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Thermoelectric Water Cooler and Heater with Intermediate Water Tank

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Abstract: This paper presents a mathematical model to investigate the effect of intermediate water tank for cascade configuration of thermoelectric modules in heating and cooling application. The system consists of two thermoelectric modules separated by an intermediate water tank. Another surface of each thermoelectric module is in contact with cold water tank or hot water tank. In the simulation, both hot and cold water tanks consist one kilogram of water. The mass of water in the intermediate water tank was set to 0.01 kg (negligible thermal mass), 1 kg (equal thermal mass) and 10 kg (large thermal mass). Set point for hot and cold water tanks was 373 K and 276 K, respectively. It was found that intermediate water tank with higher thermal mass enable a better temperature control and produces higher Coefficient of Performance for both thermoelectric modules. These findings are essential for the development of a three-stage temperature water dispenser using thermoelectric modules.

Keywords: Intermediate water tank, thermal mass, thermoelectric, three-stage temperature control.

I. INTRODUCTION

One of the limitations in capability of thermoelectric module in heating and cooling applications is the limited temperature difference between its hot and cold surfaces. For instance, at the current state of technology, it is almost impossible to simultaneously boil water at 373 K and chill water at 276 K using a single-stage thermoelectric module. A multistage thermoelectric module is a combination of several single-stage thermoelectric modules which is arranged thermally in series. One of the drawbacks of this configuration are the heat from the cold surface and ohmic heating within thermoelectric modules are accumulated in the stack of thermoelectric modules. This paper presents a new configuration of multistage arrangement of thermoelectric modules by introducing intermediate water tank that acts as thermal mass between two thermoelectric modules.

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Thermoelectric module has various applications which includes heating, cooling, temperature control, heat metering [1] and power generation [2]. The heating and cooling processes can be combined to increase the Coefficient of Performance, where the total Coefficient of Performance can be doubled compared to the Coefficient of Performance for heating or cooling [3]. For the temperature control, the use of PID controller enables a body temperature to be controlled to within 0.1 K of set point for constant and time wise temperature profiles. Heat flow through a thermoelectric module can be inferred from voltage and current produced by a thermoelectric module, and the temperature of one of its surfaces [1]. If the surfaces of thermoelectric module are maintained at different temperatures, the module can produce voltage and current, which provide electrical power [2].

Thermoelectric module is usually used in heat pump applications that requires small temperature difference. For instance, thermoelectric module was used as a heat pump for outdoor system [4]. Due to its compactness, thermoelectric module is suitable for cooling applications in the system with limited space such as in the computer [5]. For a mini refrigerator, a micro channel heat exchanger can be incorporated with thermoelectric module to increase its performance [6]. Another attempt to increase the Coefficient of Performance of thermoelectric module through combination of heating and cooling is reported in [7]. In these articles, only single stage thermoelectric was used.

To increase the temperature difference between heat and cold surfaces, the cascade arrangement of thermoelectric module is available [8]. Cascade thermoelectric cooling is integrated to electronic housing to ensure optimum temperature is maintained [9]. A two-stage cascade thermoelectric cooler was reported to have a better performance compared to the single-stage cascade thermoelectric cooler [10]. However, these arrangements did not explore the possibility of using intermediate thermal mass for the cascade arrangement of thermoelectric heat pump.

Thus, this paper presents the simulation on performance of cascade thermoelectric module with intermediate thermal mass. The temperatures and Coefficient of Performance of the system are reported in this paper.

II. METHODOLOGY

A. Description of the System

The system consists of a hot water tank, an intermediate water tank, a cold water tank and two thermoelectric modules (Fig. 1). Thermoelectric module 1 receives heat from the coldwater tank and the module rejects heat into the intermediate water tank.

Similarly, thermoelectric module 2 is transferring heat from the intermediate water tank to hot water tank.

