A Portable Hybrid Thermoelectric-Direct Evaporative Air Cooling System

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Abstract

The main objective of this work is to theoretically and experimentally investigate the feasibility of employing a thermoelectric refrigeration system to improve the air-cooling performance of a portable DEAC system. A portable hybrid thermoelectric-direct evaporative air cooling system has been fabricated based on a commercially portable direct evaporative air cooler integrated with a thermoelectric refrigeration system and tested. Its system consists of two subsystems: 1. a direct evaporative cooling system used as a main air-cooling system by inducing the hot ambient air in direct contact with the working fluid (water) circulated by a pump through a cooling (rigid sheet) pad; 2. a thermoelectric system used as a water cooling system by installing the cold side of 12 thermoelectric modules of TEC1-12708 stacked in two layers on one wall of the aluminum container filled with 5.6 liter of water and the hot side on the rectangular fin heat exchangers. The system was experimentally tested under ambient temperature and relative humidity of 28 ˚C - 31˚C and 60% - 75%, respectively. The testing results show that under the fan operation, the system is unable to cool the inlet air temperature (or 0 % cooling effectiveness). When DEAC system is in active, the cooling performance of the prototype increases by 20% and is up to 30% with higher fan speed (or 1.7 ˚C of air temperature drop). The results of TE installation can improve the cooling performance of the DEAC system by 10% and is up to 20% with higher fan speed (or 2.6 ˚C of air temperature decrease). Therefore, the concept of applying TEs to cool the water temperature in the container seems to be reliable not only for its additional cooling capacity but also contributing more convenient toward a portable DEAC system in the market.

Keywords: Thermoelectric, Direct evaporative-air cooling, Evaporative cooling, Thermoelectric applications, Portable air cooler.

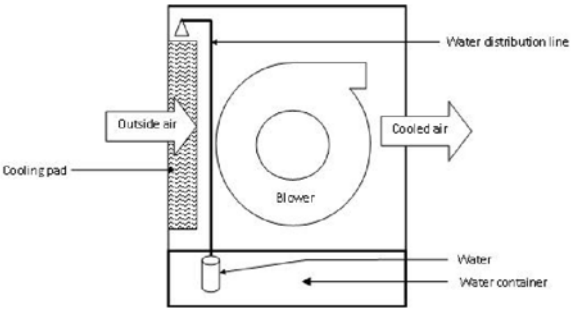
Introduction

Recently, many countries around the world consume approximately 40 to 70% of the total energy consumption of the country for conditioning and cooling the indoor air (El-Dessouky et al., 2000). Cooling of indoor air based on conventional vapour compression air conditioning (VAC) systems has been widely used in both residential and commercial sections due to high coefficient of performance (COP). However, they are noisy, bulky, costly, difficult to install, and highly efficient only when the cooling capacity is large and the load is stable. In addition, these systems utilize Chlorofluoro Carbons (CFCs) as working fluid causing the environmental effects.

On the other hand, evaporative air-cooling (EAC) is one alternative to mechanical vapor compression (MVC) and a simply available method of obtaining thermal comfort especially in the arid regions of the world. It is economical, energy-efficient (required only quarter of the electric power as compared with MVC (Cerci, 2003)), easily maintainable and environmentally -friendly (using water as the working fluid). Direct evaporative-air cooling (DEAC) is one of two common -typed EACs, where the outside air comes into direct contact with the water used through a cooling pad to produce the cooled air (Figure 1-a). This method has been applied to cool the indoor air for mobile homes, single-family housing, and industrial warehouses (David, 2007). It is also useful for a small air-cooling system as shown in Figure 1-b. However, its cooling capability in term of temperature drop is limited up to the water temperature the air flows through. This disadvantage could be overcome by applying an additional cooling system to lower the water temperature.

Thermoelectric (TE) technologies are one of environmentally friendly methods to produce cooling effect without employing refrigerant as working fluid. TE devices are made of semiconductor material electrically connected in series and thermally in parallel to create the temperature difference. The devices offer many advantages such as good compactness, precise temperature, long life span, fast thermal response (i.e. compared to air cooling fans and liquid heat exchangers) and excellent flexibility. They have been utilized in various applications such as cooling electronic devices (Naphon & Wiriyasart, 2009; Chein & Huang, 2004), refrigerator (Dai et al., 2003; Vián & Astrain, 2009; Rodríguezet al., 2009), air conditioner (Riffat & Qui, 2004; Li, 2009; Xu et al., 2007), several sensors (i.e., oxygen sensors, flux meters) (Röder-Roith, 2009; Ploteau et al., 2007), and power generation (Khalid & Mohd, 2009; Eakburanawat & Boonyaroonate, 2006; Yu & Chau, 2009; Lertsatitthanakorn, 2007; Nuwayhid et al., 2005).

