Domestic Hot Water System Combining Solar and Waste Heat from Thermoelectric Air-Conditioner

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Abstract

This paper investigates the performance of a new hybrid domestic hot water system that combines solar energy with waste heat from a thermoelectric (TE) air-conditioner. To this end, 30 TE modules model no. TEC1-12704 (module specifications: 40x40 mm, Maximum operating voltage and current: 13.5 VDC and 4.4 Amp) were used. The collector/storage tank capacity was 120 Liters. The volume of testing room for cooling was 2.5 m^3. Investigations were done by varying, namely, the voltage to thermoelectric module (50, 100, 150 VDC), water mass flow rate and air velocity passing through the TE heat exchangers: 10, 15 L/min and 2.5, 5 m/s, respectively. It was found that this system can heat up the 120 liters to 50 ^oC within 2 hours. The cooling capacity was 176 W. After that, the cooling capacity decreased as a result of the increase of water temperature returned from the tank and circulated through TE water/solid heat exchanger.

Finally, under design consideration used in this study, the optimum conditions for operating the hot water production and cooling as well are: 100 VDC, water flow rate of 15 L/min and air velocity at 2.5 m/. The corresponding highest Coefficient of performance of hybrid system is about 3.12.

***Keywords**:* Solar hot water;Thermoelectric ;Heat exchanger;Space Cooling;Heat sinks

1. Introduction

From the past to the present, the world has been high developed continuously. Human invents plenty of facilities for themselves, and everyone knows that the most important factor in invention is energy. Nowadays, the temperature of the world is changing continuously this is due to the increasing of carbon dioxide and chloroflurocarbons (CFC) resulting of the development of technology. The energy we use today for driving air-conditioning and producing hot water is too high and trend to increase every year.

In 1834, the thermoelectric (TE) heat pump phenomenon was discovered by Peltier and in 1909, Altenkirch [1] presented a theory of TE power generation and TE refrigeration. During the last two decades, TE industry development has been extremely fast. TE modules cost continues to decrease substantially. Consequently, TE applications have received increased attention despite the low coefficient of performance which varies between 0.25-0.6 [2,3]. TE cooling/heating systems are used for many applications [4-7]. TE cooling/heating units are of small size, silent, have no moving parts. Moreover, it is very simple to control the rate of cooling/heating by adjustment of the current [8]. The TE cooling system consists of two major subsystems, namely, the photovoltaic electric supply and the thermoelectric modules [9]. This research is aimed to investigate the production of domestic hot water by combining solar energy with waste heat from a thermoelectric air-conditioning. The proposed concept is very suitable for hot countries such Thailand as we have abundant sun’s ray which also creates a need for air-conditioning.

2. The Proposed Hybrid System

The hybrid system combines the thermoelectric cooling device with a collector/storage tank as schematically shown in Fig1. The absorbed heat from the refrigerated space is supplied to the collector/storage tank by a heat exchanger. In addition to waste heat, gains from solar radiation are earned by exposing the collector/storage to the sun. The title angle of the storage tank was set equal to Bangkok’s latitude (14^o).

2.1 Heat Exchangers

Two types of heat exchanger have to be used. Air-solid heat sink on the cold side of TE modules and water-solid heat sink on the hot side of TE modules. Design calculations are rather complex [10] and depend, mainly, on characteristics of TE modules. Based on commonly used techniques, two heat exchangers were designed as shown in Fig. 2.

2.2 Collector/Storage Tank

For simplicity of design of the collector/storage tank, the following assumptions were made:

1. The storage tank is designed for a three people household, each uses 35 liters of water per day, (storage tank capacity is 105 liters). The mean required hot water temperature T_f is about 38 ^oC.

