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Thermal Modeling and Experimental Investigation of a Thermoelectric Drinking Water Cooler Integrated with Heat Pipe Heatsink

J. Jamradloedluk,[1,#] P. Bamroongkhan[2,#] and C. Lertsatitthanakorn[3,#,*]

Abstract

In tropical climate regions, drinking chill water plays a vital role in physiological thermoregulation, including perspiration. Conventional (vapor-compression) cycle refrigeration for water cooling has remarkably negative influence on the environment. Thermoelectric (TE) cooling device is an alternative that exhibits potentials to reduce the environmental impact. In this paper, a TE drinking water cooler integrated with heat pipe heatsink is proposed, with such a prototype built and tested therein. The water cooler consists of two TE modules attached to heat pipe heatsinks on their hot sides and copper plate and tube heatsink on their cold sides. The effects of electric current supplied to the TE modules, ambient temperature, air and water flow rates on the system's performance are investigated. Moreover, an economic evaluation is implemented by analyzing its initial capital cost (ICC) per cooling capacity. A set of heat transfer models was developed to predict the cold water produced from the TE water cooler. The calculated results conformed with the experimental results, the absolute error is found to be 4.4%. Thus, this model can be used in the design, performance optimization and further application of TE water cooler. A comparison between prototype and the conventional water cooler indicates that the proposed system yields higher coefficient of performance (COP) despite a higher ICC.

Keywords: Thermoelectric; Drinking water; Economic; Heat pipe heat sink; Water cooler.
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1. Introduction

It is widely acknowledged that each day an adult should generally drink eight cups of water. The precise amount of water depends on the individual themself: sex, age, environment and physical activeness. However, besides quantity, the water temperature is as well commonly questioned. According to an article by Hosseinlou *et al.*[1] water slightly chilled to about 16 °C is recommended for rehydration.

[1] *Post-Harvest and Agricultural Machinery Engineering Research Unit, Faculty of Engineering, Mahasarakham University, Khamriang, Kantarawichai, Mahasarakham 44150, Thailand.*
[2] *Department of Industrial Education, Faculty of Education, Srinakharinwirot University, 114, Sukhumvit 23, Wattana, Bangkok, 10110, Thailand.*
[3] *Energy Management Technology Division, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand.*
[#] *These authors contributed to this work equally.*
**Email:* charoenporn.ler@kmutt.ac.th (C. Lertsatitthanakorn)

Refrigeration is a crucial process for abundant applications, ranging from keeping food and drink fresh to preventing overheating in electronic devices, *etc.* Conventional refrigeration systems operate on the vapor-compression cycle. However, such refrigeration systems inopportunely emit a great amount of greenhouse gases.[2] Almost every commercial drinking water cooler available in the market uses R134a—a refrigerant with a global warming potential (GWP) value of 1430[3] as the working fluid. This can considerably harm the ecosystems and thus directly impact the welfare of the biosphere, necessitating the exploration of environment-friendly and energy-efficient substitutes. Advancement in thermoelectric (TE) cooling is a promising response to the aforementioned issue. TE coolers are solid-state refrigerators that employ the Peltier effect to pump heat,[4] offering benefits in several aspects such as higher environmental friendliness, no moving parts, more compactness and lower maintenance cost.[5] Nevertheless, the main drawback of the TE cooler is the inadequate coefficient of performance (COP).[6]

For a TE cooling system to achieve the maximum COP, the thermal resistance of the heatsinks must be minimized.[7] One approach is to improve the heat dissipation from the TE module; the heat pipe heatsink is attractive due to its great amount of heat transfer (phase change latent heat) which may be 500 times as high as the best conductor available.[8] Heat pipe heatsinks have been used on the hot side of the TE module. Liu *et al.*[9] studied the method of effectiveness-number of transfer units for optimization of a TE cooling system integrated with heat pipe heatsink. The cold side was connected to the extender block, while the heat pipe heatsink was used to dissipate heat at the hot side. Results showed that the thermal extender block had significant characteristics for optimal TE cooling system design. Abderezzak *et al.*[10] built a TE refrigerator employing a novel composition of heat pipe heatsink on both the hot and cold sides of a TE module, obtaining a COP of 0.74 at a temperature difference between the hot and cold sides of 32.7 °C. A TE dehumidifier integrated with heat pipe heatsinks has been presented by our research group[11], where the prototype was composed of four TE modules. A rectangular fin heatsink was connected to the cold side, while a heat pipe heatsink was used to dissipate heat at the hot side. The optimum condition occurred at a supplied electric current of 3 A and a cold air flow rate of 1.34 g/s, yielding a cooling capacity of 93.1 W and a COP of 1.1.

There has been research conducted on the performance analysis of TE water coolers. Lertsatitthanakorn[12] used a rectangular aluminum fin heatsink to release heat from the hot side, and two TE modules to cool water in the water tank. The cold side of the modules was attached to the base of the water tank. The TE cooler could decrease the water temperature from 29 °C to 15 °C within two hours. Pourhedayat S.[13] constructed a TE water cooler with six TE modules, of which hot and cold sides were glued on metallic radiators utilizing water as the working fluid. The outlet water temperature was dependent on the hot- and cold-side water flow rates and the inlet temperatures. Al-Rubaye *et al.*[14] made a portable TE water cooler with the tank base attached directly to the cold side of the TE module and the hot side fixed to an air-cooled heatsink. Their resultant COP of 0.5 was obtained at the initial water temperature of 30 °C. Tijami *et al.*[15] designed, built and tested a solar-powered multistage TE water cooler in which the hot side of the TE module was cooled by a liquid refrigerant and an aluminum water tank was attached to the cold side. The water capacity is 5 liters, the acquired temperature gradient was between -0.003 and -0.004 °C, and the COP of 0.45 was achieved at an electric current input of 7 A. Shi *et al.*[16] developed a TE drinking water cooler using four TE modules and a fin-pin heatsink for both sides of the modules. Specific exergy costing (SPECO) theory was adopted in economic evaluation. The cooling capacity and its consequent cost depended on inlet temperatures, input power and fluid flow conditions. A high flow rate and low inlet temperature on the hot side reduced the cooling cost. There are limited researches focusing on their application in thermal modeling and economic benefits for the coupling application of TE cooling modules and heat pipe heatsinks.

