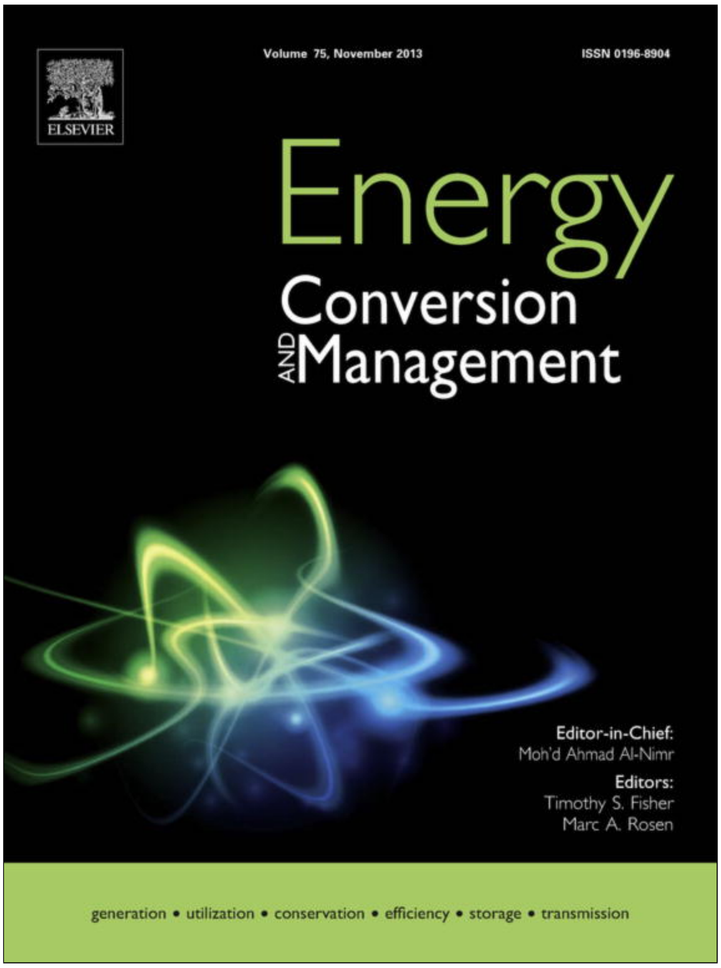
Volume 75, November 2013
ISSN 0196-8904
ELSEVIER
Energy
Conversion
AND Management
Editor-in-Chief:
Moh'd Ahmad Al-Nimr
Editors:
Timothy S. Fisher
Marc A. Rosen
generation • utilization • conservation • efficiency • storage • transmission

Energy Conversion and Management 75 (2013) 617–628

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Simulation of energy saving potential of a centralized HVAC system in an academic building using adaptive cooling technique

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ARTICLE INFO

Article history:
Received 7 February 2011
Accepted 28 June 2013

Keywords:
Transient cooling load characteristic
HVAC system
Adaptive cooling technique
Energy saving potentials
Academic building

ABSTRACT

Application of adaptive comfort temperature as room temperature set points potentially reduce energy usage of the HVAC system during a cooling and heating period. The savings are mainly due to higher indoor temperature set point during hot period and lower indoor temperature set point during cold period than the recommended value. Numerous works have been carried out to show how much energy can be saved during cooling and heating period by applying adaptive comfort temperature. The previous work, however, focused on a continuous cooling load as found in many office and residential buildings. Therefore, this paper aims to simulate the energy saving potential for an academic glazed building in tropical Malaysian climate by developing adaptive cooling technique. A building simulation program (TRNSYS) was used to model the building and simulate the cooling load characteristic using current and proposed technique. Two experimental measurements were conducted and the results were used to validate the model. Finally, cooling load characteristic of the academic building using current and proposed technique were compared and the results showed that annual energy saving potential as much as 305,150 kW h can be achieved.

1. Introduction

People will naturally adapt to any changing conditions in their environment. This natural adaptation is expressed in the adaptive approach to thermal comfort. In contrast with that, the adaptive principle state that: *if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort.* The temperature where most people are likely found to be comfortable is called neutral or comfort temperature. Humphrey and Nicol [1] found that indoor comfort temperature is closely correlated with the mean outdoor temperature. They concluded that only the outdoor temperature needs to be considered in real situations in real buildings. Another related studies found that the temperature strongly relates to adaptability of the occupants and occupants' surrounding condition [2]. Tan and Kosonen [3] conducted study on neutral temperature by allowing adaptation process from the occupant. They found that an adaptive increment of 1.9 °C in neutral temperature can be achieved. This increment offers potential energy savings for any indoor cooling or heating system.

Researches have been done in many countries to develop adaptive comfort temperature model according to the local weather condition [4–10]. The results agree each other that indoor comfort temperature for both naturally ventilated (NV) and air-conditioned (AC) building based on adaptive are warmer during summer and cooler during winter than the recommended value. Due to this fact, energy usage for HVAC system can be reduced by applying adaptive comfort temperature as indoor temperature set point without sacrificing people comfort [11]. The reductions are mainly due to heat gain reduction from building envelope, latent heat gain, ventilation air, and infiltration air. These findings are in harmony with others findings which found that cooling load from building envelope dominates total cooling loads in many buildings [12–14].

In other work, Humphrey and Nicol [15] suggested that an algorithm could be constructed to determine the optimum indoor temperature as a linear function of mean outdoor temperature. The temperature is then used as indoor temperature set point to be maintained by a HVAC system (or a free-running building). Recent works suggest that the use of the temperature results in energy saving as compare to fixed-set point, without increase discomfort among occupants [16]. The previous work, however, focused more on office and residential buildings (single type of room) with continuous cooling load rather than on academic buildings (consist of multi type of rooms) with intermittent load.