2. Calculations are made based on daily average data, namely:

   2.1 Incident solar radiation on horizontal surface 17.5 MJ/(m^2d) [11]

   2.2 Ambient air temperature 30 ^oC

   2.3 Initial water temperature 27 ^oC

   2.4 Average surface temperature of the collector/storage 50 ^oC

   2.5 Average wind velocity in Bangkok 1.5 m/s [12]

   2.6 Lateral and back heat losses from the tank are neglected (the tank is well insulated)

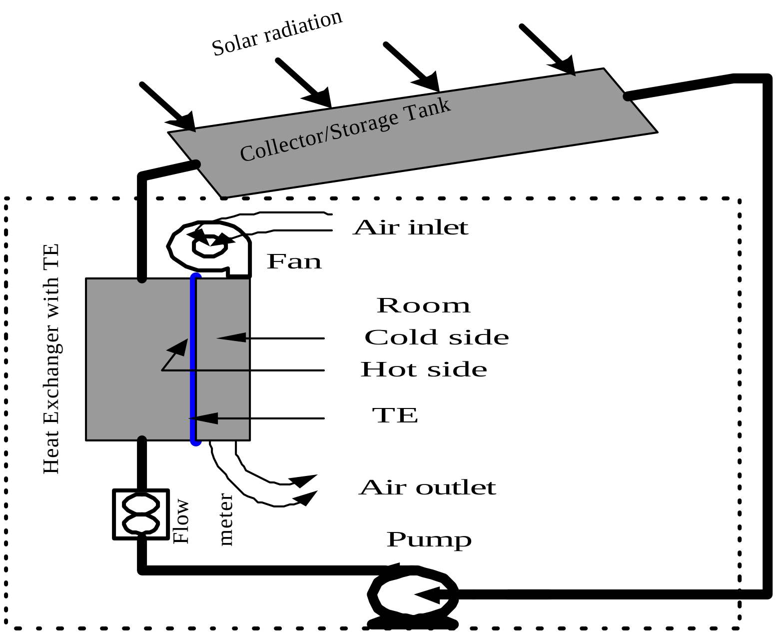


Fig. 1 Schematic view of the proposed hybrid system

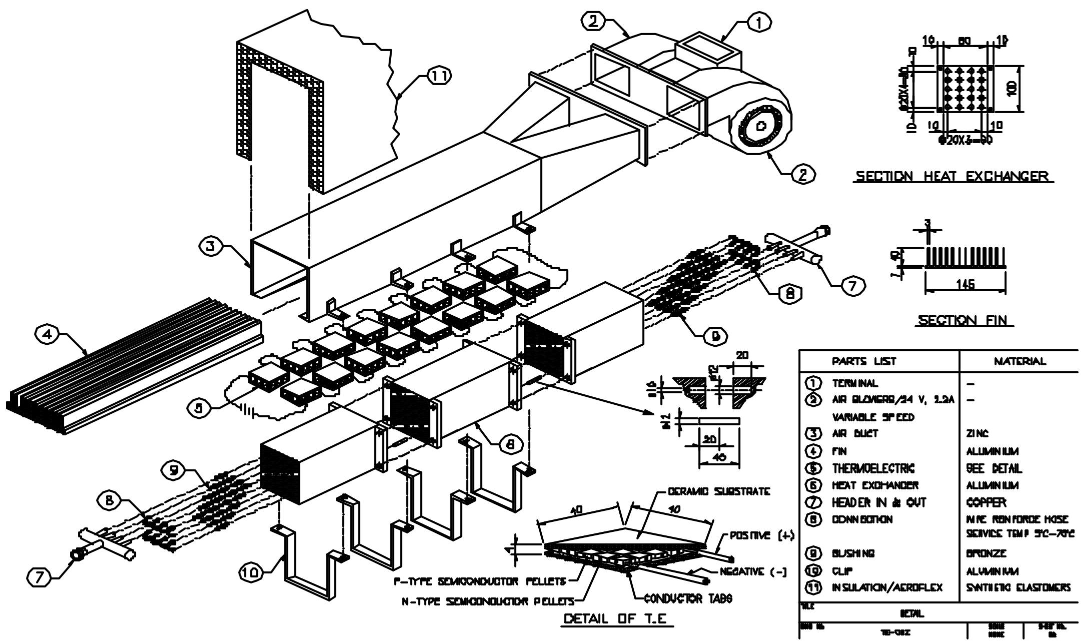


Fig. 2. TE heat exchangers

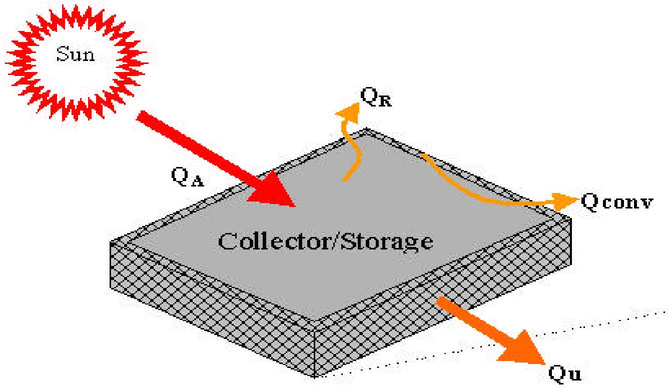


Fig. 3. Energy flow in and out of the collector/storage tank.

To estimate the size of the collector/storage tank the energy balance equations were applied. Referring to fig. 3. and based on the first law of thermodynamic, we can write:

$$Q_A = Q_u + Q_R + Q_{conv} + Q_{cond} \tag{1}$$

The above amounts of energy can be calculated as follows:

$$Q_A = \alpha\, I_{t\theta} A_{ST} \tag{2}$$

$$Q_u = MC_w (T_f - T_i) \tag{3}$$

Heat losses, Q_L, are first calculated on hourly basis. It yields

$$Q_L = Q_R + Q_{conv} \tag{4}$$

$$Q_L = A_{ST} [h_{conv}(T_S - T_{amb}) + h_{ra} (T_S - T_{sky})] \tag{5}$$

The equation of Swinbank [13] is used to evaluate the sky temperature.

$$T_{sky} = 0.0552\, T_{amb}^{1.5} \tag{6}$$

The radiation and convection heat transfer coefficients can be calculated as follows:

$$h_{ra} = \sigma\varepsilon (T_S + T_{sky})(T_S^2 + T_{sky}^2) \tag{7}$$

$$h_{conv} = 2.8 + 3v \tag{8}$$

The average daily overall heat loss can, then, be estimated based on sunshine hour, (12 hours approximately).

After some arithmetic calculations, the required surface area is about 1.2 m^2. The corresponding thickness (volume/A_{ST}) of the collector/storage tank is then 0.1 m.

