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Review on the current status of molten chloride reactor and its future prospect

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1. Introduction

As the developments of the next generation nuclear energy systems require the fuel sustainability, passive operation safety, nuclear proliferation, and reduction of highly radioactive waste, only several types of nuclear reactor systems survive to the last. Among these, molten salt reactor (MSR) is one of the most promising concepts of next generation nuclear reactor system that deliver on these requirements. MSR have great advantages in the fuel cycle and reduction of nuclear waste, since MSR can serve the online reprocessing system for the reprocessing of spent fuel. Especially, MSR utilizing chloride-based fuel, called molten chloride reactor (MCR) has been recently highlighted in USA under the DOE's Gateway for Accelerated Innovation in Nuclear (GAIN) program. This paper has summarized and reviewed the current status of MCR as an online pyroprocessing reactor, and introduced the related works in UNIST.

2. Characteristics of MCR

2.1 General characteristics of MCR

One of the most unique characteristics of MSR is the use of liquid fuel which has advantages in the elimination of fuel fabrication. Halogen elements were employed for the anion side of molten salt, since it provides a high degree of solubility of actinides in concentrations sufficient to maintain a critical system of entire nuclear plant. MCR utilizes chloride-based salt such as NaCl and KCl which gives great advantages to the operation of reactor in a fast spectrum. Then MCR can be designed to serve both waste management functions or fuel cycle sustainability functions by control a range of heavy metal conversion ratio. MCR with a low heavy metal conversion ratio can provide on-line reprocessing option to the existing LWR or SFR. In on-line reprocessing system, the spent fuel is brought into salt form and the excess uranium is removed, while MCR with a high conversion ratio employs identical step to process the used fuel salt.

The unique characteristics of MCR give some salient advantages:

1. The on-line reprocessing step or chemical processing step of MCR enables to eliminate the refuel process which reduces the reactor downtime.
2. MCR has strong negative temperature coefficient which enhances the inherent safety. In addition, the liquid state of fuel eliminates the boiling issue.
3. MCR has negative salt void coefficient and negative thermal reactivity feedback which also enhances the inherent safety.
4. The operation of liquid fuel in fast neutron spectrum removes the moderator and fuel cladding which improves the neutron economy of the reactor.
5. The low operating pressure of MCR reduces the risk of containment failure of pressurized components.
6. The high operating temperature is compatible with process heat applications. In addition, it allows the adoption of high-efficiency power conversion systems.

Instead, MCR has several challenges:

1. The heat transfer performance of molten salt fuel is poor compared to that of other liquid metal coolant like sodium, lead.
2. The liquid-state fuel requires additional systems to maintain the operating temperature above the melting temperature of fuel salt. In addition, a corrosion issue limits the choice of structure materials.
3. The high operating temperature of the system limits the temperature difference across a heat exchanger which deteriorates the heat transfer.

2.2 Fuel cycle options of MCR

In this section, detailed descriptions of two aforementioned functions of MCR are presented. As mentioned previous section, MCR has two types of design of salt processing systems; one is front-end processing system for used LWR fuel (burner) and the other is salt processing system for cleaning the fuel salt (breeder)

MCR as an actinide burner utilizes $PuCl_3$ with the mixture with minor actinides from used LWR fuel. The front-end processing system includes steps of removal of fuel rods from fuel rod assemblies, element chopper, voloxidation to remove some fission products, and separation which is identical to those of pyroprocessing technique.

The operation of MCR as a breeder, as well as actinide burner, requires fuel salt processing and cleanup to remove fission product gases, neutron poisons, noble metals.

As a result, MCR can provide two different design options of reactor system; one is an LWR-derived TRU burner and the other is a uranium-plutonium breeder. Thus, MCR can function as waste consumption or fissile resource extension.

2.3 Salt compositions of MCR

Many candidates of salt composition have been introduced to satisfy the requirements of MCR. Since the chlorine has two stable isotopes and several oxidation numbers, more complex bonding configurations are available compared to fluorine. The most promising salt composition consists of $PuCl_3$, UCl_3, and NaCl, while NaCl is the peritectic-forming carrier salt of preference due to its abundant occurrence in nature. Then $PuCl_3$ or $^{233}UCl_3$ serves as fissile fuel and $^{238}UCl_4$ or $ThCl_4$ as fertile fuels. The choice of NaCl as a cation meets several criteria including nuclear properties, physical properties, chemical behavior, and economics. NaCl has good physical and chemical properties and costs little compared to other cations like K and Ca. In addition, NaCl gives great advantages in peritectic melting points near the desired actinide molar fraction.

