Design of FCI Experiments to Understand Fuel Out-Pin Phenomena in the SFR

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1. Introduction

There is a possibility for molten fuel to be dispersed toward the outside of the core when the molten fuel erupts to coolant channel under severe accidents of the sodium-cooled fast reactor (SFR), resulting in automatic and passive termination of accidents in terms of recriticality. However, if the molten fuel is not dispersed and lumped together in the SFR accident scenarios such as unprotected transient over-power (UTOP) and unprotected loss of flow (ULOF), it has a capability to cause power excursion. Therefore, it is important to guarantee a passive nuclear safety regarding enhanced negative reactivity by fragmenting the molten fuel. In the SFR, it has a strong point that the negative reactivity is immediately introduced when the metal fuel is melted by the UTOP or ULOP accident. These characteristics of the metal fuel can prevent from progressing in severe accidents such as core disruptive accidents (CDA).

As key phenomena in the accidents, fuel-coolant interaction (FCI) phenomena have been studied over the last few decades. Especially, several previous researches focused on instability and fragmentation of a core melt jet in water. However, the studies showed too limited phenomena to fully understand. In the domestic SFR technology development, researches for severe accidents tend to lag behind ones of other countries. Or, South Korea has a very basic level of the research such as literature survey. Recently, the SAS4A code, which was developed at Argonne National Laboratory (ANL) for thermal-hydraulic and neutronic analyses of power and flow transients in liquid-metal-cooled nuclear reactors (LMRs), is still under development to consider for a metal fuel. The other countries carried out basic experiments for molten fuel and coolant interactions. However, in a high temperature condition, methods for analysis of structural interaction between molten fuel and fuel cladding are very limited.

The ultimate objective of the study is to evaluate the possibility of recriticality accident induced by fuel-coolant interaction in the SFR adopting metal fuel. It is a key point to analyze the molten-fuel behavior based on the experimental results which show fuel-coolant interaction with the simulant materials. It is necessary to establish the test facility, to build database, and to develop physical models to understand the FCI phenomena in the SFR; (1) molten fuel-coolant interaction as soon as the molten fuel is ejected to the sodium coolant channel and (2) molten fuel-coolant interaction between the remaining sodium pool and the molten fuel dropped into the bottom plenum. The current study can be divided into two phases in progress. The first phase is to select the simulant material for simulating the FCI phenomena. In the phase, an application of the observed FCI phenomena to determine the design parameters to establish an integrated FCI facility for a SFR fuel assembly design is involved. Next, the second phase is to design the integrated FCI facility which simulates the sodium coolant channel and analyze behaviors of the molten fuel in accordance with controlling parameters which might be initial temperature, injection or an up-stream velocity and the pressure for the molten fuel and the sodium coolant. From the current research, it is expected to acquire fundamental knowledge on the SFR severe accident phenomena, and provide pre-requisite information and practical experiences to the real material experiments as necessary.

This paper deals with selection of the simulant materials and design of fundamental experiments for investigating FCI phenomena.

2. Methods

The behaviors for the molten fuel are separated into in-pin motion, FCI and out-pin motion. In this part some knowledge to understand the behaviors is presented. However, in the study, only out-pin motion and FCI phenomena are focused on because they have more uncertainty than in-pin motion from a phenomenological perspective.

2.1 Fuel-coolant interaction

The molten fuel-coolant interactions can occur only under hypothetical conditions where an instability between two fluids is postulated[1]. The nature of FCI can range from benign film boiling to energetic interactions[2]. Kondo et al.[1] carried out a series of molten Wood's metal jet-water interaction experiments and showed that there were several modes of

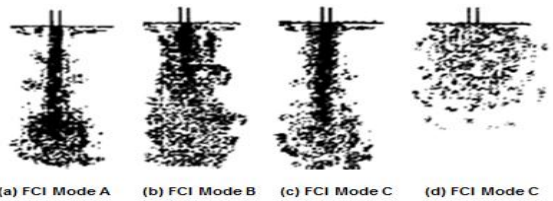


Fig. 1. Four modes in FCIs[1]

interaction behaviors observed according to various initial temperature conditions of the two fluids. It was also proven that the voiding of the coolant pool was the major factor which determines characteristics of jet breakup[2] and the quench behavior of the molten jet was enhanced due to the increase of the jet velocity, since the fragment diameter becomes small[3].