As mentioned above, no experimental results and thermal modeling have yet been published about a TE drinking water cooler integrated with a heat pipe heatsink. The main significance of this work is to employ a heat pipe heatsink to enhance its performance of a TE drinking water cooler. Performance and initial cost per cooling capacity of the proposed system are compared against a convectional water cooler (vapor-compression system). The effects of electric current supplied to TE modules, water and air flow rates to cold and hot heatsinks, and ambient temperature on cooling performance are investigated to find the optimal operating condition of the proposed system. A thermal model for the TE water cooler, based on a set of heat transfer equations, was developed to represent the state-of-the-art modeling approaches. Particularly, the evaluation of initial capital cost (ICC) per cooling capacity, which is the cornerstone of any energy system technology.

2. Experimental test rig and procedures

The TE drinking water cooler comprises two TE modules (model TEC1-12708, China) of specifications in Table 1, a copper plate and tube heat exchanger, an axial flow fan integrated with heat pipe heatsinks, pump and water storage tank, as shown in Fig. 1. Each heat pipe heatsink has six copper heat pipes of 6-mm in diameter. The evaporator section has a surface area of 52 × 54 mm^2 fixed at the hot sides of TE modules while the condensation section is enhanced by fins and forced convection mode produced by an axial flow fan. Water is employed as the working fluid in the heat pipe heatsink (Data obtained from the manufacturer). The cold side of the TE modules is attached with a copper plate and tube heat exchanger (the cold side heat sink). The copper plate is 2 mm thick, 200 mm long and 60 mm wide. A copper tube with an internal diameter of 4 mm is soldered to one side of the copper plate as shown in Fig. 2. When the TE water cooler operates, water from the storage tank circulates and the heat of water absorbed by the cold side of the TE modules, thus reducing the water temperature. In addition, two sides of the contact surface of each TE module are coated with thermal grease to minimize surface thermal resistance. A water pump is used to help circulate water, consuming 4.08 W. The water tank, insulated to diminish heat loss, has a cylindrical shape with a height of 170 mm and a diameter of 153 mm. The total volume of water in the water tank was 3 L.

Table 1. Properties of TE module.[17]

Area (mm^2)	40 ×40
Thickness (mm)	3.5
Seebeck coefficient (V/K)	0.0444
Electrical resistance (Ω)	2.545
Thermal conductivity(W/K)	0.495
Number of elements	127

Important parameters affecting the performance of the TE water cooler are measured. K-type thermocouples are

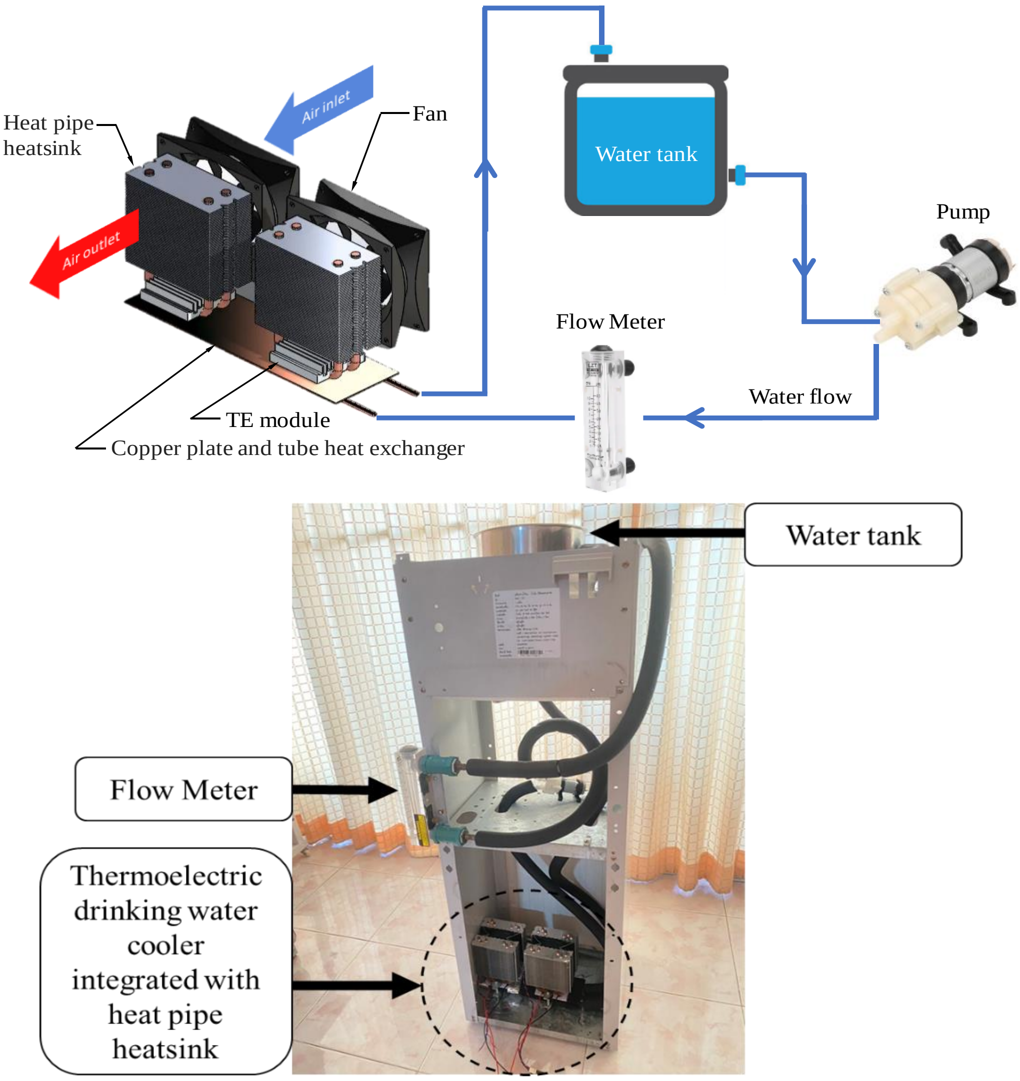

Fig. 1 Schematic view of TE water cooler and photograph of the experimental test rig.

