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Development of a Stand-Alone Thermoelectric Power Generator Using Heat of Refrigerant Leaving the Condenser and Self-Cooled by Condensate of a Split-Type Air Conditioning

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ABSTRACT

Today waste heat recovery of air conditioning is receiving considerable attention worldwide. This paper reports investigation on the development of a stand-alone thermoelectric power generator (STEG) using heat of refrigerant leaving the condenser and self-cooled by condensate of a split-type air conditioning. The STEG is composed of a small hollowed aluminum block integrated in the hot refrigerant line leaving the condenser to collect and transfer heat to the hot side of two thermoelectric (TE) modules 40 x 40 mm installed on the right and left. To cool the TE modules, water condensate circulates by gravity inside two aluminum alloy blocks. Tests were conducted using 2-tons split-type air conditioner installed in a 64 m^3 room of a residential house in Bangkok. Electrical current generated by the two TE modules was recorded separately and connected in series three times for each case. Experimental results showed that STEG can produce electrical current continuously and varied depending on the operation on the compressor. The more important the cooling, the higher is the voltage produced. The maximum recorded voltage is about 200-250 mV by each TE module and doubled with the TE modules connected in series. The average water condensate flowrate was 11.56 g/min. The average coefficient of performance (COP) and the average Energy Efficiency Ratio (EER) of the air conditioning with STEG were 1.87-1.88 and 6.38-6.42 respectively, 3% higher than those of the conventional system.

1. INTRODUCTION

Since 1970s and due to economic growth, air conditioning is widely used to ensure humans thermal comfort of all types of residences, buildings and condominiums. Technological advances, manufacturing and government regulations and labelling has led to improve performances, reduce impact on environment through the use of green refrigerants and consume less electricity. Different systems with a variety of options are available in the market to attract consumers such as multi-split type air conditioner known as VRV for commercial buildings that uses variable refrigerant flow to maintain individual zone control in each room and floor of a building, solar based systems etc. A complete review on these topics is out the space of this paper.

In Thailand, split-type air conditioning is by far the most popular due to its low cost, easy installation and maintenance. Due to these advantages, millions of units are sold yearly. The recent COVID 19 epidemy pushed Thai government like most countries worldwide to impose strict measures including night curfew to reduce contamination. People were encouraged to work from home and avoid unnecessary outdoor activities. Obviously, such measures have led to increase electricity consumption in households. Consequently, Thai government was constrained to issue some financial measures to help house owners paying electricity bills. Citizens are also facing new threats due to increased political tensions and risk of conflicts that cause important increase of oil price leading to higher costs for foods, drinks, fuels etc. Under such circumstances, alternatives energies, energy saving and waste heat recovery are expected to regain increased attention worldwide. With respect to air conditioning, various ideas and concepts were proposed to reduce electricity consumption and recover heat to generate electricity. Evaporative cooling was widely considered in the past by authors worldwide and continue to receive attention namely in countries with dry climate [1, 2]. The use of air blowing out form the condensing fan was investigated by Nethaji et al. [3] to generate electricity. More recently authors paid increased interest in the use of water condensate -a free cold energy-. Research published by Ardita et al. [4, 5] investigated the use of water condensate to reduce the temperature surrounding the condenser to pre-cool the air entering the condensing unit to improve refrigerant cooling. A maximum temperature reduction at the air outlet surface of the condenser of 2.2℃ was observed at ambient temperature 35℃ [5]. Energy conservation in room air conditioner unit by recovering cold from condensate was investigated by Nethaji et al. [6]. A recent publication [7] reported experimental investigation of using liquid suction heat exchanger with condensed cold water on the performance of air conditioning system. All published papers showed that the use of condensate water as an intermittent additional cooling on split air conditioning condenser can increase the refrigeration effect, improve cooling and coefficient of performance (COP). However, there wide applications are still limited due to several technical, practical and economical issues. The recent advances of thermoelectric technology paved the way for the development of a wide variety of new hybrid systems and applications. Let cite for instance, but not limited to, domestic hot water [8], waste heat recovery and electricity generation [9-11], cooling and refrigeration [12-14]. Evaluation of the potential recovery of compressor heat losses to enhance the efficiency of refrigeration systems by means of thermoelectric modules was investigated experimentally by Emilio et al. [15]. Performance of liquid cooling of thermoelectric module is reported by Paisarn et al. [16]. Under humid and hot climate like in Thailand with high ambient humidity year-round [17], considerable amount of water condensate is produced when operating air conditioning. About fifty percent of cooling load is due the latent heat of humidity present in the ambient air. Generally, this water condensate is dropped outside to the ground or drained directly to the system of used water. In this paper, we propose to develop a stand-alone thermoelectric power generator using heat of refrigerant leaving the condenser and self-cooled by the water condensate of a split-type air conditioning (STEG). Our motivation is due to the fact that split type air conditioning is widely used and the system proposed is quite simple and easy to assemble. A prototype of STEG was designed and integrated. Generated voltage, COP and EER are reported and discussed.

