Multi-unit Small Modular Reactor Control System Experimental Platform Design

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Abstract: Small modular reactor (SMR) is a type of advanced reactor depending on its safety, economy, and multipurpose. SMR always adopts the multi-unit scheme, which uses several nuclear steam supply system (NSSS) units to supply steam to a steam header. We call it multi-unit small modular reactor (M-SMR) here. Because these NSSSs are separate, the header pressure is hard to control. The experimental platform is designed to solve the control problem. The platform contains four NSSS units, which are connected to a header. The work medium in the loop is water. Some experimental plan is also designed based on this platform.

Keyword: multi-unit small modular reactor (M-SMR); control; steam header; experimental platform

1 Introduction

Comparing to the large pressurized water reactor nuclear power plant, the reactor with the electric power less than 300MW and the modular construction characteristics is named small modular reactor (SMR). The SMR, with the advantages of simple system, low cost, easy maintenance, inherent safety and multi-use, can shorten the construction period by modular design, manufacture and assembly. So it has great potential for nuclear energy application. Most SMR systems can operate in an extensible multi-purpose scheme, which can build a large-scale power source by operating several SMRs in parallel. The multi-unit design of the SMR means that several nuclear steam supply systems (NSSSs) are arranged in parallel, and supply steam to a steam header, which transfer the steam to the turbine for power generation or other purposes.

It is called multi-unit small modular reactor (M-SMR) here, such as mPower, NuScle, IRIS and so on [1-4]. In the M-SRM system, it is difficult to control the pressure of the steam header because each unit operates independently and supplies the steam to the same steam header. Meanwhile, the load distribution among the units is also a problem must be considered. So, the control of the header pressure and the load distribution require special attention in such a system. In fact, there are some scholars have done some research in this field. Keung Koo Kim et, al. [5,6], studied the system with four parallel units to a header, and have given the operation and control strategy of equilibrium and non-equilibrium conditions, but the steam generator used in this study is the U-type steam generator that is used to produce saturated steam, which is very different from the operation mechanism of the once-through steam generator used in most SMR at present. Sergio Ricardo P. Perillo et al. [7,8] studied the characteristics of the two-unit IRIS, especially the simulation analysis of the non-equilibrium condition, and provided the control shame. Similarly, Xiangxin Deng, [9], and Jinzhou Fu, [10], used coordinated control method and intelligent control method to study the M-SRM respectively. Zhe Dong, [11], and Haipeng Li, [12], have done experimental and computational research on the two-unit operation of the high temperature gas-cooled reactor, and obtained some meaningful conclusions. But for M-SMR, it is clear that the study of only two-unit is insufficient to demonstrate the general law. In order to investigate the general operation characteristics of the parallel system, the M-SMR with once-through steam generator is studied here. Four units experimental platform is designed for studying the operation characteristics and control scheme of the M-SMR.

2 Experimental platform design

The schematic diagram of the M-SMR is shown in Fig. 1, where four NSSSs supply steam to one steam header, and all the steam is collected by the header to supply steam to the turbine. Each NSSS unit mainly include the reactor core, steam generator and reactor coolant pump. The steam generated by the steam generator is collected together in the steam header and transferred to the turbine. If the steam pressure and temperature are not balanced among these steam generators, there will be a rebalance of energy and momentum in the header. The exhausted steam from the turbine is condensed by the condenser, and then is pumped into the steam generator by the feedwater pump. The above process forms the second loop.

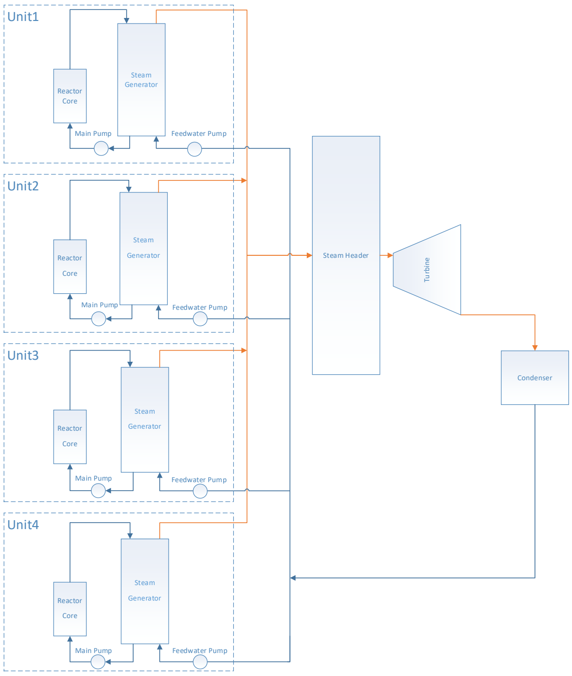

Figure 1. The schematic diagram of the M-SMR

2.1. The experimental device of NSSS

According to the characteristics of M-SMR, the pressure control of the steam header and the load distribution among these units are focused, the experimental device of NSSS is designed as Fig. 2. The experimental platform uses a higher level water tank to provide the flow pressure to simulate the steam pressure in the once-through steam generator. Therefore, the pressure control can be implemented by tuning the water level of the tank.