2.2 Out-pin motion

The out-pin motion means relocation phenomena of the molten fuel which is injected into the voided coolant channels after fuel-pin failures. The SAS4A code can simulate the molten-fuel behaviors in out-pin motion through the LEVITATE module. The LEVITATE module deals with the post-failure fuel motion in the voided regions of the coolant pool under the UTOP condition leading to fuel melting, fuel-pin breakup and fuel motion to occur almost at the same time[4]. The ULOF accident usually causes the module in the SFR. The ULOF accident proceeding, an internal cavity is formed after the inside of the fuel pin begins to melt. This cavity is filled with a mixture of fission gas and molten fuel. Over time the cavity expands continuously due to fuel melting. The presence of fission gas and fuel vapor lets the fuel-gas mixture in the cavity pressurized. The increased pressurization continuously of the cavity causes fuel-pin failure because the cladding temperature approaches the melting point as the cavity walls continue to melt. Therefore, based on the mechanism of fuel-pin failure, the LEVITATE is initiated[4].

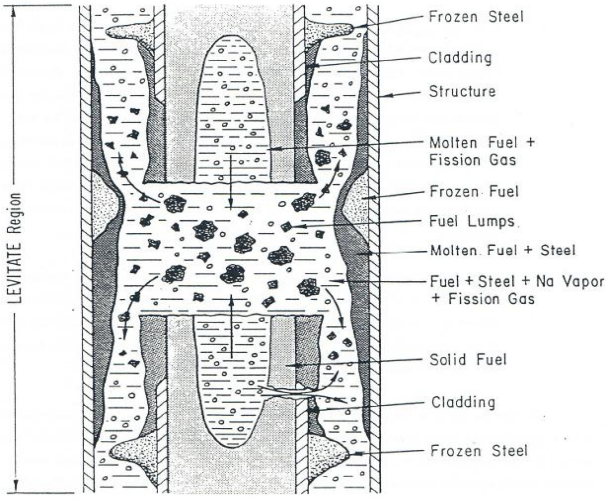


Fig. 2. The analytic model of the LEVITATE module[4]

3. Experimental Setup

Before setting experimental facilities for FCI experiment, similarity laws should be considered for a scientific design. They are separated into three parts; geometrical similarity, thermodynamic similarity and hydraulic similarity. This is especially true for the analysis of simulation experiments using a scaled model.

3.1 Selection of the simulant materials

It is important to consider amount of breakup of the molten fuel according to the objective of the study. There are main parameters for selecting simulant materials following breakup theory; Satio's correlation and Epstein's correlation[3].

$$\frac{L_{brk}}{D_j} = 2.1(\frac{\rho_j}{\rho_c})^{0.5} Fr^{0.5} \quad (1)$$

$$\frac{L_{brk}}{D_j} = \frac{1}{2E_0}(\frac{\rho_j}{\rho_c})^{0.5} \quad (2)$$

where L_{brk} is breakup length, Fr is Froude number, D_j is the jet diameter, E_0 is so-called entrainment coefficient with the value of the order 0.05-0.1, ρ_j is the jet density and ρ_c is the coolant density. As following the two correlations, the ratio of the jet fluid and the coolant fluid densities ($\frac{\rho_j}{\rho_c}$) is important parameter. Weber number is considered to analyze parameters as well as the two correlations.

$$We_c = \rho_c U_j^{\,2} D_j / \sigma_c \quad (3)$$

where U_j is jet velocity and σ_c is surface tension of the coolant.

Therefore, main parameters can be determined from $\frac{\rho_j}{\rho_c}$ and We_c ; ρ_j , ρ_c , σ_c , U_j and D_j . Reflecting some of the main parameters and other thermal properties, the simulant materials for the study are selected.