2. STEG DESCRIPTION AND EXPERIMENTAL METHODOLOGY

Figure 1 shows schematic of the proposed stand-alone thermoelectric generator (STEG) and assembly integrated in the refrigerant lines of a 2-tons split-type air conditioner installed in a 64 m^3 room of a residential house in Bangkok. The STEG is composed of a small hollowed aluminum block 40x40x30 mm integrated in the hot refrigerant line leaving the condenser to collect and transfer heat to the hot side of two thermoelectric (TE) modules 40 x 40 mm installed on the right and left, Figure 1(right). The hot refrigerant enters the STEG at the bottom and leaves at the top. The specifications of TE modules TE1-12706 used are given in Table 1. Two aluminum blocks 40mm x 40mm x 12mm, installed on the right and left, are used to cool the thermoelectric modules.

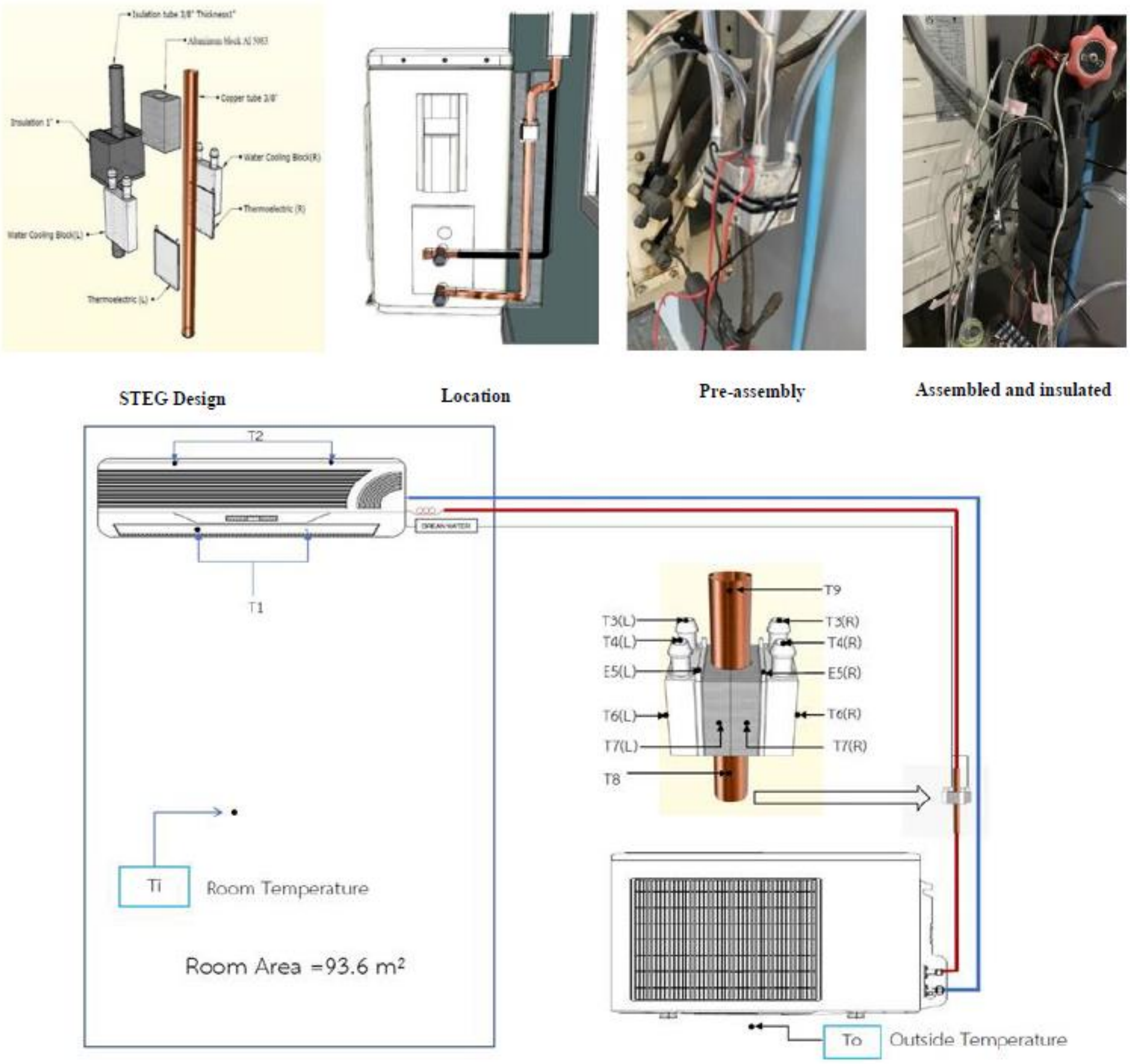

Figure 1. The proposed stand-alone thermoelectric generator (STEG) assembly integrated in the refrigerant pipe line of a split-type air conditioner

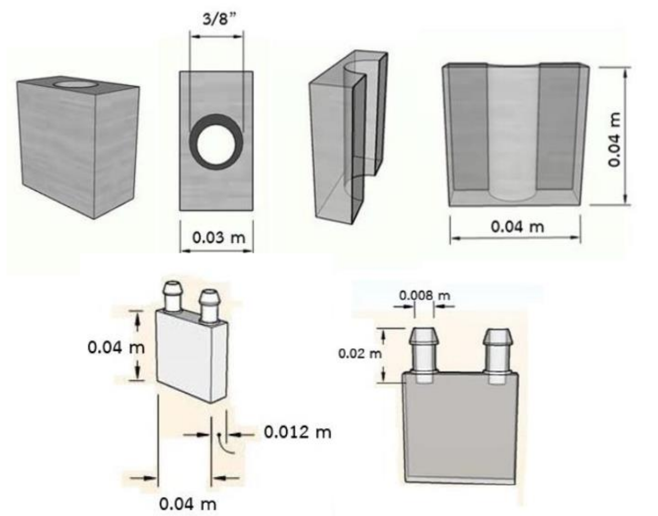

Figure 2. Dimensions of aluminum blocks for heat collecting (top) and cooling blocks (bottom)

