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Detailed Design of the Safety Residual Heat Removal System and a Circulation Pump for the KIJANG Research Reactor

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1. Introduction

The main purpose of a research reactor is to use a neutron flux in a reactor core. Open pool type research reactors are widely designed in consideration of the heat removal of the reactor core, reactor operation and its accessibility. Reactor structure assembly is generally placed at the pool bottom as shown in Fig. 1. Primary cooling system (PCS) circulates the coolant from the reactor core to the heat exchanger. Therefore the heat generated from the fuel assembly in the reactor core is removed continuously. The PCS is designed based on the required thermal design flow rate of the reactor core, uncertainty of measuring instruments and the safe functions.

Primary coolant is generally dumped into the pool and goes to the reactor core through the flow guide. The fission heat generated from the fuel assembly is transferred to the coolant, and then heated coolant goes to the PCS equipment room in order to remove the heat through the heat exchanger. The reactor outlet pipe is connected to the reactor structure as shown in Fig. 1.

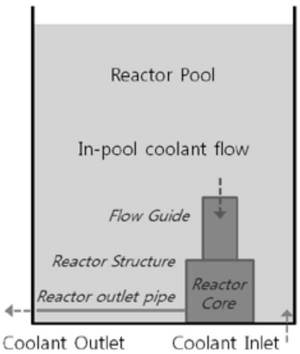

Fig. 1. Schematic diagram of an open-pool type research reactor and a flow path of the coolant.

There is also a safety residual heat removal system (SRHRS) designed to provide the flow through the reactor core to remove the core decay heat in the KJRR. The SRHRS boundary is depicted as shown in Fig. 2. Inlet pipe is connected to the reactor outlet pipe. By-pass pipe comes from the reactor pool directly and is connected to the inlet pipe at the upstream of the pump. Outlet pipe goes back to the reactor pool.

In the reactor operation, the decay heat is removed by the coastdown flow of the PCS pump just after the PCS pumps stop. As the coastdown flow decreases slowly, the SRHRS pumps start automatically to maintain the core downward flow and remove the core decay heat in sufficient time. The core decay heat is transferred by the SRHRS circulation pump into the reactor pool water as the ultimate heat sink.

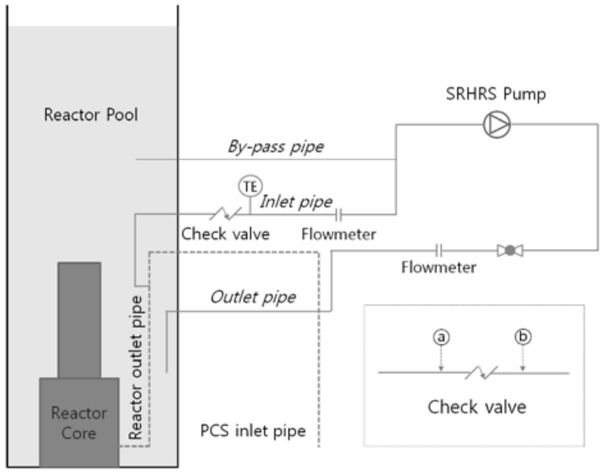

Fig. 2. Schematic diagram of the SRHRS.

2. SRHRS Design

This decay heat removal system is designed to meet the following requirements.

(a) Provide an adequate downward flow through the reactor core to remove the core decay heat.

(b) Abnormal operation of the SRHRS pump shall not affect the normal operation of the reactor and integrity of the system shall be maintained.

The required core flow rate is determined based on the core and safety analyses. A SRHRS pump capacity is calculated from the flow rate and the system design characteristic.

The check valve is installed on inlet pipe as shown in Fig. 2. It is closed by the gravity when the PCS and SRHRS pumps stop. It also keeps the closed status while the PCS pumps are in operation regardless of SRHRS operation because of the differential pressure across the check valve. Static pressure of point ‘a’ is decreased due to the pressure drop while the PCS pump is in operation. The shut-off head of the SRHRS pump is lower than the differential pressure across the check valve while the PCS pump is in operation as shown in Fig. 3. Therefore static pressure of point 'a' is lower than that of point 'b'. This operation constraint shall be applied to the pump design.

Minimum pipe velocity for full disk lift and low pressure loss characteristic are also considered into the check valve and system design.

