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Experimental Study of Hydraulic Control Rod Drive Mechanism for Passive IN-core Cooling System of Nuclear Power Plant

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1. Introduction

The control rod drive mechanism is a key device for controlling nuclear reactor power and shut down process. The hydraulic CRDMs have been studying for control rod derive systems that designed using hydrodynamic mechanism including in-vessel system, short hybrid control rod length, safe shut down during station black out condition. Several nuclear power plants already used the hydraulic mechanism for control rod systems. IRIS integral reactor studied the hydraulically driven control rod concept for spider type of PWR control rod system [1]. The pressure discharged hydraulic control rod drive system (HCRDS) was suggested for 200 MW nuclear heating reactor (NHR-200) [2]. CAREM 25 (27 MWe safety systems using hydraulic control rod drives (CRD) studied critical issues that were rod drops with interrupted flow [3]. Hydraulic control rod drive suggested fast shutdown condition using a large gap between piston and cylinder in order to fast drop of neutron absorbing rods.

A Passive IN-core Cooling system (PINCs) was suggested for safety enhancement of pressurized water reactors (PWR), small modular reactor (SMR), sodium fast reactor (SFR) in UNIST. PINCs consist of hydraulic control rod drive mechanism (Hydraulic CRDM) and hybrid control rod assembly with heat pipe combined with control rod. Experimental study involved the force induced system by the pressure difference between the inside and outside horizontally grooved cylinder which controls the elevation of the out cylinder and the hybrid control rod.

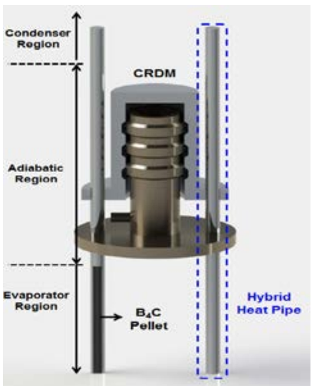

Fig 1. Schematic diagram of the hydraulic CRDM for PINCs

The schematic diagram of the hydraulic CRDM for PINCs is shown in Fig. 1. The experimental results show the steady state and transient behavior of the upper cylinder at a low pressure and low temperature. The influence of the working fluid temperature and cylinder mass are investigated. Finally, the heat removal between evaporator section and condenser section is compared with or without the hybrid control rod.

2. Experimental Equipment

The study deals with the preliminary test of the hydraulic CRDM as the hybrid control rod decay heat removal component. A new type of performance test facility for hydraulic CRDM is designed in 1/12 length scale of 4-finger control rod assembly in APR-1400. The information of test facility is shown in Table. 1.

The experimental equipment includes a circulating pump, flow meter, grooved cylinders, heater and water tank, as shown in Fig. 2. Six thermocouples were installed to measure the temperature in the liquid pool and two pressure gauges were used for measuring the pressure difference between inside and outside grooved cylinder of hydraulic CRDM part. During these tests, refrigerants (R123, FC-72) were used as a working fluid in pressurized condition, which had identical with the density ratio of pressurized water.

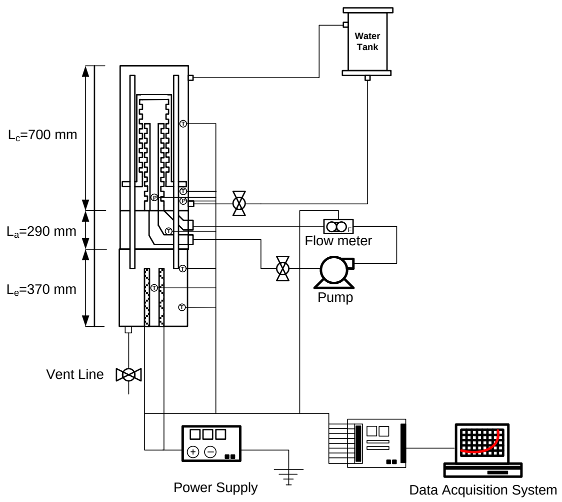

Fig. 2 Schematic diagram of test facility

Table. 1 APR1400 and Test facility information

	APR1400	Test facility	Ratio
Evaporator, Core (mm)	3,810	320	1/11.9
Hybrid control rod length (mm)	12,000	1,000	1/12
O.D. (mm)	20.73	19.05	1/1.08
Thickness (mm)	19.93	18.16	1/1.09
Assembly area (mm^2)	192.8X 192.8	200X 200	1/0.93
Power/Volume (kW/m^3)	187.4	54.2	1/3.46
Hybrid heat pipe (ea)	756	4	1/189
Time (sec)	1	1/3.46	1/3.46

3. Results and Discussion

3.1 Hydraulic CRDM Design

The hydraulic CRDM consist pump, valve, inside and outside grooved cylinder for force induced mechanism. The general hydraulic CRDMs are based on the two of cylinders. The flow between cylinders makes a driving force which controls the hybrid control rod instead of magnetic jack method. The suggested design also has the two cylinder shape and stepped pitches in the flow channel. In order to control the elevation, the revolution speed of pump was changed. To confirm the steady state characteristic such as mass flow rate and pressure difference of each step, CFD analysis is conducted. Obtained flow rate and pressure difference are well matched with experimental results.

