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Research paper

Thermal comfort study of a building equipped with thermoelectric air duct system for tropical climate

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HIGHLIGHTS

- Examines the performance of thermoelectric air duct system (TE-AD) on thermal comfort of occupants for tropical region.
- Subjective and objective measurements of comfort supplying different input current to TE-AD system.
- Provides economic comparison between TE-AD system and conventional air conditioning system.

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ABSTRACT

This paper examined the performance of a thermo-electric air duct system (TE-AD), which employs the thermo-electric module (TEMs) inside an air duct for providing thermal comfort in Malaysian environment. Twenty human subjects were exposed to test room equipped with TE-AD system operating at six different input current supply from 2 A to 7 A. Both objective and subjective measurements were carried out. Results show that with the increment of input current supply to the TE-AD system, subject's thermal response related to indoor condition of test room shifted from warm to neutral. Optimum performance of the TE-AD system was obtained at the input current supply of 6 A, more than 80% of subjects responded in the range of ±1 and meets ASHARE standards of acceptability criteria. Further increase in input current supply deteriorates the cooling performance of the TE-AD system. Economic comparison of the TE-AD system with the existing air conditioning system shows that economic saving of US$ 127.34/year can be achieved with additional benefits of Freon free, convenient installation, no moving part and reliable operation.

1. Introduction

Air conditioning in buildings to provide thermal comfort for occupants has been already the main contributor of excessive energy and fossil resource use in long tropical summers. This trend will continue to grow as cooling demand in tropical and subtropical region is increasing in coming decades [1]. In order to tackle this energy-economic crises, alternative of air conditioner for providing thermal comfort in warm-humid environment needs to be identified. A thermo-electric effect which was discovered at the start of the 19th century by Thomas Seebeck, is among the latest potential technology being researched in complying with the requirements of space conditioning [2]. TE module (TEM) is solid-state energy converters that can create a temperature difference when an electric potential is applied to the material (Peltier effect) or generates the electric potential by introducing a temperature difference (Seebeck effect) [3]. Advantages of using TEM for heating and cooling as reported in different literatures are, solid-state operation, no moving part, maintenance and gas-free, no chemical reaction, environmental friendly and lengthy life span of

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Nomenclature

TE-AD	thermoelectric air duct
PMV	predictive mean vote
PPD	predicted percentage dissatisfied index
V_n	decrease value (US$)
DV	diminishing value (US$)
n	years
C	investment cost of the TE-AD system (US$)
B	savings cost of the TE-AD system (US$)
i	interest rate

consistent operation [4]. But their application in building space conditioning is less focused by researchers because of its low-energy conversion efficiency and corresponding high material cost. In 1982 Stockolm et al. [5] used TEM for cooling small cabs of railroad and submarines. Khire et al. and Xu et al. [6,7] proposed TEM application in buildings for making active envelope. The results indicate that performance of TE cooler was dependent on thermal resistance of heat sink attached with it and plays an important role in deciding the quantity of TEM required. Gillott et al. [8] investigated the effect of TEMs on small scale building space conditioning application. Results show that maximum cooling capacity of 220 W and COP of 0.46 was achieved when TE cooling unit was operated at input electrical current supply of 4.8 A to each module. Performance of TE air-conditioners were compared with conventional vapor compression air-conditioners by Riffat and Qiu [9]. Results show that the COPs of TE air-conditioner was in the range of 0.3–0.45 while vapor compression air-conditioner was in the range of 2.6–3.0 respectively. Cosnier et al. [10] investigate air heating and cooling capacity of TEMs both experimentally and numerically. It was found that when the TE module operated at the input electrical current supply of 4 A, cooling capacity of 50 W per module, with a temperature difference of 5 °C between hot and cold side and COP in the range of 1.5–2 was achieved. Shen et al. [11] used TEM as radiant panels instead of conventional hydronic panels to develop thermo-electric radiant air-conditioning (TE-RAC) system. This system can be used for both heating and cooling purpose and optimum results were obtained when the system operates at current 1.2 A. A maximum COP of TE-RAC in the cooling mode was 1.77 and the minimum temperature achieved at cold side was 20 °C. Tan and Zhao [12] proposed thermo-electric cooling system integrated with phase change material (PCM) for space conditioning purpose. Integration of PCM increases COP of the system by 56%, as PCM stores cold energy at night and also reduces hot side temperature of TEMs thereby act as a heat sink during cooling period. However, Hermes and Barbosa [13] concluded that present TEMs was having only 1% thermodynamic efficiency as compared to Stirling and reciprocating vapor compression refrigeration systems which was having 14% thermodynamic efficiency. So in order to improve performance of the TE air-conditioning system, Tipsaenporm et al. [14] applied direct evaporative cooling techniques which enhance the cooling power from a value 53.0 W–74.5 W.

As TEMs requires direct current for generating temperature difference (Peltier effect), attracts most of the researcher towards solar powered TEM. Dai et al. [15] experimentally investigate solar powered TE and obtained the relationship between the intensity of solar radiation and coefficient of performance (COP) of a TE refrigerator. Maneewan et al. [16] introduced a concept thermo-electric roof, solar collector (TE-RSC) which not only reduces roof heat gain but also improving attic and house ventilation. He et al. [17] studied the building integrated solar thermo-electric systems, which can cool down and heat up the rooms in composite climate. The results show that the COP of 0.45 and minimum temperature of 17 °C was achieved with the system thermal efficiency of 12.06%. Zhong et al. [18] developed active solar thermo-electric radiant wall (ASTRW) system by integrating thermo-electric radiant cooling and photovoltaic (PV) panel. Experimental results show that the inner surface temperature of the ASTRW was 3–8 °C lower than the indoor temperature of the test room, which reduce the air conditioning system requirements. Mei et al. [19] analytically investigate solar driven TE air-conditioning system for vehicle application. Results show that for providing cooling capacity of 4 kW at an environmental temperature of 38 °C, electric power of 9.5 kW was required. Melero et al. [20] simulate solar assisted domestic air-conditioning system having 48 TEMs fitted in the ceiling of the enclosure. Results show that the TEMs provides sufficient temperature reduction needed to satisfy the occupants of the enclosure. Alomair et al. [21] theoretically and experimentally investigate solar TE air-conditioning system application in remote areas. They found that cooling capacity of a solar TE air-conditioner depends upon capacity and the size of TEMs.

However, thermal comfort of occupants by implementing TEM in buildings was studied by only a few researchers among which Lertsatitthanakorn et al. [22] studied thermal comfort and cooling capacity of TE ceiling cooling panel system. Results indicate that COP of 0.82 and cooling capacity of 201.6 W was achieved when the system was operated at 1 A. Also this system has met 80% acceptability criteria of ASHARE Standard-55's [23]. Maneewan et al. [24] studied thermal comfort and cooling performance of compact TE air conditioner systems for small space conditioning application. Thermal acceptability assessment based on ASHARE Standard-55's [23] was performed for three levels of input current supplied to the system. Optimum performance of the system occurred at 1 A of current flow with a corresponding cooling capacity of 29.2 W, a COP of 0.34, an average cooled air temperature of 28 °C and at a cooled air velocity of 0.9 m/s.

Although much literature concerning the application of TEMs for small scale cooling/heating or as insulation material has been published, there is limited research focusing on thermal comfort and economic benefits of TEMs for full scale building application. Also implementation of TEMs inside an air duct has not been discussed so far. So the aims of this paper are to: (1) examine the ability of thermo-electric air duct system (TE-AD) for cooling and dehumidification of indoor air of the test room; (2) determine optimum input current supply to TE-AD system that will provide feasible thermal comfort to the occupants; (3) provide sufficient thermal comfort in the tropical climate of Malaysia which is a simple, noiseless and refrigerant-free solution; (4) economic comparison of TE-AD system with existing air conditioning system.

2. Methodology

2.1. Field experiment

The experiment and data collection were conducted for three months from 1st January 2015 to 1st April 2015 using the single-room house facility equipped with thermo-electric air duct (TE-AD) system located at the campus of Universiti Teknologi PETRONAS (4°23′11″N and 100°58′47″E, Perak, Malaysia). Description of the TE-AD system is given below. The test room is of dimensions 2.8 m (width, X) × 2.7 m (depth, Y) × 2.6 m (height, Z) as shown in Fig. 1. Roof is made from clay roof tiles. Gypsum board of dimension (1.828 m × 1.219 m × 0.0063 m) is used in ceiling. Window on the north-west wall is of dimensions 0.304 m height and 0.22 m width. Window is made of plywood of thickness 2.2 cm. The window open

