Development of waste heat recovery system from transformer with Bi-Te thermoelectric modules

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Abstract

Generally, waste heat below 423 K is not recovered due to technical difficulties or high cost. However, low temperature waste heat exists in many places such as factories, etc. If recovery of such heat becomes possible, the contribution to carbon dioxide reduction could be immeasurable. The authors propose to improve overall transformer efficiency by utilizing the waste heat using system development technologies for tap water and sewer facilities, buildings, public facilities, roads, railway, etc.

This study is aimed at optimizing power generation conditions such as pressure to fix a thermoelectric module on the transformer casing, shape of cooling fins, kinds of thermal conductive resin utilized as adhesive, etc., in order to increase the efficiency of waste heat recovery from the transformer. This paper reports simulation results of experiments to determine power generation characteristics of a thermoelectric module under various conditions, etc.

The experiments were conducted while simulating transformer casing temperature (about 353 K) using the system developed by the authors. The experimental results and the equations of casing temperature and generated power confirmed that the temperature difference between the surfaces of the thermoelectric module became 35 K based on a simple cooling fin structure. It is expected in future to improve the system performance by optimizing shape of cooling fin and reducing the heat loss as much as possible and by developing a thermoelectric module for low temperature zone.

1. Introduction

The working temperature for thermoelectric conversion devices such as Bi-Te type devices, etc. is about 473 K. The temperature of waste heat that is not yet being utilized is in the low range from 293 to 473 K. Utilization of mid- to high-temperature waste heat has been advanced in the area of power generation by steam turbines, etc. [1 and 2].

The authors have developed a system aimed at recovering waste low-temperature heat. By using a Bi-Te type thermoelectric module, the system recovers waste heat generated in a substation transformer and converts it to electrical energy. The surface of a transformer casing contains heat, so an auxiliary fan is always running to provide air cooling. Fig. 1 shows a 63 MVA transformer. High temperature is generally found at the center of the tank and in the upper part of the radiator, ranging from 333 to 353 K. To efficiently recover this waste heat, the following problems need to be solved.

(1) Transformer casing cannot be modified to install a thermoelectric module.

(2) Transformer surface is not always even.

(3) Cooling method is air cooling with an auxiliary fan (Wind rate: $220m^3/min$)

(4) Temperature difference between thermoelectric module surfaces is small.

Thermoelectric modules are generally screwed with bolts in the casing of the power source. This method has a merit that it is easy to control the pressure to fix it on with bolts. But it has also a problem that its casing needs to be drilled for bolting. The authors have developed system that makes it easy to install a thermoelectric module on a transformer with rare earth permanent magnet as an option, and have carried out simulation experiments to verify its effectiveness. This paper explains the structure and principles of this system and presents experimental results to determine the electrical characteristics of a thermoelectric module under various electric conditions [3].

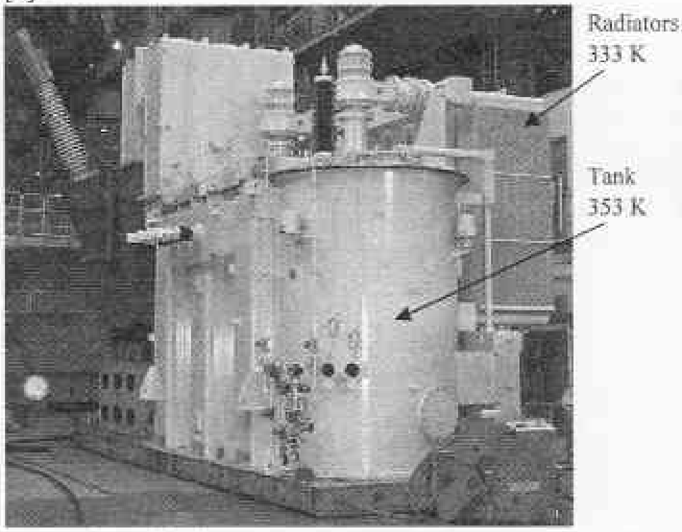


Fig. 1 63MVA Transformer (Size: W8.5m x D7.2m x H6.9m)