Figure 2 shows the dimensions of aluminum block for heat collecting (top) and cooling blocks (bottom). The condensed cold water at the evaporator circulates by gravity and enter the cooling aluminum block on the top inlet and leave at the other top outlet. This allows sufficient time to the condensed water to exchange heat to cool the TE modules. The STEG assembly was well insulated using commercial tube and plate aeroflex insulator. Table 2 outlines the specifications of split-type air conditioning used.

Table 1. Specification of thermoelectric module TEC1-12706

Model	**TEC-12706**
Operating Voltage (VDC)	12
Maximum Voltage (V)	15
Maximum Operating Current (A)	6.4
Maximum Power (W)	92
Maximum Temperature (℃)	138
Internal Resistance (Ω)	1.98
Dimensions (cm)	0.4x0.4x0.36

Table 2. Specification of split-type air conditioner used

Model		**Unit**	**CFW-IF 25**
220V/1Ph/50Hz	Cooling Capacity	Btu/hr.	25,927.45
	Running Current	Amps	10.16
	Power Consumption	Watts	2228.60
	EER	BTU/Watts	11.63
Indoor Unit	Air Flow	CFM	706
	Coil (LxHxW)	mm	901x381x25.4
	Dimension (WxHxD)	mm	1178x326x253
Outdoor Unit	Liquid size	mm (in)	9.53 (3/8”)
	Suction size	mm (in)	15.88(5/8”)
	Refrigerant	-	R22

