Simple Numerical Study of Molten Metal Fuel Behavior Inside Channel using Explicit Finite Difference Method

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1. Introduction

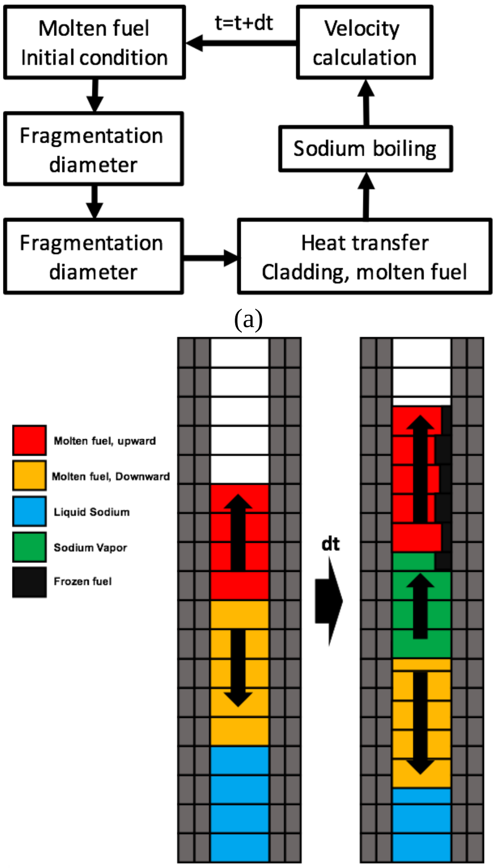
To prove the safety of SFR (Sodium Fast Reactor), high risk accidents with low probability are analyzed using different simulation codes. Unprotected accident is considered as the BDBA (Beyond Design Basis Accident) of SFR. UTOP (Unprotected Transient of Power), ULOF (Unprotected Loss of Flow) and ULOHS (Unprotected Loss of Heat Sink) are three main accidents. "Unprotected" means the SCRAM (Safety Control Rod Axe Man; emergency shutdown control rod insertion) is not activated. Many simulation results showed that the temperature of fuel increased up to its melting points and ejection of molten fuel into its coolant channel has happened. E. E. Morris [1] investigated the uncertainty in ULOHS, ULOF and UTOP. E. E. Feldman et al. [2] studied the EBR-II ULOHS accident. The result shows that the molten fuel ejection into sodium coolant channel is common in those unprotected accidents.

This ejection phase of severe accident of SFR is important because this is the branch whether the accident is terminated or goes to another level of accident. The criteria of this branch are criticality. But it is known that metal fuel with sodium coolant is good to make negative reactivity when ejection occurred. This is inherent safety characteristic of metal fuel in the SFR.

The inherent safety of metal fuel inside SFR is proposed but the real phenomena inside core is not verified. Reaction between molten metal fuel and sodium coolant is way different from that of oxide fuel and water coolant in LWR (Light Water Reactor). One reason of this difference is FCI (Fuel-Coolant Interaction). Molten metal droplet fall into sodium pool experiments are now being conducted. Satoshi Nishimura and Izumi Kinoshita [3] shows the phenomena of molten metal droplet with low velocity inside sodium pool. J. Namiech et al. [4] studied the high velocity of molten metal into the sodium. The main issue is the recriticality after molten fuel ejection. In this study, to simulate the behavior of molten fuel inside channel for different conditions, the amount of discharge to upper plenum and the distribution of frozen fuel inside channel is analyzed to apply this results to determine the recriticality.

2. Modeling of simple channel hydraulics using fragmentation of molten fuel

In this study, simple simulation of molten fuel relocation in 1D is explicitly modelled with finite difference element method. Governing equation of mass continuity is discretized with reference area. This reference area is determined to change the velocity at the boundary of each cell and to keep molten fuel move together. The algorithm of relocation calculation and simple configuration of this simulation are indicated in Fig. 1.



