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Performance Evaluation of an Active Residual Heat Removal System for Research Reactor

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ABSTRACT

In a loss of forced flow for research reactors with high thermal power, the decay heat cannot be removed sufficiently by the inertial flow of the primary cooling pumps or a passive core cooling system because the decay heat is still high after a reactor trip. Therefore, the reactor needs the active core cooling system. The performance evaluation of an active residual heat removal system (ARHRS) is carried out for a research reactor with a downward core flow and thermal power of 15 MW. The evaluation is performed to determine the required core flow by the ARHRS and operation time of the ARHRS when the forced primary flow is lost using the RELAP5/MOD3.3 code and the CHF correlations proposed by Sudo and Kaminaga. As a result of the evaluation, it was found that the core flow by the ARHRS should be maintained over 130 kg/s for 30 minutes to enhance the safety margin.

1. Introduction

In a research reactor, the core is cooled by forced convection driven by the primary cooling pumps (PCPs) during normal operation. However, if a loss of forced flow occurs due to failure of the PCPs, the residual heat in the core should be removed by the inertial flow driven by the PCP flywheels or another active cooling system until it decreases to the sufficiently low level. After the stop of the PCP flywheels and the active cooling system, the core can cool down appropriately by natural circulation flow through the reactor pool.
The core cooling concept depends on the initial thermal power level of research reactors. Research reactors with low thermal power can accomplish core cooling safely with an only inertial flow driven by the PCP flywheels. In research reactors with high thermal power, however, the inertial flow is insufficient to remove the residual heat and the fuel integrity can be threatened while the core flow is switched from a downward flow to an upward flow [1].
Therefore, the research reactor with high thermal power should have an active residual heat removal system (ARHRS) to achieve the appropriate core cooling after a loss of forced flow.

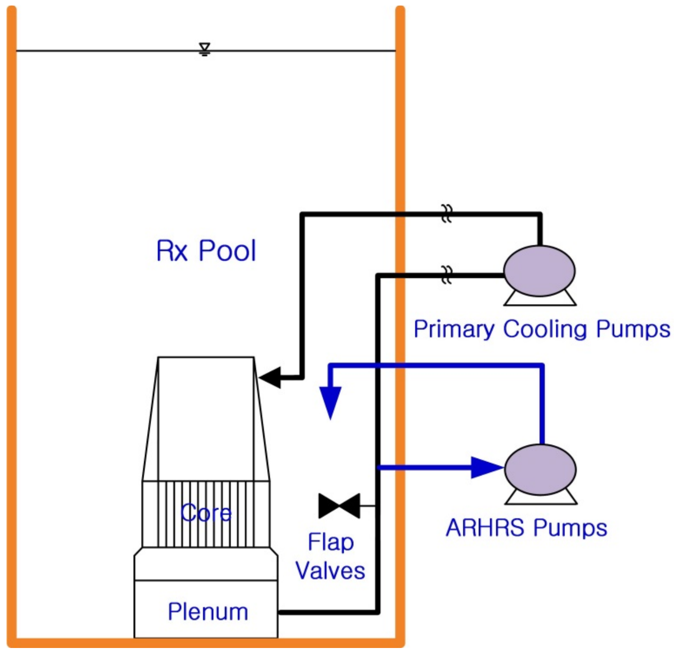

Figure 1. Schematic diagram of an active residual heat removal system

The ARHRS has additional active pumps to maintain the downward coolant flow after the PCPs stop. The ARHRS is composed of an active pump and pipe-line, as shown in Figure 1. The ARHRS inlet line is connected to the reactor outlet pipe and the outlet pipe line of the ARHRS goes back to the reactor pool.

The ARHRS pumps are in a standby during normal operation. If the PCPs stop because of electrical or mechanical failure, the residual heat is removed by the flow induced by the inertia force of the flywheels attached to the PCPs. As the inertia flow by the flywheels decreases slowly, the ARHRS pumps start to run and maintains the downward core flow. Then the core decay heat is removed by the ARHRS pumps until the decay heat decreases to the level being cooled by natural circulation. After the ARHRS pumps are stopped, the flap valves installed on the reactor outlet pipe inside the reactor pool open passively. The natural circulation loop through the valves is established and the decay heat in the core is removed into the reactor pool.

