Model development of relocation of molten metal fuel in SFR; Comparison between MESFRAC and SAS4A

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1. Introduction

After Chernobyl accident and Fukushima accident, interest about severe accident which leads to leakage of radioactive material due to core disruption is increasing with safety problem of nuclear power plant. Especially, after Fukushima accident, importance of accident analysis gets bigger and criteria for the safety issues are increasing. Not only light water reactor, GEN IV reactors are also influenced about the safety issues. Among the general GEN IV reactors, SFR (Sodium-cooled Fast Reactor) in Korea choose to use metal fuel because of its inherent safety for severe accidents. There has been a lot of results [1, 2] about safety analysis of SFR using metallic fuel core.

There are two representative severe accidents, and, they are seriously studied about CDAs (Core Disruptive Accidents). One is UTOP (Unprotected Transient Over Power) and the other is ULOF (Unprotected Loss Of Power). If power of core is increased or coolant flow in the coolant channel stops, the temperature starts to increase up to its melting temperature. Because fission gas makes pressure inside cladding higher, at some point, molten metallic fuel can eject into coolant channel which is the phenomenon of CDA. This phenomenon of ejection of molten fuel into channel has important role in the severe accident. Ejected molten fuel inside coolant channel can move to axial direction in a hydrodynamic manner and their position can make re-criticality of core. If reactivity exceeded over 1, core power excursion can make further core temperature increase. This can induce the extension of molten fuel which means the molten fuel pool. There is probability of in-vessel retention.

The final goal of this study is developing the code model which can predict the relocation of molten fuel inside SFR coolant channel and calculate the criticality to ensure the success of accident termination. In this paper, molten fuel behavior inside coolant channel is calculated and compared to SAS4A accident code to recognize the weakness of the code. This molten fuel analysis code (MESFRAC; MEtal fuel SFR Accident analysis Code) has simple form rather than other code. Heat transfer in cladding and structure, solidification of molten fuel, fuel behavior modeling have been done.

2. Modeling of MESFRAC; molten fuel hydrodynamics in coolant channel

Table I: Main assumptions in the MSFRAC code

Main assumptions
1. Only molten fuel can move inside channel and solidified fuel is fixed in channel and make flow area narrower
2. Molten fuel ejection is not modelled. As initial condition, certain cells are fully filled with molten fuel with initial axial velocity
3. Wall friction, gas friction affects the velocity of molten fuel

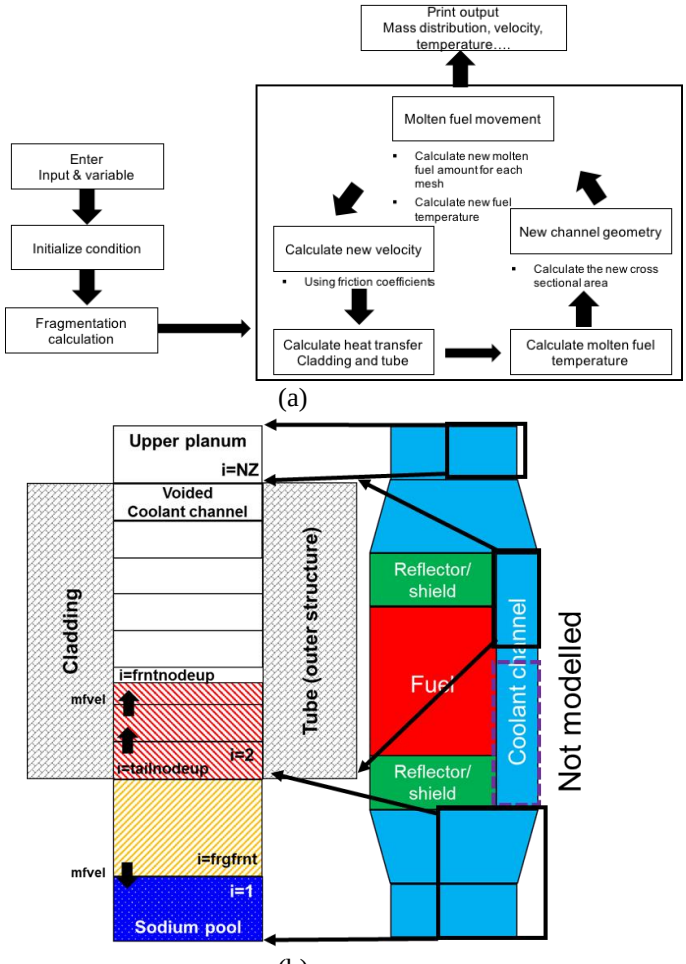


Fig. 1. (a) Flow chart of MESFRAC (MEtal fuel SFR Accident analysis Code) and calculation boundary

In this section, main MESFRAC modeling is explained. MESFRAC is one dimensional accident code based on FORTRAN. It can calculate the cladding temperature, structure temperature, molten fuel temperature and its solidification. Table I shows the main assumptions used in MESFRAC. Figure 1 shows whole flowchart and its analysis boundary.