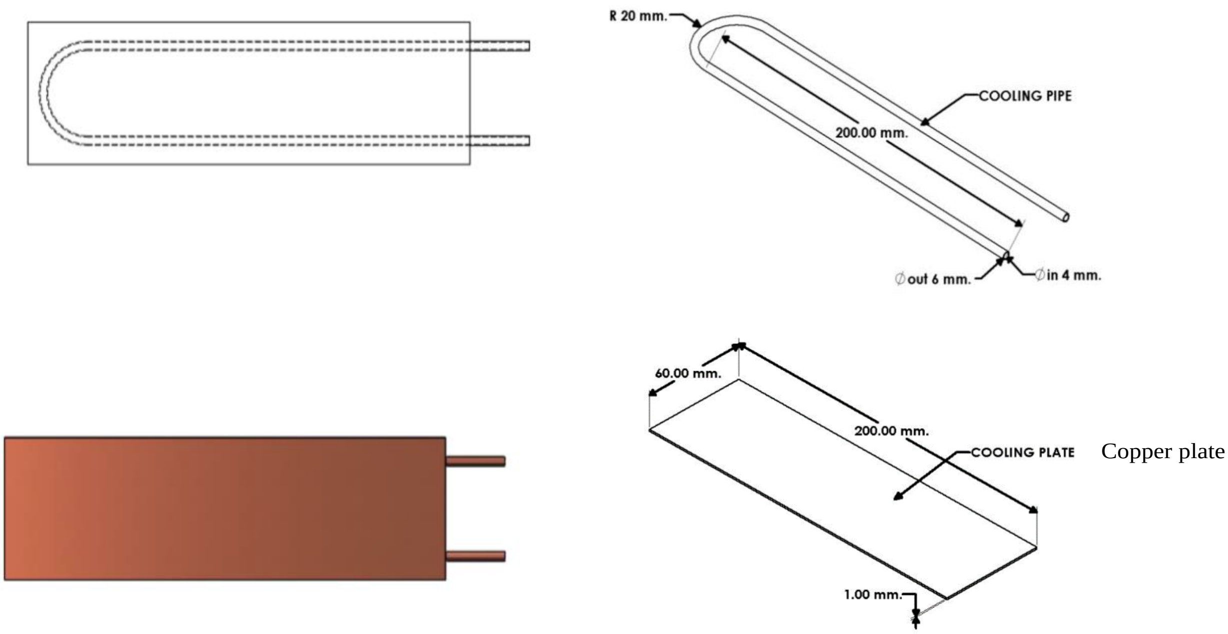

Fig. 2 Copper plate and tube heat exchanger (Cold side heat sink).

instrumented for temperatures of the air inlet and outlet, the heat pipe heatsink, the hot and cold sides of the TE modules, the water inlet and outlet of the cold side heat sink and the water in the storage tank. Data were recorded by using a data logger. Velocity of the air passing through the heat pipe heatsinks is measured by a hot wire anemometer (average of five points as shown in Fig. 3). The air velocity was used to calculate the air mass flow rate. A rotameter is used to measure the water flow rate. Input current and voltage of the TE modules, the pump and the fans are measured by a digital multimeter. DC power is supplied by the TE modules, the pump and the fans.

The uncertainty of this work is derived from the measurement error of the instrument, including the temperature, voltage, current, air velocity and water flow rate. The uncertainties were calculated using the method which was employed by Rahbar *et al.*[18] and the results are presented in Table 2.

Table 2. The accuracy, ranges and standard uncertainties associated with measuring devices.

Instrument	Accuracy	Range	Standard uncertainty
K-type thermocouples	1.0 °C	-100 to 1300 °C	0.01 °C
Anemometer	0.03 m/s	0-20 m/s	0.02 m/s
Relative humidity	3% RH	10-98% RH	1.73% RH
Flow meter	0.03 L/min	0.2-2 L/min	0.02 L/min
Multimeter:	0.1 V	0-60 V	0.06 V
Voltage	0.1 A	0-12 A	0.06 A

2.1 Thermal model of TE water cooler

A thermal model of the experimental setup was developed to estimate the performance of the TE drinking water cooler. The following assumptions are made to simplify the complex problem of modeling:

1. One-dimensional heat transfer has been assumed for all energy transfer processes.
2. Heat transfer coefficients of water are constant along the surface area.
3. All thermophysical properties are evaluated at an average temperature.

The cooling power at the cold side of the TE module is composed of Peltier heat, conduction heat and Joule heating, which is given by[19]:

$$\dot{Q}_c = \alpha I T_c - 0.5 I^2 R - K(T_h - T_c) \quad (1)$$

The heating power at the hot side of the TE module is calculated as:

$$\dot{Q}_h = \alpha I T_h + 0.5 I^2 R - K(T_h - T_c) \quad (2)$$

where $\dot{Q}_c$ and $\dot{Q}_h$ are the cooling and heating powers of the TE module, respectively, α is the Seebeck coefficient of the TE materials, I is the electric current applied to the TE module, R is the electric resistance of the TE module, K is the total thermal conductivity of the TE module, and T_c and T_h are the temperatures of the cold and hot sides of the TE module, respectively.

