The reviews of the FCI under CDAs in sodium-cooled fast reactor

ZHANG Zhi-gang*, LIU Xing-chao, and YANG Zhi

Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University Number 145, Nantong Street, Harbin 150001, China (zg_zhang@hrbeu.edu.cn)

Abstract: The molten fuel-coolant interaction (FCI) under core disruptive accidents (CDAs) in sodium fast breeder reactor (SFR) is a crucial problem on core safety study internationally. It involves multiphase, multicomponent, deformation and solidification, complex heat and mass transfer problems, which is a crux to assess the post-accident heat removal (PAHR) and core re-cooling ability. The latest experimental and numerical research status of FCI was introduced, especially the molten metal fragmentation mechanism. The sodium entrainment physical model, fragmentation induced by the thermal stress and fragmentation induced by solidification are the major breakthroughs in studying the fragmentation mechanism. Modeling of FCI process using MPS and ISPH numerical methods has made some progression. At the same time, the author summarized the work and the existing problems and made a general outlook about the research directions and trends in the future.

Keywords: sodium-cooled fast reactor; FCI; experiment study; numerical simulation

1 Introduction

SFR is one of the six reactor types (sodium cooled fast reactor, high temperature gas reactor, gas cooled fast reactor, lead cooled fast reactor, supercritical water reactor and molten salt reactor) proposed in the Generation IV International Forum (GIF), which is most likely to achieve commercial operation. It is characterized by the MOX and metallic fuel, stainless steel cladding, the rod bundle supported by hexagonal outer tube to form a complete geometric arrangement of the core, liquid sodium as the coolant, pool type structure and heat exchange system with three loops. SFR has many advantages, such as superior breeding ratio, high thermal conductivity, simple reprocessing and fabrication of fuels, good passive shutdown potential and sufficient burn-up capability. At the same time, for the high utilization rate of uranium resources (60%-70%) and the transmutation of the long-lived radioactive waste, SFR tied up the bottleneck in nuclear power development and will be the trend in nuclear utilization in the future.

Although the probability of CDAs is quite low in SFR, it is necessary to make a quantitative assessment about the positive reactivity feedback induced by molten metal fuel-sodium coolant interactions in the process of the hypothetical core disruptive accidents (HCDAs). In order to improve the ability to prevent and solve the beyond design basis accidents, various countries launched experimental and numerical study on FCI to provide relevant data and technical support for the safety design and operation with higher power SFR.

Anticipated transients without scram (ATWS) is the major reason leads to CDAs and typically includes unprotected transient over power (UTOP) and unprotected loss of flow (ULOF). Once the coolant cooling capacity is lower than the core power, it will inevitably lead to higher core temperature. With the increase of temperature, the sodium begins to boil and dry. Then the fuel pellets begin to melt and the cladding fail. Meanwhile the low temperature eutectic reaction between fuel and cladding occurs and forms eutectic metal. The molten metal fuel, molten fuel cladding material and molten eutectic metal with various modes (single droplet, continuous drops, jet) will fall and interact with liquid sodium. Post-accident heat removal (PAHR) is the key to terminate the accident. It requires the molten materials break well without large fragments formed and block the coolant channel. Therefore, the coolant is allowed to steadily inject into the core and cool the core down and the accident is prevented from further deterioration. Thus, the FCI is not only the key problem of CDAs, but also a crucial basis for evaluation the core safety design. In

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this paper, research status and progression of FCI under CDAs is reviewed, and the deficiencies, research prospects and trends in the current research are discussed. Moreover, it could provide some referential information for deepen understanding and studying FCI.

2 Research status

Since 1950s, the potential hazards of the interaction between the molten metal and coolant in the research field of nuclear reactor is proposed. The FCI is a matter of two different chemical compositions, which are immiscible with each other. And a significant temperature difference between molten metal and coolant. Severe heat and mass transfer, multiphase flow, interfacial hydraulic instability, pressure wave propagation and other complex problems are involved under fast and close contact. However, in this phenomenon the physical mechanism remains unclear, such as the solidification, fragmentation and migration characteristics of the molten metal. At present, most of the research concentrates on jet and single melt droplet of the FCI.

