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Review

A review of research progress in heat exchanger tube rupture accident of heavy liquid metal cooled reactors

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ABSTRACT

The Heat eXchanger Tube Rupture (HXTR) accident, which is also called Steam Generator Tube Rupture (SGTR) accident, is important and should be considered as a safety issue in the design and safety assessment of Heavy Liquid Metal (HLM) cooled reactors. The HLM cooled reactor is a kind of advanced reactor which is meaningful for sustainable energy development. In this paper, the research progress on HXTR (or SGTR) accident of HLM cooled reactors from 1992 to 2016 is reviewed. Currently, because of the restrictions of experimental facilities and simulation tools for HXTR accident, the main phenomena, which should be concerned, were not all well studied. For experimental research, the most studied problems were the investigations of the pressure evolution, vapor transmission, fragmentation behavior, physics of the thermal and hydraulic interactions between HLM and water; And for simulation research, the pressure evolution and steam transmission were the mostly studied. For further research of HXTR accident of HLM cooled reactors, the propagation of the pressure waves and sloshing of the primary coolant pool with mechanical impact of the heavy liquid metal on structures should be more studied. And as the basis, the experimental facilities and numerical tools for HXTR accident should be improved firstly.

Contents

1. Introduction

The Heavy Liquid Metal (HLM) Cooled Reactor (LBE or Lead Cooled Reactor) is a kind of advanced reactor of inherent safety and can be used in electricity generation, fuel breeding and long-life nuclear waste transmutation (Sathiyasheela et al., 1000; Moisseytsev and Sienicki, 2008; Tucek et al., 2006), which is important for the sustainable development of nuclear energy. The HLM cooled reactor could be designed to be a fast reactor or an accelerator driven sub-critical system (ADS). HLM could be used as the primary coolant for both fast and ADS reactors because of its good neutron properties, anti-irradiation performances, heat transfer properties and inherent safety (Sobolev, 2007). Fast reactor is the preferred reactor type in Generation IV reactors. The closed cycle

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of nuclear fuel supplied by fast reactor would lead to 60% or more utilization of Uranium resources (Sienicki, 2013). The international typical HLM cooled fast reactors are SVBR, CLEAR and BN-800 (Petrochenko et al., 2015; Zrodnikov et al., 2011; Wang et al., 2015; Saraev et al., 2010), etc. The partitioning and transmutation technology was proposed in 1960s, which is used to deal with the long life high radioactive spent fuel. The ADS is a potential option for spent fuel transmutation, which is of inherent safety. In contrast with critical reactors, not only nuclear waste transmutation capacity of ADS is stronger, but the MA neutron economy is also better. The international design and study of ADS are in progress in several countries, such as MYRRHA, EFIT and XADS (Tichelen et al., 2002; Liu et al., 2010; Suzuki et al., 2005).

For HLM cooled reactors, the primary Heat eXchanger (HX) is placed in the main vessel in contact with the primary coolant directly. And the coolant of secondary circuit is normally designed to be water. In the HX, due to the pressure difference between heavy liquid metal (LBE or lead) and water, the high pressurized water will be injected into the primary circuit when HX Tube Rupture (or SGTR) accident happens (Gu et al., 2015). Once the high pressurized sub-cooled water contacted with the low-pressurized hot primary coolant LBE (or lead), it would be vaporized immediately with a high pressure release. That might cause a threat to the reactor safety.

In HXTR accident, there are three possible phenomena which would lead to bad influences to the reactor and should be concerned with (Wang et al., 2008; Pesetti et al., 2015). The first one is the steam transmission in the main vessel of the reactor, during which the steam may be dragged into the core and insert positive reactivity. The second is the propagation of the pressure waves and cover gas pressurization, which could compromise the structural integrity of the surrounding components. And the third is the sloshing of the primary coolant pool with mechanical impact of the heavy liquid metal on structures, which is caused by the thermal coolant-coolant interaction (CCI). Thus, HXTR (or SGRT) should be considered as a safety issue in the design and preliminary safety analysis of HLM cooled reactors (Pesetti et al., 2015).