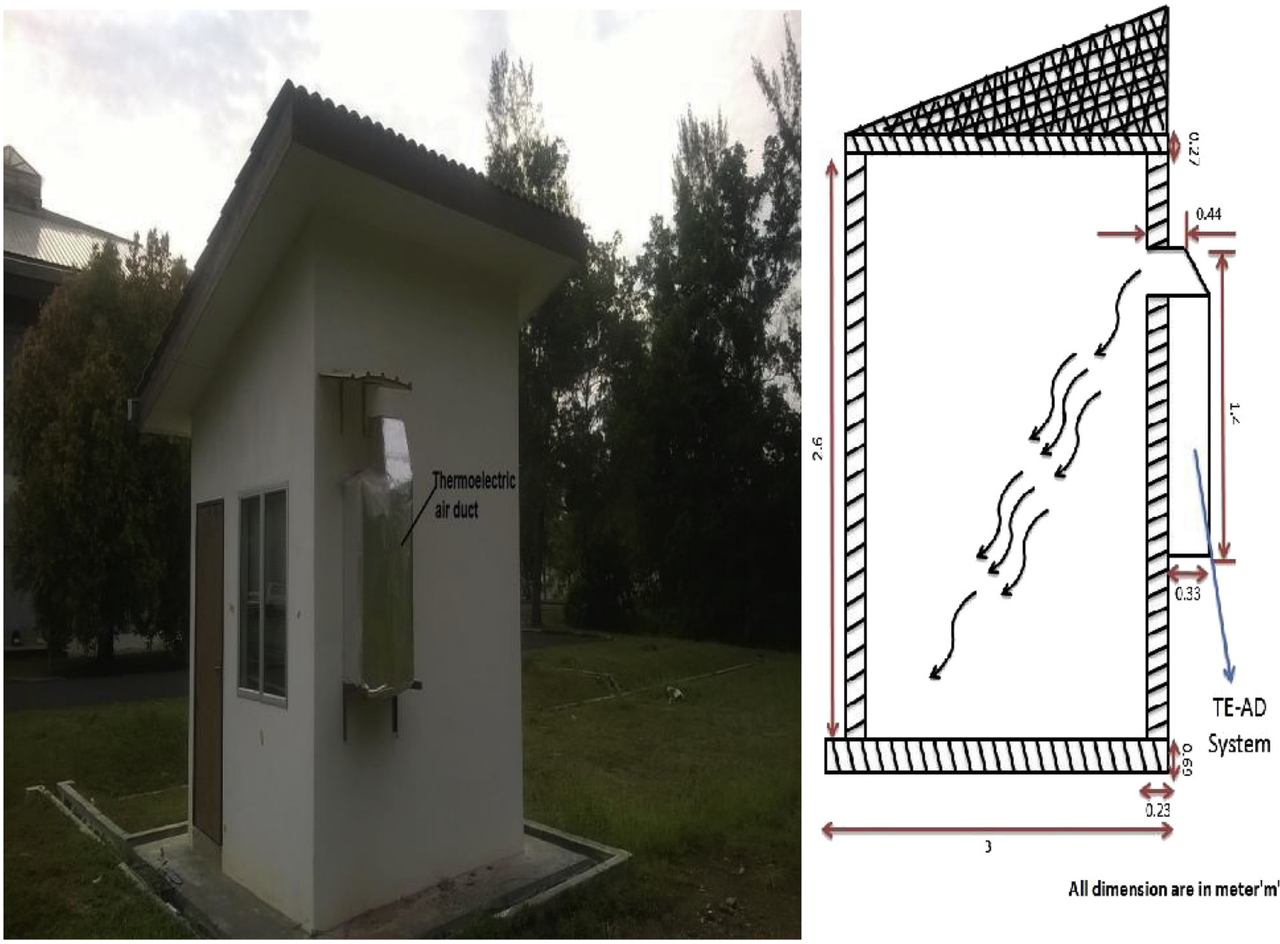

Fig. 1. Test room equipped with TE-AD system.

outside and is not provided with overhangs. A single steel door is on the north-west wall of dimensions 2 m height and 0.821 m width. The door is made of 0.45 cm thick GI metal sheet and opens outside.

2.2. System description

The TE-AD system as shown in Fig. 2 consists of an aluminum sheet housing supported by a frame and wrapped with insulation sheet. A Perspex sheet was installed at the center of the duct to house twenty four TEC1-12730 TEMs. The TE module properties are presented in Table 1. It was designed to separate the air duct into two compartments where the air was cooled in one compartment and warmed in the other by the TEMs. A small hole was drilled in a Perspex sheet to bolt the heat sink and cooled object together using the plastic screws. Dimensions of aluminum heat sink are 65 mm × 65 mm × 20 mm and aluminum cold plate is 65 mm × 65 mm × 10 mm. A thin layer coating of thermally conductive grease was applied on both hot and cold sides of TEMs for proper dissipation and absorption of heat into the surrounding medium. Both duct compartments were fitted with a fan each to enhance the performance of the TE-AD by controlling the velocity of the air flow in the duct. Both fans were connected to the speed controller to control the fan speed. The duct was insulated with an aluminum foil to prevent air leakage, thermal losses which will degrade the performance of the TE-AD. Twenty four TEMs were arranged in eight rows and three columns matrix form (8 × 3) as shown in Fig. 3. Column connected in parallel to each other and TEMs present in each column were internally connected in series.

2.3. Subjects

Ten male and ten female subjects participated in the tests and their anthropology data is given in Table 2. The participants are Malaysian citizen having average surface area of 1.62 m^2. So, the population represents Malaysian body proportion rather than the average worldwide body surface area proportion which is 1.80 m^2. The subjects were dressed up in typical summer clothes (0.5 clo). The subjects were allowed to lean backward or forward, but not allowed to walk, stand up or jump during the tests. Prior to experiment all the subjects attended a training session to get familiar with the test room, test procedure and question in the survey sheet.

2.4. Experimental procedure

The experiment was carried out by six levels of input current supply to TE-AD system i.e. 2 A, 3 A, 4 A, 5 A, 6 A and 7 A was used to measure parameters established by ISO 7730 [25] i.e. indoor temperature, indoor relative humidity, and average radiant temperature. TE-AD system was operating for 12 h for each level of input current. At the start of every test, the occupants were asked to sit

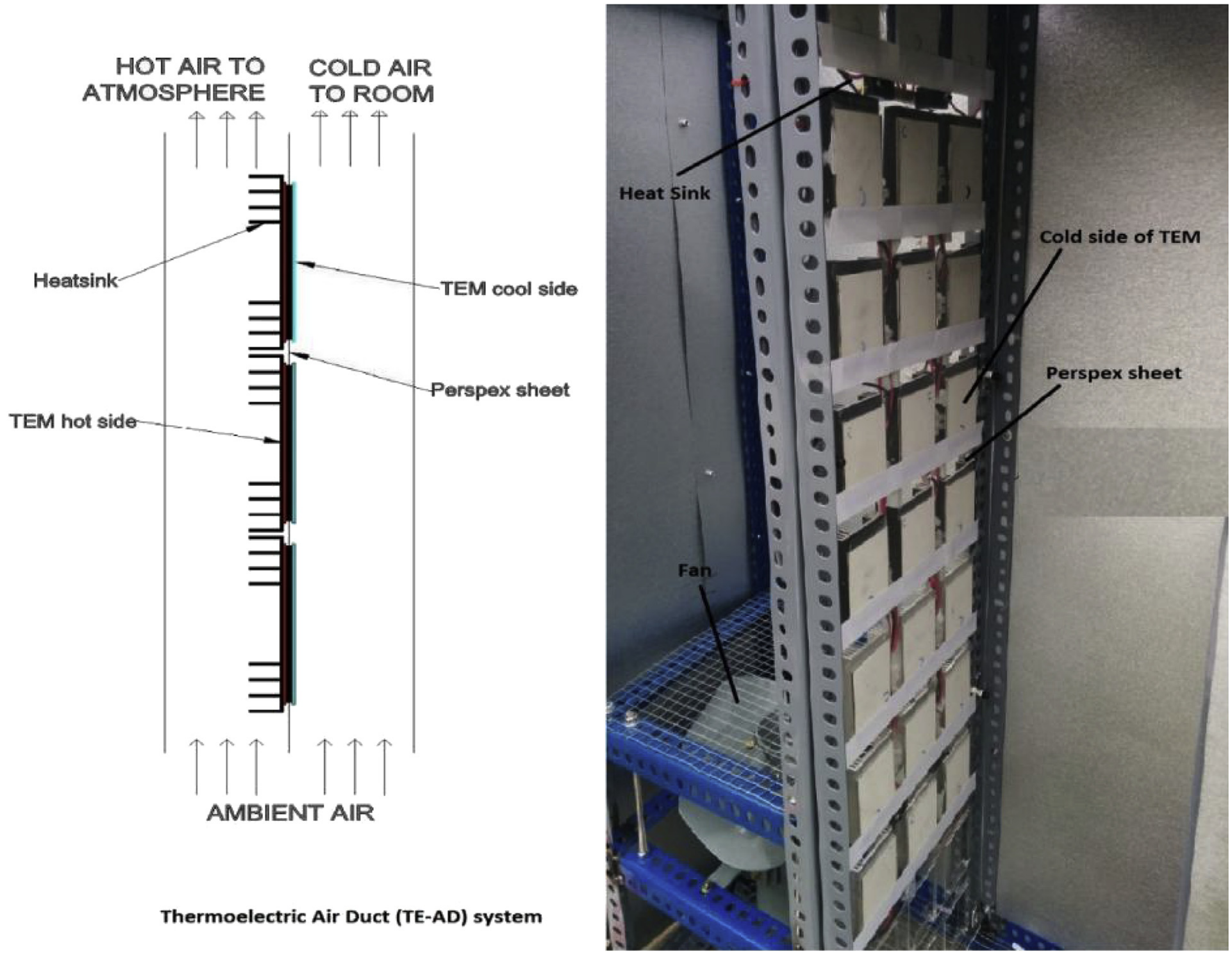

Fig. 2. Arrangement of TEMs inside air duct.

for 15 min in the test room to adjust to the environment. Each test of 12 h includes breaks of 15 min after every 1 h of test, in which occupants were asked to stretch, stand and walk around the room.