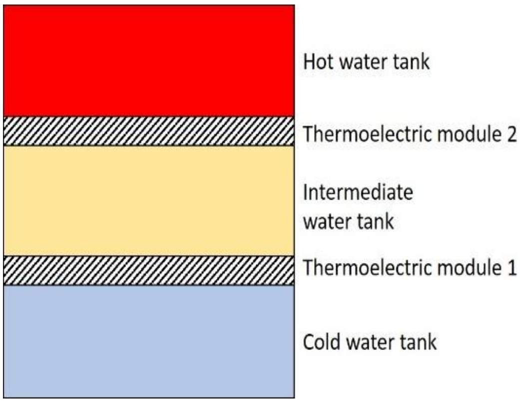


Fig. 1The arrangement of thermoelectric modules and water tanks

B. Mathematical Model

The amount of cooling provided by thermoelectric module 1 on the cold water tank ($Q_{cold-TEM\ 1}$) was calculated using (1)

$$Q_{cold\ -TEM\ 1} = 2\alpha I T_{cold} - 0.5IR^2 - \kappa(T_{int} - T_{cold}) \quad (1)$$

where α is the Seebeck coefficient, I is the electrical current, T_{cold} is the temperature of cold water tank, R is electrical resistance of the module, κ is the thermal conductance and T_{int} is the temperature of intermediate water tank.

Then, the $Q_{cold-TEM\ 1}$ is transferred to intermediate tank. The heat received by intermediate water tank ($Q_{TEM1-int}$)was calculated using (2)

$$Q_{TEM1-int} = 2\alpha I T_{int} + 0.5IR^2 - \kappa(T_{int} - T_{cold}) \quad (2)$$

The heat transfer form intermediate water tank to TEM 2 ($Q_{int-TEM\ 2}$) was calculated by (3)

$$Q_{int-TEM\ 2} = 2\alpha I T_{int} - 0.5IR^2 - \kappa(T_{hot} - T_{int}) \quad (3)$$

where T_{hot} is the temperature of hot water tank.
The heat rejected by TEM 2 into the hot tank was calculated by (4)

$$Q_{TEM\ 2-hot\ tank} = 2\alpha I T_{hot} + 0.5IR^2 - \kappa(T_{hot} - T_{int}) \quad (4)$$

The changes in temperature of cold water tank, intermediate water tank and hot water tank for the next time step were calculated using (5), (6) and (7), respectively,

$$\Delta T_{cold} = (Q_{cold-TEM\ 1})/(m_{cold} \times c_p) \quad (5)$$

$$\Delta T_{int} = (Q_{int-TEM\ 2} - Q_{TEM1-int})/(m_{int} \times c_p) \quad (6)$$

$$\Delta T_{hot} = (Q_{TEM\ 2-hot})/(m_{hot} \times c_p) \quad (7)$$

Where m_{cold} is the mass of water in cold tank, m_{hot} is the mass of water in hot tank, m_{int} is the mass of water in the intermediate tank and c_p is the specific heat of water. The m_{cold} and m_{hot} were set to 1 kg. Three cases were investigated where the ratio of mass of water in the intermediate water tank to cold tank (m_{int} /m_{cold}) is 0.01, 1 and 10.

The Coefficient of Performance of thermoelectric modules 1 and 2 are define as (8) and (9), respectively:

$$COP_{TEM\ 1} = \frac{Q_{cold\ tank-TEM\ 1}}{Power\ input\ to\ TEM_1} \quad (8)$$

$$COP_{TEM\ 2} = \frac{Q_{TEM\ 2-hot\ tank}}{Power\ input\ to\ TEM_2} \quad (9)$$

The power input was calculated using (10)

$$Power\ input\ to\ TEM = I \times (IR + \alpha \Delta T_{TEM\ surfaces}) \quad (10)$$

Where the $\Delta T_{TEM\ surfaces}$ is the temperature difference between surfaces of thermoelectric modules.

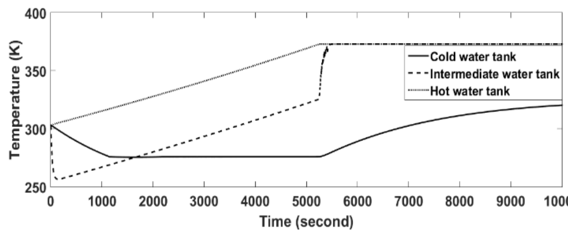
C. Temperature Control Mechanism

The temperature control mechanism was based on the set point temperatures. For the hot tank, the temperature was set at 373 K. The temperature of cold water tank was set at276 K. Once these temperatures were achieved, the electrical current supply to thermoelectric modules was set to zero. The power supplies for TEM 1 and TEM 2 are independent. In all cases, Proportional control strategy was adopted where the electrical current was set to 3 Ampere for ON and 0 Ampere for OFF.