In recent years, academic buildings were built and equipped with a centralized HVAC system. It is obvious to highlight that occupancy pattern between office/residential and academic buildings are significantly different [17]. In academic building, the room is not always occupied while in office and residential building, the

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http://dx.doi.org/10.1016/j.enconman.2013.06.054

Nomenclature

q_s	surface conduction heat flux of the wall, kJ h^{-1}
T_s	surface temperature, °C
A_s, b_s, c_s, d_s	the coefficients of the time series
S_s	radiation heat flux absorbed an the surface of the wall (solar and radiative gains), kJ h^{-1}
Wall_gain	user-defined energy flow to the inside wall or window surfaces, kJ h^{-1}
T_{star}	artificial temperature node, °C
A_s	surface area, m^2
R_{equiv}	equivalent resistant between the wall with a node, h m^2 K kJ^{-1}
$q_{c,s}$	convection heat flux an the surface of the wall, kJ h^{-1}
$q_{r,s}$	long wave radiation heat flux on the surface of the wall, kJ h^{-1}
$h_{conv,s,}$	convective heat transfer coefficient on the surface of the wall, kJ h^{-1} m^{-2} K^{-1}
σ	Stephan–Boltzmann constant
$\varepsilon_{s,}$	long-wave emissivity of the surface
$T_{a,s}$	ambient temperature, °C
T_{fsky}	Fictive sky temperature, °C
T_c	comfort temperature, °C
T_r	room temperature measured
RH_r	room relative humidity measured, %
$T_{i,sp}$	room temperature set point, °C
$RH_{i,sp}$	room relative humidity set point, %
q_{latent}	latent heat flux, kJ h^{-1}
$q_{sensible}$	sensible heat flux, kJ h^{-1}
V_a	flow rate, m^3 min^{-1}
V_{min}	minimum ventilation rate, L s^{-1}
m_a	mass of air, kg
C_p	specific heat of air, kJ kg^{-1} °C^{-1}
ρ_a	density of outdoor air, kg m^{-3}
ω	humidity, kg kg^{-1}
$h_{fg,32}$	latent heat of vaporization at 32°F, J kg^{-1}
R_p	occupant ventilation component, L s^{-1} per person
R_a	building ventilation component, L s^{-1} m^{-2}
N_p	number of occupant
A	room area, m^2

Superscripts

k	the term in the time series
i	inside
o	outside

room is usually occupied during cooling period [18]. Since cooling load in the buildings is mostly driven by the occupant [19], the difference between these two will result in different cooling load characteristic. Due to this, during cooling period, the cooling load pattern is likely to be continuous for office or residential buildings and intermittent for academic building. In addition, occupancy pattern in an academic building especially for its laboratory, workshop, and classroom is likely to change every semester or academic year.

Simulation tools have become an essential tool for HVAC system design and analysis that can be used to monitor the performance and detect any abnormalities [20]. Korolija et al. [21] used simulation tool to model the studied building and the transient thermal load. Their simulation model was able to predict the influence of building parameters and HVAC system on the energy consumption. Carriere et al. [22] used building simulation program to investigate energy saving potential in the building by using occupancy sensor. Another simulations results showed that different ambient condition and HVAC system would result in different energy consumption pattern [23,24]. It indicates that a HVAC system's strategy may have different performance on different location.

TRNSYS is a building simulation program (BSP) which has capabilities to solve complex energy system problem. A series of small components were built and connected each other to represent the problem. The components can be as simple as pump or fan or as complex as multi-zone building model. TRNSYS also embedded with capabilities to develop new component using any programming language. TRNSYS also has capability to interact with other engineering software (excel, Fluent, Matlab, etc.) [25].

The aim of this paper is to simulate energy saving potential of a centralized HVAC system in an academic glazed building in tropical Malaysia climate using adaptive comfort temperature by developing adaptive cooling technique. Building thermal model was first modeled using TRNSYS software and validated by comparing simulation results with data collected from experimental measurements. Adaptive cooling technique was then developed and added to the model to investigate the energy saving. Finally, comparison of cooling load using current system and developed algorithm with energy saving potentials were presented and discussed.

2. Methodology

2.1. Building thermal description and occupancy schedules

An academic bloc (bloc 16) located at Universiti Teknologi PETRONAS was chosen for the study. The academic building is facing east with large window glazing area (nearly 100% of glazing area) and on 32 m above sea level. It has three levels with 4 m height on each floor. Floor lay out for the block is presented in Fig. 1 [26].

As an academic block, it has offices, classrooms and workshop to support practical/research works by the students and staffs. Material used for walls, roof, and windows with the conductivity and the U-values were described in Tables 1 and 2. It can be seen that single clear window glass (with thickness 8 mm) used in the building has significantly high U-value. It is due to the type and construction of the windows. Different types and construction of the window glass would give different thermal performance as shown in [28–30]. Monthly academic schedule of the student was described in Table 3. Working schedule of the staff has 5 working days (Monday–Friday) and 8 working hours (08.00–17.00) with 1 h lunch break (13.00–14.00). This schedule is occupancy schedule for all office room type in the academic building. There was no activity during Malaysia national holidays. Daily occupancy schedule for each room in the building are presented in Fig. 2.

Activity schedule for each workshops in the bloc were based on practical schedule of each subject. Numbers of equipment used and usage factors of the equipments in each type of rooms were based on observation data and discussion with the technician/staff. Activities in the workshop with no specific schedule were not considered in this simulation.

2.2. Centralized HVAC system in the building

Centralized AC system with absorption chiller was used to cover the cooling load from all the academic blocks. Each block has three levels and each level have two wings of group zones (left and right wing). The buildings are fully sealed and fresh air is supplied by the