(a)

(b)

Fig. 1. Algorithm of relocation calculation (a) and simple configuration of this simulation (b)

In this simulation, every solution of each time dependent properties are explicitly derived. Because the channel is narrow enough, the initial axial cell is filled with molten fuel. Also it is assumed that the channel is voided because of transient power of nuclear fuel pin. [5] Initial mass is devied in two part. One is moving upper side and the other is movien downward. This kind of movement is observed in the molten metal ejection experiment. [6] Because after the ejection, after colliding the wall, the velocity of molten fuel is decreased down to half of its initial velocity. So, initial velocity of each part has half of initial velocity of ejection. To assume the molten fuel moving together, velocity for each boundary is differently assumed with generalized area. This generalized area is affected by the amount of frozen molten fuel in each cell.

Fragmentation is calculated with its teperature and initial velocity. Satoshi Nishimura et al. [7,8] used molten metal with sodium pool. Molten metalic jet droped into pool and fragmented molten fuel size and shape is discussed. They found that the fragmentation is determined with the velocity and temperature. With low velocity, fragmenation is dominant by its temperature. And for high velocity [4], J. Namiech et al found that the fragmentation is dominant with surface instability form high velocity. In this study, Weber number is criteria for determining the size of fragmentaion.

$$D_m = 3.8 \times 10^5 exp\left(-9.0 \times 10^{-3} T_{sup}\right) H_f^{-2.0} \quad (mm) \quad (5 < We < 88)$$
$$D_m = \frac{D_{m,th} + D_{m,hyd}}{2} \quad (88 < We < 200) \qquad (1)$$
$$\frac{D_m}{d_0} = 1.6 We_a^{-0.44} \qquad (200 < We < 1534)$$

After determining the fragmnet diameter, the surface area is calcuated because this surface area will be used for boiling sodium. The fragmentation shape is sheetlike, netlike, and twiglike in the low weber number experiment. But in high weber number, rough surface is observed which resulted from agglomeration of tiny particles. So it is assumed that those particle is sphere shape, and for higher weber number, surface is covered with small sphere.

To build model simply, sodium, vapor sodium, liquid metal fuel, and frozen metal fuel is considered. Also, frozen fuel is assumed have zero velocity which means that frozen molten fuel on the wall is attatched on the wall. To calcuate the velocity of moving molten fuel, 3 drag forces are considered; wall frcition, vapor drag, and fission gas. Fission gas is used for the initial velocity of molten fuel. Wall fricion and sodium vapor drag force are considerd as below. All phenomena is derived from annular molten fuel flow regeime.

$$f_{wallfriction} = 0.316 \times Re_{mf}^{-0.25}$$
$$f_{vapdrag} = 0.316 \times Re_{vap,liq}^{-0.25} \frac{\rho'_{vap}}{2D_h} \qquad (2)$$
$$Re_{Vap,liq} = D_h \times \left|u_{vap} - u_{mf}\right| \times \frac{\rho_{vap}}{\mu_{vap}}$$

3. Simulation condition

The simulation is done with 3 cases. Each will be the part of fragmentation diameter domain determined by its velocity (Weber number). And other conditions are from UTOP accident scenario. The velocity of each cases means the burnup of nuclear fuel. In the metal fuel, fission gas is accumulated by its amount of burnup increase. Accumulated fission gas will make pressure inside cavity and this pressure determines ejection velocity. Initial condition and 3 cases are represented in table I.

Table I. The simulation initial condition, geometry, and 3 velocity cases

Ejection position	11.7 cm below the top (for 1 m active core, UTOP scenario)
Injection mass	71 g (UTOP scenario molten fuel mass per pin)
Channel cross section area	5.37x10^{-5} m^2
Quenching heat transfer coefficient [10]	6000 W/K/m^2
Temperature of structure	895.15 K
Molten fuel temperature	1400 K
Pin configuration	1 pin
Molten fuel velocity	1.0 m/s 2.0 m/s, 5.0 m/s

4. Results and Discussion

The amount of ejected molten fuel mass is 71 g. So, 35.5 g is moving upward and the other 35.5 g is moving downward with initial velocity. The boiling is assumed to be quenching on the surface of molten fuel. At the starting the calculation, it is assumed all of the molten fuel towards downward is submerged in sodium pool. Because the amount of molten fuel going downward is so little, the velocity of vaporized sodium is almost neglectable. For all cases, the sodium vapor velocity was 0.15 mm/s upward. Vapor flow couldn’t drive the molten fuel discharge. Just wall friction and gravity affects the velocity of the molten fuel.