2. Components of waste heat recovery system

The components of the waste heat recovery system that the Authors have developed are shown in Figures 2 and 3. The thermoelectric module was installed on the heat source. Cooling fins were installed on the module surface with thermal conductive resin. The transformer casing comprising the heat source is made of carbon steel. Therefore, a rare earth permanent magnet with a strong magnetic force such as neodymium magnetic samarium, a cobalt magnet, etc. was used to fix the thermoelectric module. This method requires no modification on the surface of transformer casing, thus enabling easier installation than the conventional fixing methods using a stud or pewter. Furthermore, electric wiring substrates were installed at the periphery and connecting pins were set at four sides of the thermoelectric modules in order to achieve easy connection of multiple thermoelectric modules. The electrical wiring substrates also served as insulation to prevent direct transfer of heat from the rare earth permanent magnets to the fins. The cooling fins, electrical wiring substrates and rare earth permanent magnets were fixed with heat-resistant adhesive. The rare earth permanent magnets were placed slightly lower than the modules so that uniform pressure could be applied to the thermoelectric modules and thermal conductive resin with the attraction of magnet of the rare earth permanent magnets when they were installed on the heat source.

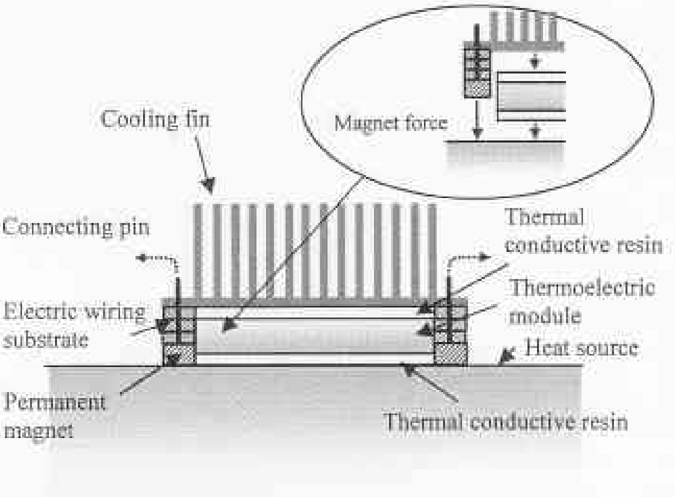


Fig. 2 Components of waste heat recovery system (Cross-sectional view)

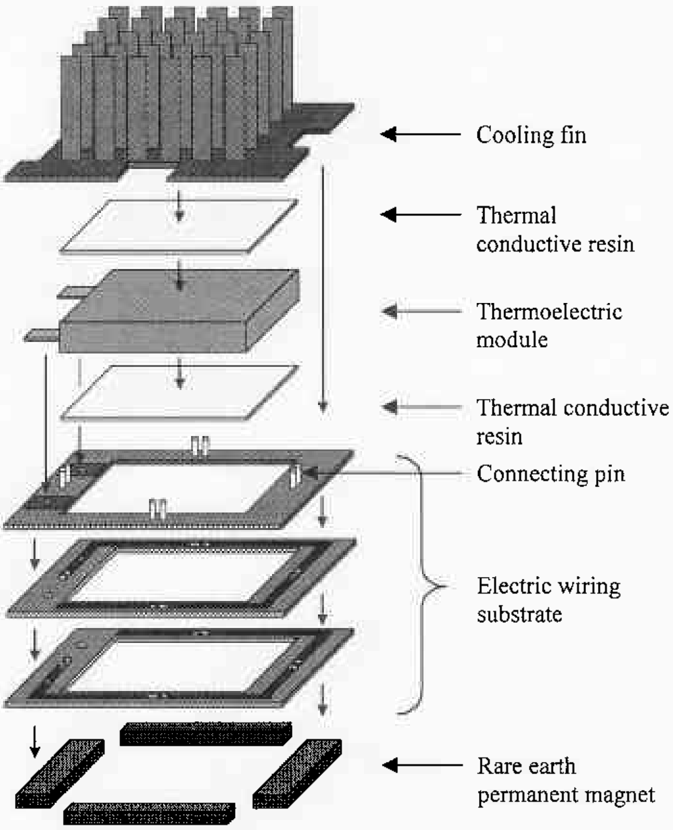


Fig. 3 Components of waste heat recovery system (Disassembled view)

3. Experiment

3-1. Experimental methods

The key point in a waste heat recovery system is how large temperature difference can be gained in a thermoelectric device within the temperature difference boundary between the high-temperature side and the low-temperature side. That is, it is necessary to minimize the temperature reduction in parts forming the waste heat recovery system other than the thermoelectric device [4].