In this paper, the main objective is to investigate the feasibility of employing a thermoelectric refrigeration system to improve the air-cooling performance of a portable DEA cooler.



(a)

(b)

Figure 1 (a) schematic diagram of DEAC (b) a commercially portable direct-evaporative cooler

Theoretical feasibility of a combined TE-DEA system

A DEA cooler based on a cooling pad has a simple diagram as shown in Figure 2-a where sensible heat of the inlet air ($Q_{s,i}$) is converted into both sensible ($Q_{s,o}$) and latent heat (Q_L) of the moisture increase by inducing the inlet air at a temperature (T_1) with a humidity ratio (W_1) in direct contact with water at a temperature (T_2) fed in a loop through a cooling pad and cooled with higher humidity (W_2) as path 1-2 (Figure 2-b). Further cooling of the fed water to a temperature of T_3 ($T_3 < T_2$) by an additional cooling system (or thermoelectric refrigeration system) can improve the air-cooling performance as path 2-3. At adiabatic saturation where the fed water temperature is at the adiabatic saturation temperature of the inlet air (T_{WB} - wet bulb temperature), the outlet air temperature can theoretically reduce to the wet bulb temperature as path 3-4.

This cooling process of the air is called an adiabatic saturation process in which there is no heat supplied or released from the air. An energy balance of this process can be derived as (Jones, 2001):

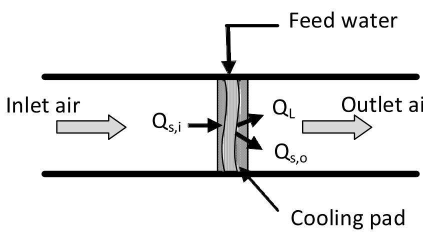
$$Q_{s,i} = Q_{s,o} + Q_L$$

Or $$c(T_i - T_o) = (m_o - m_i)((T_o - T_w) + h_{fg}) \quad (1)$$

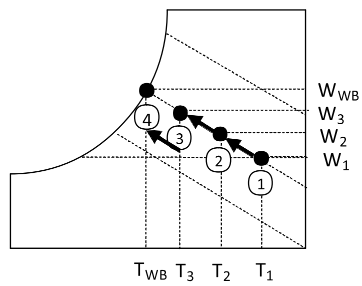
where T_i, T_o, and are the inlet, outlet air temperatures and fed water temperature, respectively $\Delta m = m_o - m_i$ is the difference between outlet and inlet mass of the evaporated water at T_o. c and h_{fg} are the specific heat of moist air and latent heat of vaporization at T_o, respectively. From Eq.(1), the first and second terms on the right side present the moisture increase sensibly heated from a temperature of T_w to a temperature of T_o and then vaporized at constant temperature of T_o. By arranging Eq.(1), the outlet air temperature (T_o) can be calculated as:

$$T_o = \frac{cT_i}{(\Delta m + c)} + \frac{\Delta m(T_w - h_{fg})}{(\Delta m + c)} \quad (2)$$

Eq.(2) presents function of outlet air temperature dependent on inlet air temperature, vapor mass increase (or moisture), and fed water temperature. From Eq.(2), it indicates that one of design parameters can increase the air-cooling performance (or decreasing the outlet air) by lowering the fed water temperature.



(a)



(b)

Figure 2 Direct evaporative cooling integrated with a thermoelectric cooling system

Description of the experimental prototype

A prototype (Figure 3) has been fabricated based on a commercial portable direct-evaporative cooler (model: CT20LAC) operating at 200 Watt of electricity with three modes of fan speed: low, medium, and high as shown in Figure 1-b. This prototype consists of two main subsystems (Figure 4): 1) direct evaporative cooling system consisting of a cooling pad, blower, and water pump; 2) thermoelectric refrigeration system made of thermoelectric modules (TEMs), regular fin heat exchangers, and fans. The cold side of TEMs is attached with one of the aluminum container walls and the hot side is attached with fins and fans, respectively. The feature of the prototype is presented in Table 1.