Table II. Shows the amount of molten fuel discharge to upper plenum. For case 1, initial velocity is 1.5 m/s, shows just 0.939 g discharge to upper plenum. This amount is about 1.3 % of total fuel ejection. And for case 2, initial velocity is 2.0 m/s, shows about 23.61 g discharge. This is about 33.25 % is discharged upward. This is significant amount compared to case 1. 5.0 m/s case shows 33.21 g, and this is 46.77 %. This data is plotted in the fig 2. This amount of molten fuel (discharged into upper plenum) does not contribute the reactivity in the active core because they are out of the active core. So, more amount of discharged molten fuel to upper, better for inherent safety of metal fuel.

Table II. The amount of molten fuel discharge to upper plenum

Cases	Amount of discharge to upper plenum
1.5 m/s	0.939 g
2.0 m/s	23.61 g
5.0 m/s	33.21 g

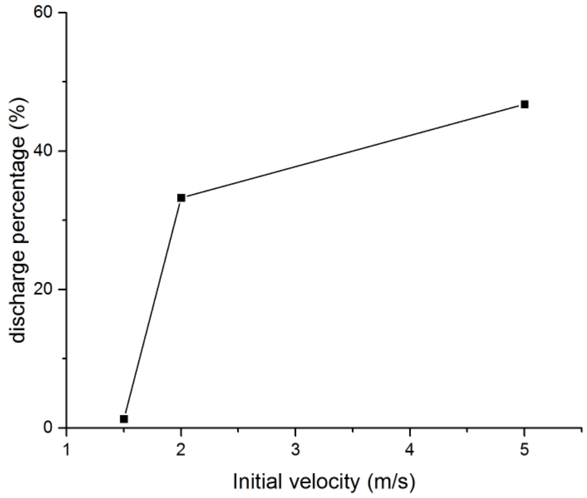


Fig 2. Discharge percentage for different initial velocity

The result shows that the discharge amount is affected by the initial velocity because the vapor drag force is not effective due to small amount of molten fuel amount into sodium channel. This means that the fission gas is more effective than sodium vapor drag force for the discharge. As velocity increase from 1.5 m/s to 5.0 m/s, the amount of discharged molten fuel is maximum at just 5.0 m/s which is not big enough for high burnup. This is because the drag force is not fully considered. In the real situation, other drag force from different component is considered.

Fig 3. shows the distribution of frozen molten fuel. For the low velocity, because the time for heat transfer is sufficient, the amount of frozen fuel is higher than other cases. This result of relocation of molten fuel can be used for point kinetics multiplied by reactivity worth to decide one accident is safe or not. Equation below is the total point kinetics considered in the sodium fast reactor. Not only relocated fuel feedback, Doppler feedback, cladding and fuel expansion feedback, coolant density feedback, core expansion feedback and cladding relocation feedback is considered.

$$\delta k = \delta k_{Doppler} + \delta k_{F,CLD\ expansion} + \delta k_{coolant\ voiding} + \delta k_{core\ expansion} + \delta k_{CR\ expansion} + \delta k_{fuel\ relocation} \quad (3)$$

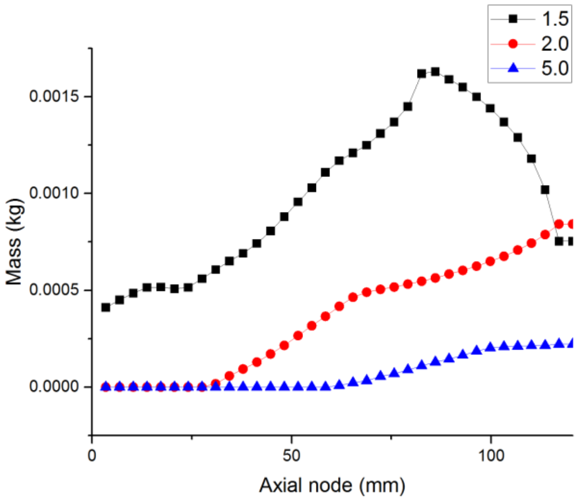


Fig. 3. The amount of frozen molten fuel for axial node

Fig. 4. shows the molten fuel velocity for each time. Because of dominant wall friction between molten fuel and wall, velocity starts to decrease immediately. For 2.0m/s case, the molten fuel goes to upper plenum just 0.05 sec. But it shows that the deceleration is bigger than the other two cases because of wall friction which is proportional to the velocity difference square. So the molten fuel is almost not frozen and discharged to upward

