International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 13, No. 3, September 2022, pp. 1568~1575
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v13.i3.pp1568-1575

Thermodynamic analysis of a thermoelectric air conditioner

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Article Info

Article history:

Received Mar 22, 2022
Revised Jun 5, 2022
Accepted Jun 29, 2022

Keywords:

Coefficient of performance
Cooling capacity
Exergy
Thermoelectric
Thermoelectric air conditioner

ABSTRACT

This paper discusses the results of tests done to investigate the performance of a thermoelectric air conditioner (TEAC). The TEAC is composed of twelve thermoelectric modules (TEMs). The TEMs were fixed to rectangular fin heat sinks on both their hot and cold sides. With an increased input voltage, the cooling capacity increased. At a 6 V input voltage flow, a suitable condition occurred. The rate of hot air flow was 0.48 kg/min, and the cooling capacity was 157.0 W, resulting in an outlet air temperature of 28 ^{o}C. The coefficient of performance (COP) was calculated and found to be 0.92. Exergy analysis is used to determine the energy flows and second law efficiencies of a TEMs system and its components. The exergy destruction and second law efficiency were observed to increase when the TEAC's input voltage was increased. The TEAC's maximum exergy efficiency was 0.35, which was low compared to the coefficient of performance.

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1. INTRODUCTION

In the early years, convectional air-conditioning (AC) systems (vapor compression systems) were widely applied in real-world situations to couples to control indoor temperature and humidity. AC systems are now typical in most houses and buildings, removing moisture and polluting interior air to provide comfort. When AC is used, it contributes 70% of total electricity consumption in a household, which is a cause for concern because AC is highly energy-intensive. Electricity is generated at a very high rate [1]. Since the cost of fuel has been increasing, we must find a way to reduce electricity use or conserve the energy used for AC to achieve thermal comfort. Furthermore, once the Freon in the vapor compression system begins to leak, it will cause permanent harm to the ozone layer, as well as be a substantial contributor to global warming and cause significant increases in energy use on hot summer days. In light of this, it is important to look for other ways to reduce the heat load on conventional vapor-compression refrigeration systems that are clean and do not use a lot of energy.

Over the years, technological improvements have resulted in various advancements in cooling systems, and one of the most recent creative developments is described in this research. The thermoelectric (TE) generator and the TE cooler are the two most common operational types that use TE technology. The TE cooler systems don't use a working fluid or have any moving components. As a result, they rely on electricity to transfer heat from the cold to the hot side of the modules [2]. Because of their many advantages, including high reliability, low weight, and packaging and integration flexibility, the TE cooler systems are extensively employed in instruments, industrial goods, ACs, and refrigeration units, among many other applications. Because there is no working fluid, there is no hazardous environmental leakage, and noise reduction seems to be a necessary feature. This results in improved dependability, less maintenance, and extended system life.

Moreover, the flexibility of such systems enables a wide variety of applications to be implemented without a significant reduction in performance [3]-[5].

The first studies on the automotive thermoelectric air conditioner (TEAC) system were conducted in 1958 when he constructed a TEAC system within the trunk of a Chrysler car. Recent years have seen an increase in interest in the use of TE cooling (TEC) systems in a variety of different applications [6]. The authors of [7] developed and tested a small TEAC for use in domestic cooling applications. Three TE modules (TEMs) make up the small TEAC. The hot and cold sides of the TEMs were attached to rectangular fin heat sinks with fans on the cold and hot sides, respectively. Thermal comfort was assessed following the ASHRAE Standard-55's acceptance standards for 80%. At 1 A of current flow, a suitable condition was achieved with a cooling capacity of 29.2 W, resulting in an average outlet air temperature of 28 ºC and an average cooling air velocity of 0.9 m/s. After calculating the coefficient of performance (COP), it was found to be about 0.34. When evaluating the performance of TE coolers, the conventional method is to look at their efficiency, which is defined as the ratio of cooling capacity to the power input to the TE cooler system.