The cooling capacity of water in the storage tank is denoted by[20]

$$\dot{Q}_w = \frac{M_w C_w (T_{wi} - T_{wf})}{\Delta t} \quad (3)$$

where $\dot{Q}_w$ is the cooling capacity, C_w is the specific heat of water, M_w is the mass of water in the storage tank, t is the cooling time, and T_{wi} and T_{wf} are the initial and final water temperatures.

The effectiveness-number of transfer unit (ε-NTU) is adopted to calculate the heat transfer from the hot side, which is given by:[9]

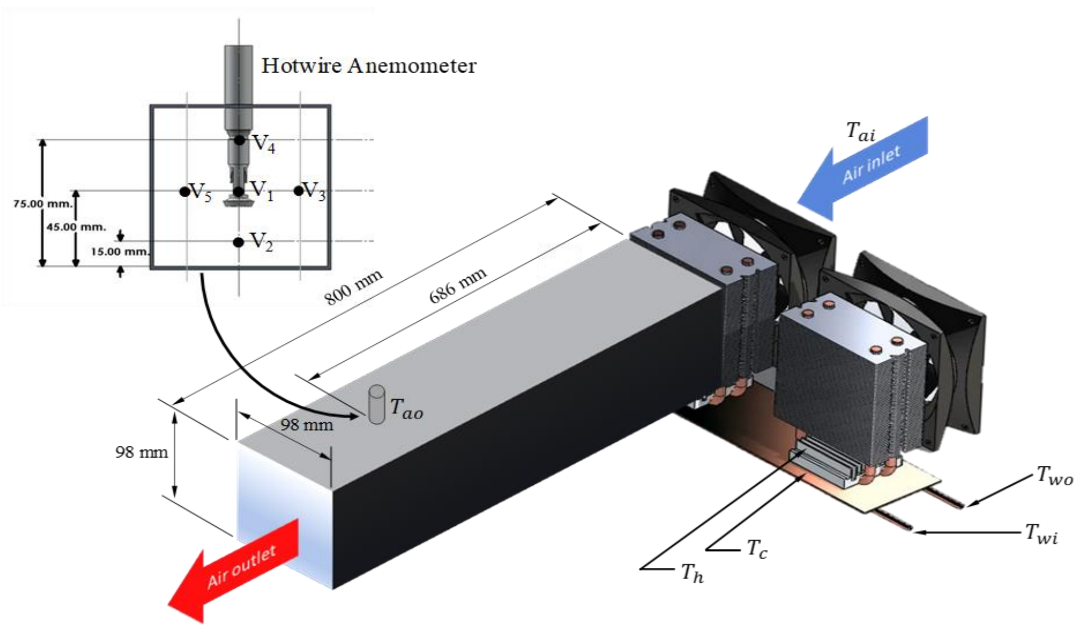

Fig. 3 Locations of temperature (T) and velocity sensors in the experimental device.

$$\dot{Q}_h = \frac{\varepsilon_h C_{pa} m_a (T_h - T_{ai})}{(1-\tau_{TE})(1-\tau_{EX})} \quad (4)$$

where C_{pa} is the specific heat of air, m_a is the air mass flow rate, T_{ai} is the input air of the hot-side heat sink, τ_{TE} and τ_{EX} are the heat losses from the TE modules and heat pipe heat sink, which is approximately 10%,[9] and ε_h is the heat pipe heatsink effectiveness, defined as[20]

$$\varepsilon_h = \frac{m_a C_{pa}(T_{ao} - T_{ai})}{m_a C_{pa}(T_h - T_{ai})} \quad (5)$$

where T_{ao} is the outlet air temperature from the heat pipe heat sink.

The cold side of the TE modules cools the water via the cold-side heat sink. Assuming that the heat convection between the water and the cold-side heat sink conforms with the Newton's law of cooling, the cooling capacity of the cold side can be calculated by[20]

$$\dot{Q}_c = hA(T_{wo} - T_c) \quad (6)$$

where A is the area of the cold-side heat sink, T_{wo} is the outlet water temperature from the cold-side heat sink, and h is the convective heat transfer coefficient of the water, which is of two cases namely:

For a forced turbulent flow in a smooth tube,[20]

$$h = 0.023 \frac{k_w}{d_i} \left(\frac{d_i v \rho}{\mu}\right)^{0.8} \left(\frac{C_w \mu}{k_w}\right)^{0.3} \quad (7)$$

For a forced laminar flow in a smooth tube,[20]

$$h = 1.86 \frac{k_w}{d_i} \left(\frac{d_i v \rho}{\mu} \cdot \frac{C_w \mu}{k_w} \cdot \frac{d_i}{L}\right)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14} \quad (8)$$

where k_w is the water's thermal conductivity, d_i is the tube inside diameter, L is the tube length, v is the water's velocity, µ is the water viscosity and μ_w is the water viscosity at the tube wall temperature.

From first law of thermodynamics at the cold and hot side of the TE module, the cooling capacity can be expressed as given below[21]

$$Q_c = Q_h - P_{TE} \quad (9)$$

The cold water at the outlet of cold side heat sink is calculated by:

$$T_{wo} = \left(\frac{Q_c}{hA}\right) + T_c \quad (10)$$

In order to obtain the outlet water temperature from the cold-side heat sink at every 5 minutes in thermal model analysis, Input variables include; ambient temperature, thermophysical properties of working fluids, water mass flow rate, area of cold side heat sink and input power to TE modules. With a given an outlet air of hot side heat sink, hot and cold sides temperatures can be evaluated using a trial-and-error technique. A spreadsheet program is developed for solving Equations (4), (5), (7) or (8), (9) and (10). The convergence condition of the outlet water temperature from the cold-side heat sink was within 5%. The value of the boundary conditions is obtained using the measured data from the experimental section. The calculation procedure is presented in Fig. 4.