The power of ARHRS pumps should be supplied from a diesel generator or a battery designed as nuclear safety class to guarantee the safety function of the ARHRS after a loss of normal electric power. In addition, to accomplish the core cooling safely, the ARHRS should be satisfied with the performance requirements such as the required flow rate and operation time of the ARHRS.

In this paper, the performance evaluation of the ARHRS is carried out for the research reactor with a thermal power of 15 MW.

2. Methods

When a forced flow is lost due to any reasons, the PCPs begin to coastdown and the core flow decreases sharply. If the core flow is not maintained sufficiently after a loss of forced flow, the fuel will be damaged because of an insufficient cooling flow through the fuel channels. Therefore, to prevent fuel damage, the performance requirements should be considered as follows:

- Phase 1: after the PCPs stop and before the reactor trips
- Phase 2: during the ARHRS pumps operation

In Phase 1, the inertial flow driven by the PCP flywheels should be maintained sufficiently until the reactor is tripped and the ARHRS pumps are operated. In Phase 2, the ARHRS pumps should be operated for a sufficiently long time to maintain the downward core flow until the decay heat decreases to a low level. In this study, the required flow and operation time of the ARHRS in accordance with each phase are evaluated.
In design of a research reactor, a critical heat flux ratio (CHFR) and fuel temperature are the major safety parameters to determine the fuel integrity during normal operation and abnormal operation. In this evaluation, the CHFR is taken into consideration to determine the fuel integrity. The CHFR is mainly affected by the local heat flux and critical heat flux (CHF) at the fuel plates. The local heat flux at the fuel plates depends on the reactor power and the CHF on the thermal hydraulic parameters such as mass flux, flow direction, coolant temperature and pressure. In this study, a thermal hydraulics analysis has been performed using the RELAP5/MOD3.3 code [2] and the CHF was calculated by the CHF correlations proposed by Sudo and Kaminaga [3].

2.1 RELAP5/MOD3.3 Model

In order to investigate the ARHRS performance, a research reactor with a thermal power of 15 MW is modeled using the RELAP5/MOD3.3 code. This model includes the reactor pool, reactor core, primary cooling system and ARHRS.
The initial operating parameters such flows, temperatures, power level and distribution, etc. are assumed to be the most limiting values in safe operating conditions. The reactor protection system initiates reactor trip with an appropriate response delay when the trip set points are exceeded. The transient reactor power is calculated using the point kinetics model and the ANS-73 decay curve [4] is used. The reactivity feedback effects by the fuel and coolant temperatures are not considered during the transient.

2.2 CHF Correlations

The CHF has been calculated using the CHF correlations proposed by Sudo and Kaminaga. The CHF correlations were developed for a narrow and vertical rectangular channel.
The scheme of the CHF correlations is illustrated in Figure 2. The CHF correlation set consists of three separate correlations based on the mass flux regions and flow directions. The mass flux regions are categorized by a dimensionless mass flux (G^*):

$$G^* = \frac{G}{\sqrt{\lambda(\rho_l - \rho_g) g \rho_g}}, \tag{1}$$

where
- G: Mass flux (kg/m^2-s)
- $\rho_{g,}$ ρ_l: Density of gas and liquid (kg/m^3)
- g: Acceleration of gravity (m/s^2).
- λ: critical wavelength, defined as