2.3 Hot water production

To assess the instantaneous ability of hot water production of this system which combines solar energy with waste heat from a thermoelectric air-conditioner, the following expression was used:

$$Qg = MC_w (T_{tk}^{P+1} - T_{tk}^{P}) \tag{9}$$

2.4 The cooling capacity

As the focus of this research was on hot water production, the cooling capacity of the system was simply calculated based on the temperature difference between return air and supply air leaving through to the heat exchanger.

$$Qc = m_a C_a (Ta,i - Ta,o) \tag{10}$$

2.5 Coefficients of performance

To describe the performance of such hybrid system, the following Coefficients of performance were introduced:

1. Cooling Coefficient of performance

$$COP_c = \frac{Qc}{P_{TE} + P_P + P_F} \tag{11}$$

2.Coefficient of performance of hot water production

$$COP_h = \frac{Qg}{P_{TE} + P_P + P_F} \quad \text{for nighttime} \tag{12}$$

$$COP_h = \frac{Qg}{P_{TE} + P_P + P_F + I_{tè} \times A_{ST}} \quad \text{for daytime} \tag{13}$$

3.Coefficient of performance of the hybrid system

$$COP_{hyb} = \frac{Qc + Qg}{P_{TE} + P_P + P_F} \quad \text{for nighttime} \tag{14}$$

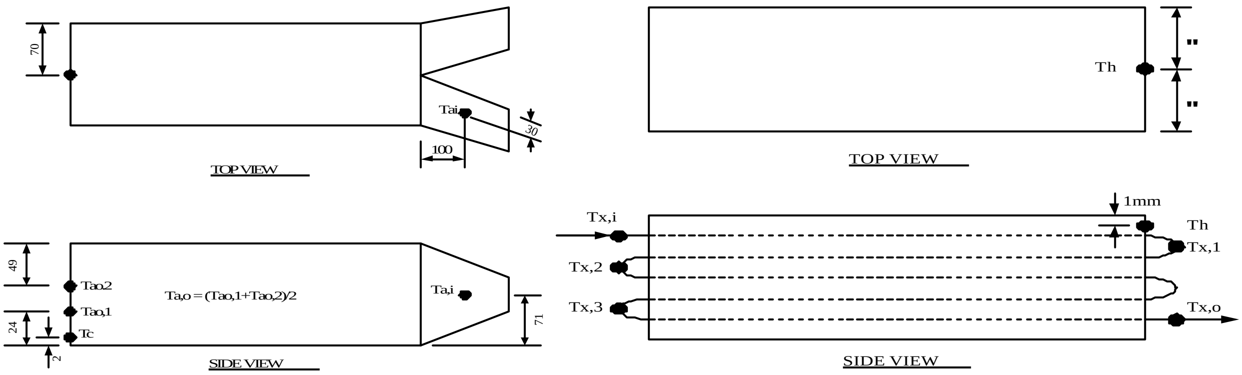
$$COP_{hyb} = \frac{Qc + Qg}{P_{TE} + P_P + P_F + I_{tè} \times A_{ST}} \quad \text{for daytime} \tag{15}$$

3. Experimental methodology

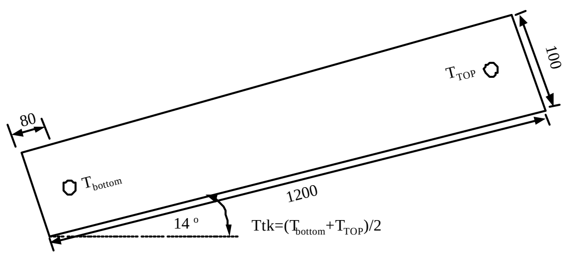
A hot wire anemometer (range: 0-50 m/s) was used to measure the supply air velocity. Thermocouples of type K (range: 0-1250^{o}C) were used to measure the temperature of air and water TE heat exchanger (at 11 points) and storage tank (at 2 points), as shown in Fig. 4. Days and conditions of experiments are given in table 1.

Table 1 Days and conditions of experiments

Date	Time (hr)	Thermoelectric VDC	Thermoelectric Amp.	Water flow rate (L/min)	Air velocity (m/s)
08 Jul.-15 Jul.1999	00.00 – 24.00	Preliminary experiment of collector/storage tank (only solar energy)			
29 Dec. 1999	10.00-13.00	100	3.7	10	5
02 Jan. 2000	20.00 – 22.00	150	5.6	10	5
	23.00 – 01.00	50	1.9	10	5
	02.00 – 04.00	100	3.7	10	5
03 Jan. 2000	08.00 – 10.00	150	5.4	15	5
	11.00 – 13.00	100	3.6	15	5
06 Jan. 2000	08.00 – 10.00	150	5.4	15	2.5



a. Air heat exchanger (cold side of TE.) b.Water heat exchanger (hot side of TE.)



c. Water tank

Fig. 4. Position of thermocouples on TE heat exchanger and water tank

4. Results and discussion

For testing the performance of the system, different scenarios were considered depending on the energy used: solar and/or thermoelectric, and at different operating times. The collector/storage was faced to the south.