The coefficient of performance (COP)-the ratio of cooling capacity to electrical power consumed by the TE modules, water pump and cooling fan of the heat pipe heatsink-is computed based on the following expression[21]:

$$COP = \frac{\dot{Q}_w}{P} \quad (11)$$

where P is the input electrical power to the TE cooler system and can be calculated as below:

$$P = P_{TE} + P_p + P_f \quad (12)$$

where P_{TE} is the electrical power supplied to the TE cooling modules, P_p is the input electrical power of the water pump, and P_f is the input electrical power to the cooling fan of the heat pipe heatsink.

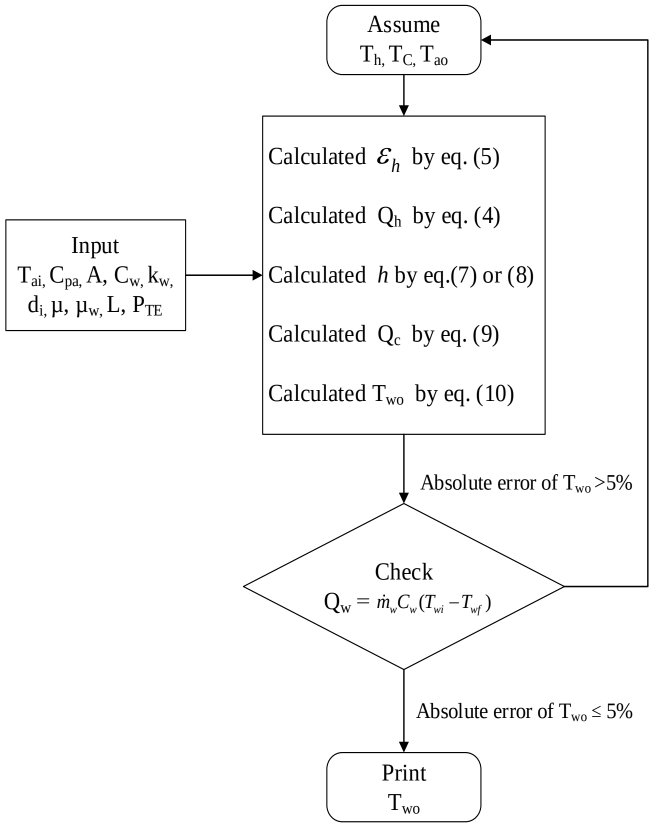

Fig. 4 Flow chart of the calculation steps.

2.2 Economic evaluation

Initial capital cost (ICC) per cooling capacity is employed as an economic measure and is evaluated by:

$$ICC = \frac{IC}{\dot{Q}_w} \quad (13)$$

where IC is the initial cost.

3. Results and discussion

3.1 Effects of electric current supplied.

The effects of electric current supplied to the TE modules on the hot and cold sides are illustrated in Fig. 5, The cold-side temperature varies upon the electric current. As the electric current increases, the cold-side temperature decreases due to an increased Peltier heat (see Eq. (1)). Consequently, the cooling load is pumped from the cold side to the hot side of the TE modules whereas the hot-side temperature increases rather consistently with increasing electric current. The outlet air temperature rises from 28.3 °C to a maximum of 32.4 °C as the current varies from 1 to 5 A as shown in Fig. 6, while the water temperature continuously decreases.

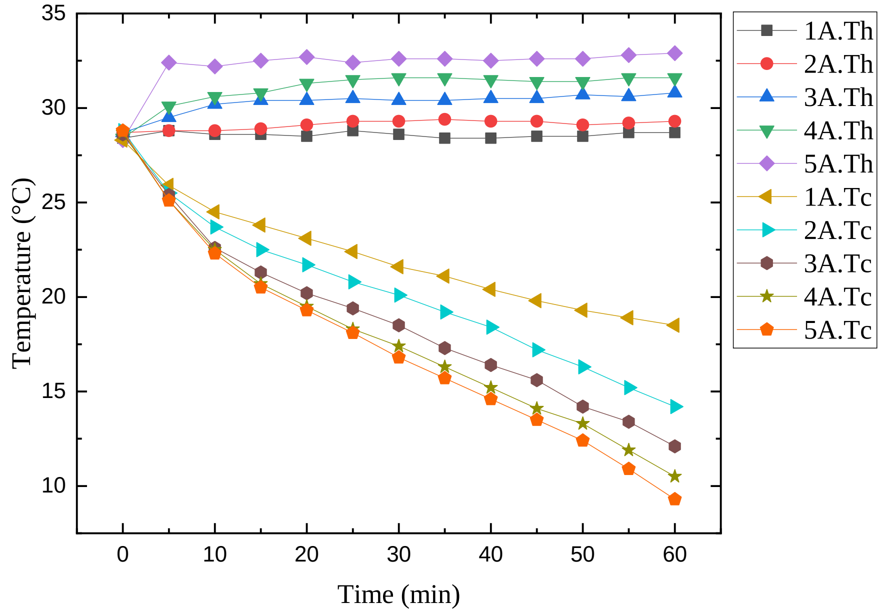

Fig. 5 Hot and cold sides under different supplied electric currents to the TE modules ($\dot{m}_a$ = 14.7 g/s, $\dot{m}_w$ = 17 g/s and T_{amb} = 26°C).

Variations in the cooling capacity and COP of the TE water cooler are represented in Fig. 7. The cooling capacity drastically increments to 92.2% at the maximum current. Meanwhile, the COP decreases because of the substantial increase in the input electric power to the TE cooler system. It can be seen that the cooling capacity and COP cannot be achieved simultaneously at the maximum current. Nevertheless, the ideal water temperature of 16 °C [1] corresponds to the electric current of 2 A, the cooling capacity of 25.3 W and the COP of 1.09.