Table I: Thermal properties regarding metal-fuel simulant

	Material	Melting Point (℃)	Liquid Density (kg/m^3)	Heat Capacity of liquid (kJ/kg/℃)	Thermal Conductivity (W/m/℃)
Molten Material	Fuel	1160	15800	0.200	22
	Wood's metal	79	8560	0.190	13
	Field's metal	62	6740	0.184	10
	Molten salt	142	1680	0.156	0.520

Table II : Thermal properties regarding sodium simulant

	Material	Boiling Point (℃)	Liquid Density (kg/m^3)	Heat Capacity of liquid (kJ/kg/℃)	Thermal Conductivity (W/m/℃)	Viscosity (mPa·s)	Surface Tension (N/m)
Coolant	Sodium	881	966	1.23	142	1.125	0.200
	Water	100	998	4.20	0.591	1.002	0.073
	DOW THERM -Q	267	965	1.65	0.122	4.965	0.035
	Acetone	57	75	2.21	0.161	0.324	0.024
	Glycerol	290	1261	2.40	0.285	1495	0.063
	Paraffin oil	200	800	2.13	0.150	1000	0.026

It is required that the simulant materials satisfy the two similarity laws; the thermodynamic similarity and the hydraulic similarity. The thermodynamic similarity in the study is defined according to the following relationships.

$$\left(\frac{\Delta h_j}{h_{j,melting}}\right)_{Prototype} = \left(\frac{\Delta h_j}{h_{j,melting}}\right)_{Test} \quad (4)$$

where $h_{j,melting}$ is melting enthalpy of the jet material and Δh_j is enthalpy between melting state and solidification point.

$$\left(\frac{\Delta h_c}{h_{c,vaporization}}\right)_{Prototype} = \left(\frac{\Delta h_c}{h_{c,vaporization}}\right)_{Test} \quad (5)$$

where $h_{c,vaporization}$ is vaporization enthalpy of the coolant material and Δh_c is enthalpy between the inlet condition and vaporization point of the coolant. Unfortunately, before analyzing the SAS4A code, the similarity cannot be evaluated previously because temperature conditions at transient state are only given from the SAS4A code.

On the other hand, the hydraulic similarity in the study can be evaluated. The similarity is given by

$$\left(\frac{\rho_j}{\rho_c}\right)_{Prototype} = \left(\frac{\rho_j}{\rho_c}\right)_{Test} \quad (6)$$

$$\left(\frac{15800\,kg/m^3}{966\,kg/m^3}\right)_{Prototype} \neq \left(\frac{8560\,kg/m^3}{998\,kg/m^3}\right)_{Test} \quad (7)$$

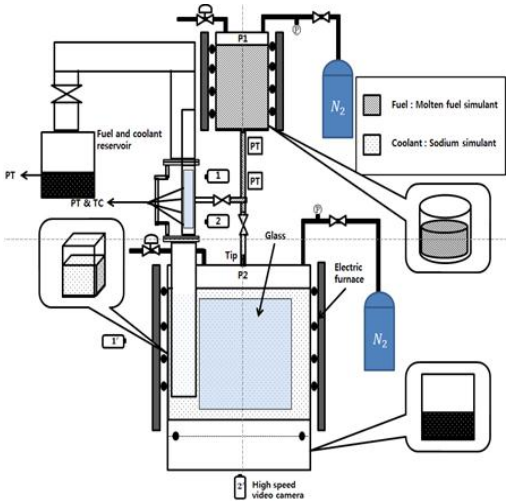
where $\rho_{j,prototype}$ and $\rho_{c,prototype}$ are the densities of the metallic fuel and the sodium for prototypes while $\rho_{j,test}$ and $\rho_{c,test}$ are the densities of wood's metal and water, respectively for simulants. As above relationship, the similarity is not compatible so that it is needed to compensate the difference of the density ratio by using Eq. (2). From Eq. (2), the density ratio can be defined as a function of the jet diameter.

$$\frac{\rho_j}{\rho_c} = \left(2E_0\frac{L_{brk}}{D_j}\right)^2 \quad (8)$$

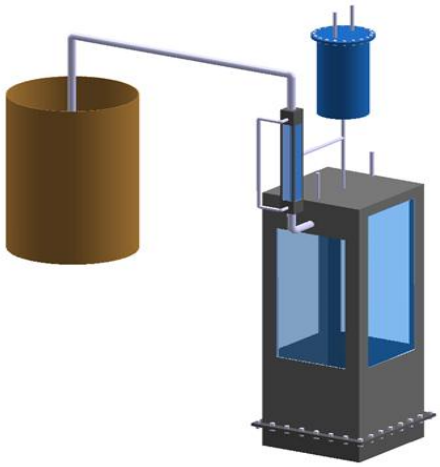
So, the difference of the density ratio can be compensated by changing the jet diameter.