4.1 Solar hot water

Fig. 5 shows the mean water temperature during the whole test period (six days). It can be seen that the storage tank water temperature (120 litter) is about 40 ^oC during 8 hour. The instant heat stored reached a maximum around 10-12 am, Fig. 6. Then, it decreased as calculation was made on instant basis according to equation 9. Although it could be concluded that this collector/storage tank can produce enough water for housed.

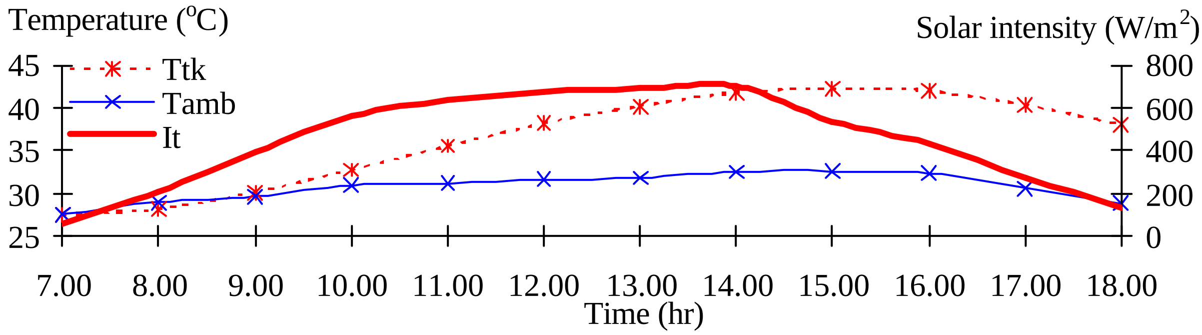


Fig. 5. Hourly variations of ambient temperature, mean water temperature and solar intensity during the measured period (08 Jul.-15 Jul.1999).

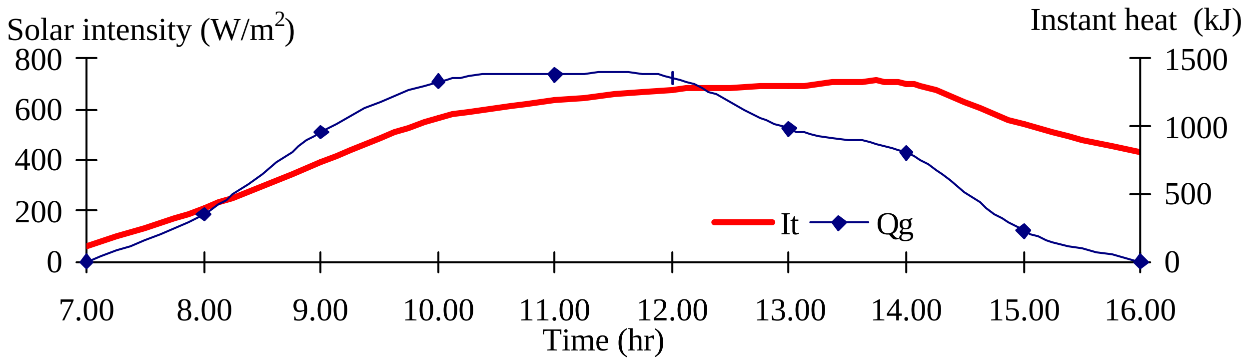


Fig. 6. Hourly average variations of solar intensity and instant heat stored by water during the test period (08 Jul.-15 Jul.1999).

4.2 Thermoelectric hot water production

Testing the thermoelectric hot water production was performed during nighttime. Fig. 7 indicates that water temperature in storage tank increased with increasing voltage. However, room temperature increases limiting, therefore, the performance of TE air-conditioner. With 150 VDC, the system can produce 120 litters at temperature about 47 ^{o}C within 2 hours. Additionally, as with solar heating, the instant heat is highest at the beginning.

Fig. 8 shows that the cold side temperature decreased during 15 minutes. Then, it started to increase due to the increase of inlet water temperature (return water from the tank) through the heat exchanger, Fig. 9. Consequently, the design of water tank and return circuit has to be done differently in order to have a cold return water temperature. The highest COPs were obtained with 100 VDC, Fig. 10.

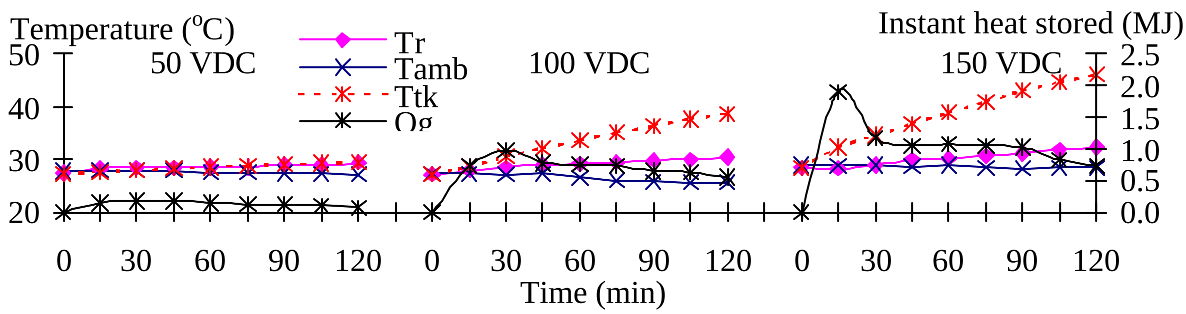


Fig. 7. Variations of ambient , water and room temperatures
(water flow rate 10 L/min, air velocity 5 m/s,02 Jan 2000).