Different parameters were measured at different locations as depicted in Figure 1 and explained in Table 3. Supply and return air temperature and relative humidity were measured using Elitech GSP-6 portable temperature and relative humidity (RH range 10-90% and accuracy ±3.0%, temperature range -40-80℃ and accuracy ±0.5℃). Air velocity was measured using Fluke 925 anemometer meter (range 0.40-40 m/s, accuracy ±2%). Thermocouple type K (range from -270 to 1260℃ accuracy ±0.4%) were used to record temperature at different positions, electrical voltage and current were measured using Keithly DAQ 6510 data logging and multi-meter system every minute. The electricity consumption of the air conditioner was measured using clamp on HIOKI power meter 3169-20 model (V range 150 V to 600 V, ±0.2% voltage and current accuracy) and recorded at 2-minutes intervals.

Table 3. The various measured parameters in the experimental setup

Position 1	Temp. and Humidity of supply air
Position 2	Temp. and Humidity of return air
Position 3	Temp. of inlet water condensate (Left & Right)
Position 4	Temp. of outlet water condensate (Left & Right)
Position 5	Electric current of TE module (Left & Right)
Position 6	Surface temp. of cooling block (Left & Right)
Position 7	Surface temp. of block aluminum (Left & Right)
Position 8	Temp. of refrigerant at inlet of aluminum block
Position 9	Temp. of refrigerant of outlet of aluminum block
Position 10	Room Temperature
Position 11	Outside Temperature

Two series of tests were conducted. In the first, electrical current generated by the two TE modules with a matched load was recorded separately whereas in the second, the two TE modules were connected in series. As ambient conditions vary from one day to another and in order to make subjective comparison, tests started at the beginning of afternoon and run for 3 hours (12:40-15:40). There were repeated three times on different days for each scenario considered. Results are reported for representative days and average data are summarized and analyzed. The air conditioning was set at 25℃ for all cases considered. The performances of split type air conditioning with STEG are also compared to the conventional system.

3. RESULTS AND DISCUSSION

Table 4. The test conditions considered and the average measured amount of water condensate

Date	**Test condition**	**Average water condensate**
14th Dec 2021	Separate TE Modules	11.22g/min
15th Dec 2021	Separate TE Modules	11.25g/min
16th Dec 2021	Separate TE Modules	11.23g/min
17th Dec 2021	Series TE Modules	16.67g/min
20th Dec 2021	Series TE Modules	10.20g/min
21th Dec 2021	Series TE Modules	11.25g/min
6th Jan 2022	Conventional Air Conditioning	15.05g/min
7h Jan 2022	Conventional Air Conditioning	14.10g/min
8th Jan 2022	Conventional Air Conditioning	14.35g/min

Table 4 summarizes the test conditions considered and average measured amount of water condensate during the tests.

3.1 Temperatures

Figures 3, 4 and 5 show examples of variations of different temperatures of the split-type air conditioner with STEG measured on 15/12/2021. It can be observed that the temperature of supply air decreased rapidly and reached relatively constant temperature around 5℃ within 15 minutes approximately, Figure 3. Similarly, the room temperature decreased within 15 minutes and remained relatively constant at around 20℃ whereas the return air temperature was practically constant around 25℃. At 14:00, the compressor stopped working for about 15 minutes so that all temperatures increased accordingly then returned to decrease due the operation of air conditioning. This typical cycle of operation continued till the end of experiment.

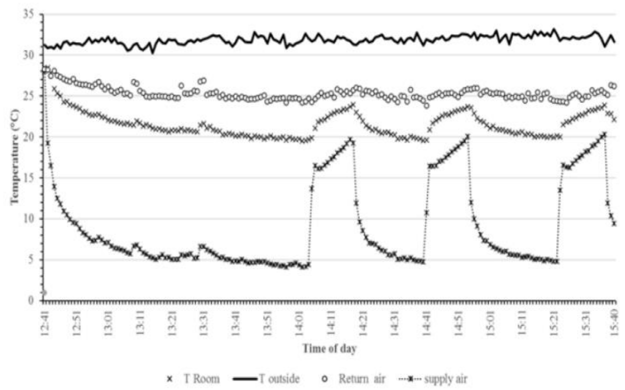

Figure 3. Temperature variations of ambient, room and supply and return air of split-type conditioner with STEG (15/12/2021)