The operating principle of the prototype is the conversion of sensible heat of the hot air to the latent heat of water vaporization by inducing the air in direct contact with the water circulated from the aluminum container through the cooling pad by using a water pump, which results in reducing the air temperature. Installation of thermoelectric refrigeration system is to remove the sensible heat from the water in the container for further improvement of the air cooling capacity.

Table 1 Prototype component detail

Prototype Detail	
Outside plastic case	Dimension: 50 cm(W)×40 cm (L) ×83 cm (H);
Water pump	Max flow rate: 600 liter/hour;
Blower	Speed: 1,050 RPM;
Cooling pad	Dimension: 34.5 cm(W) ×40 cm (L) ×4.5 cm (Thick);
Aluminum container	Dimension: 40 cm(W) ×10 cm (L) ×14 cm (H);
Fins	3 items (Dimension: 10 cm(W) ×13 cm (L) ×2 cm (Thick));
Thermoelectric modules	12 modules (TEC1-12708) stacked in 2 layers;
	Dimension: 4 cm(W) ×4 cm (L) ×0.35 cm (Thick);
	Pair number of thermocouples: 127

(a) (b) (c)

Figure 3 An experimental prototype: a) front side, b) back side, c) cooling pad

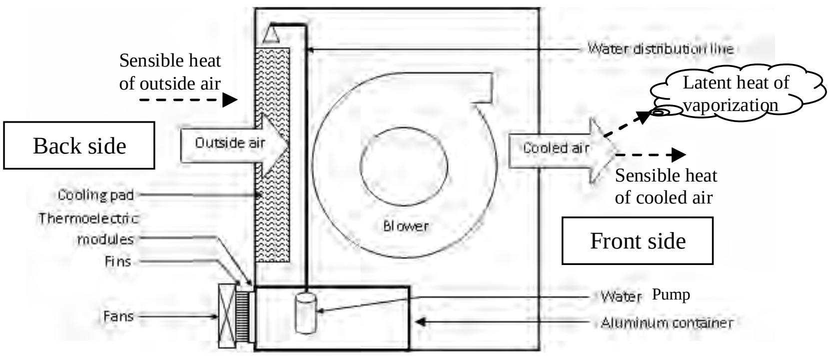


Figure 4 Diagram of a combined TE-direct evaporative air cooler

Performance analysis of the system

The system performance of the combined TE-direct evaporative cooler is evaluated by using the following equation:

$$\eta_{DEAC} = \frac{T_{db,in} - T_{db,out}}{T_{db,in} - T_{wb,in}} \times 100 \qquad (3)$$

where η_{DEAC} , $T_{db,in}, T_{db,out}$, and $T_{wb,in}$ are the cooling effectiveness, dry bulb temperature of inlet and outlet air, and wet bulb temperature of inlet air, respectively. From Eq.(3), it indicates that the cooling effectiveness of direct evaporative cooling method is limited up to the wet bulb temperature of the inlet air (or 100 percent). However, if the fed water temperature can be reduced below the wet bulb temperature of the inlet air by mean of employing an additional cooling system, the cooling effectiveness is probably higher than 100 percent.

Moreover, the coefficient of performance (COP) of 2 stage TE refrigeration system can be obtained by deriving the heat balance at each junction of two TE modules as shown in Figure 5.

$$COP_{TEM} = \frac{Q_{c,2}}{P_{TE}} \qquad (4)$$

and $$Q_{c,2} = \alpha_2 I_2 T_{c,2} - \tfrac{1}{2} I_2^2 \frac{R_2}{G} - K_2 G\left(T_{12} - T_{c,2}\right) \qquad (5)$$

$$T_{12} = \frac{\frac{0.5}{G}\left(I_2^2 R_2 + I_1^2 R_1\right) + G\left(K_1 T_{h,1} + K_2 T_{c,2}\right)}{\left(\alpha_1 I_1 - \alpha_2 I_2\right) + G\left(K_1 + K_2\right)} \qquad (6)$$

where $Q_{c,2}$ and P_{TE} are the cooling capacity and the supplied power of 2 stage TE modules. α, *R*, *K*, *I*, and *T* are the Seeback coefficient, electrical resistance, thermal conductivity, the supplied current, and temperature of TE, respectively. *G* is the structure parameter of thermocouples and is equal to the ratio of cross-sectional area to length of thermocouples. Subscripts, c, h, 1, 2, and 12 are cold and hot ends, first and second stages of TE, and interstage, respectively. In addition, α and *K* are estimated based on the following equations (Riffat et al., 2006):