$$\lambda = \left[\frac{\sigma}{(\rho_l - \rho_g) g}\right]^{0.5} \tag{2}$$

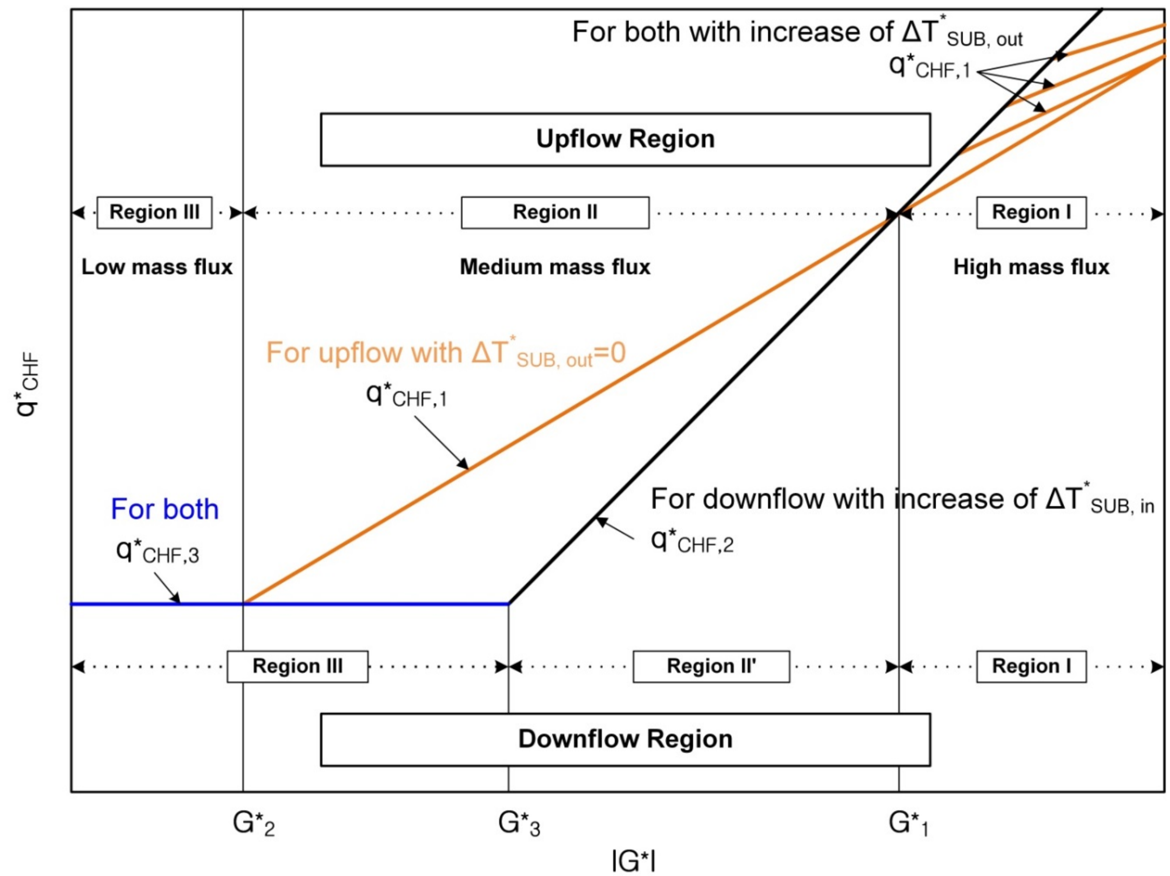

Figure 2. Scheme of CHF correlations proposed by Sudo and Kaminaga

where σ is surface tension (N/m).

According to the mass flux regime and flow direction, the CHF correlations are expressed as follows:

$$\mathrm{q}^*_{CHF,1} = 0.005|G^*|^{0.611}\left(1 + \frac{5000}{|G^*|}\Delta T^*_{sub,o}\right) \tag{3}$$

$$\mathrm{q}^*_{CHF,2} = \frac{A_f}{A_h} \cdot |G^*| \cdot \Delta T^*_{sub,i} \tag{4}$$

$$q^*_{CHF,3} = 0.7\frac{A_f}{A_h}\frac{\sqrt{W/\lambda}}{\left\{1+[\rho_g/\rho_l]^{0.25}\right\}^2} \tag{5}$$

$$\mathrm{q}_{CHF} = \mathrm{q}^*_{CHF} h_{fg}\sqrt{\lambda(\rho_l - \rho_g)g\rho_g} \tag{6}$$

where

- A_f: Flow area (m^2)
- A_h: Total heated area of a fuel plate (m^2)
- W: Channel width of channel (m)

- C_{pf}: Specific heat at constant pressure of the liquid (kJ/kg-K)
- h_{fg}: Latent heat of vaporization (kJ/kg).

