Designing MPC Controller for a Heat Exchanger Equipped with Thermoelectric Generators

Sucha Kemjariya\textsuperscript{1, a}, Wachira Daosud\textsuperscript{2, b}, Weerawun Weerachaipichasgul\textsuperscript{3, c} and Paisan Kittisupakorn\textsuperscript{1, d, *}

\textsuperscript{1}Control and Systems Engineering Research Laboratory, Department of Chemical Engineering, Chulalongkorn University, Bangkok 10330 Thailand
\textsuperscript{2}Department of Chemical Engineering, Faculty of Engineering, Burapha University, Chonburi 20130 Thailand
\textsuperscript{3}Division of Chemical Engineering, Department of Industrial Engineering, Faculty of Engineering, Naresuan University, Phitsanulok 65000 Thailand

E-mail: \textsuperscript{a}sucha.ke.1995@gmail.com, \textsuperscript{b}wachira@buu.ac.th, \textsuperscript{c}weerawun@gmail.com, \textsuperscript{d,*}paisan.k@chula.ac.th

Abstract. A thermoelectric generator (TEG) is a solid-state semiconductor device that can convert temperature differences and heat flow into electrical energy. Nowadays, industries with high-temperature production processes tend to experience unavoidable heat loss. Heat exchangers are therefore the most widely used equipment to recover these waste heat. The researcher therefore saw the benefits of bringing TEG devices to be installed in heat exchangers. It is thought that in addition to the heat exchanger being a device that helps the heat transfer of one fluid to another fluid. Can also generate electricity back to use as well. This will be of great benefit in increasing the efficiency of waste heat recovery and reducing production costs. In this research, 36 plates of Bismuth Telluride (Bi\textsubscript{2}Te\textsubscript{3}) TEG devices were installed in plate and fin heat exchangers and studied the effect of changes in the inlet flow rate of cold water at 20 °C on the effect of heat exchange and the electrical power produced by TEG. The hot water inlet flow rate was constant at 1 l/min and the temperature was constant at 85 °C. Then mathematical model was created to predict the results of the outlet hot water temperature, outlet cold water temperature, current and voltage produced. The model can predict accurately the least squares value (R\textsuperscript{2}) with values of 0.949, 0.859, 0.707 and 0.749, respectively. In addition, a multiple input, multiple output (MIMO) using model predictive controller (MPC) was designed to control the output current, and temperature can control into the setpoint effectively.

1. Introduction
In daily industrial processes, a large amount of energy is lost as waste heat. This heat loss reduces not only the energy efficiency of the process, but it also contributes to green-house gases emissions and thermal pollution [1]. And the inefficiency of energy consumption has become a huge cost leak. Therefore, planning and optimizing energy consumption are important for the sustainability of the business and the environment as they effectively reduce energy costs as well as take care of the environment at the same time [2]. Thermoelectric generators (TEG) are solid-state semiconductor devices that convert temperature difference and heat flow into a useful DC power source by utilizing the Seebeck effect to generate voltage to drive electrical current and produces useful power at a load.
In this work, the researcher has applied the thermoelectric technology together with a heat exchanger to transfer the heat of one fluid to another fluid while the fluids do not need to be mixed. This method can increase heat efficiency of the process as the waste heat can be reused to increase the temperature of the fluid as well as generate significant amount of get electrical energy [4]. For efficient heat exchange and electricity generation, mathematical modeling and process controls are critical. they also provide many benefits such as reducing energy consumption, increasing profitability, increasing safety, and achieving product specification.

Thus, this research aims to study plate and fin heat exchangers installed with Bismuth Telluride thermoelectric circuits. The effect of cold-water inlet flow rate at 1 and 1.5 L/min at 20 °C on heat exchange and power generation was studied. In the experiment, hot-water inlet flow rate and inlet temperature were set to be constant at 1 l/min and 85 °C respectively. Then mathematical mode was created to compare the results obtained from the model and the experimental result with least squares value as an indicator. A multiple input, multiple output model predictive controller is designed to control two variables, the hot water output temperature, and the generated electricity with 2 manipulate variables which are the flow rate of hot and cold-water flow. And the performances of the controller are measured with setpoint tracking simulations.

2. Process Description

The heat exchanger is made of stainless steel (SUS304). It is shaped like two stacked rectangular tanks. Between the outer and inner walls of the two tanks are insulated wood. The bottom tank is a cold tank which is 45 cm wide, 45 cm long and 30 cm deep. Inside the cool tank, there are two 45-watt submersible pumps contained, which serve to stir the water in the tank to have the same temperature at all points. The upper tank is a hot tank which is 34 cm wide, 34 cm long and 21 cm deep. The bottom of the hot tank is installed with plates and fins heat exchanger, it made of aluminium with a heat exchange area of approximately 0.3168 m². The middle between the heat sinks of the hot and cold sides is packed with Bismuth Telluride thermoelectric generators 36 sheets (model: SP1848-27145) connected in a compound circuit, which can produce electricity well in the temperature range of -40-150 °C as shown in Figure 1.

![Figure 1. Heat Exchanger Equipped with Thermoelectric Generators](image)

In this experiment. The researchers select water as a heating and cooling agent for the heat exchanger. The inlet hot water temperature is heated to 85 °C with a thermostatic bath. It was controlled to have a constant inlet and outlet flow rate of 1 l/min with ball valves. It measures and recorded flow rate and temperature data at Inlet and outlet hot water stream of the heat exchanger with turbine flow meters and type K thermocouples, respectively. The hot water that passed through the heat exchanger is recirculated back into the process for heating again. Before fed back into the heat exchanger again

The cold water fed into the heat exchanger was controlled at a constant temperature at 20 °C with a low temperature thermostatic bath. The inlet and outlet flow rates are controlled by a control valve. At
the inlet, the flow rate is measured with a Coriolis flowmeter and the outlet is measured with a turbine flowmeter. Both streams have temperature measurements with type K thermocouples and record data in data logger. The cold water that passed through the heat exchanger is recirculated back into the process for cooling again. The electricity produced from the thermoelectric, it is measured in a closed circuit with a resistance of 550 ohms with a multi-meter.