3.2 Effects of water flow rate

As visualized in Fig. 8, the cold-side temperature increases with the augmentation of the water flow rate. This phenomenon results from reduced residence time of the water flow rate and obviously the water temperature is higher than the case in which the water flow rate is lower.[21] Higher water flow rate raises water temperature, although by a lower percentage.

Cooling capacity is enhanced as shown in Table 3. This is in accordance with that reported by Ahammed *et al.*[22] The lowest water temperature is reached at the lowest water flow rate. Contrarily, COP decreases with increased water flow rate, as the water pump consumes about 2.53 times the electric power of the low water flow rate. COP is probably the most important performance indicator of TE coolers. It is noted in

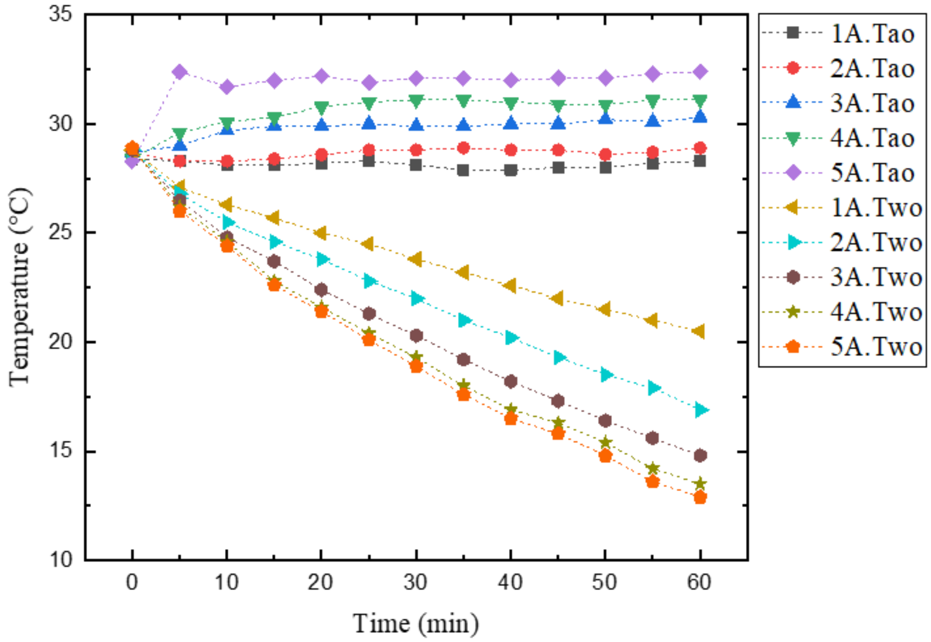

Fig. 6 Outlet air from the heat pipe heatsink and water temperatures under different supplied electric currents to the TE modules ($\dot{m}_a$ = 14.7 g/s, $\dot{m}_w$ = 17 g/s and T_{amb} = 26 °C).

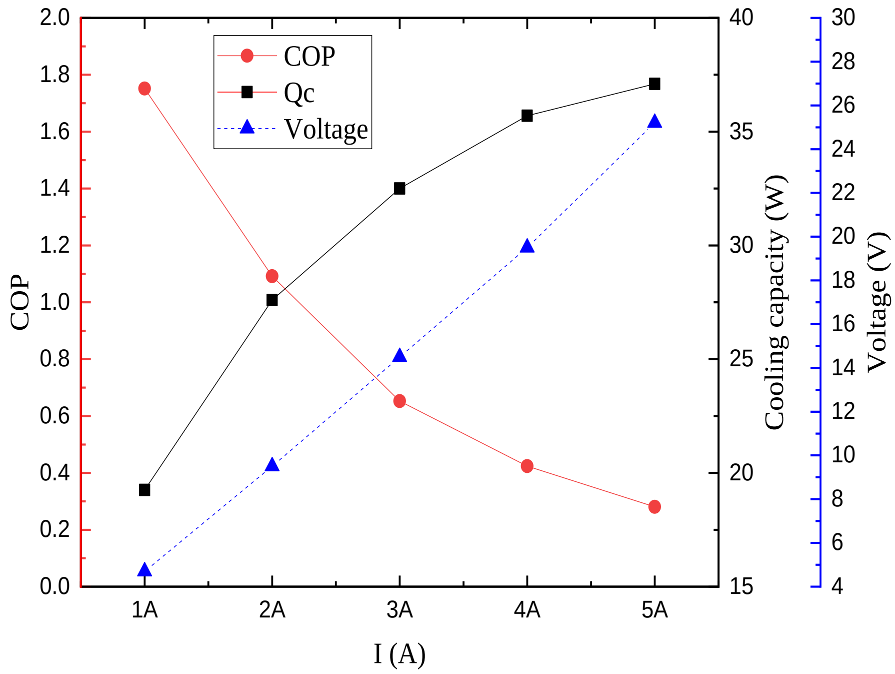

Fig. 7 Cooling capacity and COP under different supplied electric currents to TE modules ($\dot{m}_a$ = 14.7 g/s ,$\dot{m}_w$ = 17 g/s and T_{amb} = 26 °C).

this study that we suggest the maximum COP as an operating condition for a TE water cooler.

Table 3. Effects of water flow rate on cooling capacity and COP.

$\dot{m}_w$ (g/s)	P_p (W)	P (W)	Q_c (W)	COP
8.3	0.64	24.32	25.1	0.84
17	1.61	25.29	27.6	1.09
25	4.08	27.76	26.2	0.98

3.3 Effects of air flow rate through the heat pipe heatsink

Effects of air flow rate through the heat pipe heatsink on outlet air from the heat pipe heatsink, water, and cold- and hot-side temperatures are shown in Fig. 9. All temperatures have degressive slopes for the increased air flow rate. Cooling capacity and COP are also influenced by the air flow rate: higher air flow rate yields higher cooling capacity and COP (see Table 4) since the heat transfer rate of the heat pipe heatsink increases together with the air flow rate.[23] Higher air flow rates procure a higher COP, as the thermal resistance of the heat pipe heatsink decreases. In this case, a maximum COP of 1.09 is achieved for an air flow rate of 14.78 g/s.