The dimensionless subcooling temperature at the inlet or the outlet is defined as

$$\Delta T^*_{sub} = \frac{C_{pf} \cdot \Delta T_{sub}}{h_{fg}} \tag{7}$$

In the high mass flux region, the CHF is predicted by $q^*_{CHF,1}$ for both flow directions depending on an increase of $\Delta T^*_{sub,o}$. However, the maximum value is limited to $q^*_{CHF,2}$. In the region of the medium mass flux, $q^*_{CHF,2}$ is applied for the downward flow condition and $q^*_{CHF,1}$ with $\Delta T^*_{sub,o} = 0$ is considered for the upward flow condition. $q^*_{CHF,3}$ is used for both flow directions in the low mass flux region where the CHF appears by the countercurrent flow limitation.
Finally, the CHFR is calculated as

$$CHFR = \frac{q_{CHF}}{q_{RELAP5} \cdot F^E_q} \geq 1.5 \tag{8}$$

where q_{RELAP5} is the heat flux predicted by the RELAP5/MOD3.3 code and F^E_q is the engineering hot channel factor for the heat flux considering the uncertainties due to ^{235}U non-homogeneity and ^{235}U non-uniform loading per fuel plate. Sudo and Kaminaga suggested that the minimum CHFR should be larger than 1.5 in using their CHF correlation set [3]. In this study, the engineering hot channel factor and the safety limit of the CHFR, $CHFR_{limit}$, are assumed to be 1.2 and 1.5, respectively.

3. Results and Discussions

3.1 Required Core Flow

When the PCPs are stopped due to failure of the PCPs, the PCPs begin to coastdown and the core flow also decreases according to the inertia force of each PCP flywheel. This results in a reactor trip by the low core differential pressure or the low primary coolant flow. Before the reactor is tripped and the ARHRS pumps are operated (Phase 1), the core flow induced by the inertial force of the PCP flywheels should be maintained sufficiently to satisfy the safety limit of the CHFR.
Because the mass flux is between G^*_1 and G^*_3 during the Phase 1, the CHF is calculated by $q^*_{CHF,2}$. Therefore, at Phase 1, the required core flow is predicted by Equation (9) rearranged from Equations (4) and (8):

$$G \geq \frac{q_{RELAP5} \cdot F^E_q \cdot CHFR_{limit}}{\frac{A_f}{A_h} \cdot C_{pf} \cdot \Delta T_{sub,i}} \tag{9}$$

If $\Delta T_{sub,i}$ is a constant, to ensure the safety limit of the CHFR, the core flow should be maintained greater than 275 kg/s at least for the research reactor with a thermal power of 15 MW during Phase 1.