Parameters influencing the efficiency of waste heat recovery in the system developed by the authors were considered to be the shape of the cooling fins, the fixing pressure of the thermoelectric module, the kinds of thermal conductive resin, etc. Thus, the power generation conditions were optimized by a single thermoelectric module. The components of the experiment apparatus are shown in Fig.4. A steel plate simulating the transformer casing was placed on the warm plate. The thermoelectric module was placed on top of the steel plate, and the cooling fins were placed on top of the module. Both were fixed with thermal conductive resin. The power generated by the module and the temperature difference ΔT between the steel plate and the fins were measured, while the temperature of the steel plate was controlled by a temperature controller. Considering the installation condition of transformer, this experiment was performed with natural convection cooling to cut an extra cost. A ready-made thermoelectric module (HZ-14 made by Hi-Z Technology, Inc.) as shown in Table 1 was employed in the experiments.

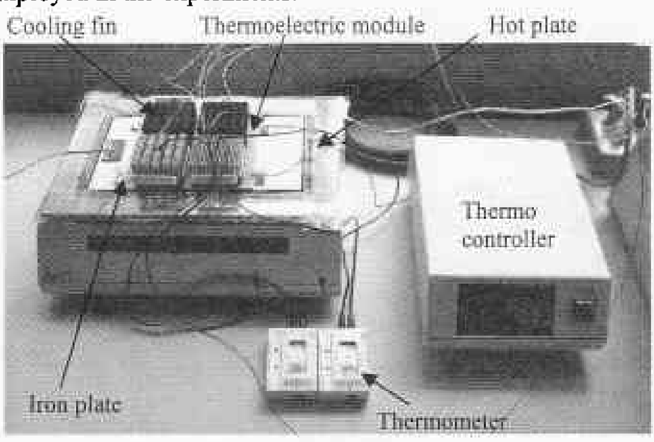


Fig. 4 Components of experimental apparatus

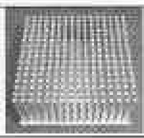
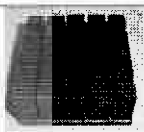
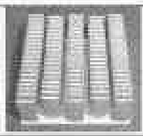
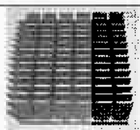
Table 1 Specification of thermoelectric module [5]

Properties	Value
Power	14 W *
Load Voltage	1.65 V
Internal Resistance	0.15 Ohm
Current	8 A
Open Circuit Voltage	3.5 V
Width & Length	6.27 cm x 6.27 cm
Thickness	0.508 cm
Weight	82 gram
Heat resistance	0.658K/W
Design Hot Side Temperature	503 K
Design Cold Side Temperature	303 K

* 200 K temperature difference

Cooling fin experiments evaluated four configurations of aluminum fins with varying numbers of fins and surface area, as shown in Table 2. Representative parameters influencing the performance of cooling fins were thermal resistance and pressure loss (resistance to wind passing through the cooling fins, etc.). Cooling fins that have lower thermal resistance show higher performance and those with lower pressure loss also show higher performance in case of our experiment.