3. Mathematics Model
From the experiments, the researchers use the experimental data to create a mathematical model for describing the phenomena occurring in heat exchangers equipped with thermoelectric devices. The model is based on the CSTR reactor equation [5]

The mass balance equations of hot and cold tanks can be described by equations (1) and (2)

$$\frac{d(\rho_h V_h)}{dt} = \rho_h F_{h,i} - \rho_h F_{h,o} = 0$$  \hspace{1cm} (1)

$$\frac{d(\rho_c V_c)}{dt} = \rho_c F_{c,i} - \rho_c F_{c,o} = 0$$  \hspace{1cm} (2)

The energy balance equations of hot and cold tanks can be described by equations (3) and (4)

$$\frac{d(\rho_h C_{ph} V_h T_h)}{dt} = \rho_h C_{ph} \left( F_{h,i} T_{h,i} - F_{h,o} T_{h,o} \right) - Q$$  \hspace{1cm} (3)

$$\frac{d(\rho_c C_{pc} V_c T_c)}{dt} = \rho_c C_{pc} \left( F_{c,i} T_{c,i} - F_{c,o} T_{c,o} \right) + Q$$  \hspace{1cm} (4)

In terms (Q) is the heat received and loss, which is defined as equation (5)

$$Q = UA \Delta T$$  \hspace{1cm} (5)

The electrical circuit of a TEG. Based on Seebeck effect, when there is temperature difference between a TEG, an open circuit Voltage can be generated, which is defined as equation [6] (6)

$$V_{opencircuit} = S (T_h - T_c)$$  \hspace{1cm} (6)

The current in the close circuit can be described by equations (7)

$$I_{closecircuit} = \left( \frac{V_{opencircuit}}{R_{internal} + R_{load}} \right)$$  \hspace{1cm} (7)

The voltage in the close circuit can be described by equations (8)

$$V_{closecircuit} = V_{opencircuit} \left( \frac{R_{load}}{R_{internal} + R_{load}} \right)$$  \hspace{1cm} (8)

The electric power in the close circuit can be described by equations (9)

$$P_{closecircuit} = V_{closecircuit} \times I_{closecircuit}$$  \hspace{1cm} (9)

4. The Experiment Data and Mathematics Model results
The input data fed to the process sets the hot-water inlet temperature at 85 °C with a constant flow rate of 1 L/min. The tolerances of flow rate and temperature are ±0.05 L/min and ±1 °C respectively. The cold-water temperature is 20 °C. During 0-1600 sec, the flow rate is 1 L/min and After 1600 sec the flow increases to 1.5 L/min with flow and temperature tolerances of ±0.26 L/min and ±0.8 °C, respectively as shown in Figure 2.
Figure 2. The input data used in the experiment (a) Hot water temperature inlet, (b) Cold water temperature inlet, (c) Hot water flowrate, (d) Cold water flowrate.

The experimental results were compared with the mathematics model. When the flow rate of cold water entering the heat exchanger is increased, the efficiency of the heat exchanger is improved. As a result, the temperature of the hot water outlet is reduced, and the electric current and voltage produced by TEG are increasing. A mathematical model can be used to describe and accurately predict the effect of heat exchangers equipped with thermoelectric devices. It was subject to the tolerances of the temperature of the hot-water and cold-water outlet, electric current and voltage not more than ±1 °C, ±0.6 °C, ±0.3 mA and ±0.2 V respectively and the least square is 0.949, 0.859, 0.707 and 0.749 respectively as shown in Figure 3.

Figure 3. The experiment data and mathematics model results (a) Hot water temperature outlet, (b) Cold water temperature outlet, (c) Current, (d) Voltage.
5. Simulation Results

In this experiment, the researchers designed a multiple-input, multiple-output MPC controller for heat exchangers equipped with thermoelectric technology using Simulink in the MATLAB software. The manipulated variable was the input flowrate of hot and cold water with constrain that the flowrate shall not be less than 0 and not more than 5 l/min and the control variable are the outlet cold-water temperature and the electric current. As shown in Figure 4.

The MPC (MIMO) strategy is initially applied to control the cold-water temperature and the electric current outlet to desired values by adjusting the manipulated variables of Hot and cold-water flowrate inlet, respectively. The simulation presents case of control study which is set point tracking case [7].

As for the set point tracking case the reference value of cold-water temperature outlet is changed to 30, 35, 32, 35 and 30 respectively. And the electric current outlet is changed by 8, 6, 8, 7 and 6 respectively. It will change every 5000 second. As shown in Figure 3.

From the study of the MPC (MIMO) controls have values of the control interval, prediction horizon, control horizon was found to be 100 and 20, respectively. Input weight of hot and cold-water flowrate are 2 and output weight are 6 and 8, respectively. It was found that the controller was able to control both control variables to the target value satisfactorily.
6. Conclusion
From the experiments it was found that the mathematical model was able to predict the temperature of the cold stream and the output electric current of the heat exchanger equipped with thermoelectric generators efficiently. In addition, the study of the control of the MPC (MIMO) controller found that it was able to control the temperature cold water and electric current output can be controlled to reach the desired target values.

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