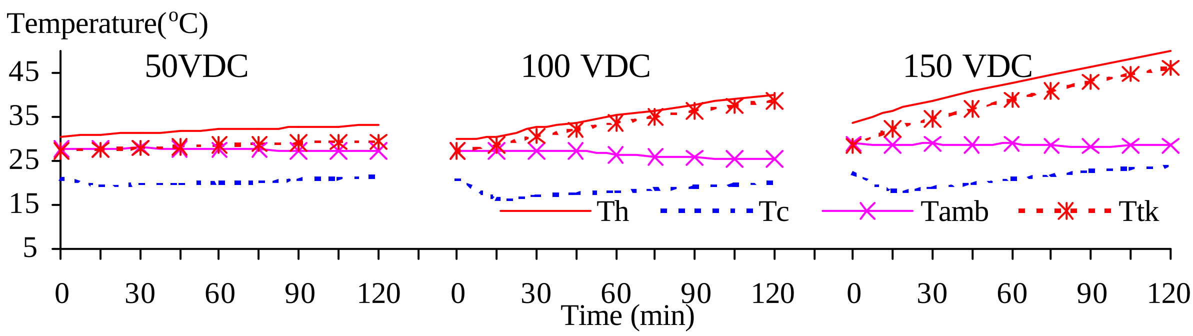


Fig. 8. Variations of hot and cold side temperatures of TE modules, ambient and water temperatures (water flow rate 10 L/min, air velocity 5 m/s, 02 Jan 2000).

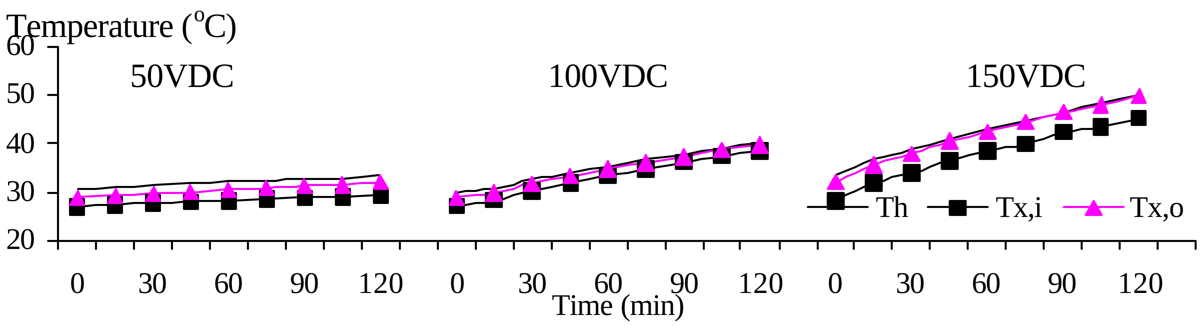


Fig. 9. Measured temperature at the inlet and outlet of water/TE heat exchanger plotted versus test duration (water flow rate 10 L/min, air velocity 5 m/s, 02 Jan. 2000).

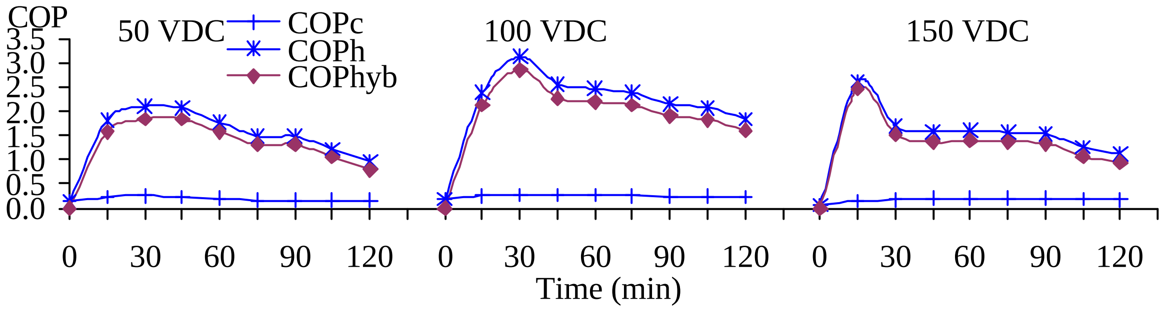


Fig. 10. Comparison of COP for cooling, heating and hybrid system (02 Jan. 2000).

4.3 Hybrid system

By considering an input voltage of 100 VDC, two tests were run by varying the water flow rate passing the heat exchanger namely, 10 and 15 L/min.

Under relatively similar ambient condition, Fig. 11 shows that the temperature of water in storage tank increased more or less similarly during the test period (2 hrs). The difference between inlet and outlet water temperature from water/solid TE heat exchanger is shown in Fig. 12. It can be seen than except at the beginning, a temperature difference was only observed with 15 L/min.