To evaluate the cooling performance and thermal comfort of a TE ceiling cooling panel (TE-CCP) system. An assessment of thermal acceptability was carried out to evaluate whether the indoor environment satisfied the ASHRAE Standard-55's acceptance standards for 80%. With a 27 ºC average indoor temperature and a velocity of 0.8 m/s, an acceptable condition was achieved at 1 A, with a corresponding cooling capacity=201.6 W, and COP=0.82 [8]. A gas-to-liquid TEAC system utilized for steady-state and transient models was investigated as well as its performance compared to the conventional automotive heating, ventilation, and air conditioning (HVAC) system. After testing, they discovered that, for the same input power, the traditional HVAC system had a cooling capacity that was five times more than the TEAC system [9].

The numerical model was used to provide a complete design and analysis of an automotive air-to-liquid TEAC system. Experiments were conducted to validate their design, which resulted in an overall efficiency of 1.55 (cooling capacity=1.55 kW) with the same 30 ºC air and liquid intake temperatures [10]. They used the thermal isolation technique [11], which simulates the whole system and increases the coefficient of performance. In addition, instead of ceramic plates, a 20 µm thick anodized aluminum covering is utilized. The authors Raut and Walke [12], constructed an air-to-air TEAC system by sandwiching six TEMs between heat sinks in a series. They tested the system on a modest passenger vehicle with a cooling capability of 222 W and found that it could chill the cabin down to 26 ºC. The researchers Chen *et al.* [13] discovered that utilizing the TEAC system in combination with the conventional HVAC system may offer comparable passenger body comfort while increasing the efficiency of the HVAC system by approximately 37%. Additionally, researchers stated that optimizing the TEAC system may result in even greater energy savings.

Atta *et al.* [14], used an optimum design method developed by [15] to rebuild and optimize the design. The optimized COP increased by about 30% when the same inputs were used. Thermal element geometric ratios (or numerous thermoelement couples) are adjusted concurrently with the supplied current using dimensional analysis. A theoretical model of an air-to-air TEAC system with a COP of 1.3 and an input power of 400 W [14]. According to Attar *et al*. [16], this model has been experimentally verified. It is based on the construction of a unit cell of TEAC in which the cold and hot ambient temperatures surrounding the unit cell remain constant and must be assumed. Because of this, depending on the temperatures assumed, the TEAC system's performance may either improve or deteriorate. Attar and Lee [17] investigate the optimization of a complete counterflow air-to-air TEAC system based on input parameters. The input power as well as the cold and hot ambient temperatures at the input are the parameters to be considered. When the TEAC system's input power is 400 W and the inlet ambient hot and cold temperatures are both 30 ºC, the system's coefficient of performance may reach 1.27 when the hot air flow rate is 120 cubic feet per minute CFM and the cold air flow rate is 60 CFM. Numerous research projects have been conducted utilizing the numerical TE model. In terms of thermal management, a study was conducted on the improvement of the thermal environment with TEC and numerical optimization of thermal performance, and a TEC equivalent thermal resistance model for power drive was proposed. They discovered that regardless of the current flowing through the TEC, different optimal numbers of p-n pairs can be used to achieve the highest COP and lowest power consumption [18]. The purpose of this study was to investigate the application of TE technology to a thermoelectric air conditioner as a method of decreasing the heat load on conventional vapor-compression refrigeration systems. The influences of the input voltage supplied to the TEMs and the air flow rate is experimentally determined. Finally, a study of TEAC's exergy efficiency. The exergy output is optimized concerning the hot side temperature, and exergy efficiency expressions for various operating circumstances are derived.

