Optimal Control of a Thermoelectric Generator Attached with a Latent Heat Accumulator

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Abstract

Generally MPPT control (maximum power point tracking) is adopted to control of a thermoelectric generator. However, in the case of generation by use of a heat accumulator MPPT control cannot obtain maximum whole electrical output during the operation period. This is because the amount of heat stored in a heat accumulator is limited and easy to be exhausted rapidly by MPPT. Therefore MEPT (Maximum Efficiency Point Tracking) control should be developed to obtain maximum power from limited heat stored in the heat accumulator. When thermoelectric generator is used for waste heat recovery, conversion efficiency is quite difficult to be measured. This is due to time delay between the change of temperature profile in the thermoelectric generator and the change of heat medium temperature. Decrease of output current is desired to enlarge output because decrease of current decreases Peltier heat and improves efficiency of heat recovery. The experimental results indicate that current fluctuated by MPPT control causes loss of power output. We proposed the optimal control in which current is 10% smaller than one of MPPT control and evaluated it experimentally. We call this control scheme MEPT control. In this evaluation 500 W class thermoelectric generator, latent heat accumulator and the test facilities included 30 kW electric heater are utilized. Experimental result shows MEPT control exceeds MPPT in total electricity recovered from heat accumulator.

Keywords

Thermoelectric Generator, Heat Accumulator, MPPT, MEPT

1. Introduction

A thermoelectric generator has been proposed to be applied for waste heat of an incinerator without a damage of thermal stress [1]. However thermoelectric generating system has not been put into practical use yet because their cost, espe-
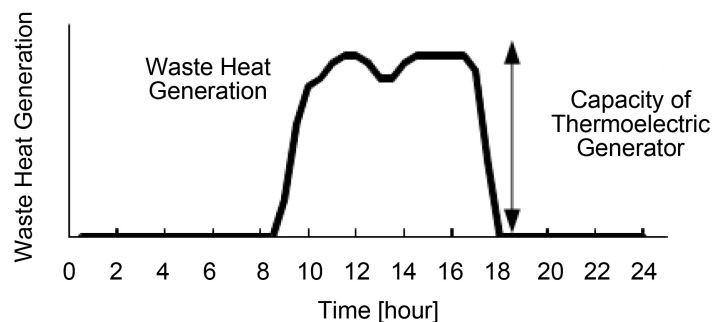
cially generating modules cost, is still high. In this paper a heat accumulator installed thermoelectric generating system for the batch operated incinerator was proposed and experimentally investigated. A heat accumulator has the potential to reduce cost of thermoelectric generating system by reduction of a capacity of employed thermoelectric generating modules. However optimal control of the thermoelectric generator attached with a heat accumulator has not been developed yet. The MPPT (Maximum Power Point Tracking) control accelerates the drop in the heat medium temperature by Peltier effect so that it cannot supply maximum electricity from heat stored in the heat accumulator. We proposed MEPT (Maximum Efficiency Point Tracking) control as an optimal control which electricity could be obtained from a heat accumulator more effectively than MPPT control.
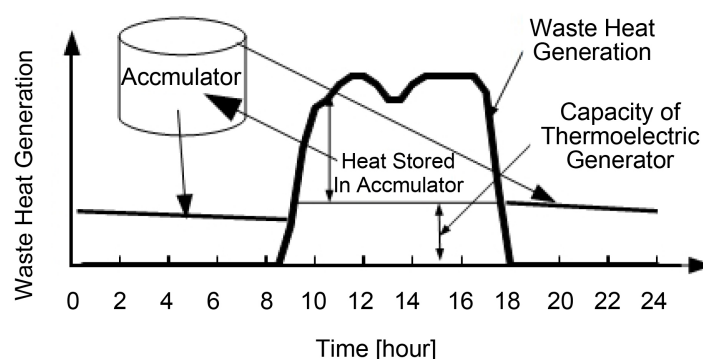
2. Effect of a Heat Accumulator

2.1. Introduction of a Heat Accumulator into a Garbage Plant

In ordinary large scale garbage plants which dispose more than 200 [ton/day] combustible waste, conventional steam turbine generators are utilized for waste heat recovery. However a steam turbine generator is not applicable to a smaller scale garbage plant which is operated intermittently. Even in such cases thermoelectric generators can be applied. In this paper application of a thermoelectric generator for small scale garbage incinerator was studied. For design of thermoelectric generator it is necessary to estimate a capacity of thermoelectric generator. If all of heat generated in an incinerator is used for thermoelectric generation, generator capacity should amount to peak value of waste heat generation as shown Figure 1. However an excess of capacity of generator increase initial cost and generating cost. Therefore a heat accumulator which can deal with peak value of waste heat generation is effective to decrease initial cost and generating cost [2].