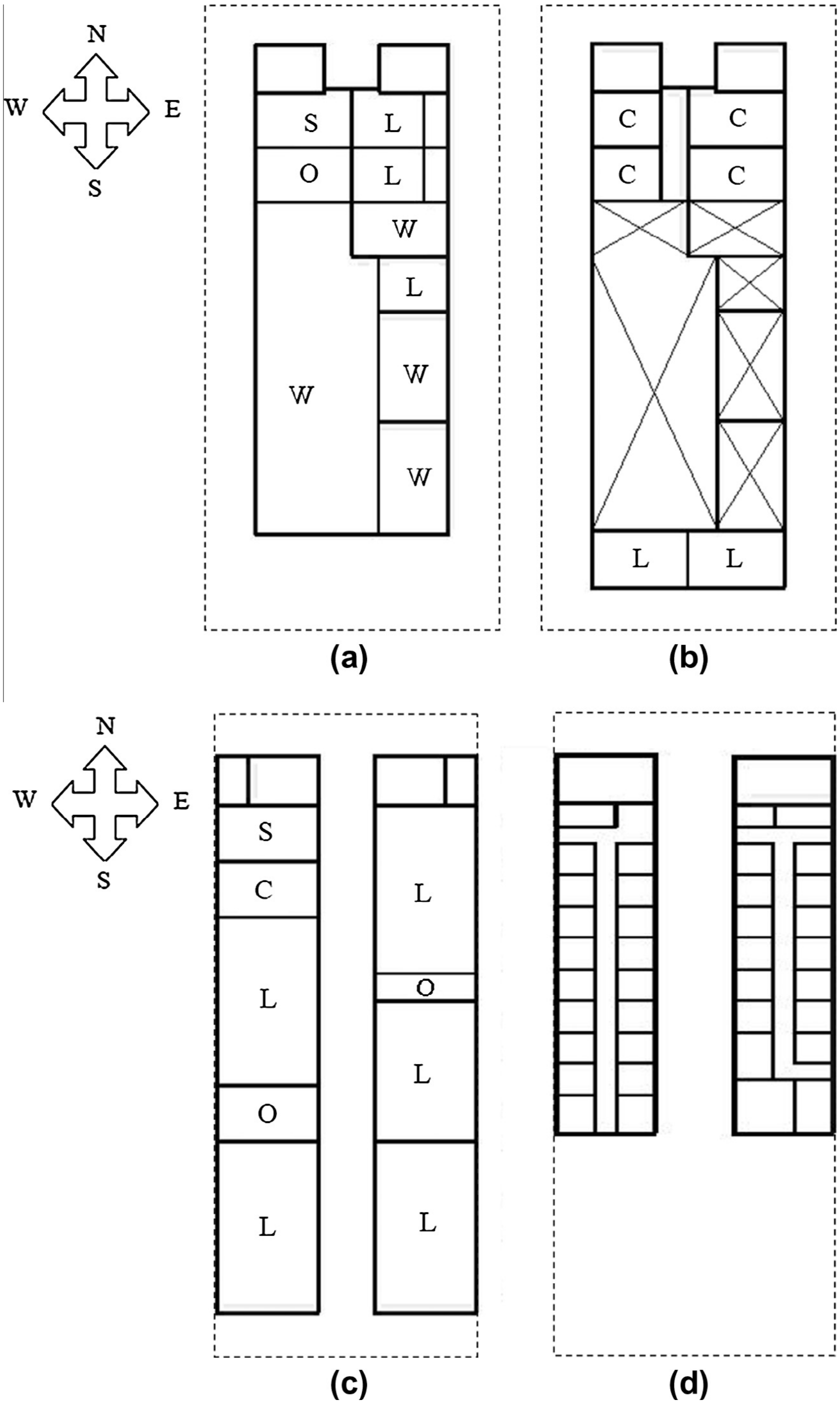

Fig. 1. Floor layout of the academic building: (a) Ground floor, (b) 1st floor, (c) 2nd floor, and (d) 3rd floor [26].

Table 1
Block 16 Building Material specification [27].

Building construction	Details (thickness–thermal conductivity)
External wall	Steel (5 mm–54 kJ/h m K), Air gap (0.047 hm^2 K/kJ), Steel (11 mm–54 kJ/h m K)
Partition wall	Plasterboard (25 mm–0.576 kJ/h m K), Air Gap (92 mm–0.047 h m^2 K/kJ), Plasterboard (25 mm–0.576 kJ/h m K)
Flooring	Concrete slab (100 mm–4.07 kJ/h m K), Common concrete (550 mm–7.56 kJ/h m K)
Window	Optiwhite glass (8 mm–0.9 kJ/h m K)
Roofing	Aluminium (1 mm–846 kJ/h m K), Rockwool (25 mm–0.162 kJ/h m K), Aluminium foil (1–846 kJ/h m K), Common concrete (10 mm–7.56 kJ/h m K)

Table 2
U-values of Block 16 walls.

Type	*U*-values (conduction) (kJ/h m^2 K)	*U*-value (overall) (kJ/h m^2 K)
Floor	6.74	6.433
Roof	6.425	4.928
Partition wall	7.474	5.522
Window	31.25	20.448
External wall	21.143	10.58

Table 3
Students academic schedule 2009.

Week	Month					
	January	February	March	April	May	June
I	B	S	S	S	E	B
II	B	S	S	S	E	B
III	S	S	B	S	E	B
IV	S	S	S	S	E	B
V	–	–	S	S	–	B
Week	Month					
	July	August	September	October	November	December
I	B	S	S	S	E	B
II	B	S	S	S	E	B
III	S	S	S	S	E	B
IV	S	S	B	S	E	B
V	–	–	S	S	–	B

B: Mid semester or semester break.
E: Examination.
S: Study week.

air handling unit (AHU) on each floor. There are two air handling unit (AHU) on each level. AHU 1 is used to provide air supply to the right wing while AHU 2 is for the left wing. A variable fan speed and a regulating valve were used to give variable supply air and chilled water flow rate by the AHU.

The HVAC system use variable air volume (VAV) system to control supply air flow rate enter the room according to the cooling load. A temperature sensor is placed in each room to monitor room temperature [31]. The AC system was operated from 7 a.m. till 7 p.m. Indoor temperature set point was 24 °C as recommended by ASHRAE and supply air temperature set point was set to 16 °C by the designer. Indoor relative humidity was kept floating depend on the indoor temperature.

2.3. Cooling load in the building

Heat gain from equipments (Q_{EQUIP}), heat gain from lighting (Q_{LIGHT}), heat gain from electronic equipments and heat gain from building envelope due to solar radiation (Q_{ENV}) would contribute to sensible cooling load (Q_{SEN}). Heat gain from occupants (Q_{PERSON}), heat gain from ventilation (Q_{VENT}) and heat gain from infiltration (Q_{INF}) would contribute to both latent (Q_{LAT}) and sensible cooling load. These heat gains were considered in the simulation.