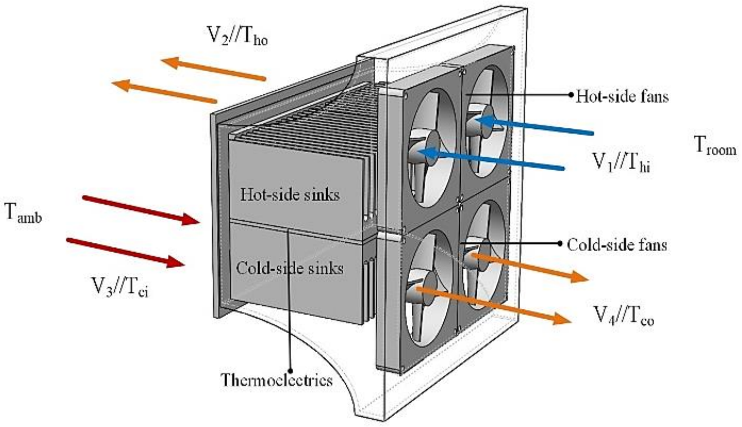
2. METHOD

2.1. System description

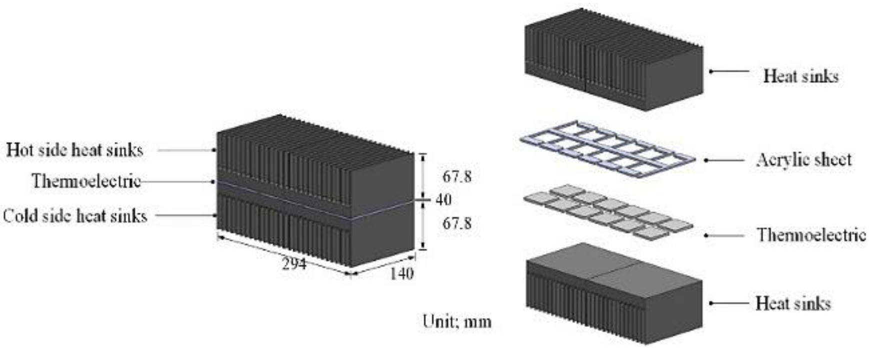
The schematic construction of a small TEAC system is shown in Figure 1(a). It comprises twelve TEMs (model TEC1-12708, China), which are constructed from bismuth tin (BiSn). Each module had a

4×4 cm^2 area. There were two rows of TEMs, each row having six TEMs linked in parallel, and the TEMs were wired together as a series to get the desired result. Aluminium rectangular fin heat sinks were added to the hot side of TEMs to increase the efficiency with which heat was released. Additionally, the cold side of the TEMs needed to be connected to the rectangular fin heat sinks to cool the air. The fins were 3 mm thick, 145 mm long in the horizontal direction, and 40 mm from the base, as shown in Figure 1(b). Four direct-current (DC) fans were used: two on the hot side to assist in dissipating excess heat into the environment and one on the cold side to enhance convection of the air flow through the cold side fin heat sink.

The test setup included temperature, air velocity, and power input sensors, as shown in Table 1. The temperatures of the hot and cold sides of TEMs, the air inlet, and the air outlet were measured using thermocouples of type K. A hot-bulb velocity probe measured the air velocity passing through the cold and hot side heat sinks. The current and voltage were measured with a multimeter. The TEAC system comprises two units. One unit is dedicated to temperature reduction and was supplied with the cold side of TEMs to lower the ambient air temperature, whereas the other is dedicated to cooling and was used to remove heat from the hot side of the TEMs. Two of these dehumidifiers work simultaneously; while one reduces the temperature of the air, the other works on the cooling system. During the experiment, voltage (V) was supplied to the TEMs at five levels: 3, 6, 9, 12, and 15 V. The cycle time was set at 60 min and the ambient temperature was 35 °C. The cold air flow rate was set to 0.66 kg/min in this study. Three variable-current DC power supplies were used to power the TEMs and drive the two fans.



(a)



(b)

Figure 1. The structure of a TEAC: (a) the specifications of hot and (b) cold side heat sinks

Table 1. The accuracy and ranges with the measuring devices

Instrument	Accuracy	Range
K-type thermocouples	±1.1°C or ±0.4%	-0 to 1250 °C
Velocity measurement (Testo model 454)	±0.05 m/s	0 to10 m/s
Multimeter (TES model 2800)	±0.2 %	400 mAmp to 10 Amp
Multimeter (Hioki model 3801)	±0.1 %	300 mAmp to 10 Amp, 20 mV to 800 V
Temperature logger LR5011	±0.5 °C	-40 to 180 °C

2.2. Analysis

Thermoelectric cooling (TEC) is a critical component of a TEAC system. Thus, the mathematical relationships and equations used to define the cooling capacity and performance of a TEAC are intimately linked to TEC. A TEAC's cooling capability and heat rejection from the hot side may be described as (1) [19]-[21].

$$Q_c = \alpha I T_c - 0.5 I^2 R - K(T_h - T_c) \tag{1}$$

Where Q_c is the cooling capacity (W), α (V/K) is the seebeck coefficient, R (Ω) is the electrical resistance, K (W/K) is thermal conductance, I (A) is an electrical current, and T_c (K) and T_h (K) are the cold side and hot side temperature of TEMs. The heat transfer equation from the hot side is as (2).