Fig. 5. shows the comparison between wall friction drag force and vapor drag force for 1.5 m/s velocity case. Wall friction drag acceleration is almost -15 m/s^2 at the starting of simulation. But drag force of vaporized sodium is almost neglectable. This is because the relatively small amount of ejected fuel as mentioned above. If larger amount of molten fuel is discharged, vapor drag can affect molten fuel to bring it up to top of fuel pin.

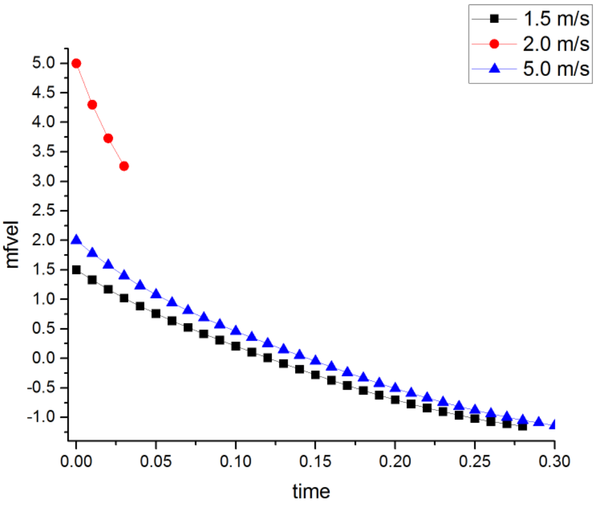


Fig. 4. The velocity of molten fuel

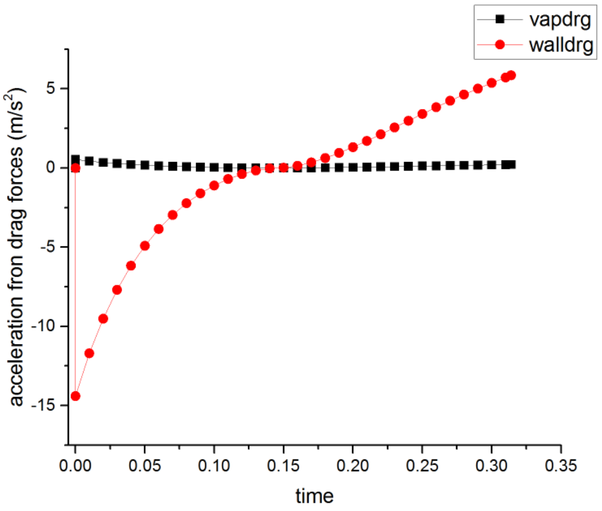


Fig. 5. the comparison between wall friction drag force and vapor drag force

5. Conclusion and further work

To estimate the amount of molten fuel and amount of discharged fuel out of active core, numerical study is done with simple 1D explicit finite difference method. The condition is referred from SAS4A UTOP accident with single pin geometry. But ejection velocity is estimated lower than it has to be which is low burnup ejection from small amount of fission gas. 1.5, 2.0, 5.0 m/s initial velocity is considered. the amount of frozen molten fuel for axial node shows that more fuel is frozen in the upper part of channel. Because of the small amount of ejection mass, the vapor drag force is not effective to make molten fuel move upwards. If it is sufficient, more amount of molten fuel will be discharged into upper plenums

Because this model is estimated roughly, many models should be added to make more accurate conclusion; different drag coefficients for different flow regime like bubbly flow regime, accurate fragmentation empirical correlation, accurate measurement of surface area of fragmentation, and so on. And finally, the point kinetics will be implemented to determine the accident termination.

ACKNOWLEDGEMENTS

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