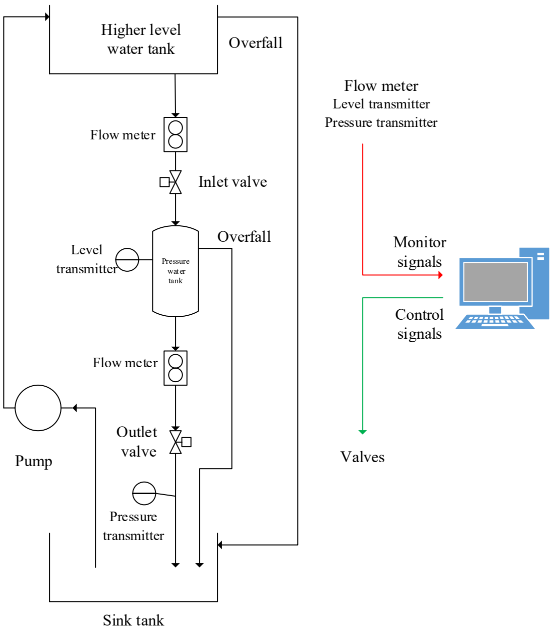

Figure 2. Design scheme of the NSSS unit

The flow meter, pressure transmitter and level transmitter are equipped with signal acquisition card whose output signal connect to the host computer for collecting the relevant signal. The two valves in this figure are both electric and controlled by the host computer, while the outlet valve simulates the turbine throttle to indicate the load change and the inlet valve simulates the feedwater valve to indicate the adjustment of feedwater. According to the ideal steady-state programming of constant coolant average temperature and constant steam pressure, the control target is to keep the water level constant to simulate the constant steam pressure. As a measured feedback, the flow meter is used to calibrate the valve opening. Meanwhile, the deviation between the pressure transmitter and the level transmitter is regarded as a signal to control the inlet valve opening.

During the simulation of load changes, the first thing we should do is change the opening of the output valve to simulate the change of the opening degree of the turbine valve. That will cause the level of the pressure water tank raising and pressure changing, so the water level will deviate from the reference value. The inlet valve needs to be adjusted until the deviation is small enough. Meanwhile, each of the detection module could be transfer date in real time to the host computer through the signal acquisition card.

2.2 Experimental platform of the M-SMR control system

For studying the problem of multi-module, it is need to connect several SMR units to one steam header. Therefore, the header is designed to connect four NSSS units and set an outlet valve in the middle. The four NSSS units are designed as section 2.1. The high water tank which has four outlets connecting to the four units. All the water from each unit is collected in the header and then flows past the pipeline which is equipped with flow meters, pressure transmitters and electric control valves. Especially, the outlet valve simulates the load input by changing its opening. Detailed design scheme is shown in Fig. 3.