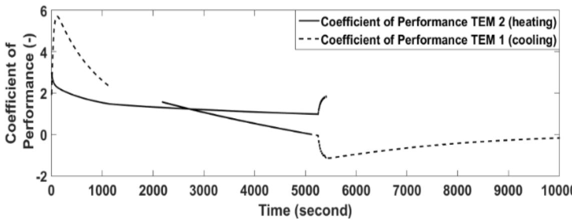
III. RESULTS

A. Negligible Thermal Mass in Intermediate Water Tank (m_{int} /m_{cold}= 0.01)

In the absence of significant thermal mass of water in the intermediate water tank, the temperatures of cold, intermediate and hot water tanks are as in Fig. 2 (a). At the beginning, the temperature of intermediate water tank drops below the temperature of cold water tank. This happens due to the rate of heat removal from the intermediate water tank is higher compared to the heat rejected into the tank. After drops to ~ 255 K, the temperature of intermediate water tank is increasing until it reaches the set point temperature of hot water tank. The temperature of intermediate water tank drops due to less heat is being pump by the TEM 1 into intermediate water tank. Then, the temperature of intermediate water tank rise because the conduction term in (1) dominates the equation. Once the cooling power produces by TEM 1 does not able to maintain the required temperature difference between intermediate water tank and cold water tank, net heat flow into cold water tank which make its temperature increases. The Coefficient of Performances of TEM 1 and TEM 2 are presented in Fig. 2(b). The highest Coefficient of Performance of both thermoelectric modules occurs at time less than 100 seconds. A small temperature difference between water tanks contribute to this high Coefficient of Performance. Once the setpoint temperature was reached, the Coefficient of Performance for the TEM 1 is reducing before it drops below zero after the temperature difference between hot and cold water tanks exceed the capability of thermoelectric module in producing net cooling effect.



(a)

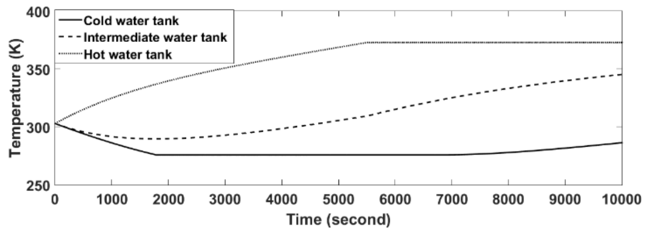


(b)

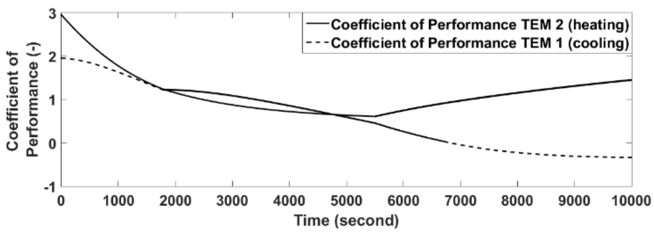
Fig. 2 Simulation with a negligible thermal mass inintermediate water tank(m_{int} /m_{cold} = 0.01) (a) Temperatures of water tanks, and (b) Coefficient of Performance of thermoelectric modules (some portion of the lines are not appear since no electrical supply to thermoelectric modules).

B. Equal Thermal Mass in Intermediate Water Tank (m_{int} /m_{cold}= 1)

Figures 3(a) and 3(b) shows the temperatures of water tanks and Coefficient of Performance of thermoelectric modules. The cold water tank temperature was maintained at set point for the duration that is longer than the system with negligible thermal mass in intermediate water tank. After the temperature difference between intermediate and cold water tanks exceed 50 K, the temperature of cold water tank increases. The use of same thermal mass in intermediate water tank improve the Coefficient of Performance of both thermoelectric modules.



(a)

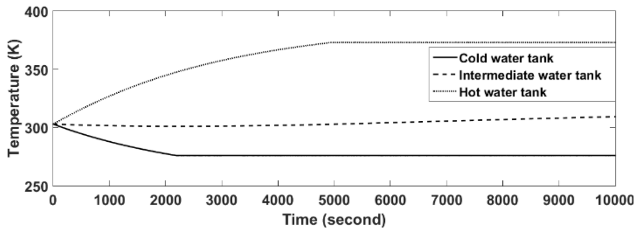


(b)