Table 2 Cooling fin specifications

Kinds	A	B
Heat resistance	0.4 K/W	0.25 K/W
Pressure loss (at 3m/sec)	37.3 Pa	34.3 Pa
Fin	256 sheets	135 sheets
Thickness	1.50 - 2.00 mm	0.55 mm
Chink	2.00 - 2.15 mm	1.45 - 1.64 mm
Size	60 x 60 x 25 mm	60 x 60 x 25 mm
Surface area	366 cm^2	603 cm^2
Shape		
Kinds	C	D
Heat resistance	0.5 K/W	0.7 K/W
Pressure loss (at 3m/sec)	19.6 Pa	6.9 Pa
Fin	103 sheets	84 sheets
Thickness	1.00 - 1.90 mm	0.75 - 0.95 mm
Chink	1.85 - 2.90 mm	3.10 - 3.85 mm
Size	60 x 60 x 25 mm	60 x 60 x 25 mm
Surface area	434 cm^2	318 cm^2
Shape		

In the thermal conductive resin experiments, three kinds of resins, i.e. silicon gel sheet, silicon grease and adhesive double coated tape, were evaluated. These resins were commonly used, could decrease the thermal stress and took into account operability and adhesion.

Table 3 Specification of thermal conductive resin

Item	Gel sheet	Adhesive double coated tape	Grease
Thermal conductivity	6.5W/m·K	0.6W/m·K	0.83W/m·K
Thickness	1.0mm	0.125mm	0.1mm
Heat resistance	0.042K/W	0.058K/W	0.033K/W

3-2. Experimental results

The relationship between the temperature characteristics of the cooling fin and the temperature of the heat source is shown in Fig. 5. The results show that the cooling effect was highest in Fin B, followed by D, C and A. Fin B had the lowest heat resistance and the largest surface area, and Fin D had the lowest pressure loss and the lowest fin density. As a result, the following were confirmed. Where there is little air cooling effect, as for a transformer in a substation, the highest cooling effect can be expected in the fin where the heat resistance is low and area of individual fins is large. The second highest is where the pressure loss is low and fin density is low.

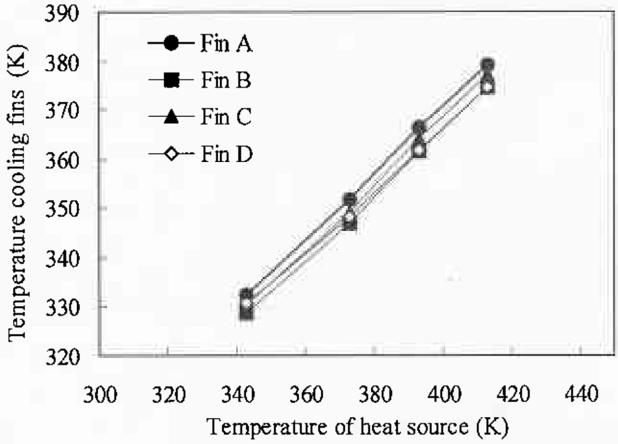


Fig. 5 Comparison of cooling fins

Thermal conductive resin are compared when the fixing pressure was set at 30kPa using Cooling Fin configuration B, which had the highest cooling effect.

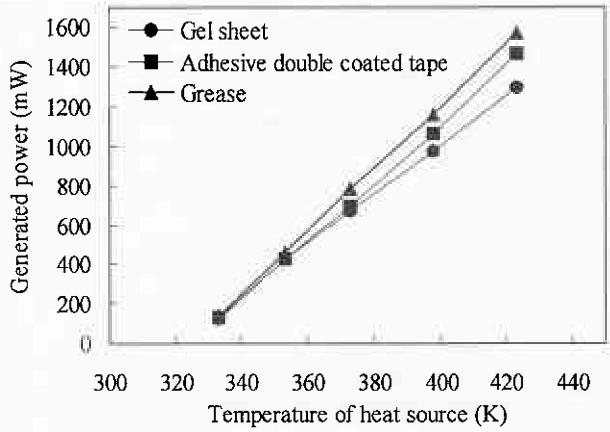


Fig. 6 Comparison of thermal conductive resin

As shown in Fig. 6, the highest power generation performance of the thermoelectric module was achieved when grease was used, followed by adhesive double coated tape and gel sheet. It is noted that the grease should be spread as thinly and uniformly as practically possible. At the same time, an uneven pressure must not be applied to the module. The experimental results show that there was a difference in generated power at a temperature of around 423 K, depending on the resin type. However, there was little difference in the temperature range below 353 K of the transformer casing, which was the focus of this study. Because the heat flow increases with increasing temperature of heat source, the heat resistance difference among three type of thermal conductive resin becomes marked as the difference of the heat loss among them [6]. Therefore taking into account of operability and adhesion gel sheets was employed for this system used in the temperature region around 353 K.

