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Feasibility of Thermoelectric Waste Heat Recovery from Research Reactor

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1. Introduction

A research reactor wastes all the heat generated from the core to environment, since the reactor only utilize the high density neutron source. Nevertheless, no waste heat recovery from research reactor has been suggested so far, because of the absence of proper waste heat recovery method applicable to the research reactors which is usually operated in low temperature. A thermoelectric generator has the most competitive method to regenerate the waste heat from research reactors, because it has no limitation on operating temperature [1]. In addition, since the TEG is a solid energy conversion device converting heat to electricity directly without moving parts, the regenerating power system becomes simple and highly reliable.

In this regard, a waste heat recovery using thermoelectric generator (TEG) from 15-MW pool type research reactor is suggested and the feasibility is demonstrated. The producible power from waste heat is estimated with respect to the reactor parameters, and an application of the regenerated power is suggested by performing a safety analysis with the power.

2. Waste Heat Recovery from Research Reactor

Figure 1 shows the system schematic of 15-MW in-pool type research reactor. The reactor system has primary cooling loop composed of a decay tank and three trains of pumps and heat exchangers. Two of three trains are operational and the remaining one is standby. Two trains of safety residual heat removal system (SRHRS) are in preparation to remove the decay heat from the core when the reactor trips and the primary cooling pump stops.

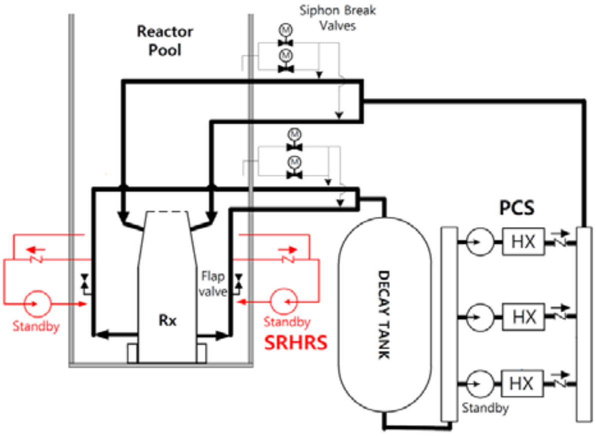

Fig. 1 Schematic of 15-MW pool type research reactor

In the research reactor, the waste heat can be regenerated at the primary heat exchanger (HX), since the coolant heated at the reactor core transfers the heat to the secondary cooling system through the HX. The heat transferred to the secondary cooling system dissipates heat to environment.

Figure 2 shows the efficiency of TEG module and the producible power according to the log mean temperature difference (LMTD) across the primary and secondary side of HX. The design LMTD is 2 K, at which the efficiency of TEG is about 0.3% and 0.2% when assuming the thermoelectric figure of merit (ZT) is 2 and 1, respectively. In practical, the ZT of commercially available TEG is about 1 [2]. However, the efficiency of TEG increases as the LMTD increases, and the producible power also increases. At LMTD of 20 K, the efficiency of TEG with ZT=1 becomes about 1.1% and the power recovered from TEG is 164 kW.

Figure 3 shows the required heat transfer area of HX and the minimum critical heat flux ratio (MCHFR) with respect to LMTD. The MCHFR is the measure of fuel integrity and is maintained sufficiently higher than the safety requirement even increasing the LMTD upto 20 K. Also, the required heat transfer area of HX becomes comparable with original HX design which is indicated with red dot, whereas the area is impractically large with small LMTD because of the low thermal conductivity of TEG.

Therefore, by increasing the LMTD from 2 to 20 K, the efficiency and producible power from TEG increases and the heat transfer area of HX decreases to reasonable value without losing the reactor safety much.

