOF accident and specific pressure condition of 0 Pa, respectively. There were approximately hexahedral cells of 1.3 M with the adequate quality.

3. Results and discussion

Figure 3 shows behaviors of molten metallic fuel inside the sodium vapor channel. Since sodium near hot spot is rapidly evaporated under the transients leading to the fuel pin failure, the sodium vapor was simulated as

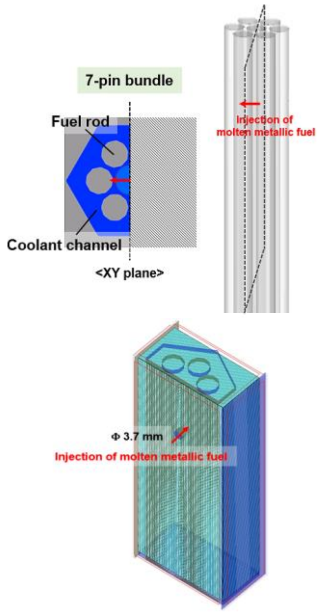


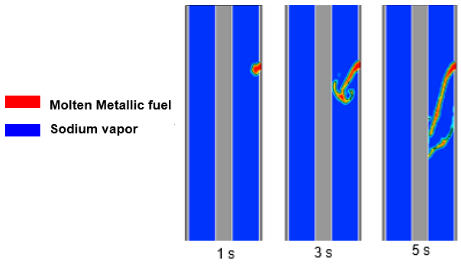
Fig. 2. Grid configuration of CFD model for 7-pin bundle

an ambient fluid. The molten metallic fuel was set to be ejected from right side because the central rod in the 7-pin bundle was assumed to be damaged.

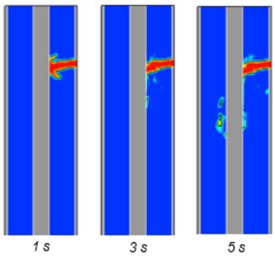
Melt deformation do not occur in all of cases, as shown in Figure 3. In a case of melt ejection velocity of 9 mm/s, the molten metallic fuel flows in the shape of jet. There is no any breakup and deformation at the melt jet except its leading edge. Although some melt seem to be dispersed at the leading edge due to the boundary layer stripping (BLS), its fragmentation intensity is insignificant. Even after colliding with other fuel rods, the melt is not broken and fragmented but rather flows down along other the rods. If the melt temperature drops below its solidus temperature through the interaction with surrounding sodium vapor, the melt would be frozen as it flows. The frozen melt would not have porous media leading to reduction of the core coolability. In other words, it is not expected to secure coolable geometry inside core if the molten metallic fuel is not fragmented by its interaction with sodium vapor. It means that the accident progress may be under

Table I: Physical properties of metallic fuel and sodium vapor

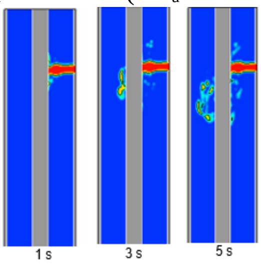
	Metallic fuel (U-10wt%Zr)	Sodium vapor
Density (kg/m^3)	14100	0.39
Surface tension (N/m)	0.57	0.20
Viscosity (mPa·s)	$5 \cdot 10^{-3}$	1.125
Melting/ Condensation point (°C)	1077 / -	- / 881



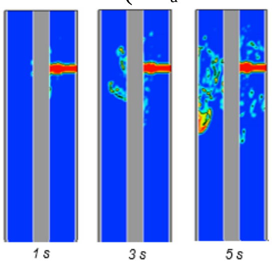
(a) V_{melt} = 9 mm/s ($We_a = 0.2 \cdot 10^{-7}$)



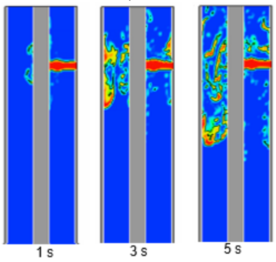
(b) V_{melt} = 18 mm/s ($We_a = 8.2 \cdot 10^{-7}$)



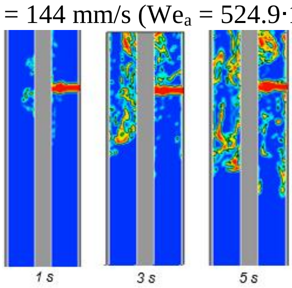
(c) V_{melt} = 36 mm/s ($We_a = 32.8 \cdot 10^{-7}$)



(d) V_{melt} = 72 mm/s ($We_a = 131.2 \cdot 10^{-7}$)



(e) V_{melt} = 144 mm/s ($We_a = 524.9 \cdot 10^{-7}$)



(f) V_{melt} = 288 mm/s ($We_a = 2100 \cdot 10^{-7}$)

Fig. 3. Behavior of molten metallic fuel in sodium vapor channel

uncontrollable state if the pin failure occurs at the beginning of the cycle (BOC).

As the ejection velocity of molten metallic fuel increases, the amount of fragmented melt also increases like cases of melt ejection velocities of 18, 36 mm/s. The impulse caused by collision with other rods contributes to these melt deformations.

From high velocity range exceeding 72 mm/s, the melt is actively broken and fragmented. The particulates formed by mechanical collision are randomly dispersed, which enlarges effective heat transfer area. Also, if the melt freezing is considered in this simulation, a debris bed having a high porosity would be formed.

4. Conclusions

All possible fragmentation behaviors were investigated using CFD simulations of Ex-pin with a modelling of the PGSFR fuel assembly. There is a safety limit in which a fragmentation of molten metallic fuel rarely occurs, which is indicated using ambient Weber number. Based on this safety limit, the core coolability may not be secured when the molten metallic fuel is not finely fragmented and frozen as it flows. It is reasonable when transient occurs at BOC. Thus, appropriate mitigation strategy to recover cooling capacity should be prepared. As a future work, additional experimental database would be established for its validation.

ACKNOWLEDGEMENTS

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