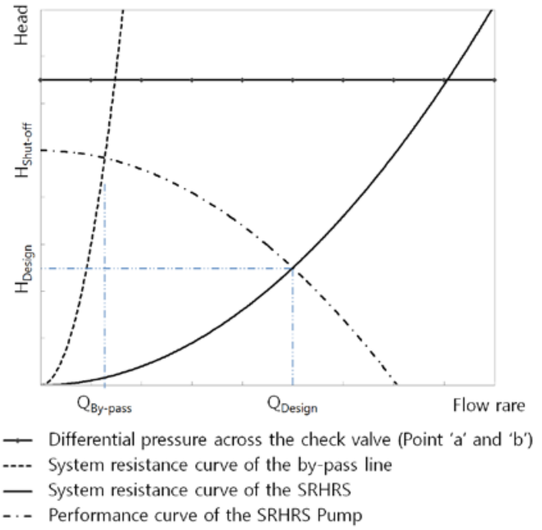

Fig. 3. Relationship between the system resistance curves and the pump performance curve.

3. Pump Design

Pump head, flow rate and $NPSH_A$ are calculated by the system designer and the pump is conceptually designed. Generally, $NPSH_R$, type, size and rpm of the pump are evaluated in early design stage. Conceptual design results of the pump are given in Table 1.

Table 1. Design results of the SRHRS Pump

Case	n_s	d_s	N_{margin}	H_{ratio}	Type
1	0.97	3.33	4	1.4	Centrifugal
2	1.94	2.15	4	1.8	Mixed

3.1 Flow rate

Pump flow rate shall guarantee the minimum required flow rate for the reactor core. Uncertainty of the instruments and design margin are also considered to calculate the rated capacity of the pump.

3.2 Pump by-pass flow rate

By-pass pipe provide the minimum required flow rate to the pump to protect equipment and piping of the system when the pump start to run abnormally while the reactor is in normal operation. In this case, flow path through the inlet pipe is not established because of the closed status of the check valve.

If there is no flow through the pump and pump shaft including the impeller is rotating, it is possible to make a mechanical failure.

3.3 Head and power

Pump head is calculated from the flow rate and system resistance characteristics.

Pump water horse power (WHP) is calculated from the following equation.

$$P_{whp} = \rho \cdot Q_d \cdot g \cdot H_d$$

Pump break horse power (BHP) is calculated from the pump hydraulic efficiency and WHP.

$$P_{bhp} = P_{bhp}/\eta_{pump}$$

Safety graded electricity is fed into the pump motor in this system as shown in Fig. 4. Pump is designed to minimize the power consumption of the pump.

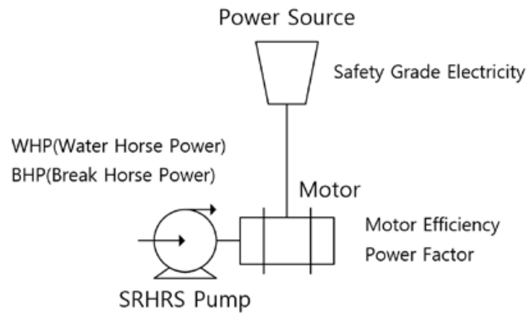

Fig. 4. Schematic diagram of the pump and power source.

3.4 Cavitation

Cavitation of the pump makes the mechanical damage of the impeller, strong vibration and loud noise. In order to maintain the normal operation of the pump without cavitation, the $NPSH_A$ shall be larger than the $NPSH_R$. Operation margin related to cavitation is generally expressed as a ratio of the $NPSH_A$ and $NPSH_R$. Pump used in the nuclear plant requires a NPSH margin of 2. NPSH margin shall be verified by the test.

3.5 Pump operation

Design results of the normalized NPSHre, head, BHP for the SRHRS pump are shown in Fig 5~7.

The normalized differential pressure across the check valve is 2 when the PCS pumps are in normal operation and the SRHRS pumps stop. Therefore the flow path through the inlet pipe shall not be established because the normalized differential pressure across the check valve is larger than the SRHRS pump shut-off head as shown in Fig. 6 and so SRHRS pump operation does not disturb the reactor operation. In this operation, pump will run with the by-pass flow rate through the by-pass pipe in order to protect pump, equipment and piping of the SRHRS.

Case 1 and 2 pumps satisfy the design constraint of the SRHRS. But, it's impossible to accept the pump design of Case 2 because of following reasons.