The heat balance method is used by TRNSYS as a base for all calculations. For conductive heat gain at the surface on each wall, TRNSYS use transfer function method (TFM) as a simplification of the arduous heat balance method [32].

$$q_{s,i} = \sum_{k=0}^{n_{bs}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{cs}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{ds}} d_s^k q_{s,i}^k \quad (1)$$

$$q_{s,o} = \sum_{k=0}^{n_{as}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{bs}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{ds}} d_s^k q_{s,o}^k \quad (2)$$

Heat gain through radiation and convection within the zone were calculated using the star network given by:

$$q_{comb,s,i} = q_{c,s,i} + q_{r,s,i} = \frac{1}{R_{equiv,i} A_{s,i}} (T_{s,i} - T_{star}) \quad (3)$$

Heat gain through radiation and convection for external surface were calculated by:

$$q_{comb,s,o} = q_{c,s,o} + q_{r,s,o} \quad (4)$$

$$q_{c,s,o} = h_{conv,s,o}(T_{a,s} - T_{s,o}) \quad (5)$$

$$q_{r,s,o} = \sigma \varepsilon_{s,o} (T_{s,o}^4 - T_{fsky}^4) \quad (6)$$

where $q_{comb,s,i/o}$ is combined convective and long wave radiation of inside/outside surface. Then, total heat gain through inside and outside surface of the wall are:

$$q_{s,i} = q_{comb,s,i} + S_{s,i} + \text{Wall\_gain} \quad (7)$$

$$q_{s,o} = q_{comb,s,o} + S_{s,o} \quad (8)$$

Long wave emissivity was 0.9 for walls. The value was based on window library. Solar absorbance coefficient for walls based on the table provided by TRNSYS. Convection heat transfer coefficient for inside and outside walls were set 11 kJ/h m^2 K and 64 kJ/h m^2 K as recommended by the software [32].

Latent and sensible heat gain from ventilation and infiltration air is calculated using [33,34]:

$$q_{sensible} = m_a C_p (T_o - T_i) \quad (9)$$

$$q_{latent} = V_a \rho_a (\omega_o - \omega_r) h_{fg,32} \quad (10)$$

Minimum ventilation rate required in each room is calculated based on ASHRAE standard as stated below [35]:

$$V_{min} = R_p N_p + R_a A \quad (11)$$

Degree levels of activities were based on the degree level of activities in each room and the portion of sensible and latent heat was referred to ISO 7730 table. Heat gains from the equipments were calculated based on rated power, usage factor, load factor and its efficiency. Convective and irradiative fraction for these heat gains were 0.7 and 0.3 while for artificial lights, the values were 0.6 and 0.4 [36].

3. Assumptions and standards

Thermal comfort zone with indoor temperature between 23.1 °C and 25.6 °C and 70% of relative humidity were considered for Malaysia region. [8,37].

Building and occupant ventilation components were considered based on ASHRAE standard as described above. Building ventilation component is at rate 0.3 L/s m^2 and occupant ventilation rates per person are 2.5 L/s per person. Infiltration air exchange due to door openings and leakage air was assumed to be 0.05/h during AC operation and 0.15/h during non-AC operation.

For calculation simplification, influence of indoor furnishing to indoor RH was neglected since indoor furnishing will affect on indoor RH level at less than 2% RH, especially during daytime operating mode condition [12].

Activity level in classroom and office was set at level 4 with sensible and latent heat values 269 kJ/h. Level 5 of activity level was applied for workshop where practical work existed. The sensible heat value is 332.33 kJ/h and the latent heat value is 342.88 kJ/h. These values were based on ISO 7730 table.

All electrical equipments, artificial lighting and machines were assumed to be used during occupancy period only. Measured

Room Number	Room Type	Number of Occupants	Activity Schedule (time)						
			Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Ground floor									
16-00-01	Laboratorium	Seldom used (practically empty)							
16-00-02	Workshop								
16-00-03	Laboratorium								
16-00-04	Workshop								
16-00-05	Workshop	15	12.00 - 13.30	11.00 - 12.30	10.00 - 11.30	12.00 - 13.30	15.00 - 16.30	NA	NA
16-00-06	Computer Laboratorium	18	NA	NA	NA	11.00 - 13.00	NA	08.00 - 13.00	NA
								14.00 - 17.00	
16-00-07	Workshop	18	NA	NA	NA	11.00 - 13.00	NA	08.00 - 13.00	NA
								14.00 - 17.00	
16-00-08	Workshop	2							
16-00-09	Workshop	17	NA	14.00 - 17.30	NA	15.00 - 18.30	NA	NA	NA
16-00-11	Office	3	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	NA	NA
			14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00		
16-00-12	Store room	Seldom used (practically empty)							
First floor									
16-01-01/02	Tool storage	Seldom used (practically empty)							
16-01-03	Classroom	36	12.00 - 12.30	09.00 - 09.30	10.00 - 11.30	09.00 - 14.30	NA	NA	NA
			14.00 - 14.30	14.00 - 15.30					
			16.00 - 16.30						
16-01-04	Classroom	40	09.00 - 10.30	10.00 - 11.30	NA	09.00 - 10.30	11.00 - 11.30	NA	NA
			12.00 - 14.30	14.00 - 15.30		16.00 - 16.30			
16-01-05	Classroom	17	NA	NA	NA	15.00 - 18.30	NA	NA	NA
16-01-06	Classroom	30	08.00 - 09.30	09.00 - 09.30	10.00 - 11.30	08.00 - 10.30	NA	NA	NA
			11.00 - 12.30	11.00 - 11.30					
			14.00 - 14.30	14.00 - 16.30					
			16.00 - 16.30						
16-01-07/08	Store room	Seldom used (practically empty)							
16-01-09	Store room	Seldom used (practically empty)							
Second floor									
16-02-01/02	Laboratory	12	NA	14.00 - 18.00	NA	NA	NA	NA	NA
16-02-03	Office	2	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	NA	NA
			14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00		
16-02-04	Laboratory	Seldom used (practically empty)							
16-02-05	Office	10	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	NA	NA
			14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00		
16-02-06	Laboratory		NA	13.00 - 16.30	NA	11.00 - 14.30	08.00 - 11.30	NA	NA
16-02-07	Office	2	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	NA	NA
			14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00		
16-02-08	Laboratory	32	NA	10.00 - 12.30	NA	10.00 - 12.30	NA	NA	NA
16-02-09	Classroom	Seldom used (practically empty)							
16-02-10/11	Store room	Seldom used (practically empty)							
Third floor									
16-03-01	Office	17	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	NA	NA
			14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00		
16-03-02	Office	14	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	08.00 - 13.00	NA	NA
			14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00	14.00 - 17.00		

Fig. 2. Daily schedule in each room of the building.

hourly weather data for ambient temperature, ambient relative humidity, global solar radiation, wind speed and wind directions were collected and inputted to the simulation as parameters for representing ambient conditions. The simulation was done for a year with 1 h time step.