$$Q_h = \alpha I T_h - 0.5 I^2 R - K(T_h - T_c) \tag{2}$$

Where Q_h is the heat rejected from the hot side of TEMs (W). A TEAC's power input can be thought of as the power supplied to the TEMs and heat sink fans [22].

$$P_{TE} = \alpha I (T_h - T_c) + I^2 R \tag{3}$$

$$P_F = V_F I_F \tag{4}$$

Where P_{TE} and P_F are the power supplied to the TEM and heat sink fans (W). As a result, a TEAC's COP can be defined as (5).

$$COP = \frac{Q_c}{P_{TE} + P_F} \tag{5}$$

A reversed carnot cycle may be used to calculate the maximum possible COP for a refrigerating machine running between two temperatures. The carnot coefficient of performance for cooling is calculated as (6) [23].

$$COP_C = \frac{T_c}{(T_h - T_c)} \tag{6}$$

To compare the performance coefficients of a TEC system and the carnot cooling cycle, the coefficient of performance ratio (c) is defined as the TEC system's performance coefficient divided by the carnot cooling cycle's performance coefficient, which is computed as (7).

$$C = \frac{COP}{COP_c} \tag{7}$$

Exergy analysis of TEAC [24].

$$Ex_i - Ex_o - Ex_d = \frac{dEx}{dt} \tag{8}$$

Ex_i, Ex_o are exergy inflow and outflow (W), Ex_d is exergy destruction (W). $\frac{dEx}{dt} = 0$, when a TEAC is in a constant state of operation. As a result, in (8) can be written as (9).

$$Ex_d = Q_c\left(1 - \frac{T_o}{T_c}\right) + P - Q_h\left(1 - \frac{T_o}{T_h}\right) \tag{9}$$

After solving this equation, the Ex_d is;

$$Ex_d = T_o\left(\frac{Q_h}{T_h} + \frac{Q_c}{T_c}\right) \tag{10}$$

But $\left(\frac{Q_h}{T_h} + \frac{Q_c}{T_c}\right)$is entropy generation $\left(S_g\right)$in a TEAC;

$$Ex_d = T_o S_g \tag{11}$$

T_o is surrounding temperature (K), and S_g is entropy generation (W/K). Thus, the second law efficiency (η_{Ex}) of the TEAC may be calculated as (12).

$$\eta_{Ex} = \frac{Ex_s}{Ex_s + Ex_d} \tag{12}$$

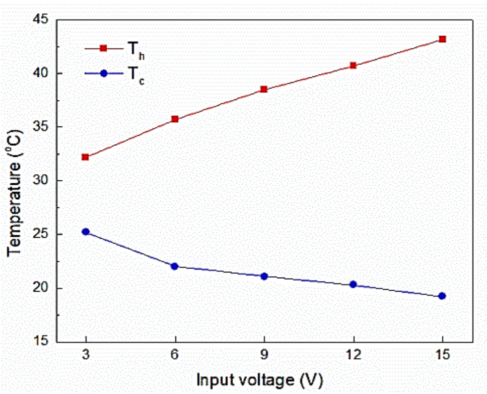
The exergy supplied (Ex_s) is the power supplied to the TEMs.

3. RESULTS AND DISCUSSION

3.1. The effect of the voltage supply

Increased input voltage has an effect on the hot and cold sides of the TEMs, as presented in Figure 2(a). Five different input voltages were used for the tests: 3, 6, 9, 12, and 15 V. The T_c decreased from 28.6 °C to 19.2 °C as the input voltage increased. Meanwhile, when the input voltage increases, the T_h increases. The maximum T_h was 43.2 °C, and the T_c was 19.2 °C at 15 V. When the input voltage is increased, the T_c decreases, and the T_h increases. The temperatures of the hot (T_{ha}) and cold air (T_{ca}) in a TEAC are represented in Figure 2(b). Each input voltage's T_{ha} increased continually, while its T_{ca} decreased. This is because the hot side can reject more heat to the hot air and the cold side can absorb more heat from the cold air.