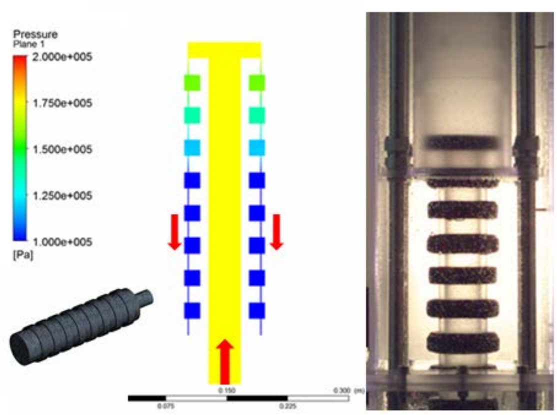

Fig. 3 CFD analysis and test section of hydraulic CRDM

3.2 Step Control with pressure difference

Mass flow path in hydraulic CRDM has very small cross section with stepped shapes for force induced system. The driving force is defined by the pressure difference, the diameter of the outer cylinder and density ratio between inside and outside cylinder (Eq. 1). Fig. 4 shows the mass flow rate and pressure of the inside and outside cylinder. The mass flow rate and pressure maintain stable state in 1-7 steps but final two steps had an unstable and low mass flow rate due to vertical oscillation cylinder.

$$(p_{in} - p_{out}) \cdot \frac{\pi d_{out}^2}{4} = mg(1 - \frac{\rho_{in}}{\rho_{out}}) \qquad (1)$$

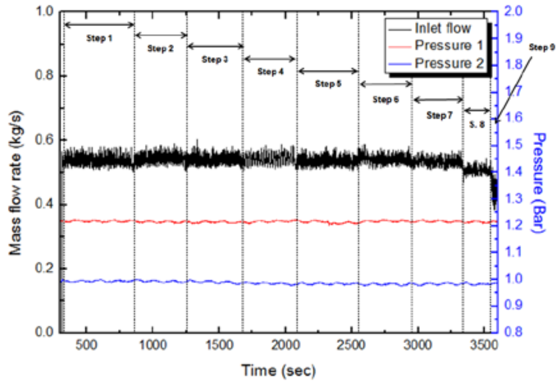

Fig. 4 Inlet mass flow rate and pressure of inside and outside cylinders

3.3 Preliminary Heat Removal Test

During the SBO condition of nuclear power plant, coolant temperature increased about 30 °C from MARS-KS code simulation. The pump and safety injection system cannot operate due to the station blackout and high pressure condition during code simulation. The preliminary test is focused on the heat removal of the hybrid heat pipe using refrigerant. The difference of the specific heat between NPP and test facility was considered for confirming the changes of liquid temperature. Cartridge heaters were used instead of decay heat and overall heat removal of the hybrid control rod was observed. The experimental result shows the temperature change in evaporator pool when the hybrid heat pipe is inserted or not used. The temperature gradient with hybrid control rod is decreased comparison with without hybrid control rod condition. Fig. 5 shows Temperature of evaporator pool and heat transfer coefficient of single hybrid control rod. Before the boiling point of refrigerant (FC-72, 1.3 bars), heat removal of bundle control rod oscillated and very small comparison with its heat removal at high temperature condition.

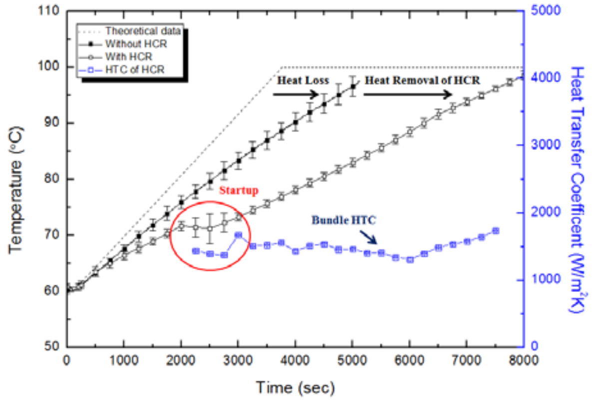

Fig. 5 Temperature of evaporator pool and heat transfer coefficient of bundle hybrid control rod.

4. Conclusions

A new type of hydraulic CRDM was designed and tested for PINCs system. The elevation control system was well controlled at low step region but 8-9 steps had unstable mass flow due to vertical oscillation of cylinder. Heat removal test of the hybrid heat pipe with hydraulic CRDM system showed the heat transfer coefficient of the bundle hybrid control rod and its effect on evaporator pool. The preliminary test both hydraulic CRDM and heat removal system was conducted, which showed the possibility of the in-core hydraulic drive system for application of PINCs.

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