(a) Insufficient design margin: The differential pressure across the check valve is too close to the pump shut-off head. It might cause the chattering of the valve disk.
(b) NPSHre: NPSHre is increased at the low flow as shown in Fig. 5. This is the characteristic of the mixed pump. NPSHre shall be tested and verified.
(c) BHP : BHP is almost same from the zero flow to the rated flow as shown in Fig. 7. High BHP at the low flow rate means the unstable operation characteristic.

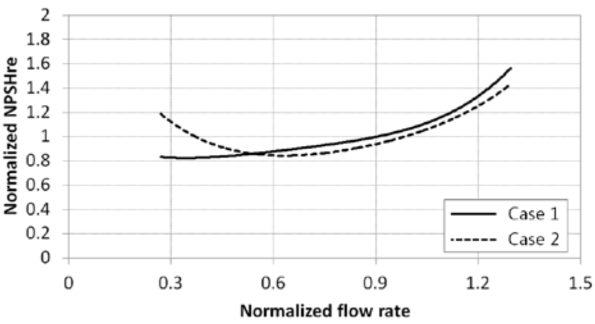

Fig. 5. Normalized NPSHre with the flow rate.

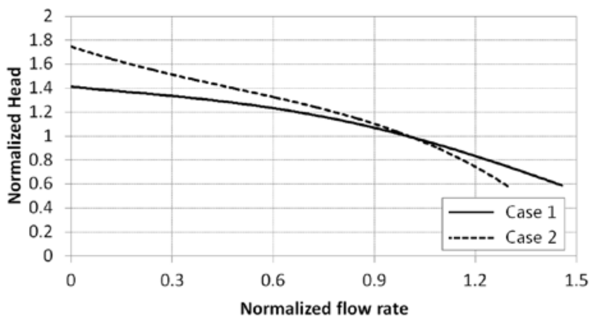

Fig. 6. Normalized head with the flow rate.

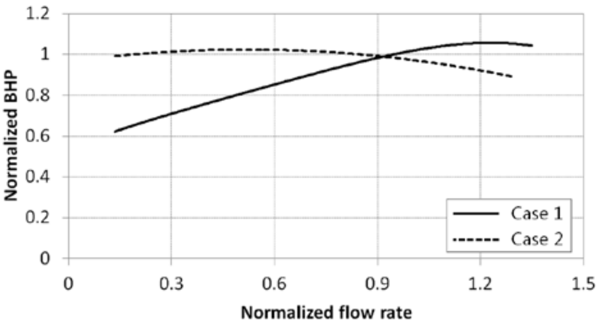

Fig. 7. Normalized BHP with the flow rate.

4. Conclusions

SRHSR is designed based on the required flow rate and system constraints. Centrifugal pump of Case 1 with a non-dimensional specific speed of 0.97 [-] and specific diameter of 3.33 [-] is chosen as the SRHRS pump for the KJRR.

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Nomenclature

d_s	Specific diameter, $D\cdot(g\cdot H_d)^{0.25}/Q_d^{0.5}$, [-]
g	Acceleration of gravity, 9.81[m/s^2]
n_s	Specific speed, $\omega\cdot Q_d^{0.5}/(g\cdot H_d)^{0.75}$, [-]
D	Diameter of the impeller outlet, [m]
H_d	Pump head at the design point, [m]
H_N	Normalized Pump head, H/H_d [-]
H_{ratio}	$H_{shut\text{-}off}$ / H_d, [-]
$H_{shut\text{-}off}$	Pump head at the zero flow rate(shut-off head), [m]
N_{margin}	$NPSH_A$ / $NPSH_R$, [-]
NPSH	Net Positive Suction Head, [m]
$NPSH_A$	Available NPSH, [m]
$NPSH_D$	Required NPSH at the design point, [m]
$NPSH_N$	Normalized NPSH, $NPSH_R$/ $NPSH_D$ [-]
$NPSH_R$	Required NPSH, [m]
P_d	BHP at the design point, [m^3/s]
P_N	Normalized BHP, Q/ Q_d [-]
Q_d	Flow rate at the design point, [m^3/s]
Q_N	Normalized Flow rate, Q/ Q_d [-]
ω	angular velocity of the impeller, [rad/s]
η_{pump}	Pump hydraulic efficiency, [-]