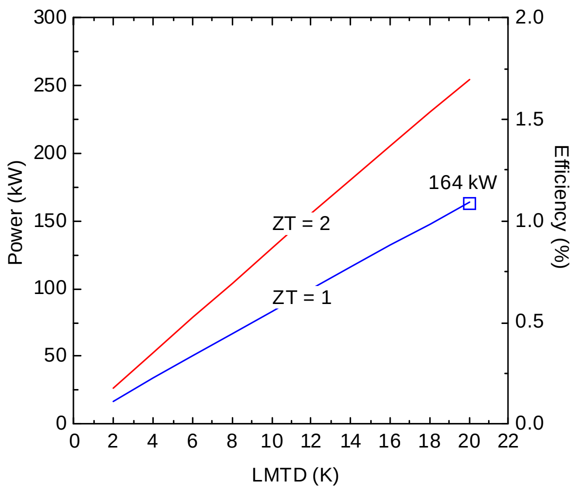

Fig. 2 Power and efficiency of waste heat recovery system with respect to heat exchanger LMTD

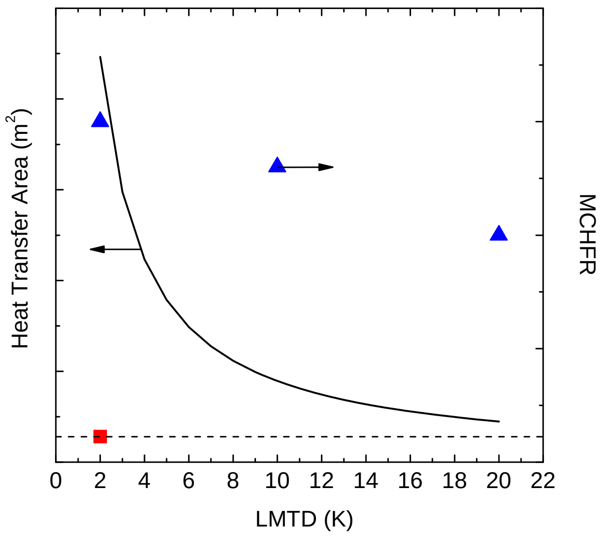

Fig. 3 Heat transfer area of heat exchanger and corresponding MCHFR during normal operation with respect to LMTD

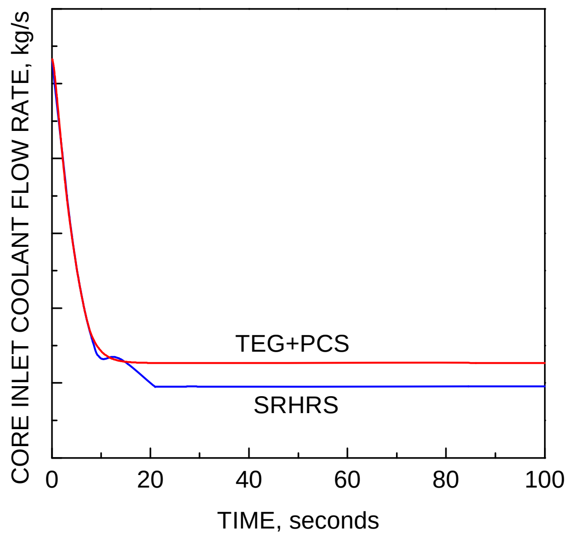

Fig. 4 Core flow rate during loss of electric power events by SRHRS and by PCS with TEG waste heat recovery

3. Safety Analysis with Regenerated Power

The regenerated power by TEG at the primary heat exchanger of the research reactor is assumed to be used for operating the safety equipment to mitigate the consequences during an accident condition. The TEG is highly reliable and fast in initiation compared to the conventional diesel generator of emergency power system, it can provide immediate power to the safety system to mitigate the accident consequences [3].

A loss of electrical power to the PCS pumps is selected as a sample problem to demonstrate the feasibility of the regenerated power in an accident situation. When the electrical power to the pumps is lost by accident, the pumps start to coast down by their own inertia. In original event sequences, the SRHRS pumps start to operate soon to supply the core flow instead of the PCS pumps.

However, with the TEG waste heat recovery, the regenerated power supply power to the PCS pumps and then the pumps cools the reactor core instead of the SRHRS, simplifying the reactor system for residual heat removal. Since the regenerated power from TEG is not sufficient to fully operate the primary cooling system, the flow rate of the primary cooling pumps decreases. Then, the regenerated power decreases because heat exchange rate at the HX decreases. Therefore, the possible flow rate and the producible power are calculated iteratively considering the pump and the motor characteristics with respect to the power generation from HX.

Although the reactor is tripped by the low flow trip signal of the reactor protection system when the accident starts, the decay tank at the reactor outlet stores a large amount of hot water and supplies it to the HX for power regeneration until the tank is filled with the cold water after the reactor trip. The time of power supply is sufficient for cooling the core until the decay heat of the core decreases to the level coolable by natural circulation. After the power from TEG is depleted, the primary cooling pumps stop and the decay heat is cooled by natural circulation.