4. Experimental data measurements

Indoor and outdoor experimental measurements were conducted for 2 weeks for validation purposes only. Indoor temperature, indoor relative humidity, supply air flow rate and supply air temperature were measured to get indoor environmental and supply air conditions. Supply air flow rate and temperature measurements are performed under the maintenance department supervision. Hence, the experiment was not discussed in this paper. Scheduled calibrations were also performed by the department to maintain the accuracy of the equipments.

Ambient temperature, ambient relative humidity, global solar radiation, wind speed and wind directions measurements were done to get outdoor environmental conditions. The first three outdoor parameters measurements were done every 5 min by Firmanda [38] while wind speed and wind direction were not measured on this locations due to technical difficulties. These measurements data were collected from nearby weather station at Ipoh.

4.1. Experimental locations and set up

Office type room with 6.75 m of width, 11.8 m of length and 4 m of height located on ground floor facing south was chosen for indoor experimental measurements. This selection was due to fixed occupancy schedule and more predictable of indoor activities in the office room. The outdoor experimental measurement was conducted on an open area near the building to accurately measure the environmental conditions.

LM 35 precision centigrade temperature sensors were used to measure indoor temperature with accuracy +3/4 °C over a full −55 °C to 150 °C temperature range and linear +10 mV/°C scale factor. HIH-5030 low voltage humidity sensors were used to measure indoor RH with accuracy +3% RH. Formula used to calculate relative humidity from the output signal was shown below,

$$V_{out} = (V_{supply})(0.00636(\text{sensorRH}) + 0.1515) \quad (12)$$

$$\text{TrueRH} = (\text{sensorRH})/(1.0546 - 0.00216T) \quad (13)$$

Indoor humidity and temperature sensors were covered with 4 stage of white-painted plastic plate to avoid error due to bright light. The sensors were placed on four different locations with different height (0.5 m, 1 m, 1.5 m and 2 m). The reason of this arrangement is to get mean indoor temperature from the four spot and on different level of height. The sensors were calibrated against hygro thermo-anemometer on the spot before being used for the measurement.

All the sensors were connected to picolog data logger which has 16 channels of analog inputs and 0.5% of accuracy. The logger collected data every 6 min from each sensor during the experiment.

4.2. Measurements of indoor and supply air conditions

During AC operation (from 7 a.m. to 7 p.m.), experimental results for indoor environmental conditions show that indoor air temperature fluctuates over 20–23.5 °C range (Fig. 3). The temperatures clearly fall below the set point 24 °C which mean that over cooling occurred. For whole experimental period, indoor RH fluctuate over 75–83% range during AC operation. Sudden increase on indoor relative humidity also occurred at the beginning of AC operation due to sudden decrease on indoor temperature. During non-AC operation, indoor temperature and relative humidity raised due to heat and mass transfer with outdoor environment.

Measured supply air flow rate and temperature data reflects cooling load characteristic of the zone (Fig. 4). The results show that there were differences on supply air temperature set point enter the zone (20 °C and 16 °C). Based on observation and discussion with maintenance department staff, supply air and indoor temperature set point was changed manually in response to occupants' complaints regarding their working environment from being too

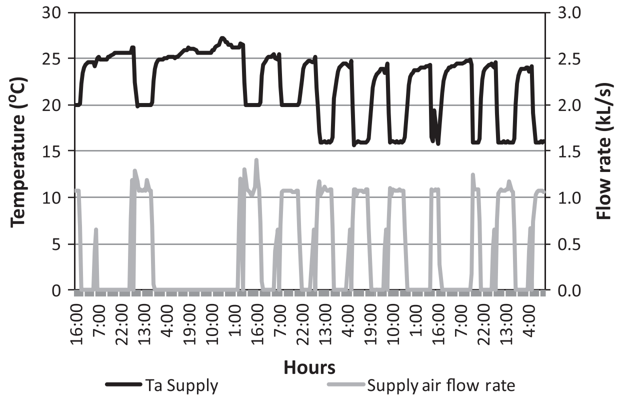

Fig. 4. Measurement of supply air temperature and flow rate entering the zone.

cold or too hot. The set points were changed to higher value if the rooms were too cold and vice versa. This information explains why supply air flow rate needed enter the zone almost the same with different set points. These results would be used to validate building thermal transient simulation model.

4.3. Measurements of ambient conditions

Highest global solar radiations mostly happen over 11.00 a.m.–02.00 p.m. period. As consequences, ambient temperature was highest and ambient relative humidity was lowest during the period (Fig. 5). During nighttime, ambient temperature decrease periodically and reaches minimum over 05.00–07.00 a.m. period. In contrary, the relative humidity increase periodically and usually reaches maximum during that period of time.

5. Comparison of experimental and simulation results

The simulation results was compared with the experimental results by using some measured data of weather conditions, supply air flow rate and supply air temperature as inputs. Indoors environmental parameters used for the comparison were indoor temperature and indoor relative humidity.

Indoor temperature comparison between experimental measurement and simulation model for weekends and weekdays are shown in Figs. 6 and 7, respectively. During weekends (holiday period) the simulation results of indoor temperature falls within +1 °C of the experimental values while predicted indoor relative

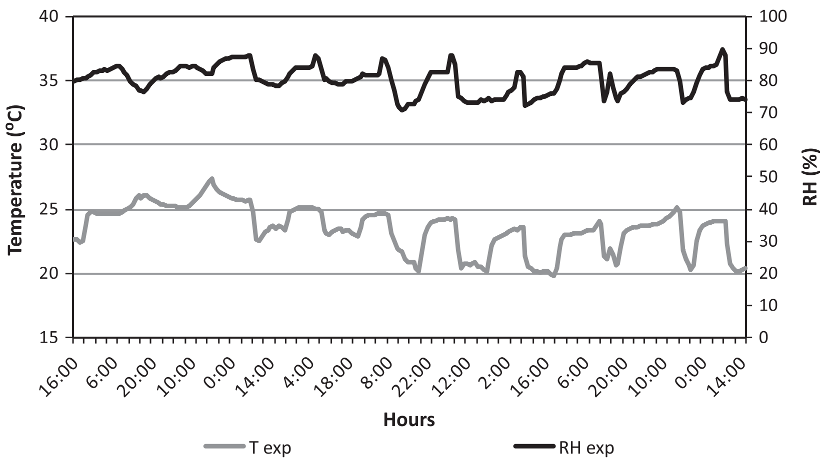

Fig. 3. Experimental measurements of indoor temperature and relative humidity.