3.2 Fundamental design for the experimental facility

The schematic design of the experimental facilities is shown in Fig. 3. There are two storage tanks; the above tank is filled with the molten fuel simulant. The other is



(a)



(b)

Fig. 3. Schematic design of experimental facilities (a) in 2-D and (b) in 3-D

the coolant storage tank. It is used to observe breakup behavior of the molten fuel jet in the coolant. There is another tank to simulate single sub-channel in the SFR. As shown in Fig. 4, it is shown that the sub-channel tank is made in two ways for the geometrical similarity and visualization. It is also designed to convert the facility to be possible to use sodium instead of water. Nitrogen pressurizers are used to inject the molten jet at a reasonable velocity. It is available to eject the fuel jet at a specified velocity both horizontally and vertically. Electric furnaces are used to control the simulant materials temperature. High speed cameras are used to visualize the experiment procedures.

The experimental facilities should satisfy the geometrical similarity to obtain meaningful results. In the study, there is a geometrical similarity only considering the single sub-channel as a prototype. Unlike other similarities, the similarity will be valid because the single sub-channel tank for test facility will be designed to have same dimension geometrically with the prototype.

$$\left(\frac{L}{D}\right)_{Prototype} = \left(\frac{L}{D}\right)_{Test} \quad (9)$$

$$\left(\frac{1000\,mm}{2.396\,mm}\right)_{Prototype} = \left(\frac{1000\,mm}{2.396\,mm}\right)_{Test} \quad (10)$$

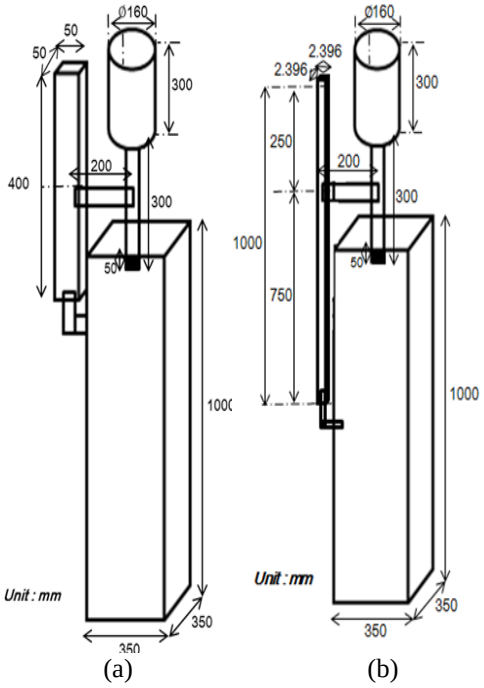


Fig. 4. Simple experimental schematic involving dimensions of main facilities (a) for visualization and (b) geometrical similarity

4. Summary and future work

Regarding the severe accidents in the SFR, it is necessary to prevent recriticality of the molten fuel which ejects to the sodium coolant channel. At the initial phase of the SFR severe accidents, it is asserted that molten metal fuel will be dispersed or flow down without plugging the channel when it comes into the coolant channel. The study will be contributed to building the thermal-hydraulic modeling through experimental results by using the simulant materials to understand the fundamental physics of the FCI phenomena in the SFR.

In the present work, the selection of the simulant materials and the design of fundamental experiments for investigating FCI phenomena were conducted. However, the schematics are not fixed yet. The position of each facility should be determined prudently because of setting visual measurements such as high speed camera or particle image velocimetry (PIV). Further, it is required to determine the test conditions or major parameters such as temperatures of the two fluids, boiling injection velocities, flow velocities, nozzle sizes and nozzle shapes. The test matrix is under preparation for FCI tests to show the possibility of early termination of severe accidents.

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