Fig. 13 indicates that the total heat stored at water flow rate of 15 L/min is higher than that at 10 L/min due to the increased rate of heat transferred from thermoelectric modules. With 15 L/min the temperature difference between air inlet and outlet (Ta,i – Ta,o) is higher than that at 10 L/min, Fig. 14. This is due to the cold side temperature, which decreased when the water flow rate increases. That means the cooling capacity is higher with the high water flow rate.

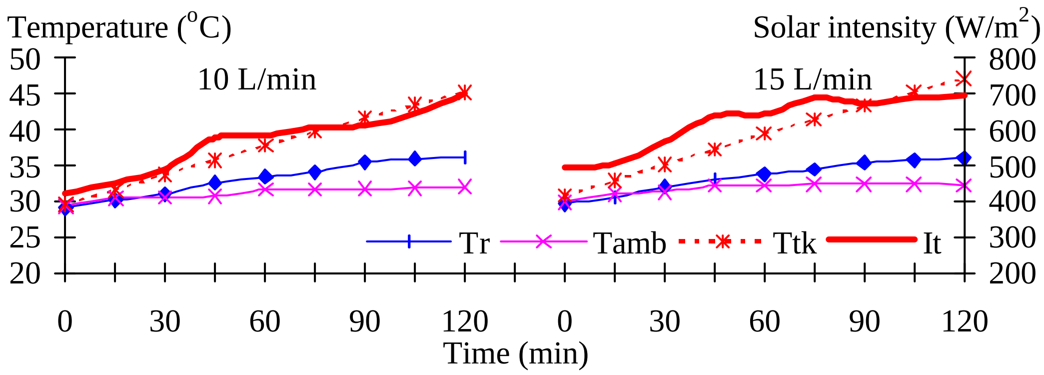


Fig. 11. Water temperature for two-water flow rate passing the heat exchanger at 10 L/min (11 am-13 p.m., Dec.29) and 15 L/min (11 a.m.-13 p.m., Jan. 03).

Figs. 15 to 17 give the results of tests with input voltage at 150 VDC. Two velocity of air passing through the cold side TE heat exchanger were considered: 2.5 and 5 m/s. Tests, were done at 08 AM. on Jan 03, (5 m/s) and at 08 AM on Jan 06 (2.5 m/s).

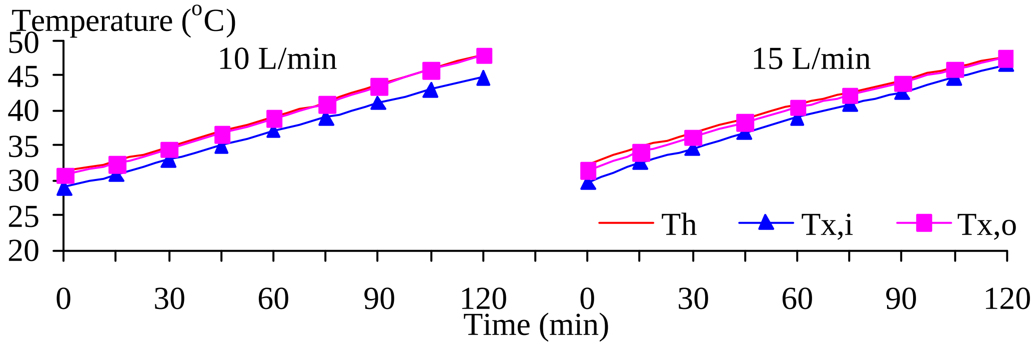


Fig. 12. Inlet and outlet temperatures of water of the heat exchanger and TE hot side temperature for different water flow rates 10 L/min (11 am-13 p.m., Dec.29) and 15 L/min (11 a.m.-13 p.m., Jan. 03).

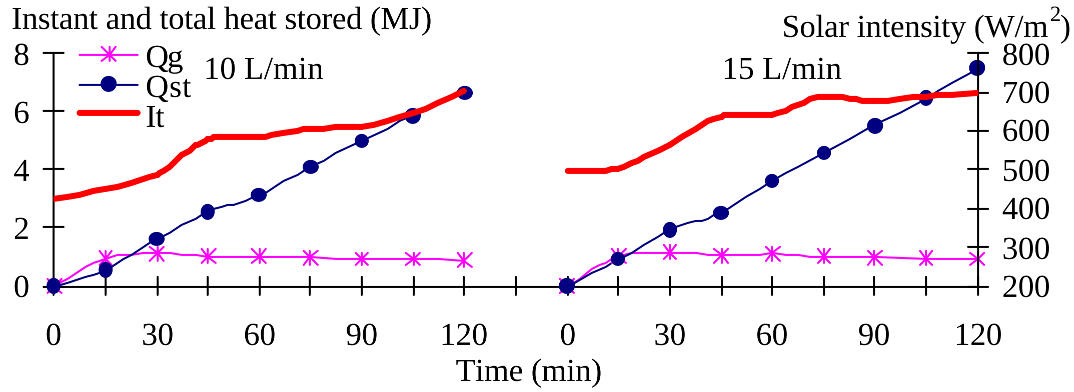


Fig. 13. Comparison between instant and total heat stored for two different water flow rates 10 L/min (11 am-13 p.m., Dec.29) and 15 L/min (11 a.m.-13 p.m., Jan. 03).