Data collection comprises physical estimation and subjective assessment. The physical estimation intended to gather the microclimatic parameters, for example, air temperature, globe temperature, relative humidity, air speed and solar radiation. K type thermocouples were fixed at different locations of the test room and TE-AD system, to collect the temperature data with the help of data loggers. Globe thermometer was used to measure mean radiant temperature. The devices were installed from 7:30 a.m., and the data collection started at 8a.m. Research protocol of Class II was chosen for this study which required all estimation sensor probes to be put at the point (1.00 m above floor) beside the sitting respondent [26]. The portable solar meter was used to measure the solar irradiation at the time of operation of the TE-AD system. All the data were collected regularly from 8a.m. to 8 p.m. at 1-min intervals with different instruments; accuracies and range of the measuring instruments are listed in Table 3. By careful analysis of filled questionnaires subjective sensation, feelings and opinions of occupants were obtained. During every session of test questionnaire developed according to UNI EN ISO 7730 [25] and UNI EN ISO 10551 [27] were distributed. The questionnaire was subdivided into three main parts based on the study conducted by different authors [28,29]. Occupant's thermal sensation, predictive mean vote and thermal preference were accessed in first section. The thermal sensation scale and predictive mean vote were based on the traditional ASHRAE 7-point scale (−3 cold, −2 cool, −1 slightly cool, 0 neutrality, 1 slightly warm, 2 warm and 3 hot). Mc Intyre (preference) based on three scales was used to access thermal preference of occupants (warmer, maintained and cooler).

Thermal comfort, humidity sensation and humidity acceptability response of occupants ranged from −3 to 3. The second segment of the survey asked a few questions significant to thermal adjustment of the occupants. The third section dealt with demographic information such as gender, age, and duration of living in Malaysia, activity levels, marital status and the clothes occupants were wearing.

Table 1
TE module properties.

Type	Dimension (mm)	N	I_{max} (A)	U_{max} (V)	Q_{cmax} (W)	T_{max} (°C)	R_{TE} (Ω)	S_{TE} (V/K)	K_{TE} (W/°C)
TEC1-12730	62 × 62 × 4.8	127	30	15.4	266.7	68	0.27	0.051	0.5177

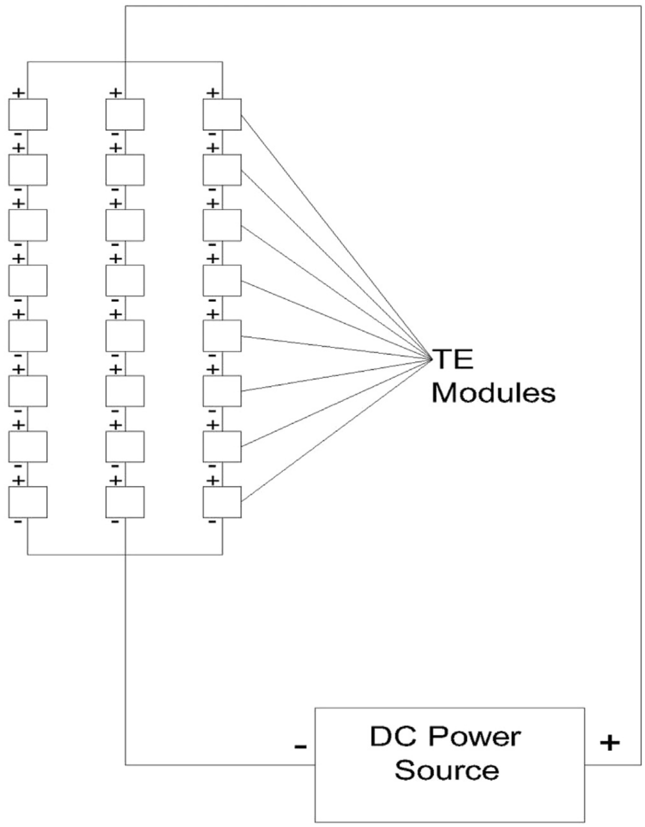

Fig. 3. Electrical arrangement of TEMs in TE-AD system.

3. Results and discussion

3.1. The objective measurement

Data were recorded as per ISO 7730 [25], provides four environmental parameters and rest individual parameters listed in Table 2. Environmental parameter includes ambient temperature, average radiant temperature, air velocity and relative humidity listed in Table 4 used to calculate PMV and PPD value as per ISO 7730 [25] and Fanger's model [30]. Indoor operative temperature and relative humidity variation with time at input current supply of 4 A–7 A is presented in Fig. 4. It was depicted from Fig. 4 that during initial and final hours of operation of the TE-AD system i.e. 8 a.m.–10 a.m. and 6 p.m. till 8 p.m., operative temperature was low as compared to peak time operation i.e. 11 a.m. to 5 p.m. This was due to low outside temperature which results in low heat transfer during initial and final hours of operation as compared to peak hour. While relative humidity was higher during initial and final hours of operation which was reduced as the temperature of air increase during peak hour operation. Measured PMV and PPD value at different input current supply to TE-AD system operating for 12 h a day are presented in Figs. 5 and 6. To simplify the understanding of occupant's response, votes collected were divided into three time frame, first half represents occupant's response from 8:15 a.m.–11 a.m. and second half or peak half represents occupant's response from 11:15 a.m. to 6 p.m. and last or third half represents response from 6:15 p.m. to 8 p.m. When TE-AD system was running at input supply of 2 A and 5 V, PMV distribution is well within −0.17 to 2.17 while PPD ranges from 5% to 84% with mean PMV and PPD of 1.34 and 47.06% and operative temperature varied from 24 °C to 31.5 °C as shown in Figs. 4–6. It was interpreted from the above results that, occupants feel warm indoor condition and more than 50% were thermally dissatisfied.

Input current supply when increase from 2 A to 3 A, PMV distribution is well within −0.19 to 1.76 while PPD ranges from 5% to 64.8% with mean PMV and PPD of 0.93 and 29.59% for operative temperature ranges from 24 to 30.5 °C. However, in both cases more people are satisfied during initial and final hours of the test, as both operative temperature and relative humidity are lower. When the TE-AD system operated at input supply of 4 A and 5 V, both PMV and PPD distribution decrease to −0.42 to 1.53 and 5%–52.4% with mean PMV and PPD of 0.68 and 21.92% for operative temperature ranges from 24 °C to 29.5 °C as shown in Figs. 4–6. Further increase in input supply to 5 A and 5 V, decreases PMV to −0.6 to 1.1 and PPD

Table 2
Anthropology data of subjects.

Sex	Sample size	Age	Height (m)	Weight (kg)	BMI[b]
Male	10	27.4 ± 6.3[a]	1.71 ± 2.1	69.4 ± 1.2	22.4 ± 2.1
Female	10	26.3 ± 2.4	1.64 ± 0.6	54.6 ± 0.8	19.6 ± 1.4

[a] Standard deviation.
[b] Body Mass Index = weight (kg)/[height (m)]^2.

Table 3
Detail specification of equipment used in the experiment.

Apparatus	Type	Quantity	Function	Specification
Thermoelectric modules (TEMs)	Heibei TEC1-12730	24	To create a temperature gradient from an applied electric current	Maximum Current Input = 30.5 A@15 V Q_{max} = 257 W@T_h = 25 °C Q_{max} = 282 W@T_h = 50 °C
DC power supply	CPX400DP	1	To supply current into TEMs	Dual output, each with: 420 W, V_{max} = 60 V, I_{max} = 20 A. Voltage and current draw can be adjusted.
Heat sinks	Finned aluminum	24	To improve heat dissipation on hot side of TEM	
Anemometer		1	To measure air speed for controlling fan speed	
Thermocouple	Type-K	10	To measure temperature	Kept at 0 °C, measured accuracy within ±0.1 °C
Globe thermometer		1	To measure mean radiant temperature	Diameter = 150 mm Range = −50 to 300 °C with accuracy of ±0.1 °C
Advanced solar power meter		1	To measure solar irradiation	Resolution: 1 W/m^2 Spectral response: 400–1100 nm Accuracy ±2 W/m^2
Fan	HDEF-12 exhaust fan	2	To assist TE-AD by controlling air flow into the duct	230 V, 56 W 9″ Diameter Speed = 1400 rpm Max air flow = 10–15 m^3/min
Data logger	midi Logger GL220	1	To record measured data	Every 10-min intervals record

Table 4
Summary of environmental conditions.