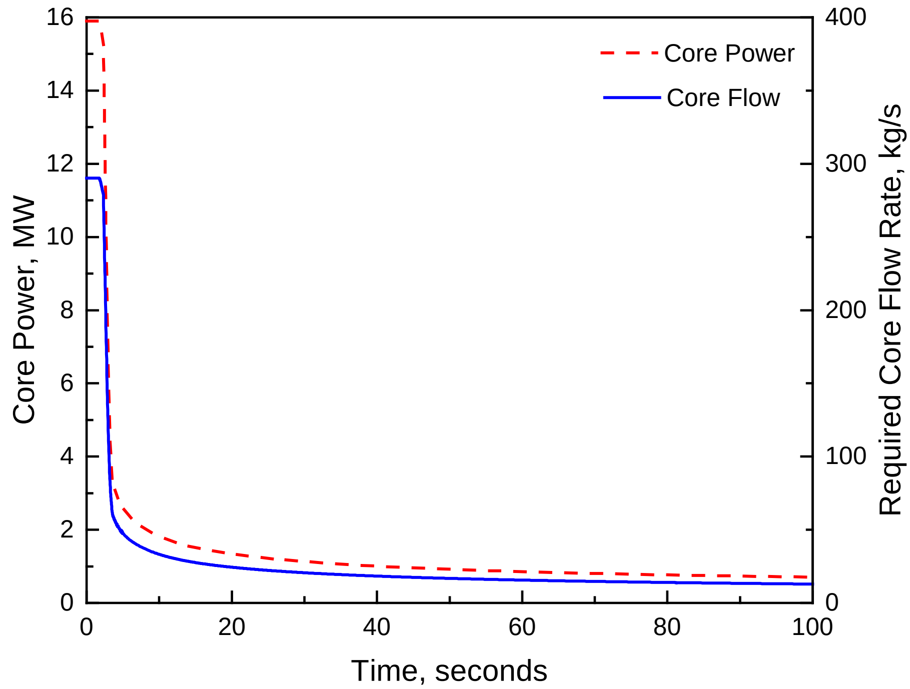

Figure 3. Required core flow with the core power history

As the ARHRS pumps are operated after the reactor is tripped, the means of the core cooling is switched from the PCPs to the ARHRS pumps. During the ARHRS operation (Phase 2), the core flow by the ARHRS pumps should be maintained sufficiently for a long time to satisfy the safety limit.

Since the mass flux regime is G_1^* and G_3^* during Phase 2, the required core flow is calculated by Equation (9). During Phase 2, the required core flow depends on the heat flux in the core because the core power decreases due to a reactor trip.

After the reactor trip, Figure 3 shows the minimum required core flow, which is predicted by Equation (9) to satisfy the CHFR safety limit of 1.5. The required core flow decreases as the core power decreases after the reactor trip. Therefore, to enhance the safety margin, the core flow should be maintained over the minimum required core flow after a loss of forced flow.

3.2 Required Operation Time of ARHRS

The ARHRS pumps are operated appropriately in the case of a loss of normal electric power because the electrical power of the pumps are supplied from the battery designed as the nuclear safety class. However, if the ARHRS pumps are stopped because of the limitation of the battery capacity, the core flow direction is switched from the downward flow to the upward flow due to the buoyancy force driven by the core decay heat. At that time, the fuel integrity might be threatened without sufficient core cooling flow. Therefore, the ARHRS pumps should be operated for sufficient time to ensure the fuel integrity until the core decay heat reaches below a low level that can be removed by natural circulation.

Since the CHF is limited to $q_{CHF,3}^*$ in the low mass flux region between G_3^* and G_2^*, as shown in Figure 2 regardless of the flow direction, the limited CHF is predicted to be around 60kW/m^2 from Equations (5) and (6). In addition, the maximum heat flux predicted from Equation (8) including the heat flux hot channel factor is around 30kW/m^2.