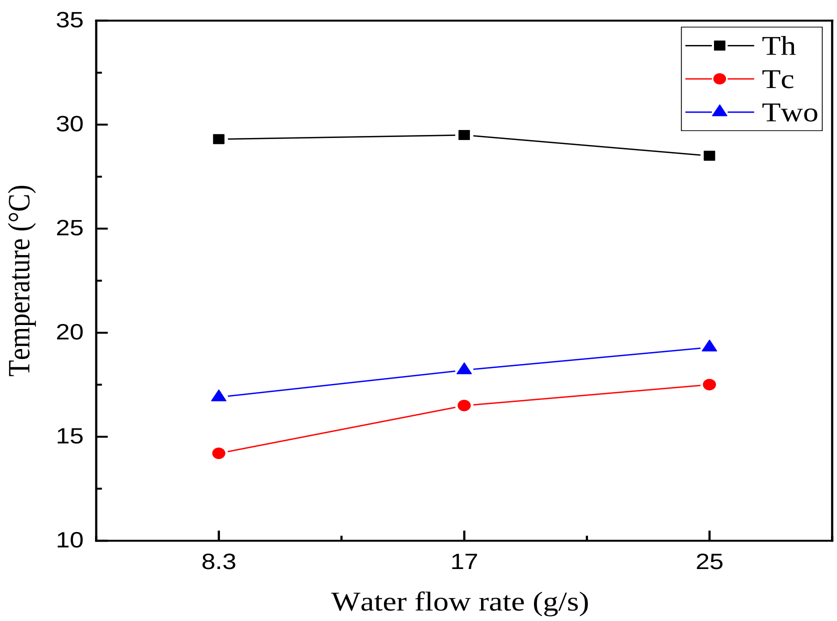

Fig. 8 Effects of water flow rate on the hot and cold-side and water temperatures ($\dot{m}_a$ = 14.7 g/s, I = 2 A and T_{amb} = 26 °C)

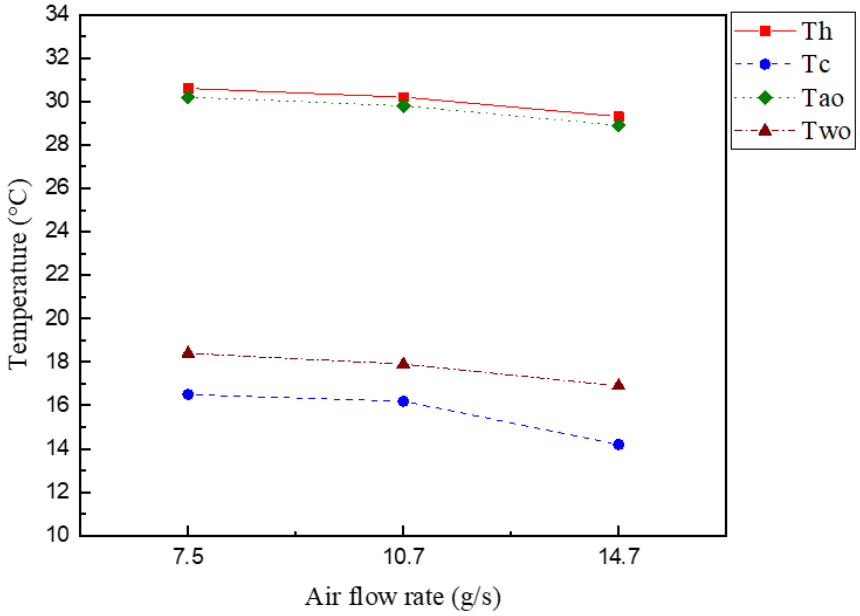

Fig. 9 Effects of air flow rate on the hot and cold-side, outlet air from the heat pipe heatsink and water temperatures (I = 2 A, $\dot{m}_w$ = 17 g/s and T_{amb} = 26 °C).

Table 4. Effects of air flow rate on cooling capacity and COP.

$\dot{m}_a$ (g/s)	P_f (W)	P (W)	Q_c (W)	COP
7.5	1.14	21.75	24.1	1.01
10.71	2.61	23.22	24.8	1.04
14.78	4.68	25.29	27.6	1.09

3.4 Effects of ambient temperature

In this section, the ambient air temperatures were simulated using an air conditioner. Fig. 10 depicts variations of the water, hot-air, and hot- and cold-side temperatures at different ambient air temperatures. Escalating ambient air temperature noticeably reduces heat dissipation from the condensation zone of the heat pipe heatsink,[8] resulting in the hot-side temperature's increase from 29.3 to 31.4 °C, which in turn reduces the cooling capacity and COP of the TE modules by 30.1% and 34.5%, respectively, as shown in Table 5. Meanwhile, the water temperature at a lower ambient air temperature is lower than at a higher air temperature (See Fig. 9). To conclude, ambient air temperature is a dominant factor, for a lower ambient temperature contributes to an improved COP of the TE cooling system.

Table 5. Effects of ambient temperature on cooling capacity and COP.