Environmental parameters	2 A	3 A	4 A	5 A	6 A	7 A
Mean temperature outdoor (°C)	27.5	27.1	27.3	27.2	26.7	27.3
Minimum T_{out} (°C)	24	24	23	24	23	23
Maximum T_{out} (°C)	34	33	33	34	34	33
Standard deviation	2.8	2.9	3.01	2.6	2.9	2.9
Mean temperature indoor (°C)	27.6	26.8	26	25.7	24.1	25.4
Minimum T_{in} (°C)	23.4	22.8	21.7	22.6	21	22.2
Maximum T_{in} (°C)	34.3	33.6	32.8	31.9	29.1	30.3
Standard deviation	2.8	2.45	2.9	2.5	2.22	2.5
Mean radiant temperature (°C)	27.7	26.9	26.2	25.8	24.2	25.5
Minimum MRT (°C)	23.5	22.9	21.8	22.7	21.2	22.3
Maximum MRT (°C)	34.5	33.7	32.9	32	29.3	30.4
Standard deviation	2.9	2.3	2.6	2.7	2.3	2.4
Mean wind speed out (m/s)	1.8	1.7	1.8	1.3	1.6	1.7
Minimum wind speed out (m/s)	0.9	1.0	1.1	0.7	0.8	1.2
Maximum wind speed out (m/s)	1.8	2.1	3.2	2.4	2.2	2.9
Standard deviation	0.1	0.2	0.1	0.3	0.78	0.2
Mean wind speed in (m/s)	0.1	0.1	0.09	0.1	0.09	0.1
Minimum wind speed in (m/s)	0.05	0.04	0.03	0.05	0.06	0.04
Maximum wind speed in (m/s)	0.14	0.20	0.17	0.18	0.21	0.19
Standard deviation	0.06	0.05	0.04	0.05	0.07	0.06
Mean relative humidity out (%)	84	79	74	71	69	73
Minimum relative humidity out (%)	50	52	55	49	53	48
Maximum relative humidity out (%)	98	99	96	97	95	99
Standard deviation	6.2	5.3	4.8	5.8	3.6	4.9
Mean relative humidity in (%)	79	73	68	61	53	65
Minimum relative humidity in (%)	48	47	45	44	41	49
Maximum relative humidity in (%)	93	89	84	76	69	81
Standard deviation	4.2	3.3	5.4	3.7	4.2	5.3

to 5%–30.4% with mean PMV and PPD of 0.51 and 13.96% for operative temperature ranges from 23.5 °C to 28.5 °C. Except peak summer hours from 1 p.m. to 5 p.m., PMV distribution is well within recommended range of ±1 and PPD is less than 15%. Optimum performance of TE-AD system was reported when system was running at input supply of 6 A and 5 V, PMV distribution varied from −0.72 to 0.92 while PPD ranges from 5 to 22.8% with mean PMV and PPD of 0.18 and 12.31% for operative temperature ranges from 23 to 28 °C as shown in Figs. 4–6. Mostly occupants were thermally satisfied with both PMV and PPD score falls in the

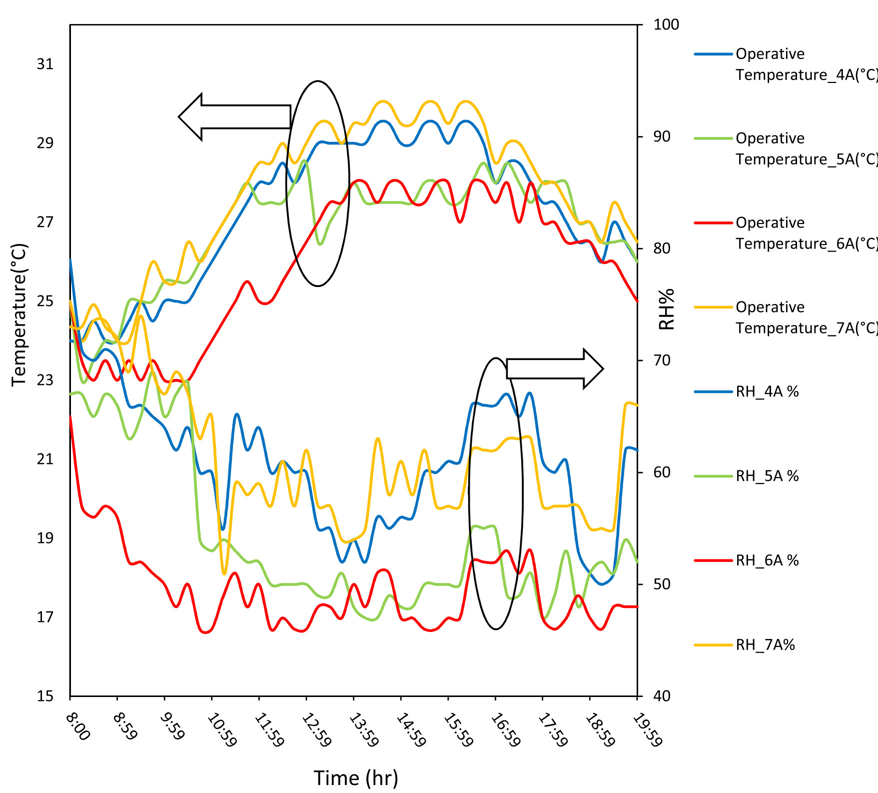

Fig. 4. Variation of operative indoor temperature and relative humidity with time for different input current.

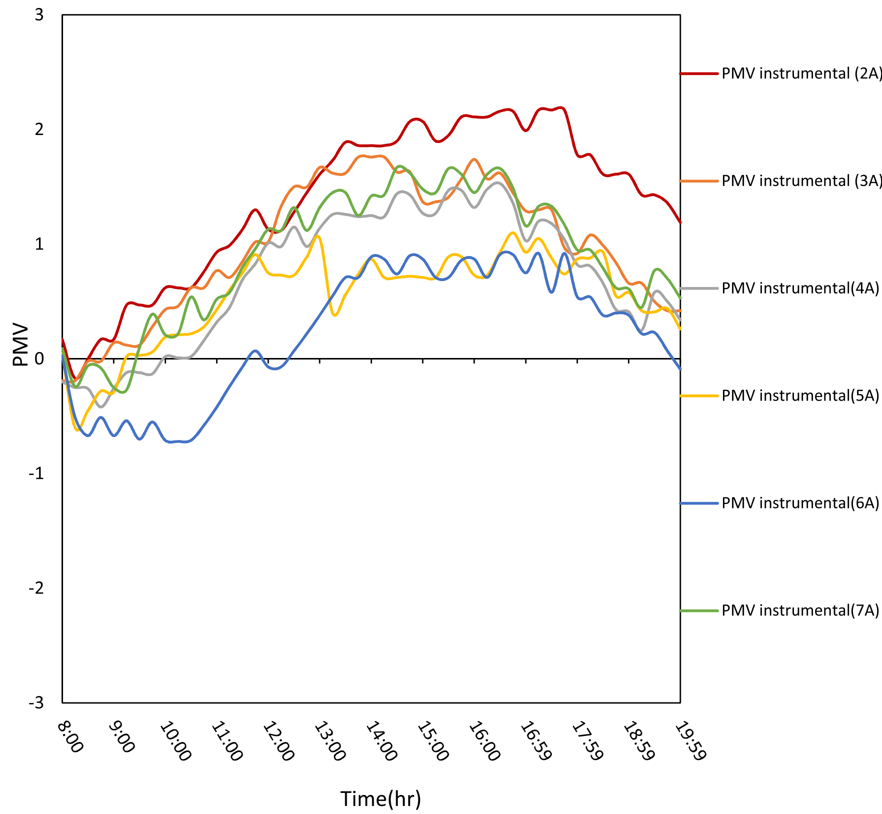

Fig. 5. Variation of PMV with time at different input current to TE-AD system.

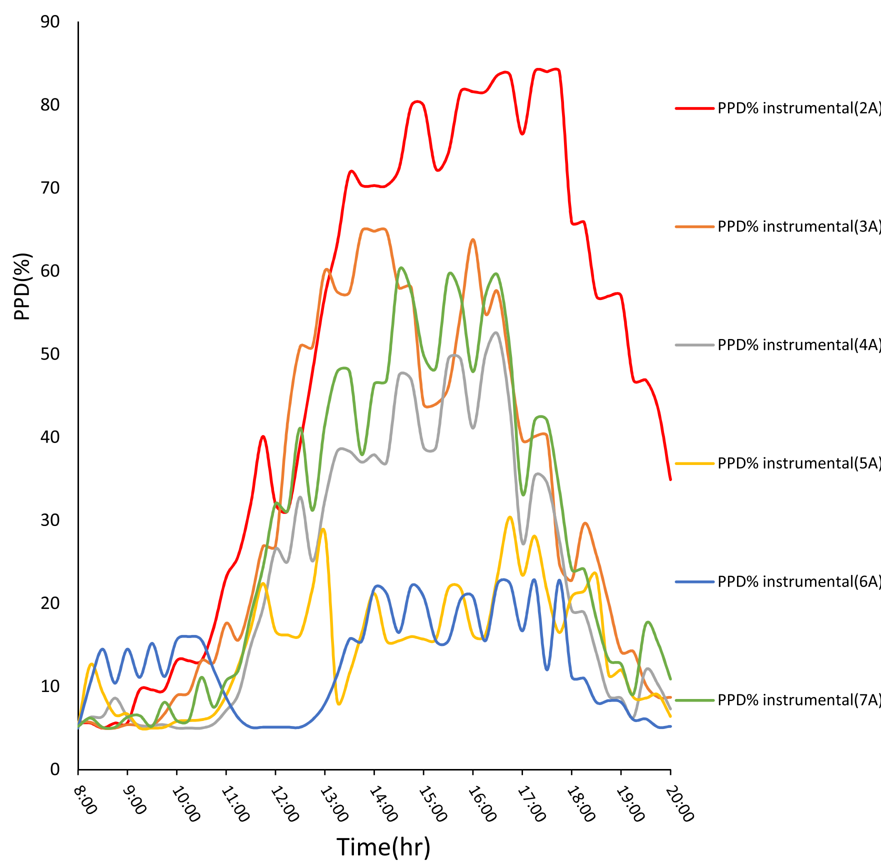

Fig. 6. Variation of PPD% with time for different input current supply to TE-AD system.

recommended range of ±1 and less than 15% of ASHARE acceptability criteria.