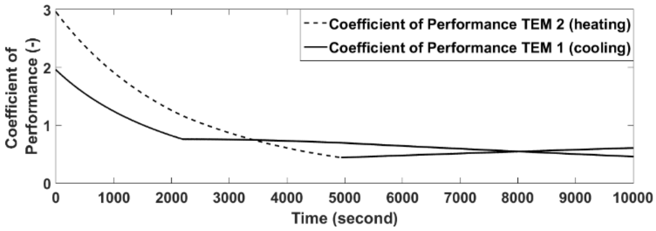
Fig. 3 Simulation with an equalthermal mass in intermediate water tank(m_{int} /m_{cold} = 0.01) (a) Temperatures of water tanks, and (b)Coefficient of Performance of thermoelectric modules

C. Large Thermal Mass in Intermediate Water Tank (m_{int} /m_{cold}= 10)

The effect of large thermal mass in the intermediate water tank is depicted in Figure 4(a). High thermal mass of intermediate water tank enables it to maintain its temperature. This make the set point temperature of hot and cold water tanks are maintained for more than 5000 seconds. By comparing the Coefficient of Performance of thermoelectric modules with the negligible and equal thermal mass of intermediate water tank, the high thermal mass intermediate water tank lead to higher Coefficient of Performance (Figure 4(b)).



(a)



(b)

Fig. 4 Simulation with a large thermal mass in intermediate water tank (m_{int} /m_{cold} = 10) (a) Temperatures of water tanks, and (b) Coefficient of Performance of thermoelectric modules

IV. DISCUSSION

The use of intermediate water tank reduces the temperature difference between surfaces of thermoelectric module. By operating at a lower temperature difference, the module can operate at a higher Coefficient of Performance. This provides an opportunity to reduce power consumption by thermoelectric module. Another advantage is the set point temperature is reached more quickly because a thermoelectric module can pump heat at higher rate if the differences in its surface temperature is lower.

The mathematical model presented in this paper is purely based on energy balance, where the process of heat and mass transfer is not considered. For instance, the thermal contact resistance between the surface of thermoelectric module and tank may slightly reduce rate of heat transfer and lead to higher temperature difference at the interface [11]. Another important heat transfer mechanism for this thermoelectric-tank system is the heat convection between the surface and water. Forced convection is required to ensure a good heat transfer from the surface of tank to water. The analysis on matching thermal resistance of thermoelectric module and its intermediate system is also essential [12].

Use of electric auxiliary heater could be useful in assisting thermoelectric module to reach higher temperature. For instance, if the Coefficient of Performance of thermoelectric module is less than 1, power supply to thermoelectric module can be disconnected and heating is continued by using an electric heater. The decision in switching the operation from thermoelectric module to electric heater when the Coefficient of Performance is less than 1 is because it is more likely for an electric heater to operates with an efficiency that is approaching 100%. This make the use of electric heater is more economical compared to thermoelectric module.

The intermediate water tank can provide another level of temperature for water dispensing. If the temperature of water in the intermediate tank can be controlled to a specified temperature, it could be used for other purposes such as warm water dispenser. However, a complex control algorithm that able to manage heat flow is required. Other than control algorithm, modification of physical equipment such as an additional water tank may be added to the system. Alternatively, another thermoelectric module can be used to control the temperature of water in the additional water tank to the setpoint.

V. CONCLUSIONS

The existence of intermediate water tank enables the set point temperature of cold and hot water tank to be maintained for more than 7000 seconds. The effect of thermal mass of intermediate water tank is also significant to ensure the Coefficient of Performance of thermoelectric modules are within an acceptable range. A higher thermal mass may improve the Coefficient of Performance, but the drawback is the system will be bulky. Furthermore, if the system needs to be portable such as hot and cold water dispenser, a high mass may lead to difficulties in transporting the system. The findings presented in this paper are relevant for the development of water dispenser at three different temperatures. However, a control mechanism is required to ensure the system is working as intended.

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Mohamad Asmidzam Ahamat obtained his Master of Engineering in Mechanical Engineering and Doctor of Philosophy (Mechanical Engineering) from University of Bristol, United Kingdom in 2008 and 2012, respectively. Since 2012, he serves as a lecturer at Universiti Kuala Lumpur. His research is mainly related to thermal fluid engineering, but he also doing researches in other specializations in mechanical engineering. He has published more than 50 articles in journals, conferences and magazines. In 2019, he had successfully authored two books on production of refrigeration effect and best practices in academic writing. Two of his conference papers were selected as the recipient of Best Paper Award. He is a registered Graduate Engineer with the Board of Engineers Malaysia.

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