As shown in Figure 2 a heat accumulator is proposed to be utilized for thermoelectric generation for heat recovery of waste heat in such incinerator so that the capacity of the thermoelectric generator and also the initial cost can be reduced. The excess waste heat which is more than the capacity of the thermoelectric generator is stored in the heat accumulator. The stored heat is used when

Figure 1. Hourly variation of waste heat generation.

Figure 2. Hourly variation of waste heat generation and heat transfer with an accumulator.

waste heat generation is smaller than the capacity of the thermoelectric generator.

2.2. Latent Heat Accumulator

There are two types of heat accumulators: sensible heat storage and latent heat storage. Latent heat storage employs PCM (Phase Change Material) as heat storage medium. A latent heat accumulator is more suitable for thermoelectric generation because stable operation temperature around melting point can help to achieve high conversion efficiency. Therefore the efficiency of thermoelectric generation is proportional to the temperature difference between heating medium and cooling medium. Table 1 shows properties of PCM of middle range of temperature. We employed KOH-NaOH eutectic mixture as heat storage material in our experiment. Melting point of KOH-NaOH is 170 degC suitable for employed thermoelectric generator and commercially available as industrial raw material.

3. Experimental Evaluation of Latent Heat Storage Thermoelectric Generation

3.1. Experimental Facilities

The experimental facility which consists of the heat accumulator which employs KOH-NaOH eutectic mixture, heat medium oil heating and circulating system which employs 25 kWe class electric heater, water cooler and 500 W class thermoelectric generator is schematically shown in Figure 3. The specifications of the employed thermoelectric generator are shown in Table 2.

The electric heater employed in heat medium oil heating and circulating system imitates waste heat generation. When the heater is switched off, heat stored in the heat accumulator is supplied as heat source of the thermoelectric generation for heat discharged mode.
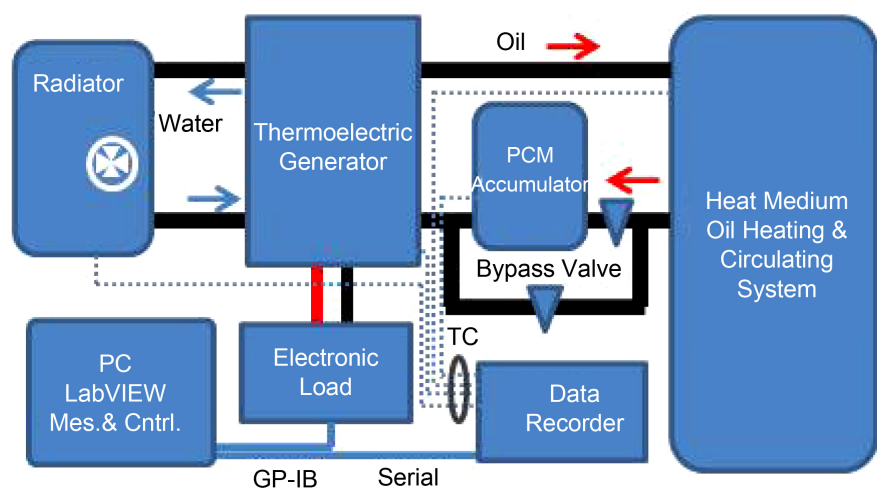
Figure 4 shows the experimental results when inlet temperatures of heat medium oil and cooling water are 250 [degC] and 25 [degC] respectively, and flow rates of heat medium oil and cooling water and 18 [liter/m] and 20 [liter/m] respectively. For safety reason, the temperature and the flow rate of heat medium

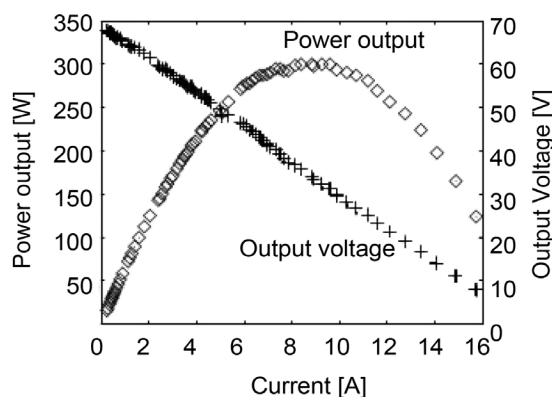Table 1. Properties of phase change material of intermediate-temperature [3] [4].