As input supply was further increase to 7 A and 5 V, cooling capacity of thermo-electric module decreases because hot side become hotter and start transfer heat to cold side of TE module. Figs. 5 and 6 shows the variation of PMV and PPD with time, and it is clear that both PMV and PPD distribution increase to −0.27 to 1.67 and 5.1%–60% with mean PMV and PPD of 0.857 and 26.86% for operative temperature ranges of 24 °C–30 °C.

3.2. The subjective measurement

The personal and environmental data were collected by standard response scales used in the survey. The occupant's subjective thermal response was used to determine thermal sensation vote (TSV), PMV, thermal preference. Figs. 7 and 8 represent the bar chart showing percentage vote distribution of actual TSV and PMV of occupants when TE-AD system was operated at different input current supply. It was observed that as the input current supply increases from 2 A to 3 A, occupant's both TSV and PMV response changes from hot to slightly warm. 25% and 35% of occupants which was reporting hot (+3) and warm (+2) TSV shifted their votes to 40% warm and 55% slightly warm TSV. While PMV shifted from 15% hot and 40% warm to 25% warm and 65% slightly warm, with no one reporting hot condition at 3 A. When the input current supply was further increase to 4 A both TSV and PMV response of occupants shifted toward neutral. 35% and 25% of occupants marked (0) while remaining gives slightly warm rating (+1) and only 15% gives (+2) response in both TSV and PMV. When the TE-AD system was operated at 5 A input current supply, 40% occupants TSV rates slightly cool and 45% occupancy rate neutral while only 15% rate slightly warm. In PMV response, 35% rate slightly cool and 55% rate neutral however only 10% rate slightly warm condition. None of the occupants rated warm and hot condition in either of the two responses.

Optimum results were obtained when the TE-AD system was running at 6 A and 5 V. Vote distribution of TSV shows that 45% occupant's rate slightly cool while rest rate cool and neutral indoor condition. Interesting it was also found that 5% of occupants rate cold (−3) were mostly women. From PMV distribution it was found that 30% of occupant rate neutral while 40% and 25% rate slightly cool and cool. When input current supply was further increase to 7 A both TSV and PMV shifted towards warm side. 25% and 20% of occupant's rates warm (+2) while 45% and 30% rates slightly warm in both TSV and PMV. So the cooling performance of TE-AD system, decrease and thermal perception of occupants start shifting toward the warm part.

Moreover, occupants thermal preference was evaluated which was used to know the thermal satisfaction of occupants. If the occupants feel that indoor condition of test room was thermally satisfactory, they have to rate (0) or maintained, if not they can rate either (−1) warmer or (+1) cooler. By analyzing the data collected at different input current supply to the TE-AD system, it was found that more than (70%) and (45%) of occupants rate (0) or maintained at 6 A and 5 A input current supply. While in rest of the other cases, mostly occupant rate in the warmer side as shown in Fig. 9.

3.2.1. Thermal sensation, thermal comfort and air quality

Fig. 10a–c represents mean overall variation of TS, TC and AQ votes with time for different input current supply to the TE-AD systems. During adaption period TS mean occupants response ranges from 1 to 2 (slightly warm to warm) while TC response ranges within 0–1 (neutral to slightly warm) and 1 (slightly good) for AQ response. As the time pass and occupants become more stable, rates slightly lower than the adaptation period for all responses. During break periods given after every consecutive 1 h of experiment, mean occupants TS and TC response ranges in between 0 and 1 except for an input current supply of 2 A and 3 A. Occupants mean AQ response during break period ranges within 0–1. To simplify the understanding of occupant's response, votes collected

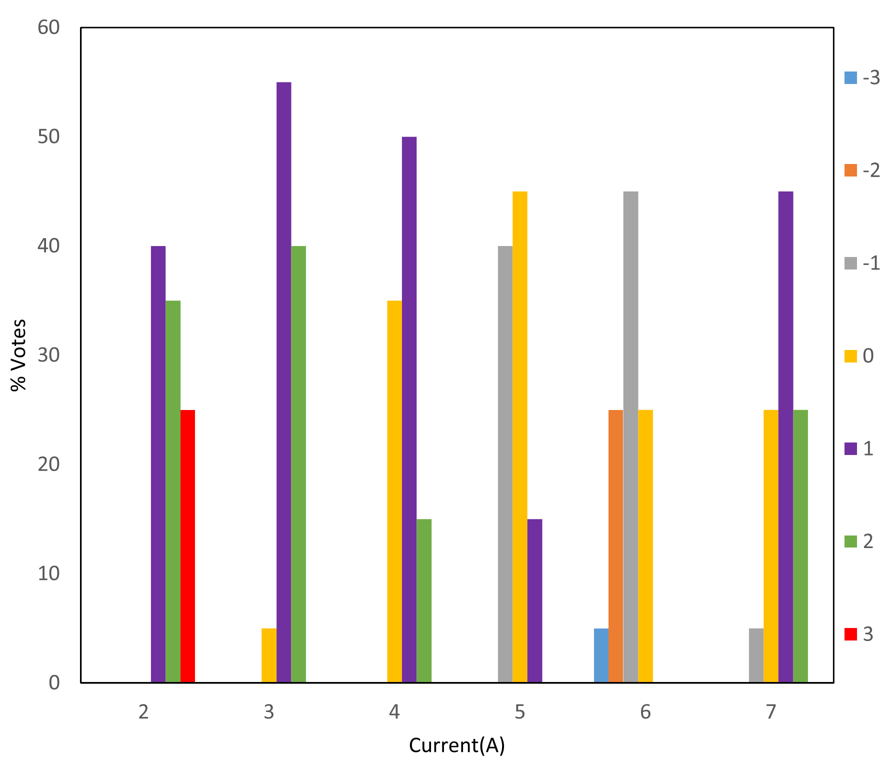

Fig. 7. Statistical summary of thermal sensation votes of subjects at different input current supply to TE-AD system.

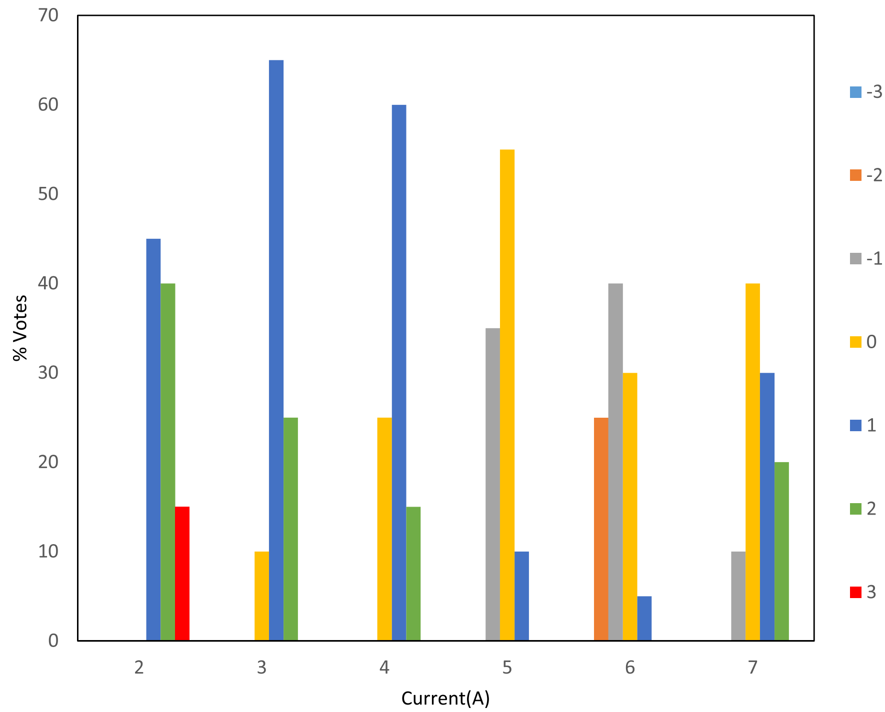

Fig. 8. Statistical summary of predicted mean votes of subjects at different input current supply to TE-AD system.