The experimental materials on FCI include copper, stainless steel, aluminum, mercury, tin, zinc, Freon -11 and lead bismuth alloy. Water and sodium are generally chosen as coolant. The mass of molten metal varies from a few grams to several hundred kilograms. The molten metal injecting into the coolant tank or coolant injecting into the melt pool are the main contact modes. The height ranges from a few centimeters to several meters and the molten metal temperature ranges from several hundred degrees Celsius to several thousand degrees Celsius. The heating methods cover electric heating, thermite heating and heating by induced coil.

At present, there are a lot of experimental facilities in EU; FARO of the EU joint research center, SMPR, LMPR and MFTF of the British Atomic Energy agency, SIGELCO, GEYSER and CORECTⅡof the French Central Electricity authority, SIMBATH, THINA and THEFIS of the Karlsruhe Research Center of Germany are renowned experimental facilities that related to the FCI research. Based on these experimental facilities, the experiments with molten metal between a few kilograms and hundreds kilograms were conducted, which were more close to the real core environment.

Considering the FCI experiment involving sodium is difficult and costly and there is a certain relationship between the FCI in LWR and SFR, such as the solidification and fragmentation of molten metal in sodium or water. Therefore, many domestic and oversea scholars have done a series of FCI experiments in LWR, which have reference value for understanding the fragmentation mechanism in SFR. Patel and Sa Kondo, *et al.* experimentalized the FCI by using mercury and wood metal to interact with water. The hydraulic characteristics of single droplet and jet were investigated though the direct information about FCI in SFR was not obtained, it is found that the probability of energetic FCI is quiet low in SFR compared with LWR. Thus, it can provide the referenced experience for studying the fragmentation of the molten metal in liquid sodium [1-2].

Swift, Armstrong, Schins and Gabor, who conducted experiments earlier by using uranium, uranium alloy, copper and stainless steel to interact with sodium at high thermal conditions. Some basic information about FCI in SFR was obtained, it is of great significance for further understanding and comprehension. However, the experimental data was limited and the research content was not systematic. To date, the discussion of the mechanism was not enough to form a complete theoretical basis. Thus it cannot be utilized as the effective numerical simulation studies[3-6]. Details of the experiment about the FCI involved sodium are shown in Table 1.

Based on the research on the mass of the molten material in the cooling pool and the ability of the core re-cooling, Yutaka Abe observed the process of the melt broken by injecting molten metal jet into the visible water pool and obtained fragment sizes which are quite close to those obtained from the K-H instability theory. The effects of jet velocity, diameter, and melt and coolant temperature were also researched. He has speculated that the mass of the molten material in the coolant pool is determined by the size of the debris in liquid metal cooled fast breeder reactor (LMFBR) [7-8]. Wiktor explored the mechanism of thermal explosion by conducting the reaction of molten copper droplet with water. He believed that the formation of shell indicated some interior changes when the molten material interact with water, but he did not explain the specific process of change and just thought that the suddenly phase change and internal tension lead to the breakup of the molten copper droplet, increasing the contact area and heat transferred to water fleetly and leading to the vapor explosion [9]. Based on the reaction between molten uranium, zirconium alloy cladding droplets and water, Genk analyzed the shape and size of the debris and concluded that the pressurization of the entrapped coolant inside the molten droplet with solid shell lead to fragmentation. He also proposed that the secondary droplets produced by the first breakup would continue to entrap the water, which would lead to further breakup and produce a chain reaction [10]. All of these research about molten metal-water interaction promoted the proposed entrainment model. After that, Sugiyama conducted an experiment that injected 100g molten tin and zinc jet into the water pool to simulate the phenomenon of FCI in SFR under the condition of super-cooling. He proposed a thermodynamic fragmentation mechanism, namely [11]. It was also found that the probability of entrainment of the molten zinc jet was less than the molten tin jet under the same thermal condition. Sugiyama believed that this difference could be caused by the two different kinematic viscosity, however, he did not verify it. Lu Qi, *et al.*, have done the experiments to study the process of explosive boiling with high temperature of the molten metal surface in 2016, and it showed that the physical properties of the molten metal could affect the process of FCI. The metal with high melting point, low specific heat capacity, high thermal conductivity and dynamic viscosity is difficult to appear the phenomenon of fine fragmentation, which confirmed Sugiyama's conjecture [12]. It has laid a foundation for studying the fragmentation mechanism of the FCI in SFRs though these are not the direct exploration.