Phase Change Material	Composition	Melting Points	Heat of Fusion
		[degC]	(kJ/kg)
Polyethylene	-	135	209
KOH-NaOH	50 - 50	170	231
Pentaerythritol	-	188	322
LiOH-NaOH	30 - 70	210	362
KOH-LiOH	71 - 29	227	273
$NaNO_2$-NaOH	27 - 73	239	279
$LiNO_3$	-	250	370
$NaNO_3$-NaOH	19 - 81	258	296
LiCl-LiOH	37 - 63	262	453
Na_2CO_3NaOH	7.2 - 92.8	283	324

Table 2. Thermoelectric generator specification.

Manufacturer	KUBOTA Co Ltd. Japan	Rated Power	527 [W]
Model	KNSB-001	Rated Voltage	41.1 [V]
Thermoelectric Material	Bi-Te	Rated Current	12.8 [A]
Unit Size	900 mm × 740 mm × 500 mm	Rated Heat Medium Oil Temperature	261 [degC]
Module Size	70 mm × 70 mm × 5 mm	Rated Cooling Water Temperature	358 [degC]
Number of Modules	60	Rated Heat Medium Oil Flow rate	37.3 [l/m]
Heat Medium (Hot/Cod)	(Heat Medium Oil/Water)	Rated Cooling Water Flow Rate	23.8 [l/m]

Figure 3. Experimental facilities.

oil are reduced from rated values. When the thermoelectric generator has the equivalent circuit that is connected the constant voltage source and the constant

Figure 4. Experimental results.

resistance, the Voltage-Current characteristics shows straight line and the Output-Current characteristics shows parabola. However as a result shown in **Figure 4** V-I curve is not straight and P-I curve is not parabola. The peak area where the maximum power is obtained in P-I curve is slightly broad. This is because the properties of the modules connected in series and parallel vary according to temperature profile in the thermoelectric generator.

3.2. MPPT Control of a Thermoelectric Generator

Generally a thermoelectric generator is controlled by MPPT which is realized by hill climbing method. But current control based MPPT control employed for photovoltaic is not suitable for the large scale thermoelectric generator which has broad peak. This is because it is difficult to determine the adequate current control step which depends on temperature difference. So load resistance was proposed to be used for control parameter for MPPT control.

Figure 5 shows variation of MPPT controlled load resistance in variation of temperature of heat source. Load resistance is suitable for the MPPT control parameter because controlled load resistance fluctuates for almost same width in any heat source temperature as shown **Figure 5**. Load resistance controlled for maximum power increases from 3 [ohm] to 4 [ohm] when heat source temperature increases from 50 [degC] to 250 [degC].

3.3. Proposed Optimal Control of a Thermoelectric Generator

As mentioned above, even in the steady state operation, the control width is 10% of load resistance. When thermoelectric generator is operated by stored heat in discharged mode, controlled load resistance fluctuates more than 10%. In discharge mode heat source temperature decreases and it is more difficult to determine the maximum power point. Therefore, in such a case, an excess control to the lower load resistant causes significant increase of Peltier heat and acceleration of consumption of stored heat in the heat accumulator. For the reasons mentioned above it is reported that MPPT control cannot obtain the maximum electricity from limited energy stored in the heat accumulator. [5] Therefore we proposed MEPT (Maximum Efficiency Point Tracking) control to obtain the
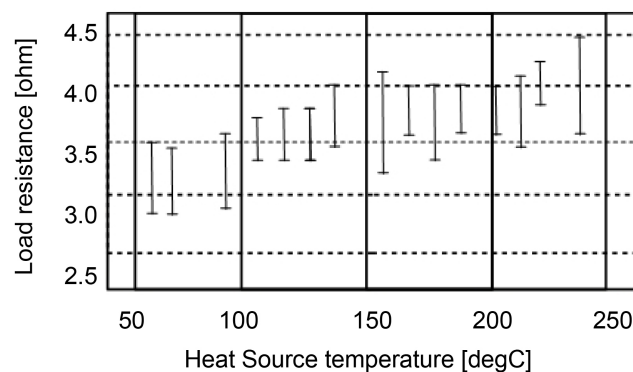
maximum electricity from limited energy. But when using limited energy stored in an accumulator heat source temperature is not constant and decrease gradually, so that it is difficult to determine the maximum efficiency point exactly.