were divided into three time frame, first half represents occupant's response from 8:15 a.m.–11 a.m. and second half or peak half represents occupant's response from 11:15 a.m. to 6 p.m. and last or third half represents response from 6:15 p.m.–8 p.m. During first and last half of experiment when the TE-AD system was running at input current supply of 2 A and 3 A occupants mean TS vote's ranges within 1–2. Occupant's thermal comfort and perceived air quality votes distribution is well within −1 to 1 and 0 to 1. Operative

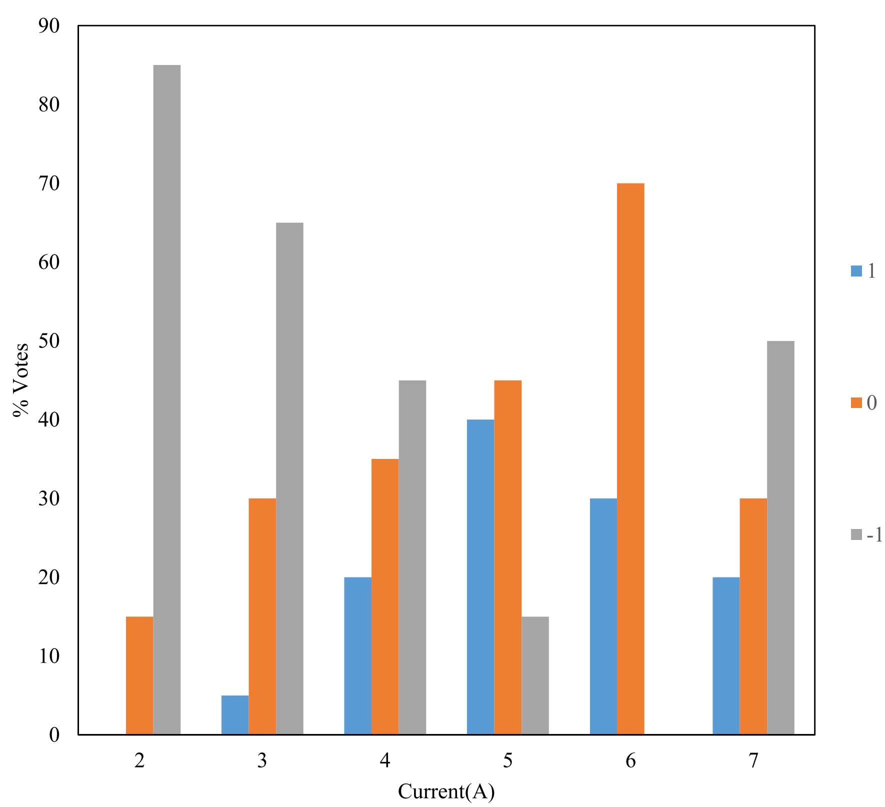

Fig. 9. Statistical summary of thermal preference of subjects at different input current supply to TE-AD system.

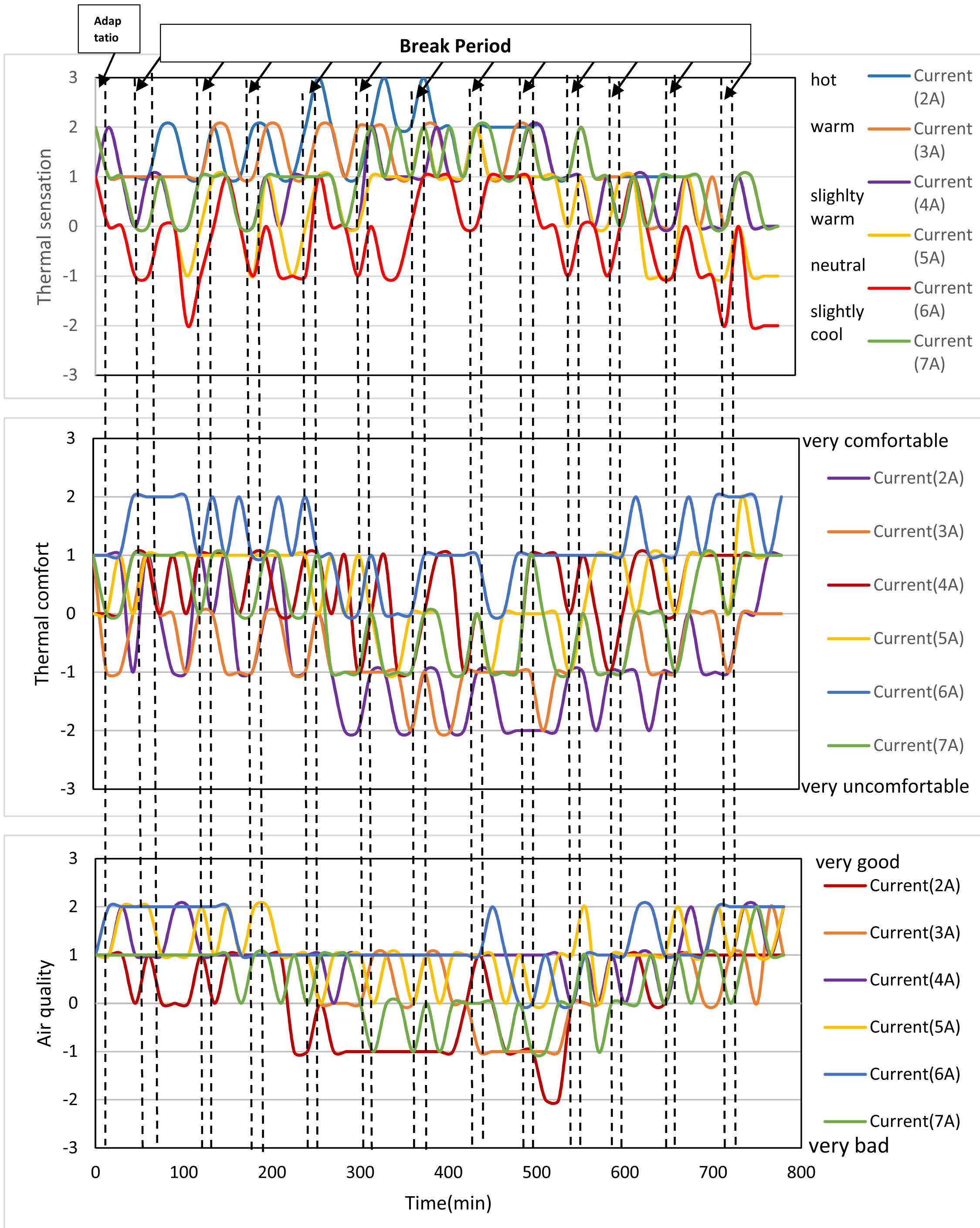

Fig. 10. Mean overall thermal sensation, thermal comfort, and air quality response over time.

temperature and relative humidity during first and last half of experiment is relatively lower than the second half therefore mean occupants response falls in the range of ±1. During second or peak half operative temperature increases which shifted mean TS response of occupants from 1 to 2 and also 3 in some cases. While TC response shifted from −1 to −2 (slightly uncomfortable to uncomfortable) and mean AQ response shifted from 0 to −2 (neutral to bad). Now when the input current supply to the TE-AD system increases from 3 A to 4 A and then to 5 A, mean TS, TC and AQ responses shifted toward cool, comfortable and acceptable condition in all half's of experiment. TE-AD system when operated at 6 A gives optimum results in all three votes and time frame. Mean occupants TS response in all the three half ranges within 0 to −2 (neutral to cool). Mostly occupants were thermally satisfied and also responded 0–2 AQ vote. By further increasing input current supply to 7 A, mean TS response shifted toward warmer side and TC response shifted towards slightly uncomfortable side while AQ remain in the range of 0–1.

Fig. 11a represents the boxplot of TS response for six input current supply to the TE-AD system. The median TS response were