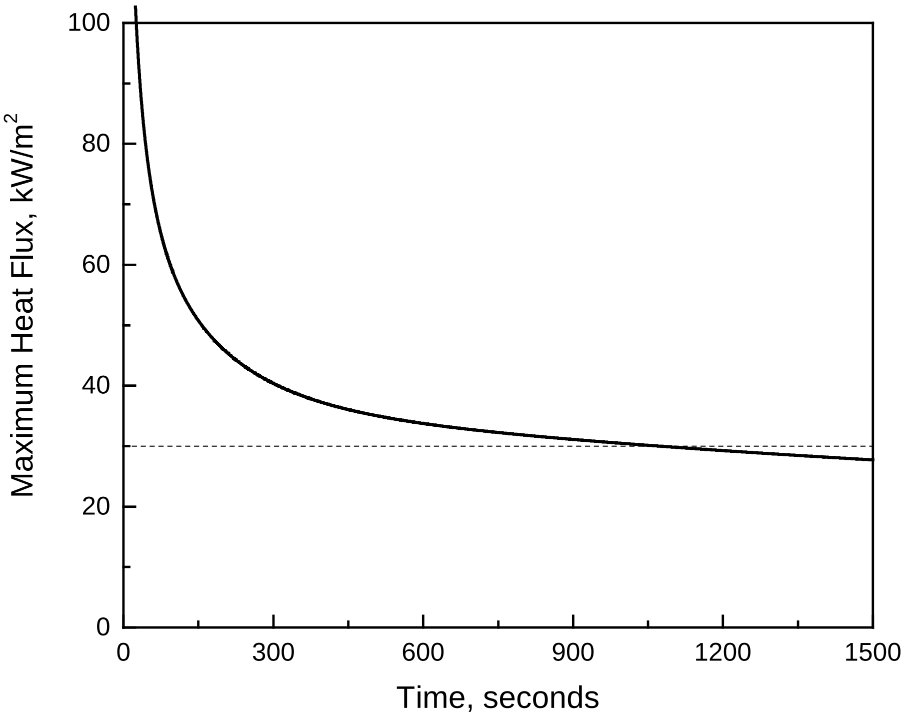

Figure 4. Behavior of the maximum heat flux after reactor trip

This means that the downward core flow should be maintained until the maximum heat flux reaches below around 30kW/m^2 to satisfy the safety limit of the CHFR.
Figure 4 shows the maximum heat flux after the reactor trip. The maximum heat flux reaches 30kW/m^2 at around 1,100 seconds, i.e., the downward core flow should be maintained by the ARHRS pumps for 1,100 seconds after the reactor trip. To enhance the safety margin, however, the operation time of the ARHRS should be determined considering additional uncertainties.

3.3 Performance Evaluation of ARHRS

Sensitivity calculations were carried out based on the required core flow by the ARHRS and operation time of ARHRS for a loss of forced flow event.
When the forced flow is lost due to a failure of the PCPs, the PCPs begin to coastdown as the inertia force of the flywheels and core flow decrease. The reactor protection system is activated with a delay by the low core differential pressure or the low primary flow, and the control rods then drop to the core. When the primary flow reaches the prescribed set point after the reactor trip, the ARHRS pumps are operated to remove the core decay heat for a certain period of time. After the ARHRS pumps are stopped, the flap valves installed on the reactor outlet pipes inside the reactor pool open passively. The core flow direction is switched from a downward flow to an upward flow and natural circulation is developed through the flap valves by buoyancy force driven by the decay heat generated in the core.
Figure 5 shows the behavior of the core flow versus the capability of ARHRS. In this calculation, since the PCP coastdown flow is assumed to sufficiently cover the required core flow before the reactor trip, the core flows according to the ARHRS capability are the same before the ARHRS pumps are operated. In addition, the core flows driven by the ARHRS are assumed to be maintained over the required core flow.