Efficiency and power of the large scale thermoelectric generator was theoretically calculated as shown in **Figure 6**. This calculation is based on the condition that inlet temperatures of heat medium oil and cooling water are 220 [degC] and 25 [degC] respectively, and flow rates of heat medium oil and cooling water and 18 [liter/m] and 20 [liter/m] respectively.
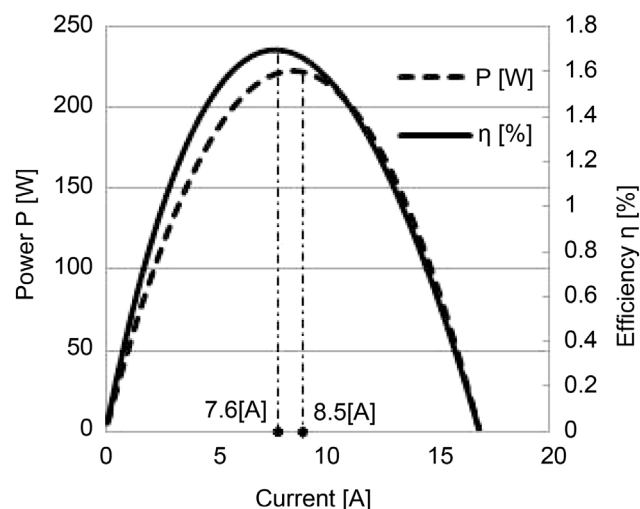
Figure 6 shows that the current at the maximum efficiency point is 7.5 [A]. This is about 10% smaller than the current at the maximum power point. Therefore we proposed that maximum efficiency point should be determined as the point where the load resistance is 20% larger than the matching load.

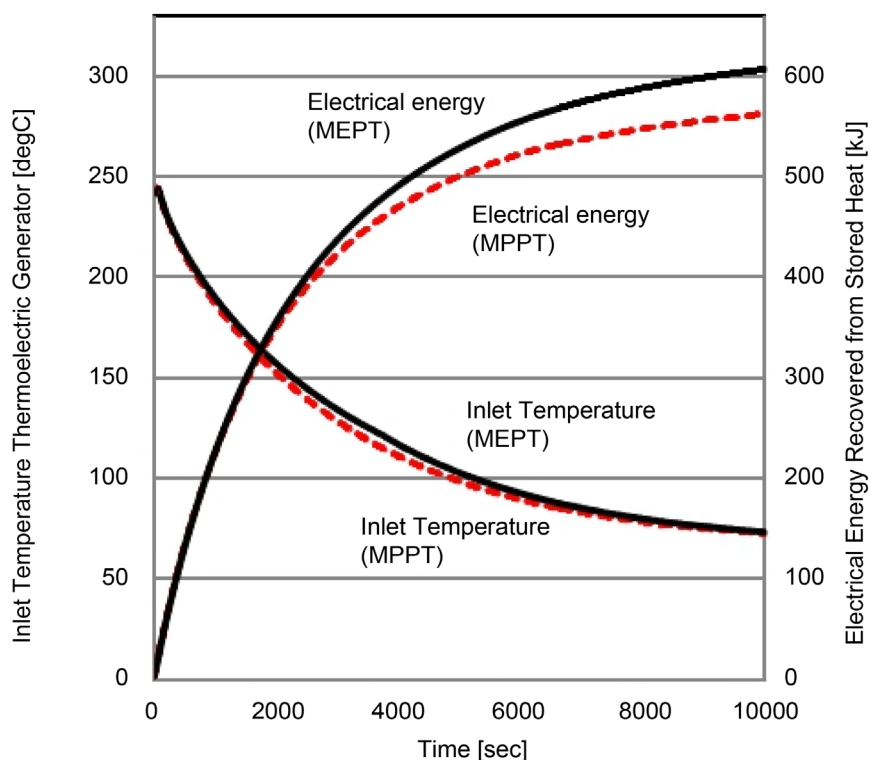### 3.4. Experimental Evaluation of MEPT Control

Proposed MEPT control was experimentally evaluated compared to MPPT control. Typical results are shown in **Figure 7**. A significant difference between MPPT control and MEPT control was not observed in their inlet temperatures. But obviously MEPT control exceeds MPPT control in recovered electrical

Figure 5. MPPT controlled load resistance.

Figure 6. Theoretical power and efficiency vs current.

Figure 7. Recovered electrical energy and inlet temperature vs current.

energy. During 1000 [sec] operation MPPT control and MPET control obtained 563 [kJ] and 607 [kJ] respectively.

4. Conclusions

In this study optimum control of a thermoelectric generator attached with a latent heat accumulator was proposed and experimentally evaluated. The obtained results are as follows:

1) Load resistance controlled for maximum power increases from 3 [ohm] to 4 [ohm] when heat source temperature increases from 50 [degC] to 250 [degC].

2) MEPT control current is 10% smaller than MPPT control current.

3) MEPT control exceeds MPPT control in recovered electrical energy.

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