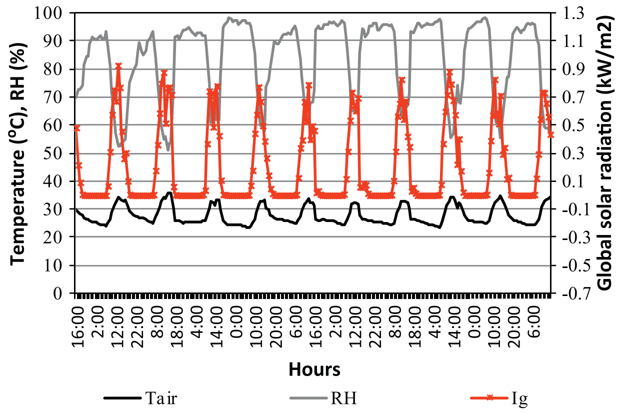

Fig. 5. Experimental measurements of outdoor conditions (ambient temperature, ambient relative humidity and global solar radiation) [35].

humidity falls within +5% of the experimental values. However, the error occurred during weekdays (under HVAC operation) were higher than on weekends (as shown in Fig. 7). The errors on the indoor temperature and relative humidity were found within +1.5 °C and +10%, respectively. The reasons for this are due to the unpredictable infiltration air, effect of vapor storage and thermal mass which hard to be perfectly matched with the real one and effect of uniform indoor air temperature assumption that was used in the simulation. In general, simulated indoor temperature for both weekends and weekdays show good agreement with measured values for most of the day. 90.8% of the simulated temperature values were found to be within +1.5 °C with the measured values. The difference occurs may be due to climatic difference between building area and outdoor experiment area.

The simulated results for indoor relative humidity also follow closely with the measured values for most of the day during weekends and weekdays (as shown in Fig. 5). Compare to measured values, 98.33% of the simulated relative humidity values were found to be within +10%. It may be due to influence of indoor temperature which amplify the difference. The simulation model was found to have performance as good as the model developed by Aynur et al. using DOE for their study [39].

The simulation model was then used to predict cooling load characteristic of the building for a year and to investigate energy saving potential from the system using proposed technique.

6. Development of adaptive cooling technique

6.1. Comfort temperature in Malaysia and linear equations for adaptive comfort temperature

Regarding to Hussein et al. [8], neutral temperature for air-conditioned and non-air-conditioned building in Malaysia based on thermal sensation vote (TSV) are 24.4 °C and 28.4 °C with acceptable comfort temperature ranges 23.1–25.6 °C and 26–30.7 °C, respectively. For naturally ventilated (NV) buildings, De dear and Brager [40] found that linear equations for adaptive comfort standard can be written as:

$$T_c(^\circ C) = 0.31T_{rm} + 17.8 \quad (14)$$

$$\text{Upper 80\% acceptable limit}(^\circ C) = 0.31T_{rm} + 21.3 \quad (15)$$

$$\text{Upper 90\% acceptable limit } (^\circ C) = 0.31T_{rm} + 20.3 \quad (16)$$

$$\text{Lower 80\% acceptable limit } (^\circ C) = 0.31T_{rm} + 14.3 \quad (17)$$

$$\text{Lower 90\% acceptable limit } (^\circ C) = 0.31T_{rm} + 15.3 \quad (18)$$

People's clothing and adaptation behavioral already consider under this adaptive model, so no need to take humidity, air speed limits and people's clothing into consideration when the standard is applied. The standard becomes guidance to indicate optimum and acceptable indoor comfort temperature range for different climate zones of the world (based on the mean monthly outdoor air temperature).

For air-conditioned or cooled building, Humphreys and Nicol [4] found that equivalent relationship between the mean monthly outdoor air temperatures (T_{rm}) with the comfort temperature (T_c) is:

$$T_c(^\circ C) = 0.093T_{rm} + 22.6 \quad (19)$$

From the findings, adaptive comfort model for Malaysia was developed by modifying Eqs. (13) and (18) based on comfort temperature in Malaysia. By assuming that the slope of Malaysian model and previous model are similar, adaptive comfort model for Malaysia is found to be:

$$T_c = 0.31T_{rm} + 19.74 \quad \text{for NV building} \quad (20)$$

$$T_{c,max} = 0.31T_{rm} + 22.04 \quad \text{for NV building} \quad (21)$$

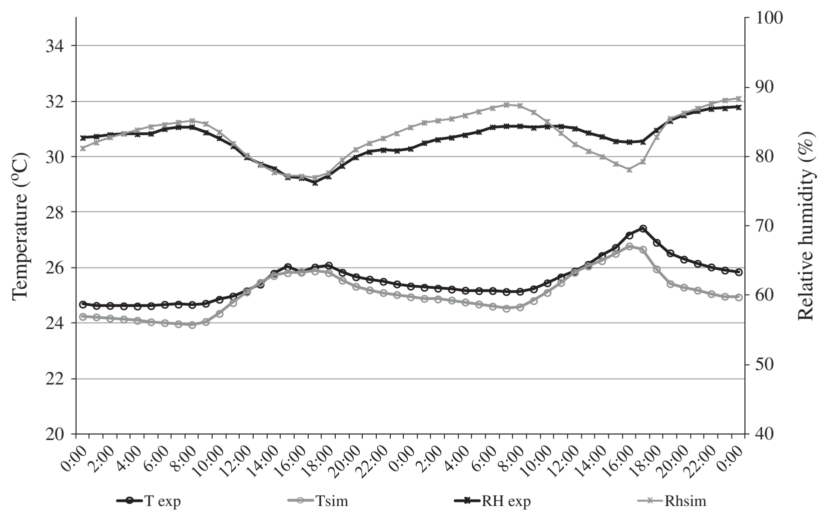

Fig. 6. Comparison of predicted and measured indoor temperature and relative humidity during weekends.