$$\alpha = \left(\alpha_0 + \alpha_1 T_m + \alpha_2 T_m^2\right) \times 10^{-9} \qquad (7)$$

$$K = \left(K_0 + K_1 T_m + K_2 T_m^2\right) \times 10^{-6} \qquad (8)$$

where α_0, α_1, and α_2 are equal to 22224.0, 930.6, and -0.9905, respectively. K_0, K_1, and K_2 are equal to 62605.0, -277.7, and 0.4131, respectively. Tm is the average temperature of hot and cold side of TE modules.

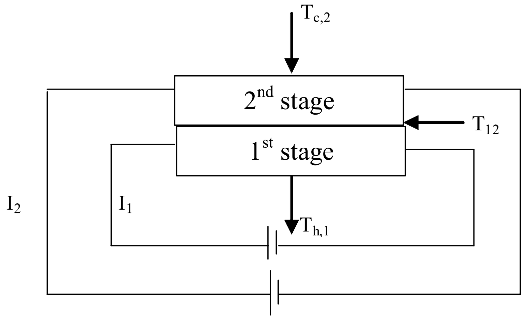


Figure 5 Schematic diagram of two-stage TE

Experimental setup

The experimental set up and the measurement locations are presented in Figuer 6. All measured parameters for the system performance evaluation of the combined thermoelectric-direct evaporative air cooler are shown in Table 2. K-type thermocouples and humidity sensors (HIH-4030) used to measure the temperatures and humidity of the air, respectively, are recorded every minute by the datalogger. A hot-wire anemometer (VELOCICALC-Model 8345) was used to measure the air flow.

Three types of experiments were conducted under the testing conditions specified in Table 3 to investigate the feasibility of utilizing thermoelectric refrigeration system to improve the cooling performance of the direct evaporative cooling system:

- Type 1: Fan operation (Fan) - This experiment was set up to investigate the air-cooling performance of the prototype when the blower is only in operation.
- Type 2: Direct evaporative air cooling operation: (DEAC) - This experiment aims to evaluate the cooling performance of the prototype when the blower and water pump are in operation and the fed water temperature is at the room temperature.
- Type 3: Thermoelectric-DEAC (TE+DEAC) - This experiment was carried out to evaluate the system performance when thermoelectric modules and DEAC operate.

In each experiment, the blower (fan) speed was also adjusted in three levels as low, medium, and high and executed for 2 hours with 5.6 liter of water in order to study its effect on the cooling performance of the system.

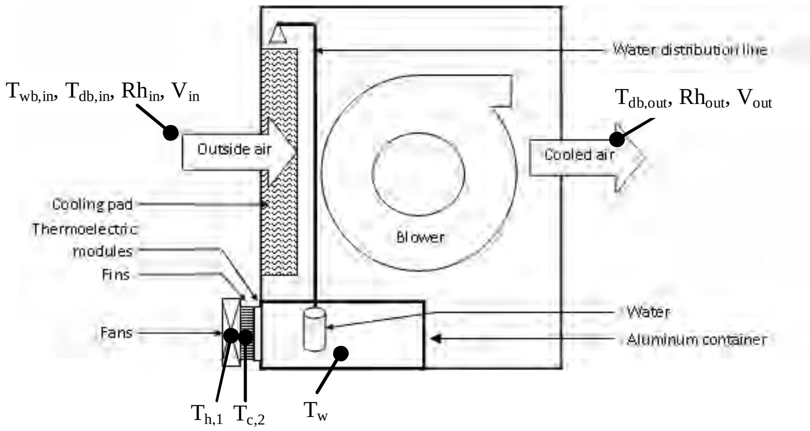


Figure 6 Diagram of experimental set up

Table 2 Measured parameters

Parameter Detail	
Inlet and outlet air temperature	$T_{db,in}$, $T_{db,out}$;
Inlet and outlet air velocity	V_{in} , V_{out};
Inlet and outlet air relative humidity	Rh_{in} , Rh_{out};
Wet bulk temperature of inlet air	$T_{wb,in}$;
Water temperature in the container	T_w;
Hot end temperature of 1st stage TE and cold end temperature of 2nd stage TE	$T_{h,1}$, $T_{c,2}$;