Table 1 Experimental Study on FCI involved sodium

years	conductor	materials	mode	mass (g)	thermal condition	hydraulic condition	number of data	main research
1965	Swift	uranium, stainless steel, zirconium, aluminum, lead, *etc*.	solid, molten droplet	unknown	high(the highest is 2350℃)	low	29	understand the FCI phenomenon, whether the chemical reaction
1971	Armstrong	stainless steel	continuous stream	9-29	high	high	6	FCI phenomenon, fragment size
1982-1986	Schins	stainless steel, copper	jet	2500-4000	high	high	4	effect of sodium boiling on fragmentation
1988	Gabor	uranium and uranium alloys	jet	3000	super heating temperature:100-800℃	low	13	X optical visualization experiment, debris size
2002-2007	Nishimura	copper	jet	20-300	low (the highest is 1282℃)	from low to high	46	experimental study on metal jet FCI
2005-2014	Zhang zhi-gang	copper, aluminum, stainless steel	single droplet	1-5	from Low to high(the highest is 1820℃)	from low to high (the highest is 7.8m/s)	134	system experimental condition, mechanism study

On the basis of Sugiyama, *et al*, Nishimura and Zhi-gang Zhang conducted a series of experiments by utilizing copper, silver, stainless steel and uranium to interact with sodium to research the fragmentation mechanism. The model of entrainment proposed by Sugiyama was verified and improved. Besides, the effects of the initial temperature of the jet and the droplet, initial temperature of the sodium, initial weber number, heat capacity and the physical properties of the molten metal were also investigated[13-22]. These experiments are of great significance for understanding the fragmentation process and the migration characteristics. Especially, the model of entrainment is a milestone in study of the fragmentation mechanism of the melt in FCI in SFRs. In addition, Xue-wu Cao *et al*, proposed another thermodynamic fragmentation model of the single molten droplet, which was fragmentation induced by the solidification of the droplet surface [23]. He believed that once the molten droplet and coolant contacted with each other, the droplet surface rapidly formed a solid crust due to the intense heat transfer, and the formation of the solid shell would squeeze the interior of the liquid material and generate higher pressure and extrude it out, which would lead to appearance of spikes on the surface and the break of the droplet under coolant flow. The fragmentation rate was also simulated according to the model. It was similar to the fragmentation mechanism of thermal stress proposed by Hsiao [24] *et al*. Although some progression has been made in studying the fragmentation mechanism of molten metal in liquid sodium, the environment of experimental and the real core are quite different. The real core environment and FCI phenomenon is more complex and the process of experiments are not visible, so the fragmentation mechanism of melt cannot be fully explained by the entrainment model and solidification model. Therefore, there are still a lot of work to do.

It is an indispensable part of effective numerical simulation in order to better assess the CDAs in SFRs, and effective numerical simulation must be verified by accurate and reliable experimental data. The SIMMER code, specifically for the analysis of CDAs in LMFRs, was originally developed in 1974 by the Los Alamos National Laboratory in the United States, and it has been gradually upgraded from SIMMER Ⅰ to SIMMER IV by International cooperation [25-27]. As the result, the most updated version of SIMMER IV is a three-dimensional, multi-velocity-field, multi-phase, multi-component, Eulerian, fluid-dynamics code coupled with a fuel-pin model and a space and energy dependent neutron transport kinetics model. Suzuki, Yamano, Morita and other researchers have used SIMMER code to analyze the phenomenon of FCI in LMFBRs, and the results of the simulation and the experimental data showed a great agreement. SIMMER code can roughly analyze the safety of LMFBRs after decades of development, but the physical models contained in the SIMMER code are not complete and still need to be continuously improved to further increase the reliability and progressiveness.