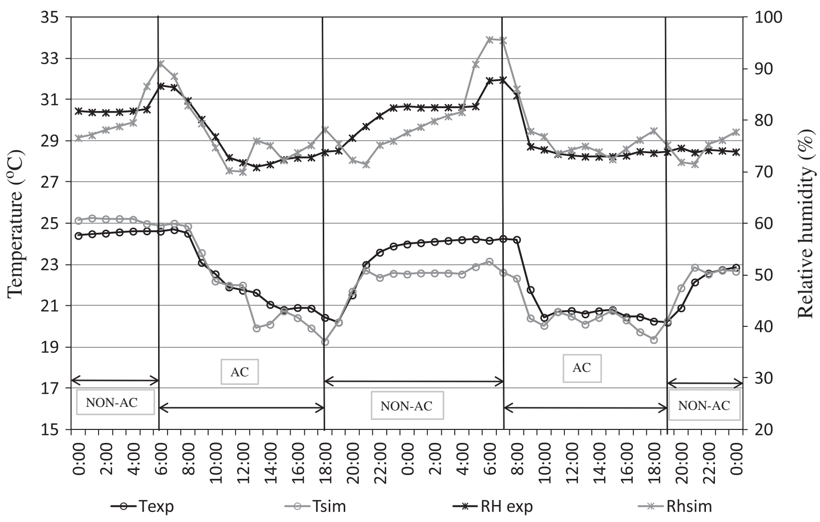

Fig. 7. Comparison of predicted and measured indoor temperature and relative humidity during weekdays.

$$T_{c,min} = 0.31T_{rm} + 17.34 \quad \text{for NV building} \tag{22}$$

$$T_c = 0.093T_{rm} + 21.8 \quad \text{for AC building} \tag{23}$$

$$T_{c,max} = 0.093T_{rm} + 23 \quad \text{for AC building} \tag{24}$$

$$T_{c,min} = 0.093T_{rm} + 20.5 \quad \text{for AC building} \tag{25}$$

In case of the studied building, there were two main periods existed. They are occupied and unoccupied periods. Before the students and lecture enter classrooms and workshops (unoccupied period), they will expose to ambient conditions demanding comfort temperature in Eqs. (19)–(21). Inside the air-conditioned room (occupied period), their demand of comfort temperature becomes as stated in Eqs. (22)–(24). After the session, they will expose to ambient conditions demanding comfort temperature in Eqs. (19)–(21) after sometimes.

In this paper, comfort temperatures in Eqs. (19) and (22) were chosen as indoor temperature set points during unoccupied and occupied periods in the proposed technique, respectively.

6.2. Calculating the mean monthly outdoor air temperature and monthly indoor comfort temperature

The weather data collected for a past year was used to calculate mean monthly outdoor air temperature. The result was then used to calculate monthly indoor comfort temperatures for occupied and unoccupied periods as shown in Table 4. The results show that maximum gap from calculated monthly comfort T_c in a year were only 0.22 °C and 0.72 °C for occupied and unoccupied periods, respectively. It can be seen that T_c on January–June of the year has highest value (representing hot period). Period July–December represents rainy/cold period where T_c was found to be lower than that during hot period.

Since the proposed technique used weather data in the past to define the indoor temperature set points, monthly calculated T_c may be different with actual running monthly T_c. Nevertheless, the difference will be small and a new set of T_c can be easily applied if there is any significant change on the ambient temperature.

6.3. Development of adaptive cooling algorithm

Algorithm to accommodate HVAC operation during occupied and unoccupied period using adaptive comfort temperature was

Table 4
Mean monthly indoor comfort and outdoor temperature.

Month	T_{min}	T_{max}	T_{rm}	T_c	
				Occupied	Unoccupied
January	24.14	32.42	28.28	24.43	28.51
February	24.34	33.34	28.84	24.48	28.68
March	24.45	33.75	29.10	24.51	28.76
April	24.21	32.47	28.34	24.44	28.53
May	24.31	32.62	28.46	24.45	28.56
June	23.81	31.82	27.82	24.39	28.36
July	23.64	31.48	27.56	24.36	28.28
August	23.84	31.67	27.75	24.38	28.34
September	23.80	31.64	27.72	24.38	28.33
October	23.30	30.27	26.79	24.29	28.04
November	23.51	31.22	27.37	24.35	28.22
December	23.31	31.06	27.19	24.33	28.17
Average			27.94	24.40	28.40

shown in Fig. 8. HVAC operation was set from 7.00 a.m. to 7.00 p.m. every day, except during holidays. Two sensors: temperature and relative humidity sensors were put in the room to measure room temperature (T_r) and relative humidity (RH_r). Another occupancy sensors placed in each room of the building was used to detect occupancy. The sensor send signal to the HVAC system to decide indoor thermal set points ($T_{r,sp}$ and $RH_{r,sp}$) prior to occupancy. If the room is occupied, the $T_{r,sp}$ is as stated in Eq. (22) while if the room is unoccupied, the value is as stated in Eq. (19). $RH_{r,sp}$ was set to 70% during HVAC operation hours as recommended by ASHRAE and kept floating during the off-hours. Initially the system determines the required supply air flow rate based on currently measured indoor temperature (T_r), indoor relative humidity (RH_r), $T_{r,sp}$, $RH_{r,sp}$, and supply air conditions (T_s and RH_s). In this case, RH_s is always set to 100% since dehumidification process is always exist under humid climate.

There are six combinations of measured T_r, nd RH_r that result in different action from the system. These actions are based on the rules as described in the following text:

1. If $T_r > T_{r,sp}$ and $RH_r \geqslant RH_{r,sp}$, then, the system would increase m_{sa}.
2. If $T_r < T_{r,sp}$ and $RH_r \geqslant RH_{r,sp}$, then, the system would decrease m_{sa}.
3. If $T_r < T_{r,sp}$ and $RH_r < RH_{r,sp}$, then, the system would increase T_s.
4. If $T_r > T_{r,sp}$ and $RH_r < RH_{r,sp}$, then, the system would decrease T_s.