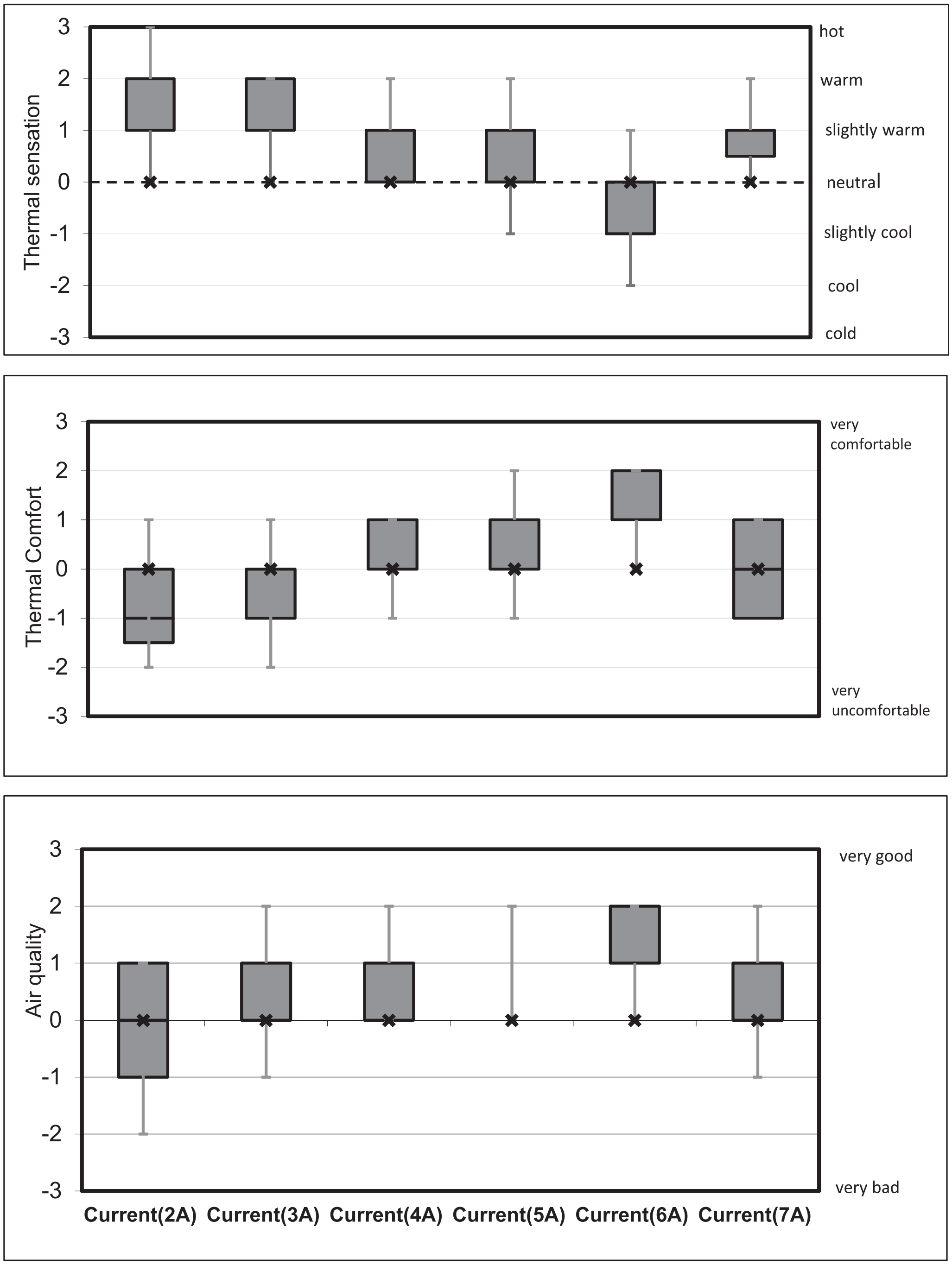

Fig. 11. Variation of thermal sensation, thermal comfort, and air quality response over input current supply to TE-AD system.

almost 1 (slightly warm) for input current supply of 2 A–5 A. For input current supply of 2 A, 3 A and 4 A distribution is well within 0–2, indicating that almost all the responses were warm. For input supply of 5 A distribution is well within −1 to 2, indicating that except few response of warm almost all other responses were slightly warm or neutral. By increasing input current supply to 6 A, the median TS response were shifted to 0 (neutral) while distribution is well within −2 to 1, indicating that except few response of slightly warm almost all other responses were slightly cool. Further increase in input current supply to 7 A deteriorates the cooling performance of TE-AD system and median TS response again shifted to 1 (slightly warm) while distribution is well within 0–2.

The TC votes present in Fig. 11b shows that occupants feel slightly uncomfortable when TE-AD system operates at 2 A and 3 A and median votes were −1 (slightly uncomfortable). Distribution of votes is within −2 to 1, indication that occupants were not thermally satisfied with the cooling performance of TE-AD system. By increasing the current supply to 4 A and then to 5 A, occupants median TC votes shifted toward 1 (slightly comfortable) while distribution lies in the range of ±1 and −1 to 2, indicating that by increasing current supply comfort level of occupants and more occupants are slightly comfortable. Optimum results in term of TC votes was achieved when the TE-AD system operating at 6 A. A median of TC vote is 1 (slightly comfortable) and distribution is well within 0–2, on indicating that nearly all the occupants were thermally comfortable. As the input supply increases to 7 A median TC votes shifted to 0 (neutral) and most of the occupants votes that the condition is slightly warm or warm.

The AQ response presented in Fig. 11c shows that except for test condition of 2 A and 7 A, almost all other condition subjects median response is 1 (slightly good). This indicates that air quality inside the test room is acceptable and variation of input current supply to the TE-AD system has slightly increase the acceptable rating.

3.2.2. Humidity sensation and humidity acceptability

Fig. 12a represents the boxplot of HS response for six input current supply to the TE-AD system. The median HS response were almost 0 (neutral) except for input current supply of 2 A and 5 A where HS is −1 (slightly humid) and 1 (slightly dry). For input current supply of 2 A and 3 A distribution is well within −3 to 2 and −2 to 3, indicating that almost all the responses were humid. For input supply of 4 A distribution is well within ±2, indicating that except few response of dry almost all other responses were humid. By increasing input current supply to 5 A, HS response were shifted slightly dry range while distribution is well within −1 to 2, indicating that except few response of slightly humid almost all other responses were slightly dry. HS response at 6 A is toward slightly dry region and distribution is well within −1 to 2. Further increase in input current supply to 7 A shifted HS response towards 1 (slightly dry) while distribution is well within −2 to 3.

Fig. 12b represents humidity acceptability rating of occupants for different input current supply. The median HA votes for 2 A input current is −1 (just unacceptable) while distribution is well within −3 to 1, indicating that occupants are not comfortable with indoor humidity condition. For input current supply of 3 A and 7 A

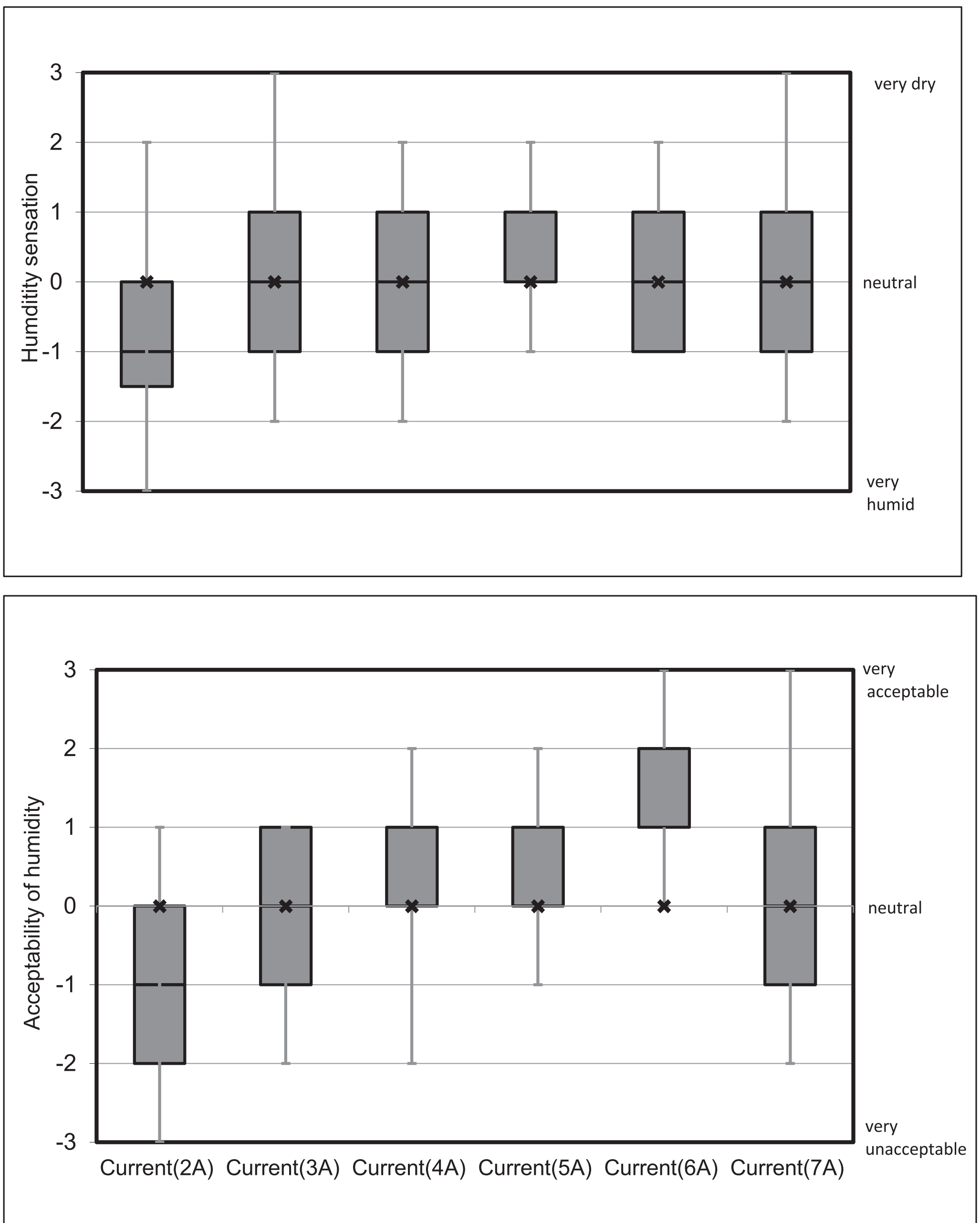

Fig. 12. Variation of humidity sensation and acceptability of humidity with input current supply to TE-AD system.

median HA votes was 0 (neutral) and mostly occupants votes in the range of ±1, indicating that respondent were just accepting the indoor condition. For input current supply of 4 A, 5 A and 6 A median HA votes was 1, indicating that mostly occupants were comfortable with indoor humidity condition and suggesting to operate the TE-AD system at 6 A as distribution is well within 0–3 (acceptable).