4. Discussions

4-1 Amount of heat transfer of waste heat recovery system

Heat is transferred in the waste heat recovery system shown in Fig. 7 as: heat source → thermal conductive resin → thermoelectric module → thermal conductive resin → cooling fin. Then, the heat resistance of each component was calculated and the amount of heat transfer of the waste heat recovery system was obtained.

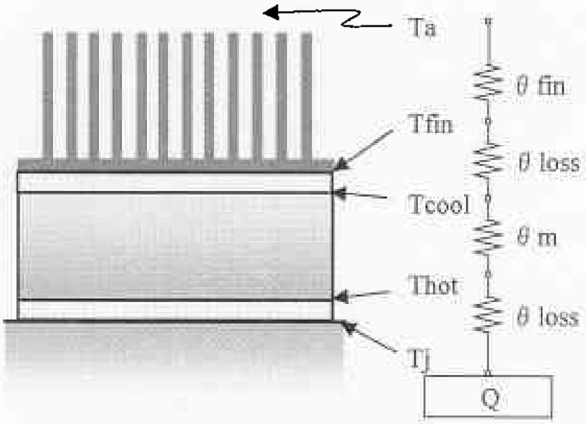


Fig. 7 Amount of heat transfer of waste heat recovery system

T_a is surrounding temperature, T_{fin} is fin temperature, T_{cool} is temperature of cooling side of thermoelectric module, T_{hot} is temperature of hot side of thermoelectric module, T_j is surface temperature of heat source, θ_{fin} is heat resistance of cooling fin, θ_{loss} is heat resistance of thermal conductive resin, θ_m is heat resistance of thermoelectric module and Q is amount of heat transfer. Q in the waste heat recovery system can be expressed by Equation (1), where the temperature difference between the heat source and surrounding temperature is ΔT and heat resistance of the system is θ.

$$Q = \frac{\Delta T}{\theta} = \frac{T_j - T_a}{2 \times \theta_{loss} + \theta_m + \theta_{fin}} \qquad \text{Equation (1)}$$

As an example, Table 4 shows Q and θ at a heat source temperature of 353 K and a surrounding temperature of 298 K under the experimental conditions where θ_{fin}, θ_m and θ_{loss} were 0.25 , 0.658 and 0.042 K/W , respectively.

Table 4 Temperature distribution of waste heat recovery system (potential measurement)

Item	Symbol	Value
Amount of heat transfer of system	Q	55.5W
Heat resistance of system	θ	0.99K/W
Surrounding temperature	T_a	298.0K
Fin temperature	T_{fin}	311.9K
Temperature of cooling side of thermoelectric module	T_{cool}	314.2K
Temperature of hot side of thermoelectric module	T_{hot}	350.7K
Surface temperature of heat source	T_j	353.0K
Temperature difference between both side of cooling fin	ΔT_{fin-a}	13.9K
Temperature difference between both side of thermal conductive resin	$\Delta T_{cool-fin}$ ΔT_{j-hot}	2.3K
Temperature difference between both side of thermoelectric module	$\Delta T_{hot-cool}$	36.5K

4-2 Temperature difference of thermoelectric module

The temperature difference between both side of the thermoelectric module $\Delta T_{hot-cool}$, which corresponds to the generated power at heat source temperature 353 K shown in Fig. 6 was calculated based on the relation between the generated power and $\Delta T_{hot-cool}$ of HZ-14. As the result, $\Delta T_{hot-cool}$ was obtained to be about 35 K shown in Fig. 8.

Moreover, Fig. 8 shows the tendency for $\Delta T_{hot-cool}$ to increase with increasing pressure to fix a thermoelectric module on the transformer casing. This system employs rare earth permanent magnets to fix thermoelectric modules on the transformer casing. The pressure of these magnets is 30KPa. On the other hand, the pressure is more 1MPa when clamping bolts are employed. Therefore, in order to improve the power generation performance by increasing $\Delta T_{hot-cool}$, it is necessary to minimize the heat resistance on both side of thermoelectric module by optimizing shape of cooling fin and reducing the thickness of the thermal conductive resin and by increasing pressure to fix a thermoelectric module.