According to Figure 3, cooling capacity increases with increasing input voltage and ranges between 79.1 W and 240.0 W for an input voltage of 3 to 15 V. The cooling capacity increased as the input voltage increased and reached its maximum value of 240.0 W at an input voltage of 15 V. However, the COP decreased as the input voltage increased from 0.84 to 0.53. At a voltage of 6 V, the maximum coefficient of performance is 0.99. When the input voltage exceeds 6 V, the COP decreases significantly. The difference in the COP between input voltages of 6 and 15 V is 53.54%, while the cooling capacity increased by approximately 32.92% from 3 to 15 V. The high COP of the TEAC system typically corresponds to low cooling capacity, while the low COP corresponds to high cooling capacity. Therefore, the goal of the TEAC system optimization process is to find the best balance point for both.



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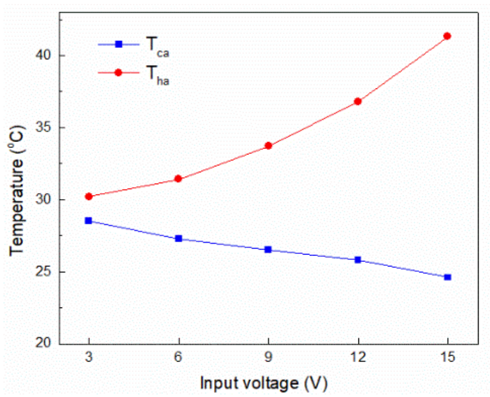


(b)

Figure 2. The hot and cold sides of TEMs: (a) hot and cold air temperatures of TEAC and (b) versus input voltage (cold air flow rate: 0.66 kg/min, T_{amb}: 35 °C)

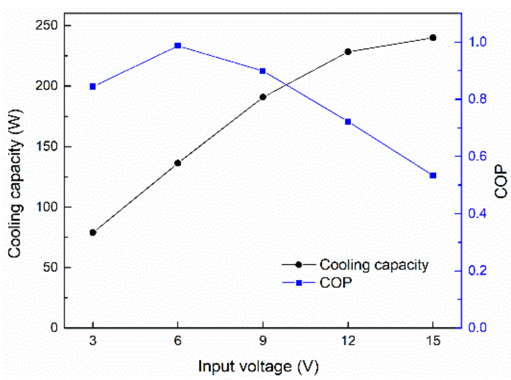
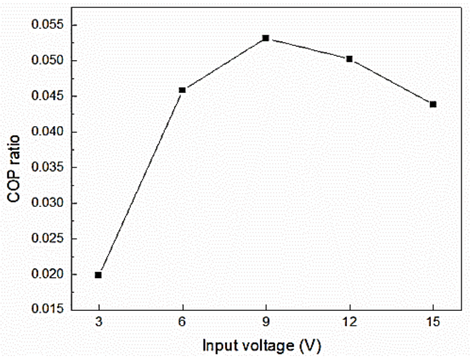
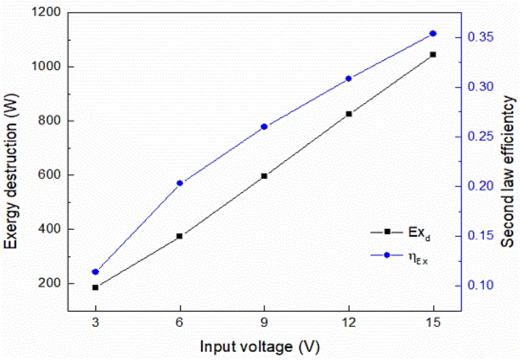


Figure 3. The effect of the input voltage on the cooling capacity and COP of a TEAC (cold air flow rate: 0.66 kg/min, T_{amb}: 35 °C)

The COP ratio versus the input voltage is represented in Figure 4(a). As the input voltage increases, the COP ratio increases, implying that the TEC system's COP approaches that of the Carnot cooling cycle. When the input voltage was increased, the T_c decreased and the difference between the T_c and T_h increased. As a result, the COP of the carnot cooling cycle is reduced, as shown in Equation 6. Figure 4(b) shows that when the input voltage increases, the exergy destruction, and second law efficiency increase. Moreover, the cooling capacity ranges between 79.1 and 240.0 W at 3 to 15 V. The obtained exergy efficiency is low in comparison to the COP values. The lower efficiency is a result of the energy in the TE components degrading from electrical to low-grade heat [25]. As such, it should be accompanied by low-exergy resources [26]. When electric power from a photovoltaic array is used directly to power the TEC system, this is referred to as a low exergy resource-coupling configuration. According to [25] and [27], this type of design may be the best way to match solar energy with the energy needs of the TE cooling system.