2.1 Main conservation equation modeling

As explained last section, MESFRAC uses one dimensional geometry in the calculating channel hydraulics. MESFRAC deals with the boundary from the position of fuel disruption point to upper plenum. And It assumes that the geometry of channel from rupture point to upper plenum point is not different. And also, it is assumed that the lower position of fuel disruption has sodium pool to make quenching and fragmentation of molten fuel [3, 4]. The molten fuel moving downward meets sodium pool and the high temperature from molten fuel can boil the sodium. The fragmentation of molten fuel can determine the area between boiling heat transfer. Sodium vapor from this boiling can make driving force of molten fuel movement to upper plenum. Molten fuel velocity can be calculated by the integral of acceleration with time in equation (1). Wall friction, gravity and gas drag force induced by relative velocity between molten fuel and sodium vapor gas.

Based on the result of velocity of molten fuel, the position of molten fuel is calculated. Only molten fuel and solidified fuel is considered inside coolant channel. If there is no solidified fuel, volume fraction of molten fuel inside shell remain as 1. And if there are solidified molten fuel inside coolant channel, the sum of molten fuel and solidified fuel remains 1. The solidified molten fuel is fixed in the position where it is frozen.

Through heat transfer calculation, cladding temperature, molten fuel temperature, and structure temperature are calculated. In the case of heat transfer, 2 dimensional calculation is modelled. Heat is transferred in a radial direction and axial direction inside cladding and structure. Fuel inside cladding is not considered. The solidification of molten fuel inside channel is calculated from the amount of ejected heat of molten fuel in the certain time step.

$$v_{mf} = v' - g\Delta t - \frac{wallfric}{2D} v'|v'| + dragcoef(v' - v_{vap})|v' - v_{vap}| \quad (1)$$

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right) + \frac{\partial}{\partial Z}\left(k\frac{\partial T}{\partial Z}\right) + g \quad (2)$$

3. UTOP+ULOF accident simulation results and comparison with MESFRAC

3.1 UTOP+ULOF accident description and initial condition of molten fuel ejection

To compare the molten fuel behavior inside channel, SAS4A [5] accident code is used. The UTOP with ULOF accident is chosen because flow inside coolant channel is almost zero. In the case of MESFRAC, it cannot simulate the flow of sodium inside channel. The accident input is about 3500 MWth pool type with 25 channel plant input deck. Core uses the U-Pu-Zr fuel and they used the metal fuel property. But, because SAS4A accident code can simulate just oxide fuel, the results are not representative for metal fuel accident. SAS4A averaged one channel into single pin. In the Table II, this shows the geometry of averaged pin in the SAS4A accident input deck. This geometry is also applied to the MESFRAC

In the case of UTOP, the externally programmed reactivity is added in 0.1 $/s and in the case of ULOF, whole pumps (3 pumps) are stopped with flow half time of 0.3 seconds. Because every channels loses its coolant flow, many channels show the molten fuel ejection. This dramatic change of core geometry, the negative reactivity is secured and accident terminated in 0.325 seconds after fuel ejection. The result of first coolant channel which shows fastest ejection is used in the comparison with MESFRAC.

Table II: Problem Description

Parameter	Value
Number of pin per subassembly	271
Number of subassemblies in channel (channel 1)	6
Coolant flow area [m^2]	2.999e-05
Hydraulic diameter [m]	3.23e-03
Cladding outer radius [m]	3.6195e-03
Axial length [m]	1.0668

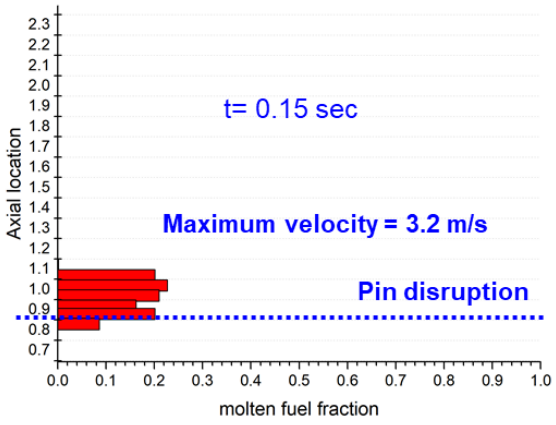
3.2 Results of relocation of molten fuel and comparison between MESFRAC and SAS4A

Figure 2 shows the SAS4A results of volume fraction for axial direction in each time step. Each time step means the time taken from the molten fuel ejection. In SAS4A, the calculation boundary starts from the bottom