3. Current status of MCR

When firstly MSR was proposed as one of Gen IV reactors, it considered fluoride-based fuel. However, the first MSR utilized chloride-based fuel, and currently USA focused on MCR under DOE's support program.

3.1 History of MCR

The first concept of MSR was first proposed at Oak Ridge National Laboratory (ORNL) as a means to power military aircraft under Aircraft Nuclear Propulsion program, and then two thermal-spectrum reactors were developed and operated with over 13,000 full-power hours of operation. Then, Alexander [1] from ORNL proposed an MSR breeder system in the fast spectrum in the early 1960s which utilized $NaCl/KCl/PuCl_3$ salt. In the 1960s-1970s, Taube et al. [2] from the Swiss Institute of Energy Research investigated several MSR in fast spectrum utilizing $PuCl_3/NaCl$ salt. In addition, Nelson et al. [3] from Argonne National Laboratory summarized the fuel properties and nuclear performance of molten chloride fueled-fast reactor. The physical and chemical properties of the fuel with uranium and plutonium trichlorides for three different types of reactors were included. In the 1980s-1990s, Ottewitte et al. [4] from Idaho National Engineering Laboratory assessed the feasibility of molten chloride fast reactor concept in very fast neutron spectrum. In the 21st century, Holcomb et al. [5] from ORNL evaluated the development of fast-spectrum molten-salt reactors (FS-MSR) as a realistic reactor and fuel cycle option providing possible reactor configurations, design features/options and performance considerations.

3.2 Current status and challenges of MCR

Recently, department of energy's office of nuclear energy (DOE-NE) in USA decided to invest in the molten chloride fast reactor through a public-private partnership under GAIN program. The supporting institutions consist of TerraPower, ORNL, Electric Power Research Institute (EPRI), and Vaderbilt University being funded by government over 5 years. With a goal of development of commercial prototype by 2035, the program is planning to complete early validation of MCFR by 2019. Besides, Moltex Energy LLP initiated the development of simple reactor based on molten chloride fast reactor concept. The current design of MCR developed by Moltex utilizes 30% $UCl_3/NaCl$ of fuel salt and 10% NaF/48%KF/42% ZrF_4 of coolant salt. Both studies focused on the great advantages of chloride salts for producing a harder neutron spectrum and thus improving actinide burning and breeding. These advantages can afford the technical solutions for current issues in nuclear field such as nuclear waste management and development of Gen IV reactor operating in fast spectrum; the actinide burning can reduce the existing spent fuels and future generated wastes, and the breeding can minimize the generation of nuclear waste in the future. However, although the conceptual designs of MCR were developed, the detailed information of chloride salt has not been studied yet. Especially, the exact composition of chloride salt has not been decided yet, and thus the thermal-hydraulic characteristics of salt has not been investigated clearly.

3.3 Previous researches in UNIST

The research on molten salt including chloride-based salt is difficult to carry out in lab-scaled facility, since the high melting temperature and operating temperature require large heat input and additional components to prevent solidification. To initiate the research on the application of molten chloride salt, in UNIST, two research plans were established to find out the thermal-hydraulic characteristics of chloride salt and to design the optimized heat transport system of MCR; one is a numerical method using thermal-hydraulic code and the other is experimental method using similarity technique. Previous studies developed both a lab-scale single-phase natural circulation experimental setup and thermal hydraulic codes such as CFD, MARS code for molten salt, as shown in figures 1-3, to investigate the thermal-hydraulic characteristics of molten salt including chloride-based salt [6].