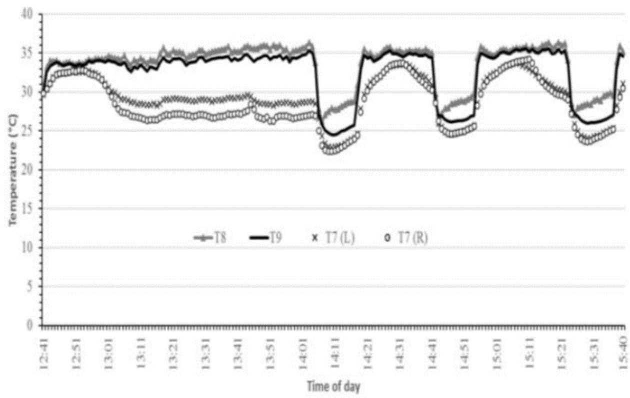

Figure 4. Temperature variations at inlet (T8) and outlet (T9) of STEG and surface temperature (T7) of right and left sides of heat absorbing aluminum block (15/12/2021)

Figure 4 shows the measured temperature of the hot refrigerant at the inlet (T8) and outlet (T9) of STEG and surface temperature at the right (T7R) and left (T7L) sides of heat absorbing aluminum block. At the beginning of test, the temperature of refrigerant at outlet (T9) of STEG was lower than inlet (T8) due to heat absorbed by the aluminum block and transferred to the TE modules. At 14:00, this difference has become important as the compressor stopped working and no refrigerant flows through the STEG. Then, with the re-operation of cooling around 14:00, this difference decreased and temperatures returned to usual variations as mentioned earlier. Here too these variations were repeated following the ON-OFF functioning of cooling. During the first hour, some difference between the surface temperature at the right (T7R) and left (T7L) sides of heat absorbing aluminum block was observed. This is probably due the fact that water condensate did not flow equally on the two sides.

Figure 5 shows that there are some small differences between the inlet and outlet temperature of water condensate and surface of the cooling aluminum block of the left (top) and right (bottom) sides of thermoelectric modules due to location and surrounding. This difference was reduced considerably after the first hour due to the continuous operation of system.

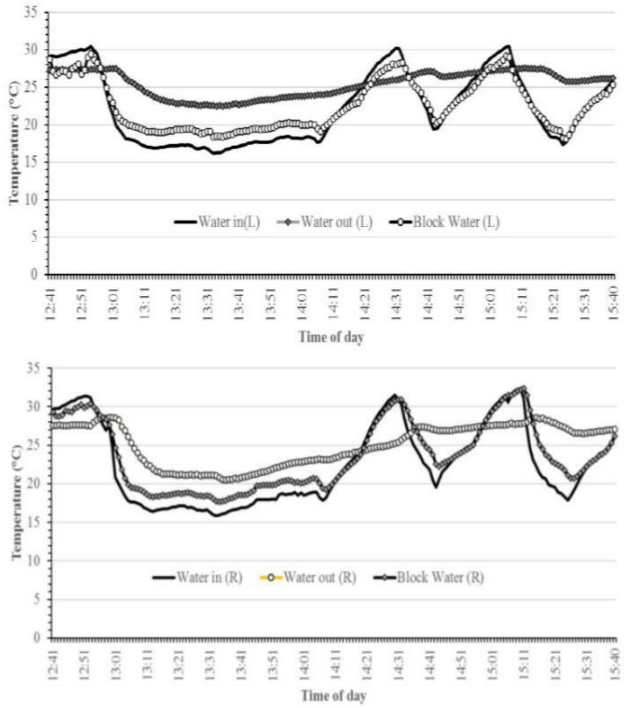

Figure 5. Inlet-outlet condensate water temperature and surface of the cooling aluminum block of the left (top) and right (bottom) sides of thermoelectric modules (15/12/2021)

3.2 Electrical voltage

Figure 6 shows the measured electrical voltage generated by the left and right sides thermoelectric modules for the three days tested.