Figure 4 and 5 shows the minimum critical heat flux ratio and the maximum fuel temperature during the event either with SRHRS or with PCS and TEG power regeneration. The MCHFR decreases from the accident initiation and reaches the minimum at the reactor trip. Then, the MCHFR remains sufficiently high after the reactor trip. Similarly, the maximum fuel temperature reaches the maximum at the reactor trip. The MCHFR and the maximum fuel temperature are almost identical in both cases, since they are determined by the pump coastdown characteristics rather than the method of residual heat removal. The reactor is safely shut down and the fuel integrity is ensured in both cases, since the decay heat from the core decreases sufficiently low and it is cooled by natural circulation after the power from TEG is depleted.

Although the efficiency and cost for waste heat recovery is quite limited in the research reactor, the TEG system is still competitive when it is used as a safety system, which is relatively cost-independent compared with the other application. The safety grade emergency diesel generator usually has drawbacks in cost and availability.

Further optimization of the waste heat recovery system is also need to be followed to enhance the overall efficiency and system performance. For example, adapting passive cooling method at the secondary cooling system reduces required power for power regeneration during an abnormal situation. Also, changing the arrangement of HX to be serial along primary cooling system enables more power to be regenerated even when one pump fails to operate, and also increases system reliability of waste heat recovery.

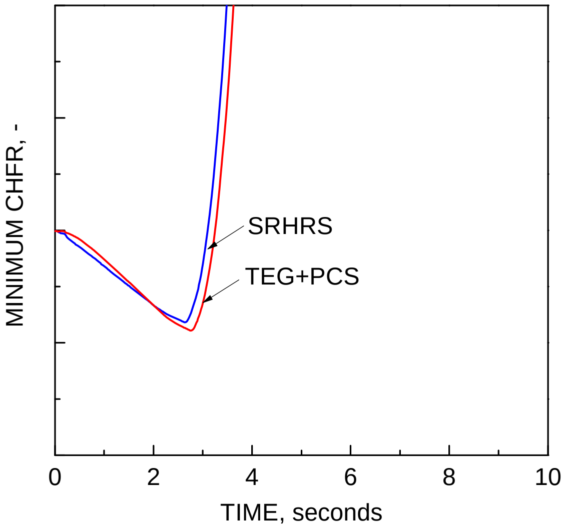

Fig. 4 MCHFR during loss of electric power events by SRHRS and by PCS with TEG waste heat recovery

5. Conclusions

A feasibility of thermoelectric waste heat recovery from a 15-MW in-pool type research reactor is demonstrated by assuming the installation of TEG at the primary heat exchanger of the reactor. The producible power from TEG is estimated with respect to the LMTD of the HX and the required heat exchange area is also calculated. By increasing LMTD from 2 K to 20K, the efficiency and the power increases greatly.

Also an application of the power regeneration system is suggested by performing a safety analysis with the system, and comparing the results with reference case without the power regeneration. The reactor safety is ensured with the applicability of the system in safety analysis.

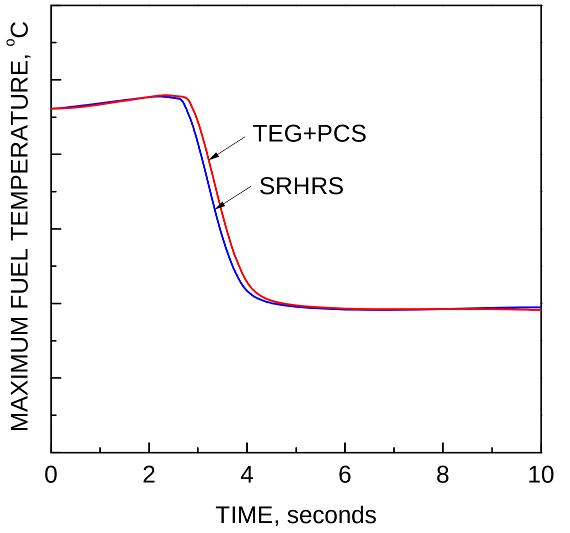

Fig. 5 Maximum fuel temperature during loss of electric power events by SRHRS and by PCS with TEG waste heat recovery

Acknowledgement

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