Normally, there are mainly two research methods for HXTR accident, the first one is experimental investigation and the second is numerical simulation. Experimental investigation could supply experimental data which may support the verification and validation (V&V) work for transient simulation codes. Numerical simulation could show the accident transient process. And both the two methods could serve the design and safety assessment of HLM cooled reactors. As the experimental facilities for heavy liquid metal and water interaction are usually costly and a relevant code for CCI simulation is relatively difficult to develop, so far, the research on HXTR accident of HLM cooled reactors is still limited. In this paper, the research and development (R&D) work on HXTR (or SGTR) accident of HLM cooled reactors from 1992 to 2016 is reviewed, which aimed at supplying an abundant and meaningful review literature for the further studies of this typical accident.

2. Experimental research progress

2.1. Experiments based on small test facilities

Small test facility for the investigations of the interaction between heavy liquid metal LBE and pressurized water was developed by Japanese Atomic Energy Agency (JAEA), and the relevant two kinds of experiments were carried out by Nakamura et al. (1999) and by Sibamoto et al. (2001). The chosen experiments were the injection of sub-cooled water into a hot stagnant LBE pool and the injection of hot LBE into saturated water, respectively. Both the two kinds of experiments were carried out on the same small test facility developed by JAEA. There were two main objectives of the two experiments. The first one was to investigate the phenomenology of the thermal and hydraulic interactions between HLM and water, and the second was to verify the numerical code (Kondo et al., 1992; Yamano et al., 2003) used for the simulation of the interaction between HLM coolants and water. The details of the two kinds of experiments could be seen in literatures (Flad et al., 2010; Sibamoto, 2002; Mishima et al., 1999; Sibamoto et al., 2005). The former experimental results showed satisfactory agreements with the simulation results, which verified the numerical code well. And the latter demonstrated several features of molten fuel-coolant interaction (FCI). The results showed that the violent water vapor expansion happened at the initial melt impact on the water, and the heterogeneous distribution of the water and pool melt formed a crust between the melt and pool water (Sibamoto et al., 2001).

Takahashi and Sa et al. of Tokyo Institute of Technology carried out a series of LBE droplet into water experiments to investigate the fragmentation behavior and characteristics of thermal-hydraulic interaction between HLM and water (Sa et al., 2011; Sa and Takahashi, 2010). High frequency piezo pressure transducer and high-speed camera were employed to observe the violent boiling and pressure evolution during the experiments. The relevant experiments carried out by Takahashi et al. mostly focused on the mechanism study of the phenomena during the interaction between LBE and water. The experimental results indicated that the fragmentation occurred when the temperature of the interface between water and the molten metal droplet was higher than the homogenous nucleation temperature of water and lower than the minimum film boiling temperature. The peak pressure in fragmentation of LBE droplet increased as the droplet temperature increased, but it remained constant with the increase of the water subcooling (Fig. 1).

Huang et al. of Chinese Academy of Sciences (CAS) developed also a small test facility for the experiment of LBE droplet into water (Huang et al., 2015) (Fig. 2). Some visualization experiments on interface fragmentation behavior of heavy liquid metal LBE with water were conducted. These experiments aimed at the investigation of the phenomena and mechanism of boiling heat transfer and vapor explosion at the interface between liquid LBE and water. The results showed that the fragment median mass diameter decreased with the increasing of LBE or water temperature. The vapor explosion occurred when the temperature of interface between LBE droplet and water was higher than the homogenous nucleation

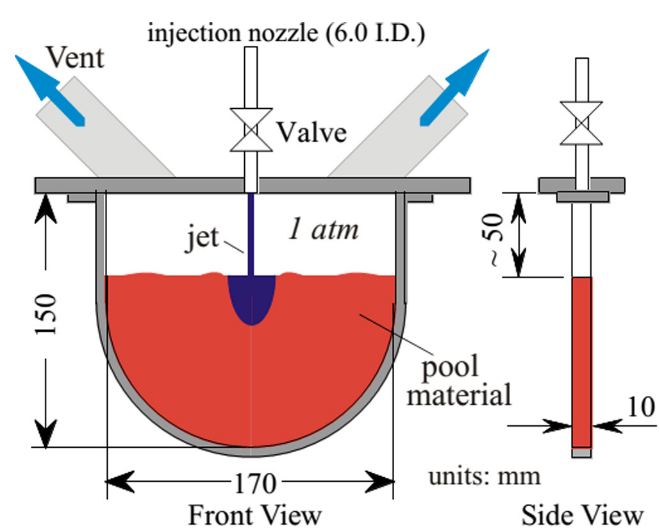

Fig. 1. Schematic of the test facility for LBE/water injection experiments (Flad et al., 2010).