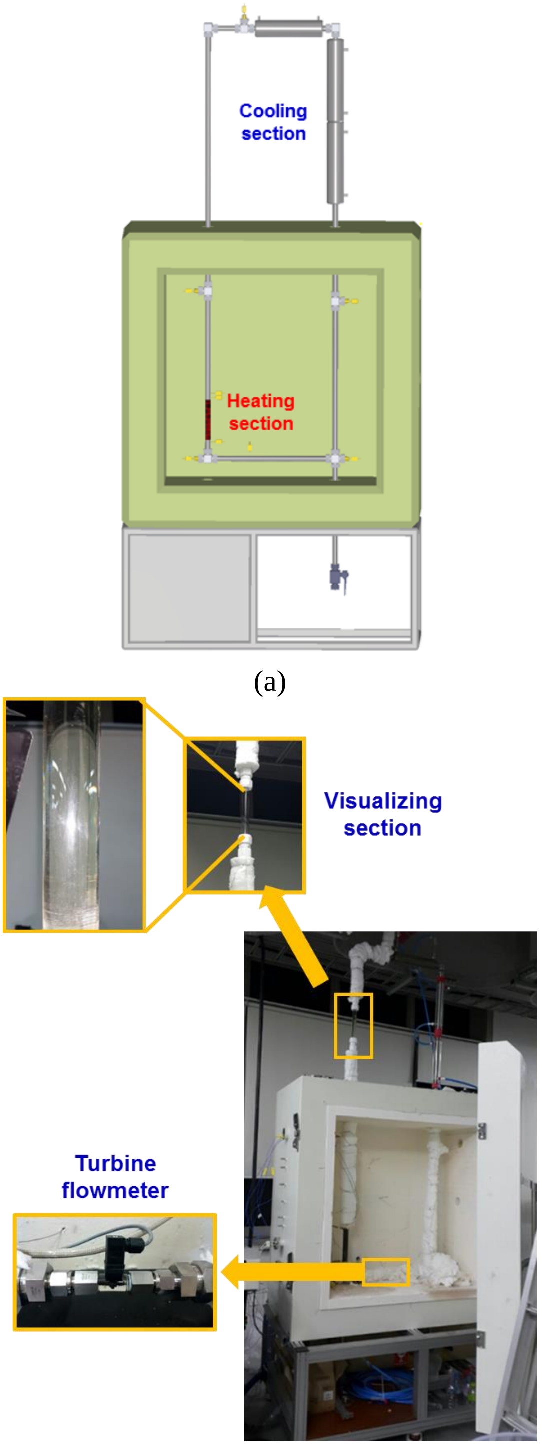

Fig. 1. UNIST's single-phase natural circulation experimental facility: (a) Schematic drawing, (b) Major components

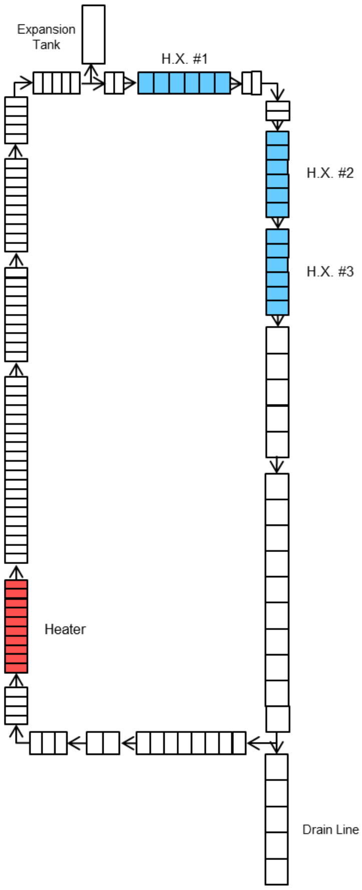

Fig. 2. Nodalization of MARS simulation for natural circulation loop

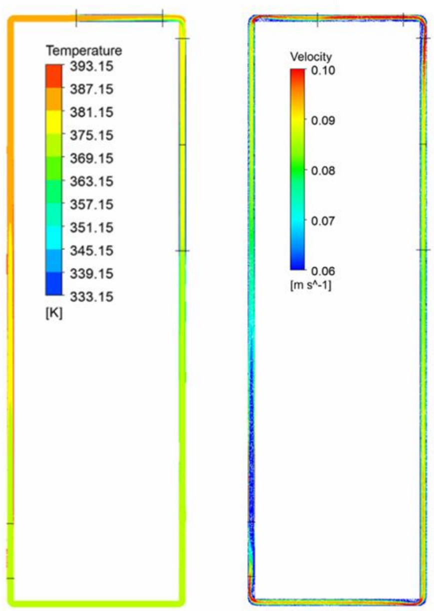

Fig. 3. CFD simulation results of DOWTHERM RP natural circulation

Based on the similarity technique, natural circulation experiments were performed under low-power conditions using heat transfer oil (DOWTHERM RP) as a simulant. Although the experimental data showed little difference from the existing correlations, the feasibility of experimental simulation by using a scaling law was confirmed. In addition, MARS code for heat transfer oil and fluoride-based salt was developed by implementation of thermophysical properties. The properties which were input into the fluid property generator of fluids package in MARS enabled to produce the reasonable simulation results for molten salts. The developed experimental and numerical platform in UNIST can provide the further expanded research plan with molten chloride salt.

4. Conclusions & Future plan

Recently, the interests in the molten chloride salt have arisen. The use of chloride-based salt gives great advantages to the reactor operating in a fast spectrum. Then MCR can serve waste management functions or fuel cycle sustainability functions, which can solve the current issues in nuclear field. Thus, research plan was established in UNIST which includes the investigation of thermal-hydraulic characteristics of chloride salt and optimization of heat transport system of MCR, using both numerical method and experimental method.

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