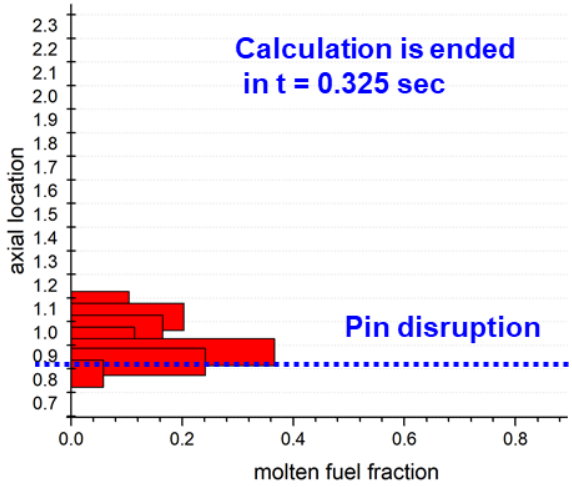
of lower plenum, the 0.92 m marks the pin disruption. But in the case of MESFRAC, it doesn't calculate the position of molten fuel below fuel disruption point. So the disruption position indicated in the origin.

SAS4A results shows the small value of volume fraction because when molten fuel ejects to the coolant channel, there is already sodium inside coolant channel. 0.28 is maximum value of molten fuel volume fraction. After disruption, SAS4A models the process of ejection, the total amount of molten fuel inside channel keeps increasing. After ejection, it takes 0.325 seconds to terminate the accident which means sufficient negative reactivity from fuel relocation. In spite of the stop of pump and coolant flow, the position of molten fuel is moved slightly upward. This came from the pressure gradient because of boiling of sodium inside channel. Short simulation time makes no solidification inside channel. Total 21.285 kg is ejected to coolant channel and 0.0217 kg is solidified to the structure inside 1 channel with 6 subassemblies with 271 pins.

The initial condition of MESFRAC is after whole fuel whose amount is going to eject in SAS4A. So the increase of mass total volume fraction is not shown. And also, totally voided channel is assumed, the volume fraction of molten fuel increases up to 1. In this case, the movement of molten fuel is from the momentum of axial velocity. The boiling drag couldn't expel the molten fuel up to upper plenum. Because the velocity of molten fuel is also too slow, wall friction effect doesn't affect the movement of molten fuel. The modeling of ejection of molten fuel and sodium inside channel should be modelled.

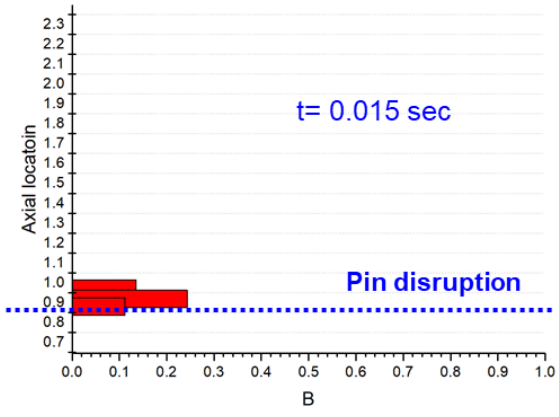


(b)



(c)

Fig. 2. Results of SAS4A ex-pin molten fuel volume fraction in the axial channel for each time steps



(a)

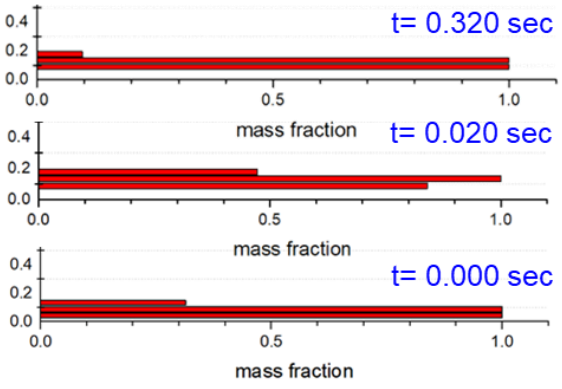


Fig. 3. Results of MESFRAC ex-pin molten fuel volume fraction in the axial channel for each time steps

4. Conclusions and further work

In the case of SFR severe accident, to calculate the reactivity of disrupted core, the relocation of molten fuel inside coolant channel is modelling with FORTRAN base. This simple code calculates the in-channel hydrodynamics with 1 dimensional and calculates heat transfer with 2 dimensional way. Up to now, only 3 component is modelled in the channel; liquid molten metal fuel, solidified molten metal, sodium vapor. And channel is assumed totally voided. This condition is different to SAS4A simulation. SAS4A calculates initially from ejection of molten fuel inside channel filled with liquid or partially voided sodium. To minimize the effect of coolant flow, UTOP+ULOF accident is chosen and compared to each other. Results shows the weakness of MESFRAC and 3 biggest modelling should be done. The list is below.

1. The simulation boundary should start from bottom of lower plenum to upper plenum.
2. Liquid sodium inside channel should be modelled. In the case of LOF accident, fully voided channel is hard to form.
3. Ejection from pressure gradient from inside pin to channel should be modelled.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear R&D program (NRF-2013M2B2B1075734, NRF- 2016M2A8A6900481, NRF-22A20153413555) through the National Research Foundation of Korea (NRF) funded by the Korea government (MSIT).

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