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Original Article

Investigation of Characteristics of Passive Heat Removal System Based on the Assembled Heat Transfer Tube

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ABSTRACT

To get an insight into the operating characteristics of the passive residual heat removal system of molten salt reactors, a two-phase natural circulation test facility was constructed. The system consists of a boiling loop absorbing the heat from the drain tank, a condensing loop consuming the heat, and a steam drum. A steady-state experiment was carried out, in which the thimble temperature ranged from 450°C to 700°C and the system pressure was controlled at levels below 150 kPa. When reaching a steady state, the system was operated under saturated conditions. Some important parameters, including heat power, system resistance, and water level in the steam drum and water tank were investigated. The experimental results showed that the natural circulation system is feasible in removing the decay heat, even though some fluctuations may occur in the operation. The uneven temperature distribution in the water tank may be inevitable because convection occurs on the outside of the condensing tube besides boiling with decreasing the decay power. The instabilities in the natural circulation loop are sensitive to heat flux and system resistance rather than the water level in the steam drum and water tank. RELAP5 code shows reasonable results compared with experimental data.

1. Introduction

According to the International Atomic Energy Agency's definition, a passive component is a component that is self-sustained without external energy [1] and can be activated by natural laws, e.g., gravity, inertia, negative feedback. For instance, with the help of inertia, heavy flywheels on the main pump in the primary circuit in pressurized water reactors can prolong the run time of the coolant pump. The negative feedback of temperature and reactivity helps prevent the nuclear reactor core from being supercritical. These passive techniques in nuclear energy were classified by Zhou et al [2].

Of these passive techniques, the driving mechanism behind natural circulation is the density difference in the

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system loop caused by gravity. Natural circulation eliminates the possibility of pump failure. Consequently, it has been widely employed in the passive residual heat removal system (PRHRS), which usually comprises a heat exchanger, a heat source (decay heat), a heat sink, and pipelines where single- or two-phase fluid acts as a heat carrier. Park et al [3] conducted an experimental investigation into the heat transfer and natural circulation of the PRHRS for an integral type reactor called SMART (System-integrated Modular Advanced ReacTor) using a high temperature/high pressure thermal–hydraulic test facility. The operating pressure was 3.5 MPa. The results showed that their emergency cooldown tank was large enough to remove the core decay heat. Due to the complete condensation of steam in the upper part of the emergency cooldown tank, an uneven distribution of fluid temperature was recorded along the vertical direction. A PRHRS for the secondary circuit of pressurized water reactors was built and the natural circulation characteristics at the steady and transient states were studied by Wu et al [4]. The relevant experiments showed the feasibility and efficiency of the PRHRS. A Compact Integral Effects Test (CIET 1.0) was conducted at the University of California, Berkeley, CA, USA [5,6]. CIET 1.0 was scaled based on an earlier design of 900 MWh advanced high-temperature reactor. The direct reactor auxiliary cooling system in CIET 1.0 used for decay heat removal is a single-phase loop without boiling. Wang et al [7,8] planned to build a PRHRS for the molten salt reactor (MSR) based on NaK heat pipes in Xi'an Jiaotong University, Shanxi, China.

Numerical analysis of the PRHRS has been widely carried out using RELAP5 code, which was developed at the Idaho National Engineering Laboratory, Idaho Falls, USA. RELAP5 is also the basis of some other codes. For instance, the MARS code, based on RELAP5, was used for parameter study of the PRHRS in a SMART plant [9]. The effects of hydraulic resistance, valve actuation time, and initial pressure were evaluated. Nevertheless, the capability and reliability of RELAP5 has been questioned by some researchers, since numerical damping was built in RELAP5 to achieve stable solutions. Numerical damping overwhelms instabilities and renders the simulation of instabilities nonconservative [10]. Kozmenkov et al [11] validated the RELAP5 code against measurement data from natural circulation experiments performed at the CIRCUS (CIRculation Under Start-up) facility. The calculation results were in good agreement with the experimental data. The experimental results of CIET 1.0 were also used for the validation of RELAP5-3D and an excellent agreement under steady-state natural circulation was found. Mangal et al [12] found a significant difference between the numerical results and the experimental data for the parallel circulation loop. But the prediction of two-phase stable flow showed a good agreement with experimental data for the high pressure natural circulation loop. In Martin and Taylor's [13] research, some deficiencies including geometric multidimensional and form loss effects were found. There is no consensus on the capability of RELAP5 code. More validations of the PRHRS are needed.

Even though many studies have been carried out on the PRHRS in nuclear reactors, more investigations, especially experimental ones, are needed for the PRHRS of MSR with a high temperature thimble and low operation pressure. Consequently, we built a single tube natural circulation loop composed of an assembled tube, a steam drum, a heat exchanger and associated pipes. The assembled heat transfer tube was modified based on Sun et al's [14] design. The water tank is large enough for heat removal. The purpose of this work is to evaluate the feasibility of the PRHRS and study the system behavior under different operating parameters. A passive heat removal experiment was carried out. Effects of some important parameters including heat power, water level in the water tank, system resistance, and water level in the steam drum were analyzed. The capability of RELAP5 code predicting the stable flow of the PRHRS was also validated.

2. Experimental apparatus

Fig. 1 shows the assembled tube schematic of the PRHRS. The assembled tube consists of a center tube and a bayonet. Water flows downward in the center tube from the steam drum, reverses at the bottom of the bayonet, then flows up in the annulus between the bayonet and the center tube and returns to the steam drum from the top of the bayonet. Heat is input from the outer surface of the bayonet, so water boils and steam is generated in the annulus. The mixture density of water and steam in the annulus is lower than that in the center tube. Thus, the circulation in the assembled tube can be driven by density difference. For convenience, the water loop below the steam drum is called the *boiling loop*. Water and steam are separated in the steam drum by gravity. Then steam flows up and condenses in the condenser. The condensed water flows back to the steam drum due to gravity. The steam loop above the steam drum is called the *condensing loop*.

The bayonet is partially inserted into the thimble that reaches temperatures as high as hundreds of degrees Celsius. Heat in the gas gap filled with air between the bayonet and the thimble is transferred by conduction and radiation. Convection is so weak that it can be ignored. The gas gap is to increase the temperature gradient to prevent boiling crisis on the inner surface of the bayonet. A high-temperature tube furnace is used to create a high temperature on the outer surface of the thimble. Heat is transferred by radiation from the heat wire in the furnace. The heat section of the tube furnace is divided into three segments, each of which can automatically control and adjust temperature due to proportional–integral–derivative technology. The furnace is wrapped by adiabatic ceramic fiber of 250 mm in thickness, and the adiabatic layer on the outer surface of the associated pipes is 50 mm thick. Heat dissipation from the circulation loop can be ignored. The assembled heat transfer tube is a full-scale tube modified based on Sun et al's [14] design. The sufficient condenser arranged in the water tank has seven condensing tubes. To some extent the design of the condenser is arbitrary because the purpose of the condenser is to keep the natural circulation system running under a low pressure closed to the atmosphere. We hope that this experiment can give us some information about the assembled tube running at a low pressure under natural circulation with the high temperature thimble. The detailed dimensions of the system components are listed in Table 1.

When the furnace is started, the water inventory in the loop is gradually heated to saturation. As the temperature and