3.2.3. Overall acceptability

Fig. 13 represents overall thermal, air quality and humidity acceptability. It is observed that as the input current supply increases acceptability percentage increases. This behavior of the TE-AD system is because heat absorption of a TEM from the environment is based on two effects. First is Peltier effect, which is related to the current through TEM and second is Joule effect which is related to the square of the current through TEM [31]. When the input current supply to the TE-AD system was low, the Peltier effect was weak, resulting in less operative temperature reduction and dehumidifying rate. As the input supply increases cooling capacity of TEM increases and ambient air circulated via TE-AD system, comes in contact with the cooling side of TEMs that was lower than the dew point temperature of surrounding air, dry bulb temperature starts reducing. As the cooling process proceeds at some point it achieves the estimated dew point temperature of the air. At this point the water vapor inside the air changed into the dew particles due to which dew particles were formed on the ceramic surface of TEMs. Thus, temperature and humidity level of the air was reduced. This increasing trend was limited up to 6 A of input current supply after that acceptability rate decreases. Because at higher input current supply, Joule effect become dominated, resulting increase in heat energy release on the hot side of TEMs. Fan and heat sink used to exhaust the heat generated at hot side of TEM becomes insignificant and the extra heat generated was transferred back by conduction towards the cold side of TEM. This reduces the cooling performance of TE-AD system and occupant's response shifted towards the warmer region.

3.3. Economic analysis

An economic analysis of the TE-AD system over conventional air conditioning system was accessed by calculating the impact of an indoor set point on electricity saving [32]. Another test room equipped with a 1-ton-capacity split-type air conditioner of same dimension and specification as of test room with TE-AD was used for comparison. Room temperature and energy consumption by the TE-AD system and air conditioner were recorded during a 12-h day. Ambient temperature varied between 24 and 34 °C, whereas the set-point temperature varied between 24 and 28 °C. The maximum daily energy consumption of the air conditioner was 10.23 kWh at a set-point temperature of 24 °C, while the minimum was 6.53 kWh at a set-point temperature of 28 °C. Therefore, the mean decrease in energy consumption equivalent to a 1 °C increase of set-point (from 24 to 28 °C) was about 9.04%. The set point temperature of room temperature for almost all office of Malaysian is in between 24 and 26 °C. For the convenience of comparison, few assumptions were made in figuring the costs as follows:

- The life span of the TE-AD system was assumed to have 22 years and air conditioner from the manufacturer's estimate.
- According to Malaysian markets the inflation rate is around 0.9% and the interest rate is about 3.25% as mentioned by Bank Negara Malaysia (BNM) [33].

Diminishing value (DV) method is used to calculate depreciation value of TE-AD system as it can effectively estimate decreasing value in whole accounting life of the system. Annual DV of both the system was calculated by:

$$V_n = \text{Initial cost} \times (1 - \text{DV factor})^n \quad (1)$$

The DV factor was selected to be 15%, 10% and 7.5%, respectively with respect to the life expectation of an air-conditioners.

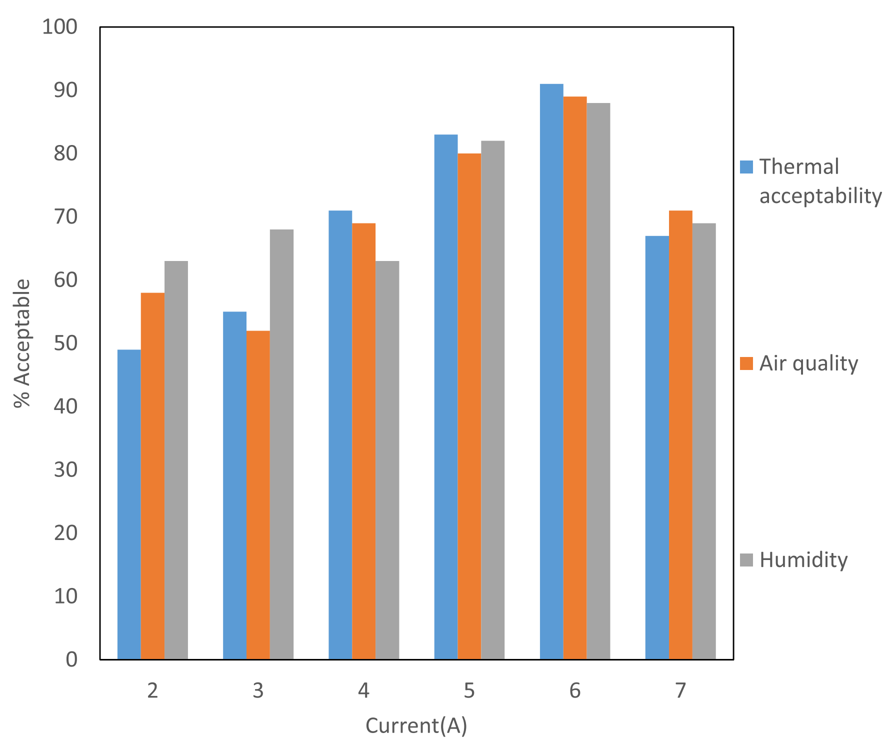

Fig. 13. Variation of percentage acceptability of thermal, air quality and humidity with input current supply to TE-AD system.

Table 5
Data for the TE-AD system and air conditioner.

	Type	Split air condition	TE-AD system
Cooling	Cooling capacity, W	2500–3500	350–650
	Input electric power, W	900–950	600–720
	COP_c	2.3–3.0	0.6–0.9
	Work permit temperature range, °C	18–40	26–40
Noise (indoor/outdoor), Db		37/52	25
Size (mm^3)		870 × 195 × 290 (Indoor) 840 × 540 × 300 (Outdoor)	660 × 330 × 1400
Weight (indoor/outdoor), (kg)		9/31	10
Life expectancy, years		~15	~20
Equipment cost, US$		275–315	700–750

Operating costs exclude maintenance costs and only power consumption is considered in this paper.

$$\text{Annual operation cost} = \text{Annual power consumption} \times \text{electricity price} \tag{2}$$

A payback period was utilized to determine the time needed for electricity savings funds that could be credited to the utilization of TE-AD system. The payback period was defined as the time required by TE-AD system to recover the funds consumed in an investment and can be calculated by using expression

$$C = B\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \tag{3}$$

Table 5 shows the specification data of two type of air conditioning system and there economic evaluations were furnished in Table 6. It is noted that when TE-AD system was operating at 6 A and 5 V input supply saves 1007.4 kWh/year as compare to 1 ton split air conditioner. Also electrical energy saving of TE-AD system is US$ 127.34 with payback period of 6.4 years.

4. Conclusions

This paper investigated the thermal comfort and economic performance of a TE-AD system for test room space conditioning application. The main conclusions are:

1. Subject's thermal response related to indoor condition of test room shifted from (+2) warm to neutral (0) as the input current supply increase from 2 to 5 A.
2. Both objective and subjective measurement shows that optimum thermal, air quality and humidity acceptability was achieved when TE-AD system was running at input supply of 6 A and 5 V and meet ASHARE standard criteria.
3. Cooling performance of TE-AD system decreases with increasing input current supply to TE-AD system above 6 A, resulting in shifting of thermal perception of occupants from neutral to slightly warm or warm. This limitation arises because of inadequacy of heat sink and fan to carry away heat from the hot side of TEMs, resulting in heat transferring back to cold side and decreasing cooling capacity of TEMs.
4. Economic benefits of TE-AD system as compared to existing air conditioner system are:
   - Electrical energy saving of 1007.4 (kWh/year).
   - Economic saving of 127.34 (US$/year) with operation cost of 201.53 (US$/year).
5. The payback period of the TE-AD system was found to be as 6.4 years.

Table 6
Economic analysis of air conditioners.

Comparative items	AC type	
	Split air condition	TE-AD system
Electrical energy consumption (kWh/year)	4161	3153.6
Electrical energy saving (kWh/year)	0	1007.4
Operation cost (US$/year)	328.87	201.53
	0	127.34
Value of air conditioner after 10 years of operation (US$)	58.07	177.21
Payback period (years)	NA	6.4

In conclusion, the TE-AD system exhibits good alternative of conventional air conditioner system in providing thermal comfort for the occupants of building in tropical climate region. For future study, implication of TE-AD system in composite climate region need to be assessed. Thermal comfort analysis by considering effect of age, economic group and tenure need to be examined. A figure-of-merit ZT value of the thermoelectric module used in this work has only 0.82 value. Research on the improvement of COP value and energy performance of TE-AD system by using TEM having ZT factor more than 2.0 should be considered. The sociological study of the awareness of the benefits of TE-AD system particularly among a building's shareholder is recommended. Research on reducing dependency of TE-AD system on fossil resources by integrating photovoltaic technology with TE-AD system is recommended.

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