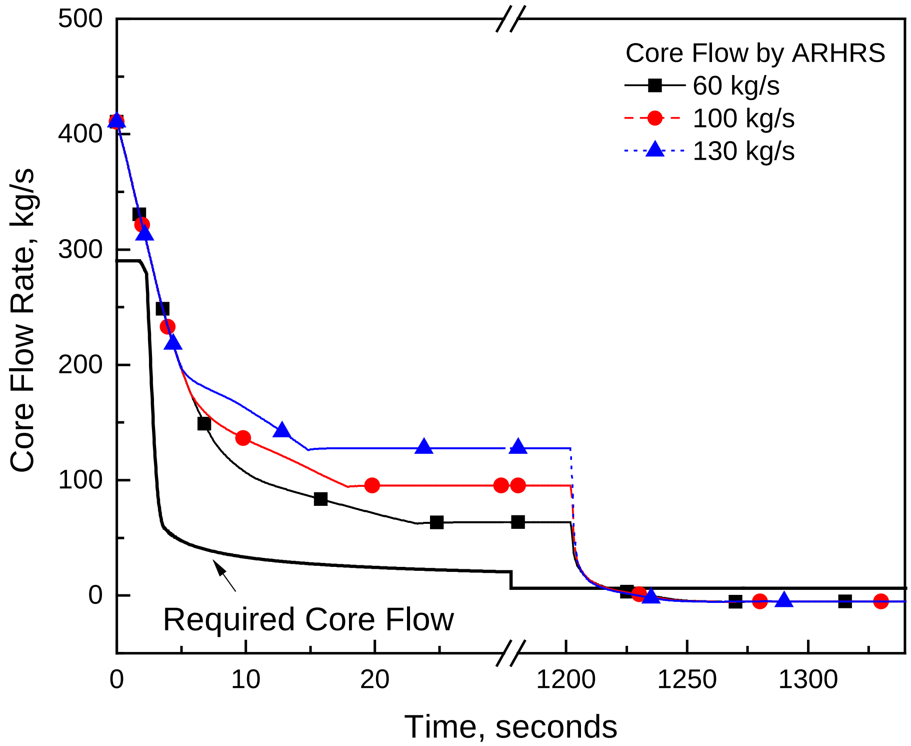

Figure 5. Core flows versus ARHRS capability

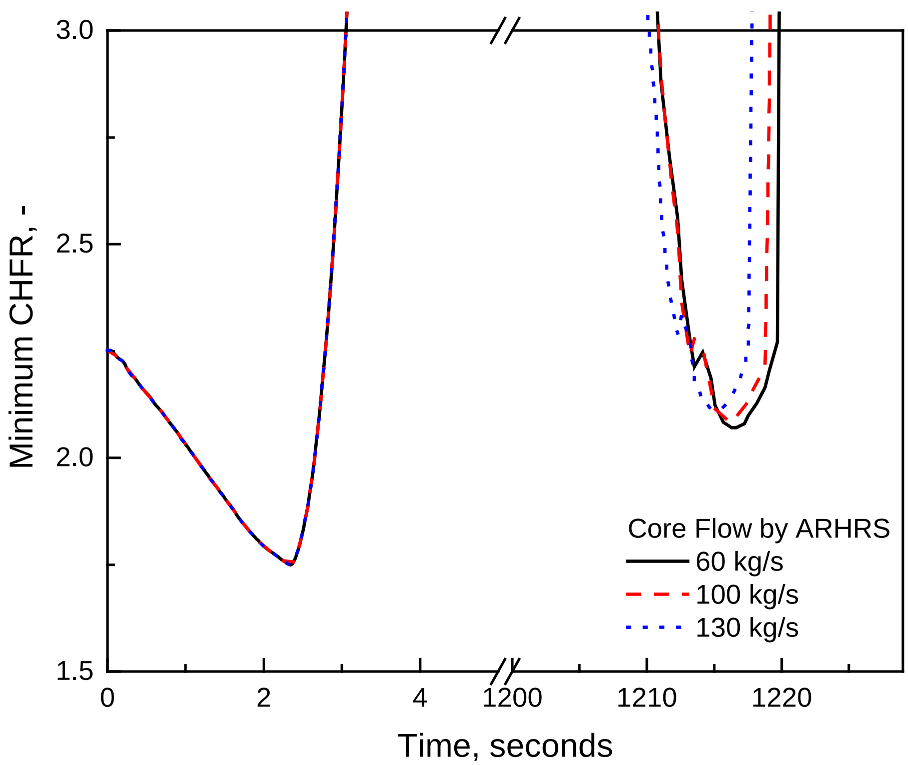

Figure 6. Minimum CHFRs versus ARHRS capability

Figure 6 shows the minimum CHFRs with the ARHRS capability at the time of the reactor trip and the core flow reversal, respectively.