Table 3 Measured parameters

Condition Detail	
Ambient temperature	28 °C – 31 °C;
Relative humidity	60% – 70%;
1st thermoelectric (6 modules)	16 Volt; 2 A
2nd thermoelectric (6 modules)	8 Volt; 1 A
Fan (3 fans connected in parallel)	12 Volt ;

Results

Three experiments were carried out in order to evaluate the air-cooling performance of the prototype. Inlet and outlet air temperatures are used to present its air-cooling performance. Figure 7 shows the air-cooling performance of the prototype in term of outlet air temperature drop under the ambient condition in case of fan operation. The outlet and inlet air temperatures under fan function are slightly different between 31°C – 32°C. Increase of the fan speed is not able to decrease the outlet air temperature. In addition, the difference between inlet and outlet humidity is due to its gradient.

Figure 8 presents the air-cooling performance of the prototype when the direct evaporative cooling system is in active and the water temperature is at approximately 25 °C. The outlet air temperature obtained is slightly dropped, approximately 1.7 °C below the inlet air temperature with higher relative humidity while the fan speed is increased.

Figure 9 presents the air-cooling performance of the prototype when both direct evaporative cooling system and thermoelectric refrigeration system operate. By combining the thermoelectric system into the evaporative cooler, the water temperature is reduced from 28 °C to approximately 22 °C while the outlet air temperature is decreased 2.6 °C below the inlet air temperature with moisture increase in the outlet air. In this operation, the supplied power to the TE modules is totally 80 Watt with COP of 0.06.

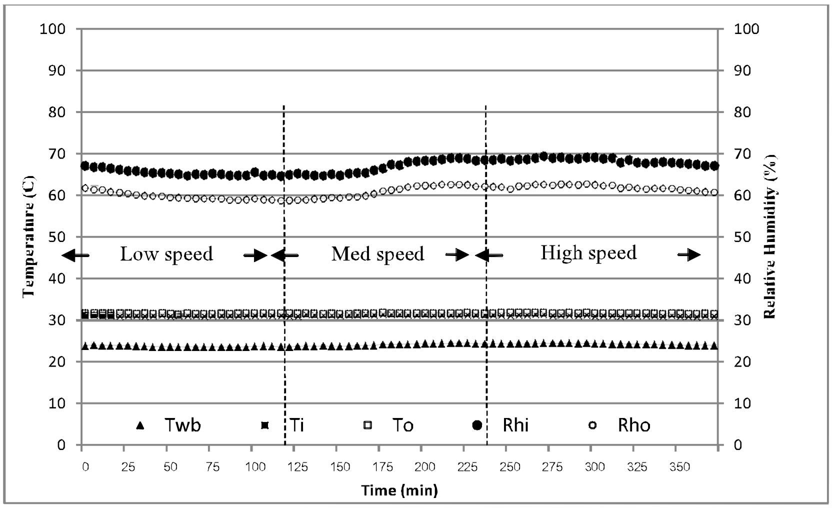


Figure 7 Comparison of inlet and outlet air temperatures and relative humidity (Case: Fan Operation)

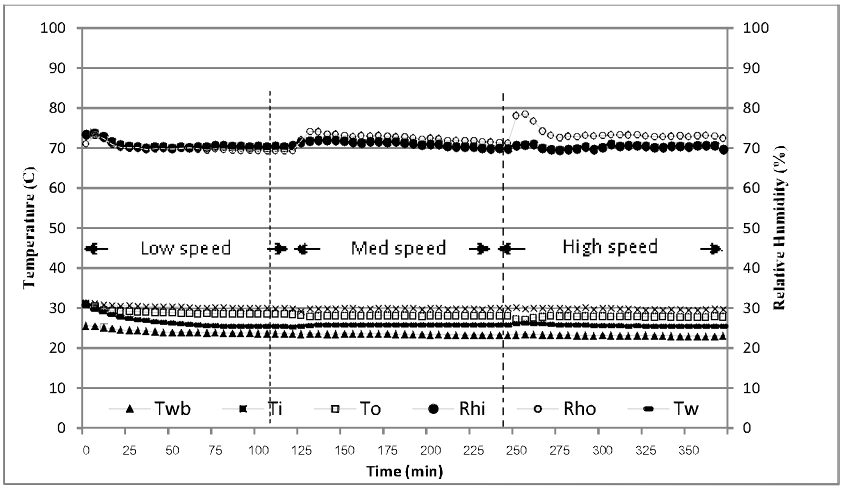


Figure 8 Comparison of inlet and outlet air temperatures and relative humidity (Case: DEAC Operation)