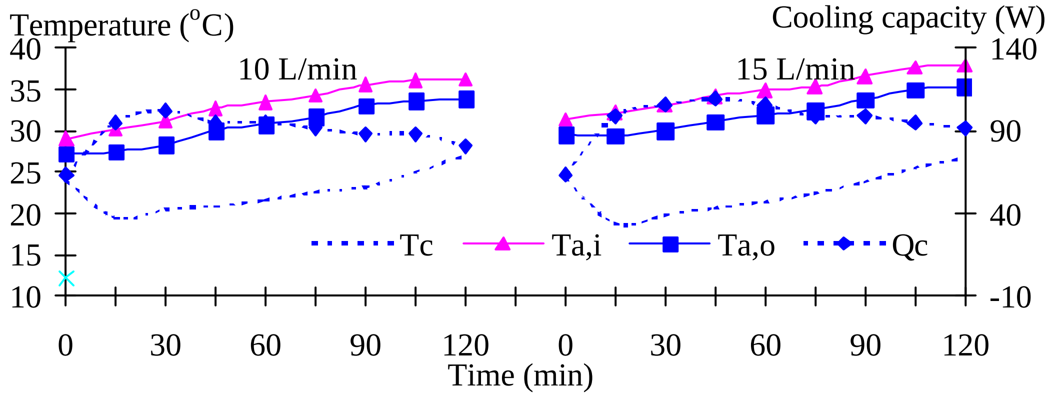


Fig. 14. Inlet and outlet air temperature of cold side TE heat exchanger for two water flow rates (11 a.m.-13 p.m,Dec.29) and 15 L/min (11 a.m.-13 p.m., Jan. 03).

Fig. 15 shows the variations of room temperature, hot and cold side temperature of thermoelectric, ambient temperature and solar intensity. Temperature differences between hot and cold side increases when air velocity decreases, while the temperature of hot side is relatively constant. So the temperature of supply air (leaving the TE cold side heat exchanger) decreases (Fig.16) leading to higher cooling capacity, Fig. 17.

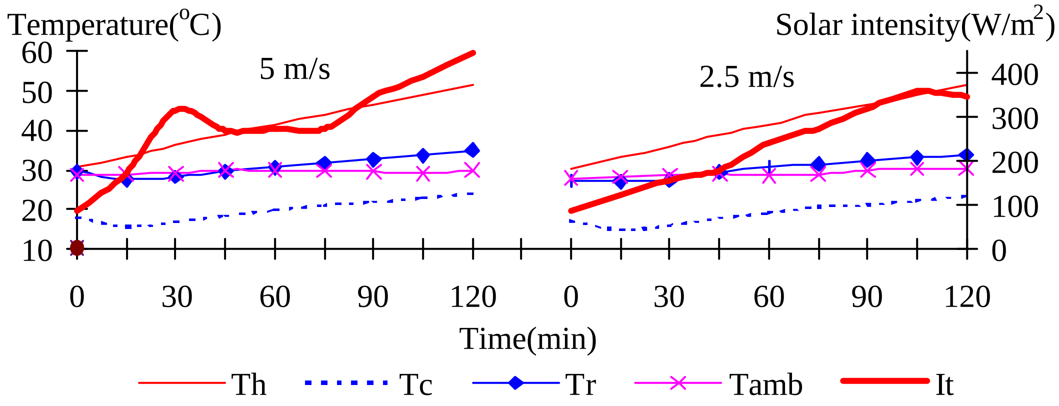


Fig. 15. Comparison of temperature variations for two velocities of air passing the cold side TE heat exchanger.

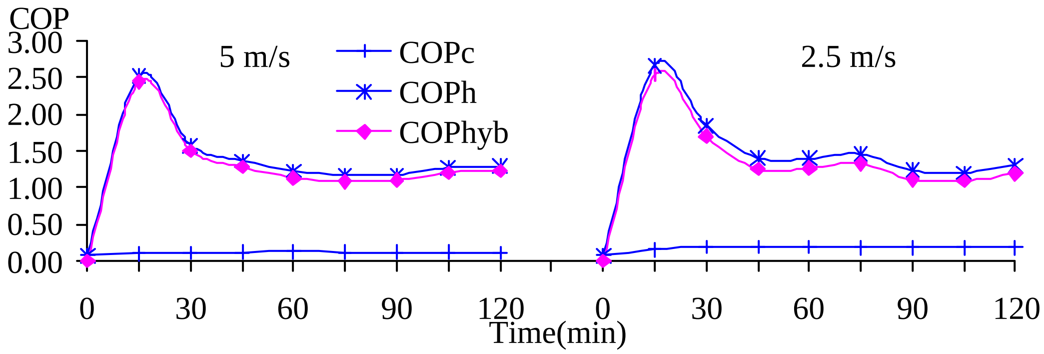


Fig. 16.Comparison between cooling capacity and air exchanger temperature difference, for two air velocities 2.5 and 5 m/s.