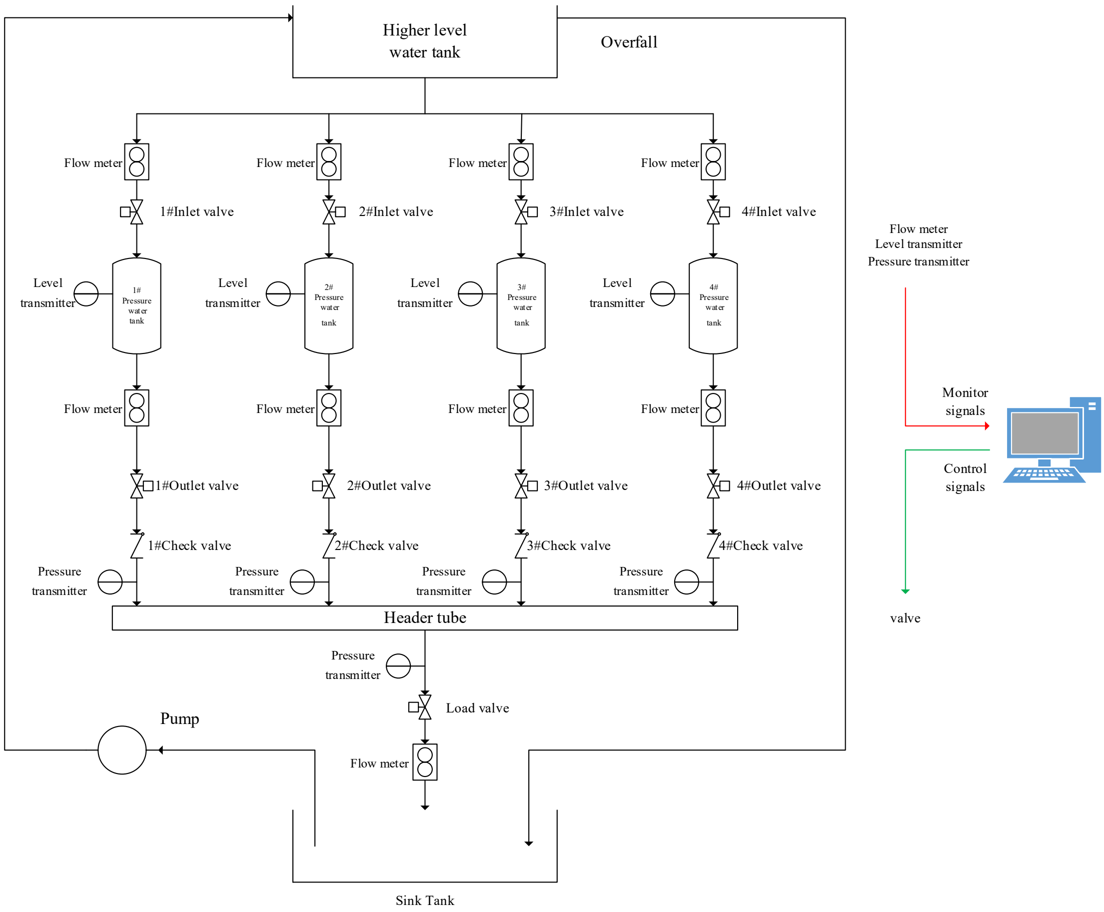

Figure 3. Design scheme of the experimental platform of the M-SMR control system

In Figure. 3, four experimental NSSS units are connected to the same header to simulate the mutual coupling problem of the NSSS unit. For SMR, the ideal steady-state programming with constant coolant average and fresh steam pressure is advanced [13]. So, the scheme, designed according to this programming, require a constant pressure on the head tube during loading. In this case, the change of load is represented by the flow, in which the discharge volume of each NSSS simulates its shared load, and the discharge volume of the head tube simulates the total load. Therefore, this design can test the coupling between the NSSS units and the changes of the parameters of head tube in the dynamic process, so as to study the characteristics of the system, and then gives the head tube pressure control scheme and the NSSS unit load distribution scheme. In this design, the water circulation circuit is used to simulate the physical part of the NSSS and the main pipe, which has various monitoring components connected with the host data acquisition board including the flowmeter, pressure gauge and level gauge for inputting the collected signal to host. The water inlet valve and water outlet valve, primarily actuating mechanisms, are electric control valve which control signal given by the host. The control part adopts the digital PID mode, which combined with the physical circuit to form the experimental platform of M-SMR control system.

3. Experiment scheme

The purpose of this experiment is to analyze the dynamic characteristics of M-SMR in load follow and to design the corresponding control scheme. Therefore, several operation scheme are given as follow.

Case 1 Uncontrolled scheme

While the outlet flow rate of each unit is equal under steady condition, change the outlet valve of the header, and get the level of each unit back to the set value by adjusting only the inlet valves and keeping the outlet valves unchanged. Collect the relevant data to observe the dynamic characteristics of each unit and header in this process. The same method is used while the outlet flow rate of each unit is different under steady condition.

Case 2 Balanced load scheme

While the outlet flow rate of each unit is equal under steady conditions, change the outlet valve of the header, and change the outlet valve of each unit in the same proportion, adjust the inlet valves on the premise of the fixed outlet valves to return the level of each unit back to the set value. Collect the relevant data to observe the dynamic characteristics of each unit and header in this process. The same method is used while the outlet flow rate of each unit is different under steady condition.

Case 3 Unbalanced load scheme

While the outlet flow rate of each unit is equal, change the outlet valve of the header, and adjust the outlet valve of each unit according to the pre-set non-equilibrium ratio. Then fixed the outlet valves, and adjust the inlet valve of each unit to get the level back to the set value. Collect the relevant data to observe the dynamic characteristics of each unit and header in this process. The same method is used while the outlet flow rate of each unit is different under steady condition.

Case 4 Constant load scheme

While the header outlet valve keep constant, change a NSSS unit outlet valve opening, then given a flow disturbance and adjust the inlet valves of other units, so that the level of each unit is kept at the set value. Collect the relevant data to observe the dynamic characteristics of each unit and header in this process.

4. Conclusion

A design scheme of M-SMR control system experiment platform and designed a corresponding experimental scheme are proposed here. The dynamic characteristics of M-SMR are obtained by experimental research, and finally a suitable control system is designed. Meanwhile, there are a variety of sensors and actuators in the physical circuit, so the experimental platform can also carry out the fault diagnosis experiment.

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