(a)

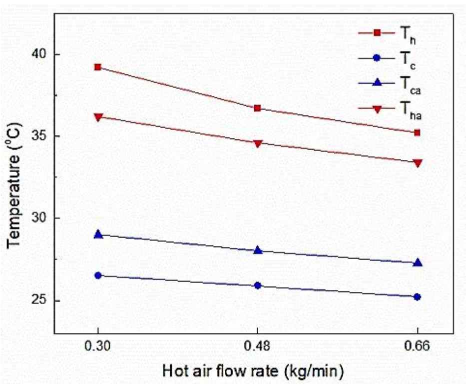


(b)

Figure 4. Variation of COP ratio: (a) exergy destruction and second law efficiency and (b) for different input voltage supplies

3.2. The effect of the hot air flow rate

Figure 5(a) shows the cooling air flow rate through the heat sink on the cold and hot sides of the TEMs. Three different hot air flow rates were used in the testing (0.30, 0.48, and 0.66 kg/min). As the air flow rate increased, the T_c and T_{ca} decreased slightly. When the air flow rate was increased, the T_h and T_{ha} decreased more than the T_c. In this experiment, when the hot air flow rates were 0.30, 0.48, and 0.66 kg/min, the T_{ca} decreased from 35.0 °C to 29.0 °C, 28.0 °C, and 27.3 °C, respectively. Additionally, the cooling capacity was increased slightly. With increasing hot air flow rates, the cooling capacity increased from 146.2 W at 0.30 kg/min to 161.1 W at 0.66 kg/min, and COP reached its maximum value of 0.92 at 0.48 kg/min, as shown in Figure 5(b). This was in contrast to the fact that the COP dropped with an increased air flow rate. There is no reason to employ the maximum air mass flow rate in this investigation, as the maximum air flow rate did not improve heat transmission and increased the electricity consumption of the hot side fan.



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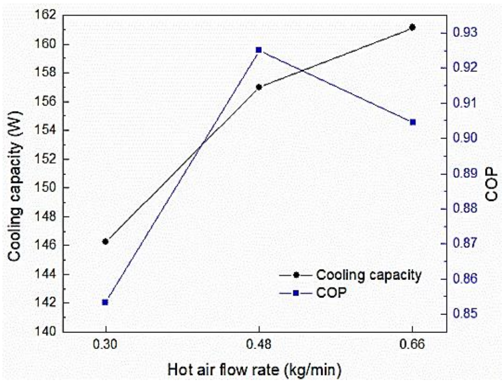

(b)

Figure 5. The effect of the hot air flow rate on the hot and cold sides of TEMs, cold and hot air temperatures of TEAC (a) cooling capacity and COP (b) of TEAC (input voltage: 6 V)

4. CONCLUSION

The cooling performance and COP of a TEAC system were investigated experimentally. Experimental results showed that the input voltage supplied to the TEMs and the air flow rate through the hot side heat sink exerted a significant influence on the COP and the cooling capacity. The cooling capacity increased as the input voltage increased and reached its maximum value of 240.0 W at 15 V. The COP varied between 0.84 and 0.53 depending on the voltage applied to the TEMs, ranging from 3 V to 15 V. Additionally, as the input voltage increased, the exergy increased. Low exergy resources should match the TEC system's low exergy demand. The operating parameters employed in this study were 6 V of an input voltage applied to the TEMs and a hot side air mass flow of 0.48 kg/min. The cooling capacity is 157.0 W with a coefficient of performance of 0.92 and an outlet air temperature of 28 ºC. The exergy efficiency is lower than the COP, owing primarily to the degradation of the TE components' energy from electricity to low-grade heat. Consequently, the idea of using a solar cell to power a TEC system could be very interesting to look into.

ACKNOWLEDGEMENTS

This work was financially supported by The International Research Network Program (IRN) NO. IRN5703PHDW01, The Thailand Research Fund (TRF).

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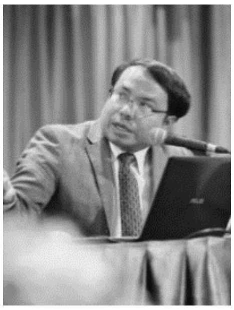

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