As for numerical simulation study on the fragmentation of melt in FCI, Ming Guo, Zhi Yang, and Fang Wang used the moving particle semi-implicit (MPS) method and incompressible smoothed particle hydrodynamics (ISPH) to simulate the molten metal (including jet, continuous drop, single droplet)-sodium interaction respectively. They compared the simulation results to the related experimental data and obtained some progress [28-30]. It is a preliminary exploration to acquaint the process and fragmentation mechanism of the melt. Therefore, the simulation work is still not enough, and we need to continue to develop and improve the relevant simulation methods in order to learn more about the mechanism of the FCI in SFRs.

3 Problems and prospects

Although FCI in SFRs has been studied for decades, it cannot fully and systematic explain the fragmentation mechanism. The SIMMER code can be used to fit the experimental results, however there are still some limitations, such as the contained core material is not complete. The problems of the research on FCI in SFRs at present are summarized as follows:

(1) The study of continuous droplets between a single droplet and a jet has not been involved;

(2) The study of the interaction between eutectic metal with coolant has not been carried out;

(3) The visualization study of FCI fragmentation process in sodium pool by X ray is in the exploratory stage, and the result is not ideal, it is necessary to improve the experimental technology;

(4) The results of numerical simulation are not ideal, thus it is necessary to continue to improve the relevant model and develop more effective calculation program;

(5) It is deficient of the large-scale experimental study of sodium FCI which is proportional to the real core accident.

Due to the results of the experimental research of the process of the FCI in SFRs are non-ideal and costly, so we need to do more work on numerical simulations in the future. At present, the numerical method for simulating FCI is limited to MPS and ISPH as well as the SIMMER code which is special for CDAs in LMFBRs. More effective numerical methods are needed to be developed in order to simulate the FCI process in SFRs more accurately and the experimental research on the fragmentation mechanism is needed to continue to carry out. Since the lumped parameter SIMMER code needs more computational resources, the CFD computation code using ISPH and MPS are more flexible to explore the molten metal fragmentation mechanism. It is expected the improvement of ISPH and MPS code could supplement SIMMER code. Meanwhile, the experimental apparatus should be designed proportional to the real core in order to more accurately reproduce the accident core environment.

4 Conclusions

The molten core material-sodium coolant interaction under CDAs in SFR is essential to assess the core safety and re-cooling ability.

(1) In experimental research, the entrainment and entrapment physical model, fragmentation induced by thermal stress and fragmentation induced by solidification are breakthroughs in study of the fragmentation mechanism of molten metal. However, due to the invisible of the experimental process and the complexity of the real core environment, it needs to continue to research on the mechanism of fragmentation. At the same time, the experiment is proportional to the real core environment should be carried out under limited conditions.

(2) In numerical simulations, SIMMER code is still constantly improved and updated. MPS and ISPH methods are not mature enough to accurately simulate the process of FCI in SFRs and need to be improved at present.

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List of acronyms

ATWS	Anticipated Transients Without Scram
CDA	Core Disruptive Accident
FCI	Fuel-Coolant Interaction
GIF	Generation IV International Forum
HCDA	Hypothetical Core Disruptive Accidents
ISPH	Incompressible Smoothed Particle Hydrodynamics
LMFBR	Liquid Metal cooled-Fast Breeder Reactor
MOX	Mixed Oxide Fuel
MPS	Moving Particle Semi-implicit method
PAHR	Post-Accident Heat Removal
SFR	Sodium cooled-Fast breeder Reactor
UTOP	Unprotected Transient Over Power
ULOF	Unprotected Loss Of Flow
LWR	Light Water Reactor
K-H instability	Kevin-Helmholtz instability

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