T_{amb} (°C)	Q_c (W)	COP
26	27.6	1.09
30	21.2	0.81

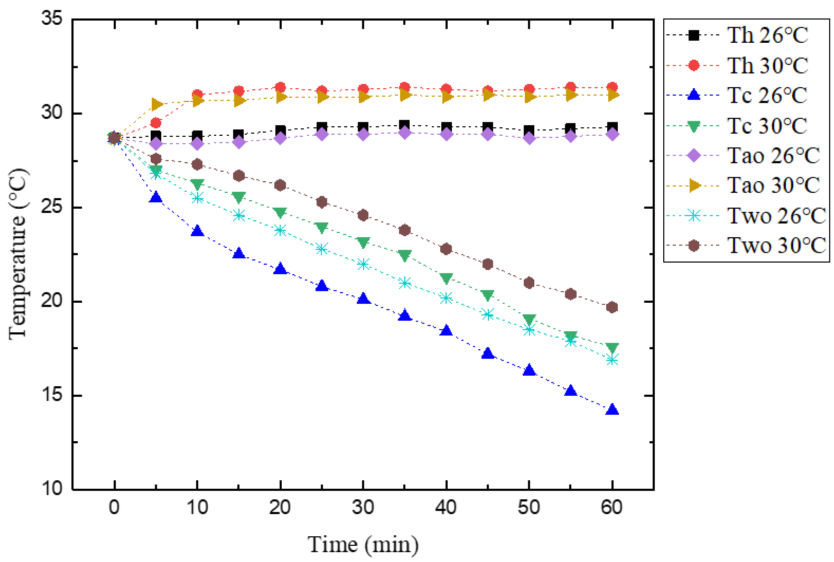

Fig. 10 Effects of ambient temperature on the hot and cold-side, hot-air and water temperatures ($\dot{m}_a$ = 14.7 g/s ,$\dot{m}_w$ = 17 g/s and I = 2 A).

3.5 Thermal model validation

To validate the thermal model developed a comparison with the experimental results for the electric current supplied to the TE modules at 2 A has been carried out. Fig. 11 shows a comparison of the thermal model and experimental data. It is observed that the average value of error in cold water is 4.4%. The value is acceptable, and the model can be used to design a TE water cooler described in this study.

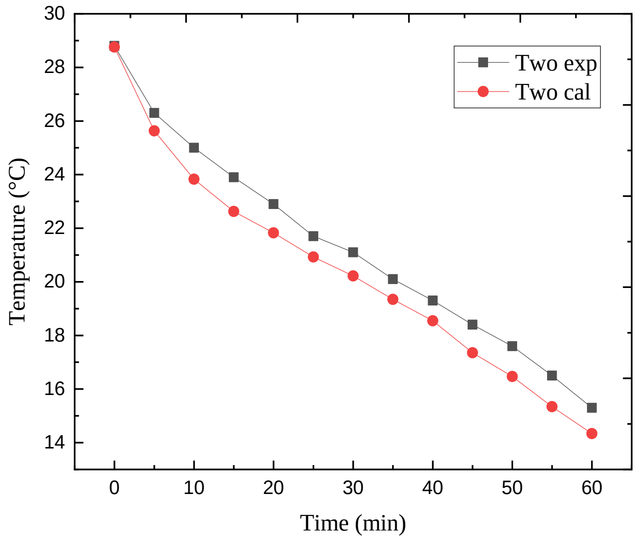

Fig. 11 Comparison between measured and simulated cold water.

3.6 Comparison with a conventional drinking water cooler

In this section, the initial cost and performance of this prototype are compared against the conventional drinking water cooler purchased from a local manufacturer.[24] The refrigeration system works on vapor compression and consists of a R-134a position-type hermetic compressor, a water tank equipped with the evaporator, a natural air-cooled condenser and a capillary tube. The compressor consumes an electric power of 80.85 W. Table 6 presents the comparisons on water temperature, cooling capacity, COP and initial cost between both coolers during a testing period lasting 60 minutes. Cooling capacity of the convectional cooler is higher than the TE water cooler, hence the lower water temperature. However, the COP of the TE cooler is higher by 33% due to the conventional water cooler using natural air-cooled convective heat transfer mode for both evaporator and condenser. For economic assessment, total cost analysis of the TE water cooler includes key components: TE modules, pump, frame, cold and hot heatsinks. Initial capital cost per cooling capacity of the TE prototype is higher than that of the mass-produced conventional one, yet manufacturing cost is expected to reduce as the production scales up. On the other hand, operational cost of the TE water cooler should be lower as a higher COP and no required maintenance.[5] Besides, due to the advantages of accurate temperature control and compact structure,[25] TE coolers can be preferred for specific applications. Additionally, TE coolers can be powered by direct current (DC) electric sources such as photovoltaic cells. Thus, especially for portable applications, these systems are promising an non-refrigerant systems.

Table 6. Comparisons of the performance and economic evaluation between the TE water cooler and conventional water cooler.[24]

Items	TE water cooler	Conventional water cooler[24]
Initial water temperature (°C)	28.8	27.4
Final water temperature (°C)	16.5	11.1
Mass of water (kg)	2	3
Refrigerant	-	R134a
Cooling capacity (W)	27.6	58.9
COP	1.09	0.73
Initial cost (USD)	79.13	112.80
Cost per cooling capacity (USD/W)	2.87	1.92

4. Conclusions

In this study, attempts have been made to produce chilled water by a TE cooler integrated with a heat pipe heatsink as a promising drinking water cooler. An increase in the electric current results in a decreased COP, while the cooling capacity increases. Therefore, operating with lower currents would be beneficial for achieving higher TE COPs. At the end of the one-hour experiment, the suitable operating conditions are an electric current supplied to TE modules of 2 A and air and water flow rates of 14.7 g/s and 25 g/s, respectively. The corresponding cooling capacity is 27.6 W with a COP of 1.09 and a water temperature of 16.5 °C, which meets the suggested drinking water temperature.[1] The calculated results from the thermal model were in good agreement with the experimental results. It could be used to predict the cold water temperature produced by the TE water cooler. Comparisons of COP and ICC are made between the proposed system and the conventional water cooler: both COP and ICC of the proposed system are higher. Ultimately, system optimization is an advanced topic that needs to be further investigated and a solar-powered TE water cooler is an appealing topic for further development.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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