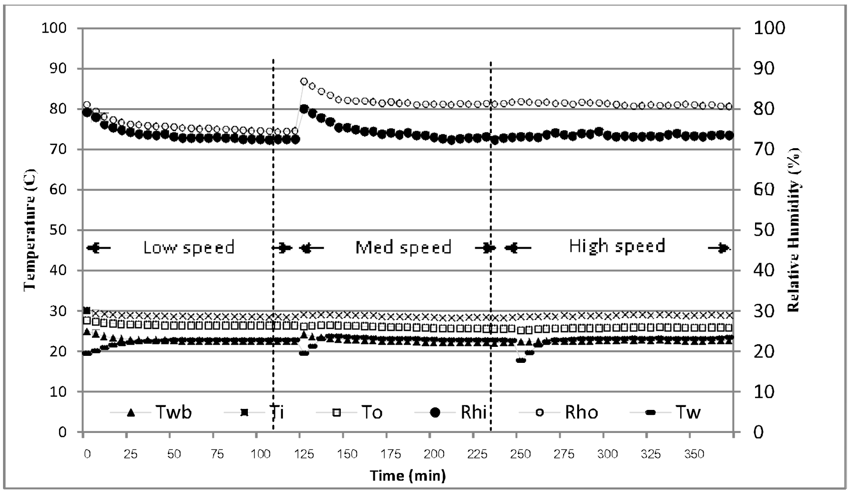


Figure 9 Comparison of inlet and outlet air temperatures and relative humidity (Case: TE+DEAC Operation)

Figure 10 presents the cooling effectiveness of the prototype for all studied cases. For fan operation, due to slight temperature difference between inlet and outlet air, its cooling effective is estimated closely to 0%. Conversion of the sensible heat of the inlet air into the moisture by DEAC process can improve the cooling effectiveness by 20% -30%. Reduction of the water temperature by thermoelectric refrigeration system can increase another 20% of the effectiveness.

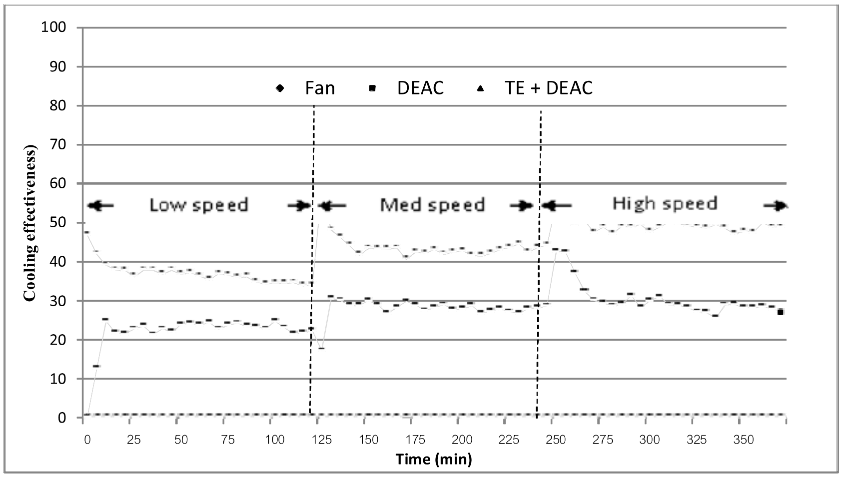


Figure 10 Cooling effectiveness Comparison of fan, DEAC, and TE+DEAC

Conclusion and Discussion

A portable hybrid thermoelectric-direct evaporative air cooling system has been fabricated and tested. The testing results show that under the fan operation, the system is unable to cool the inlet air temperature (or 0% cooling effectiveness). When DEAC system is in active, the cooling performance of the prototype increases by 20% and is up to 30% with higher fan speed (or 1.7 °C of air temperature drop). The results of TE installation can improve the cooling performance of the DEAC system by 10% and is up to 20% with higher fan speed (or 2.6 °C of air temperature decrease). Therefore, the concept of applying TEs to cool the water seems to be reliable and possible for commercial development. However, due to low COP of 0.06, the TE refrigeration system and water container should carefully redesigned, specially the heat exchanger at the hot ends of TE in order to improve the cooling performance of the TE system.

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