It was observed that the two TE modules start generating electrical voltage since the beginning of test and increased quite rapidly. A relatively stable voltage was generated after 30 minutes of operation. It varied depending on the prevailing ambient conditions and the operation of the compressor, the temperature of refrigerant and the amount of water condensate. Obviously, the more important the cooling, the higher is the temperature difference between the two sides of TE modules and the higher the voltage produced. The maximum recorded voltage is 373.8 V on 15/12/2021 and the average recorded voltage is about 200-250 mV by each TE module for the three days considered.

This electrical voltage generated by the STEG practically doubled and was about 500V with the two thermoelectric modules connected in series, Figure 7. It is worth to remind that the amount of generated voltage depended closely on the ambient conditions which varied from one day another and the amount of water condensate flowing by gravity through the cooling blocks were not controlled. That's explain the differences observed between the three days.

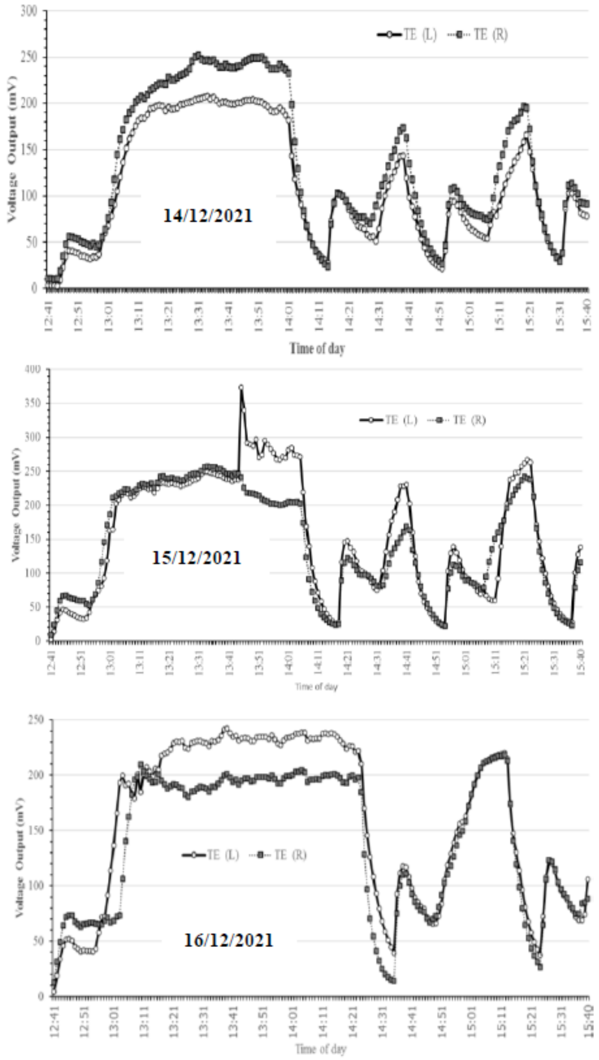

Figure 6. Electrical voltage generated by the left and right sides thermoelectric modules for three days

3.3 Performance

Figure 8 shows a comparison of variations of coefficient of performance (COP) and energy efficiency ratio (EER) between the conventional air conditioner and that installed with STEG for the two scenarios considered for three representative days. It can be observed that the COP and the EER of the three system configurations varied more or less similarly. The average performances calculated using data of the three days of each configuration are given in Table 5. It can be noticed that the average COP and EER of the split-type air conditioning with STEG were approximately 3% higher than those of the conventional system. Even though very limited, this clearly demonstrate that the integration of STEG in a conventional split type air conditioning is interesting as it can lead to performance improvement, generate free electricity at limited cost and it is practically maintenance-free.