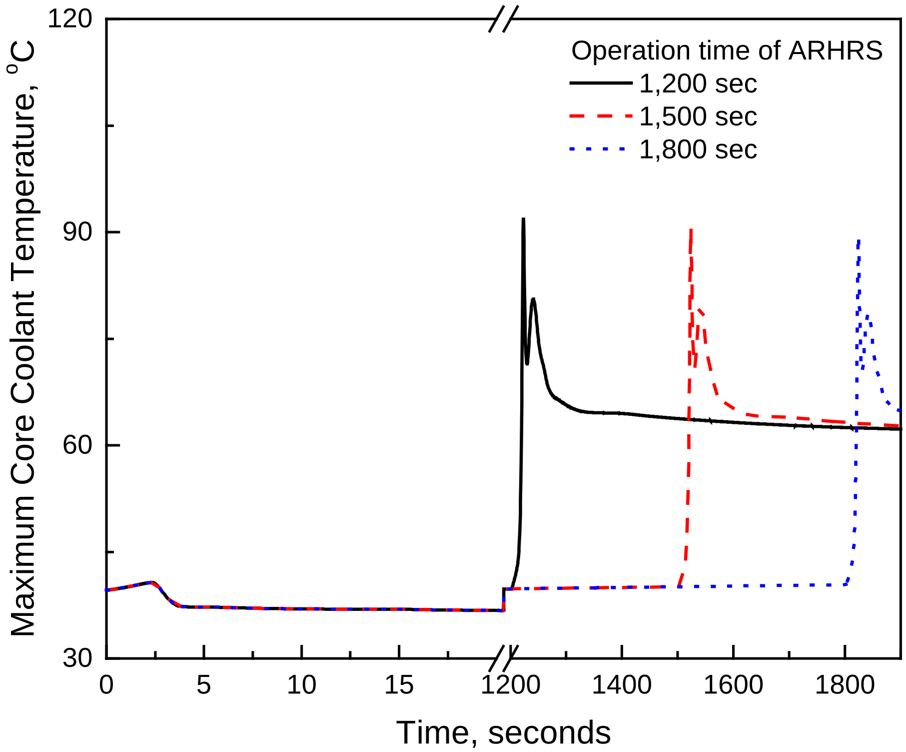

Figure 7. Maximum coolant temperatures versus operation time of ARHRS

The minimum CHFRs are the same and satisfy the safety limit of the CHFR before the reactor trip because the core flows are the same according to the ARHRS capability. After the reactor trip, the minimum CHFRs depend on the ARHRS capability but they are still greater than the safety limit of the CHFR because the core flows driven by the ARHRS are greater than the required core flow.

However, when the core flow driven by the ARHRS is 60 kg/s, the flap valves would be opened because the suction force driven by the ARHRS pumps is low. If the flap valves open, the core flow is reduced because the coolant is bypassed though the valves. In the case of the core flow of 100 kg/s driven by the ARHRS, if one ARHRS pump does not operate during the loss of forced flow event by single failure criterion, the flap valves also would be opened.

The opening of the flap valves could result in a reduction of the CHFR. Therefore, to prevent the opening of the flap valves, the core flow driven by the ARHRS should be greater than 130 kg/s.

Figure 7 shows the maximum coolant temperatures at the flow channel with the operation time of the ARHRS. As the operation time of the ARHRS increases, the maximum coolant temperature at the flow channel decreases during the flow reversal in the core because of the lower decay power. It was found that the ARHRS pumps should be operating for a sufficiently long time to enhance the subcooling margin during the flow reversal.

4. Conclusions

Performance evaluations of the ARHRS were performed for a research reactor with a downward flow and a thermal power of 15 MW when a loss of forced flow occurs. The RELAP5/MOM3.3 code and the CHF correlations proposed by Sudo and Kaminaga are used in this evaluation.

It was found that the core flow should be maintained over 275 kg/s driven by the PCPs to satisfy the safety limit of the CHFR until the reactor is tripped and that the required core flow driven by the ARHRS depends on the core power after a reactor trip. In addition, the ARHRS should be operated for 1,100 seconds at least after the reactor trip to ensure the safety limit of the CHFR. However, the core flow driven by the ARHRS should be maintained at over 130kg/s and the ARHRS should be operated for about 30 minutes to enhance the safety margin.

As a further study, a performance evaluation of the ARHRS will be carried out for research reactors with various thermal powers and flow channel geometries.

5. Acknowledgement

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6. References

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