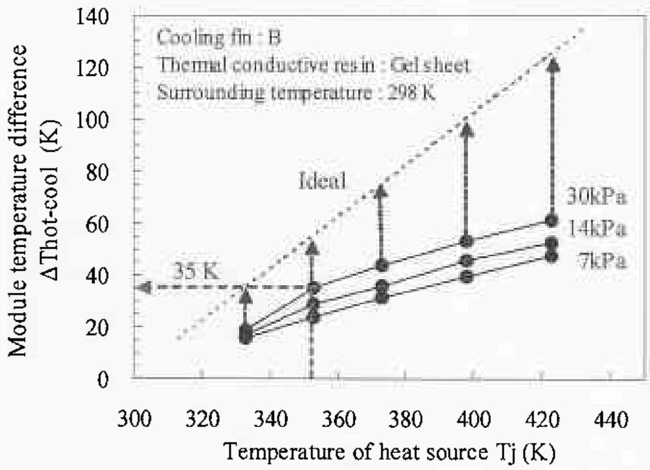


Fig. 8 Temperature of heat source and temperature difference between module surfaces

4-3. Temperature difference of cooling fin and thermal conductive resin

To make a survey of heat resistance of cooling fins and thermal conductive resin, the temperature distribution on the heat recovery system was measured. Table.5 shows the measuring results.

Table.5 Temperature distribution of waste heat recovery system (Actual measurement)

Item	Symbol	Value
Surrounding temperature	T_a	298.4K
Fin temperature	T_{fin}	312.0K
Temperature of cooling side of thermoelectric module	T_{cool}	314.3K
Temperature of hot side of thermoelectric module	T_{hot}	349.5K
Surface temperature of heat source	T_j	353.0K
Temperature difference between both side of cooling fin	ΔT_{fin-a}	13.6K
Temperature difference between both side of thermal conductive resin	$\Delta T_{cool-fin}$	2.3K
	ΔT_{j-hot}	3.5K
Temperature difference between both side of thermoelectric module	$\Delta T_{hot-cool}$	35.2K

The results show that ΔT_{j-hot}, which means the temperature difference between both side of thermal conductive resin sandwiched between heat source and thermoelectric module, is larger than theoretical calculation. It causes $\Delta T_{hot-cool}$ decreasing.

Then, the temperature difference of cooling fins ΔT_{fin-a} constitutes 24.9% of summation of ΔT losses and that of thermal conductive resin constitutes 10.6% (cool side: 4.2%, hot side: 6.4%). Therefore, in order to improve the power generation performance by increasing $\Delta T_{hot-cool}$, it is necessary to optimize shape of cooling fin and the thermal conductive resin.

5. Conclusions

The following could be confirmed from the experimental results as optimum conditions to fix a thermoelectric module on a transformer casing for improving the efficiency of waste heat recovery from the transformer.

(1) The highest cooling effect was found in the cooling fins, where heat resistance was low, area of individual fins was large and density of fin arrangement was small for small air cooling effect cases found in substation transformers.

(2) Thermal conductive resin with small thickness had low heat resistance, so it contributed to higher power generation. However, since there was little difference in the temperature region below 353 K, a gel sheet was employed taking into account operability, etc.

The heat resistance of thermal conductive resin and cooling fins greatly influences the power generated from the waste heat recovery system. It is possible to further increase the power generation by decreasing the heat resistance, which is accomplished by decreasing the thickness of the thermal conductive resin and optimizing the shape of the cooling fins. Furthermore, though thermoelectric modules from Hi-Z were employed in this experiment for investigation of waste heat recovery system, the authors aim to improve the system performance by developing a thermoelectric module for low temperature zone.

In future, it is planned to improve performance through verifying the reliability of the system such as the influence of the magnetic field, the effect of an expanded area of waste heat recovery on power generation and the effect of forced cooling instead of natural cooling etc.

6. Acknowledgements

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7. References

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