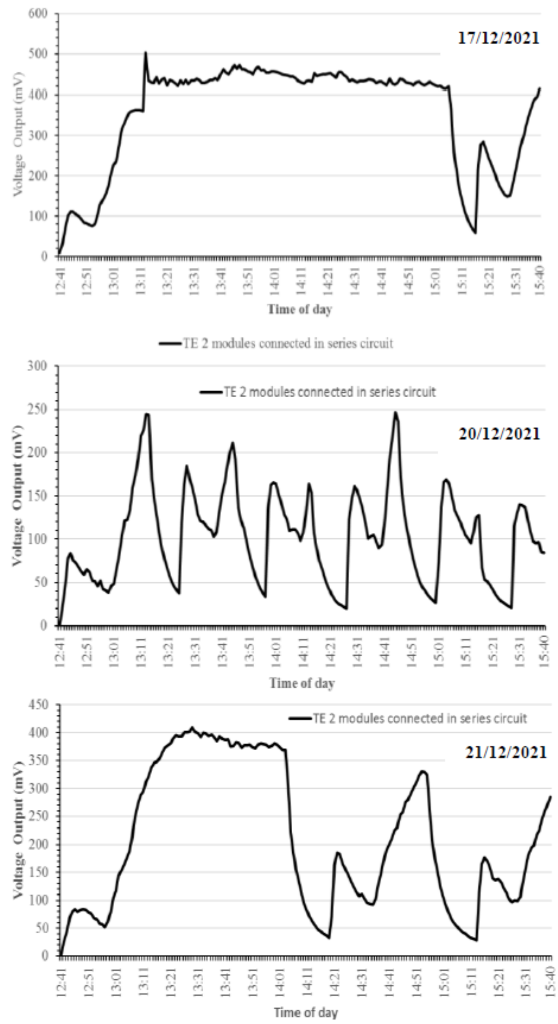

Figure 7. Electrical voltage generated by the STEG with the two thermoelectric modules connected in series for three days

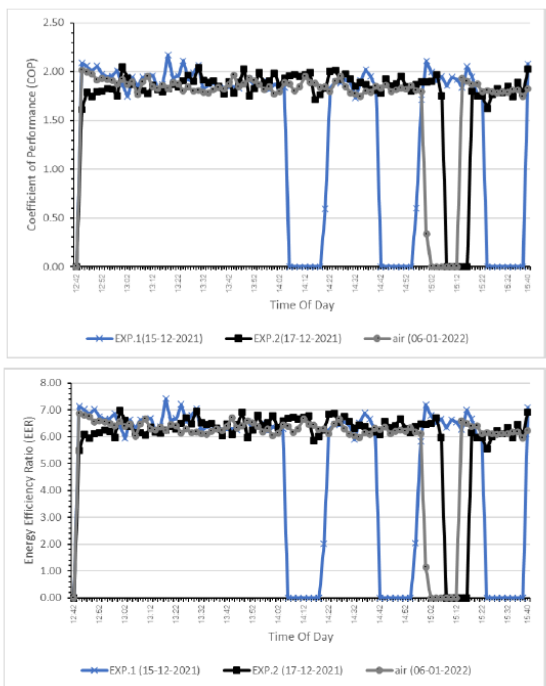

Figure 8. Comparison of coefficient of performance (COP) and energy efficiency ratio (EER) between the conventional air conditioner and that installed with STEG

Table 5. The averaged performances of the split-type air conditioning calculated using data of the three days of each configuration

Test Conditions	COP	EER	%
Conventional	1.81±0.01	6.19±0.06	-
Separate TE	1.87±0.05	6.38±0.18	3.03
Series TE	1.88±0.20	6.42±0.89	3.55

4. CONCLUSION

Experimental investigation reported on the performance of a stand-alone thermoelectric power generator (STEG) using heat of refrigerant leaving the condenser and self-cooled by water condensate circulating by gravity of a split-type air conditioning confirmed good potential for application. STEG can produce electrical current continuously and varied depending on the operation on the compressor. The more important the cooling, the higher is the voltage produced. The maximum recorded voltage is about 200-250 mV by each TE module and doubled with the TE modules connected in series. The average water condensate flowrate was 11.56 g/min. The average coefficient of performance (COP) and the average energy efficiency ratio (EER) of the air conditioning with STEG were 1.87-1.88 and 6.38-6.42 respectively, 3% higher than those of the conventional system. Further investigation includes increasing the number of TE modules, varying operation conditions of the air conditioning and controlling flowrate of water condensed on the two sides. Finally, even though leads to limited performance, the integration of STEG in a conventional split type air conditioning is an interesting option as it can generate free electricity, lead to performance improvement at limited cost and practically maintenance-free.

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