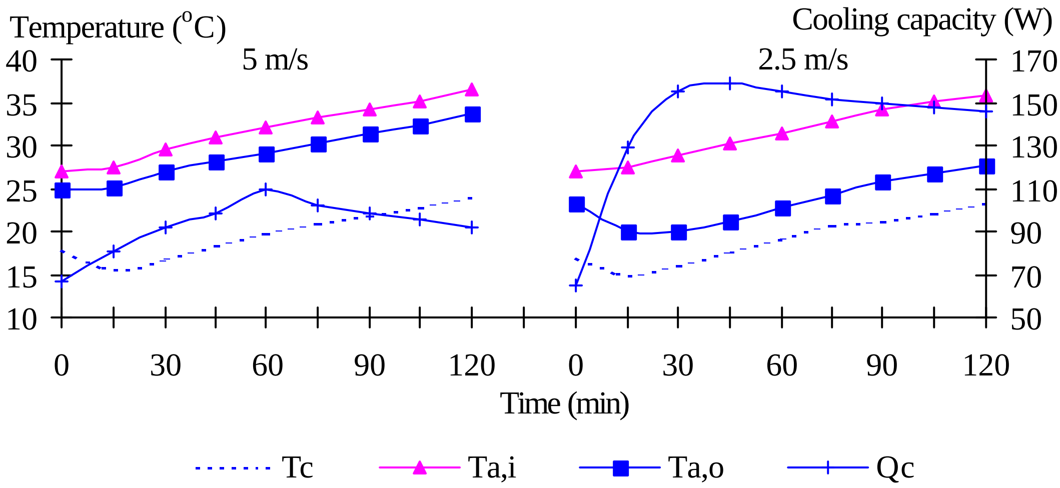


Fig. 17. Comparison of coefficients of performance of system for two air velocities, 2.5 and 5 m/s.

5. Conclusion

As a result of air-conditioner and domestic hot water uses, which have become necessary to modern daily life, today the temperature of the world is changing continuously. This research was aimed to serve both requirements while saving environment, as no CFC is employed.

By combining solar energy with waste heat from thermoelectric air-conditioner a hybrid was designed and tested.

Under the design condition used here, results from initial tests of the hybrid solar–thermoelectric domestic hot water system could be summarized as follows: it can produce 120 litters hot water at 50 ^{o}C within 2 hours.

The recommended operating conditions for both hot water production and cooling are: 100 VDC to thermoelectric, water flow rate of 15 L/min and air velocity of 2.5 m/s.

The highest cooling capacity was (176 W) at beginning of nighttime operation. It decreased rapidly with time as return water temperature increased limiting, therefore, the performance of the thermoelectric air-conditioner.

For installing such a system, the main recommendations are the following:

1. The required hot water temperature should not exceed 50 ^{o}C. In fact, above this limit, the efficiency of the system and the ability of cooling decrease considerably.

2. The hot water demand should be steady and water has to be withdrawn continuously.

3. The storage tank should be designed differently. For constant use of water and cooling, there is no need for insulating the back side of the tank. This in fact would help in avoiding the steady increase of water temperature, which limits the performance of the TE air-conditioner. Although, a secondary water/air heat exchanger has to be installed before the return water enters the TE air-conditioner.

There is a large potential for development of the proposed system as it is intended to provide space cooling and hot water. Such requirements are extremely high for hospitals, hotels, residences etc.

Acknowledgements

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Nomenclature

A_{ST}	Absorbing surface	m^2
C_a	Specific heat coefficient of air	kJ/kg.K
COP_c	Cooling Coefficient of performance	
COP_h	Coefficient of Performance of hot water production	
COP_{hyb}	Coefficient of performance of the hybrid system	
C_w	Specific heat coefficient of water	kJ/kg.K
h_{conv}	Convection heat transfer coefficient	$W/m^2.K$
h_{ra}	Radiative heat transfer coefficient	$W/m^2.K$
I_t	Solar Radiation, Global	MJ/m^2
$I_{t\theta}$	Solar radiation on a incline surface	$W/(m^2d)$
M	Mass of heated up water	kg
m_a	Air mass flow rate	kg/s
P_F	Power of fan	W
P_P	Power of pump	W
P_{TE}	Power of thermoelectric	W
Q_A	Available energy	W
Qc	Ability of cooling	W
Q_{cond}	Heat loss due to conduction	W
Q_{conv}	Heat loss due to convection	W
Qg	Instant heat stored	W
Q_L	Total heat loss	W
Q_R	Heat loss due to radiation	W
Qst	Total heat stored	MJ
Q_u	Useful Energy	W
Ta,i	Inlet air temperature	^oC
Ta,o	Outlet air temperature	^oC
Tamb	Ambient temperature	^oC
Tc	Cold side temperature	^oC
T_f	Final temperature of hot water	^oC
Th	Hot side temperature	^oC
T_i	Initial temperature of cold water	^oC
T_r	Room temperature	^oC

T_{Sky}	Sky Temperature	K
Ttk	Mean temperature in the storage	^{o}C
T_{tk}^{P}	Temperature at time = t	^{o}C
T_{tk}^{P+1}	Temperature at time = t + Δt	^{o}C
Tx,i	Inlet water temperature at the heat exchanger	^{o}C
Tx,o	Outlet water temperature at the heat exchanger	^{o}C
U	Overall heat transfer coefficient	$W/m^2.K$
V	Velocity of air	m/s
v	Wind velocity	m/s
α	Absorptivity of collector/storage surface	
ε	Emissivity of collector/storage surface	
σ	Stefan-Boltzman constant	$W/m^2.K$
ρ	Mass density	kg/m^3

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