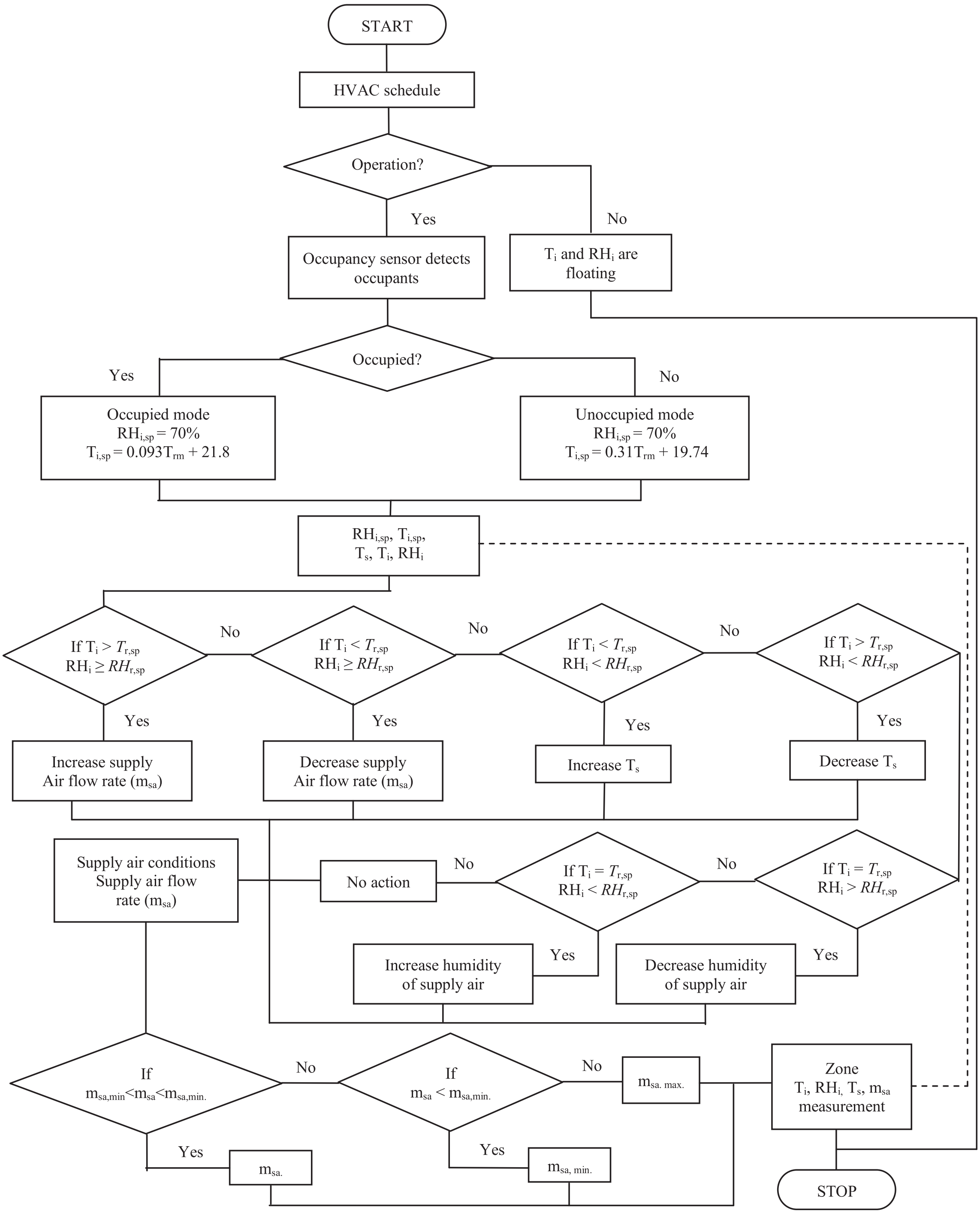

Fig. 8. Flow chart of proposed control system for the HVAC system.

5. If $T_r = T_{r,sp}$ and $RH_r > RH_{r,sp}$, then, the system would reduce the humidity of supply air using dehumidifier, otherwise the system would keep the current settings.
6. If $T_r = T_{r,sp}$ and $RH_r < RH_{r,sp}$, measurements are outside the seven possibilities describe above, the system would keep current supply air conditions at current flow rate if humidifier is not available, otherwise it could control the indoor parameter by using the humidifier.

Three online measurements were performed during cooling process i.e. supply air temperature, indoor air temperature and indoor relative humidity. These measurements are feed back to the system as basis to make required action (as described above). The supply air flow rate, chilled water supply and return temperature were then used to decide how much chilled water flow rate is needed.

7. Simulation results: cooling load comparison between current system and proposed technique

Transient simulations using current HVAC system and adaptive cooling technique have been carried out for a year. Indoor temperature 24 °C and relative humidity 70% were used as indoor environments set points to reflect the current system. Developed algorithm using adaptive comfort principles was then applied as a proposed HVAC system. The results were then compared and discussed.

7.1. Total cooling load of the building

Comparison of weekly cooling load of the building using current and proposed technique for a year was presented in Fig. 9. The results represents current cooling load characteristic of the building theoretically. From the graph, it can be seen that sensible and latent cooling load of current AC system was higher than it proposed by the algorithm for whole months of the year. Potential energy saving in term of cooling load reduction was found to be up to 305,150 kW h. The saving was due to 44.99% of cooling load reduction from current AC system.

7.2. Cooling load in the workshop

Typical intermittent cooling load characteristics of workshop in the building during occupied and unoccupied period were presented in Fig. 10. The figures show the characteristic between current system and proposed algorithm.

During occupied period, the sensible heat rise significantly during practical session when occupant exist and machines were operated. During unoccupied period, the cooling loads existed were only heat gain from building envelope, building ventilation component and infiltration. It can be seen that proposed technique also reduces the latent cooling load. The reductions were mainly due to higher indoor temperature set point during unoccupied period by which decrease the relative humidity. However, during occupied period, latent cooling load using the algorithm was found to be higher than that with current system. It is due to fact that there was an additional latent heat from reducing indoor temperature (from T_c in Eq. (19) to T_c in Eq. (22)) besides latent heat gain from occupant and ventilation air needed.

Breakdown cooling load of the workshop for a year using both systems are presented in Fig. 11. It is clear that total cooling load with proposed technique was lower than with current system. Cooling load from building envelope, latent heat, ventilation and infiltration were found to be the main components reduced by the algorithm. Total cooling load reduction was found up to 49.44% for a year compare to the current system.

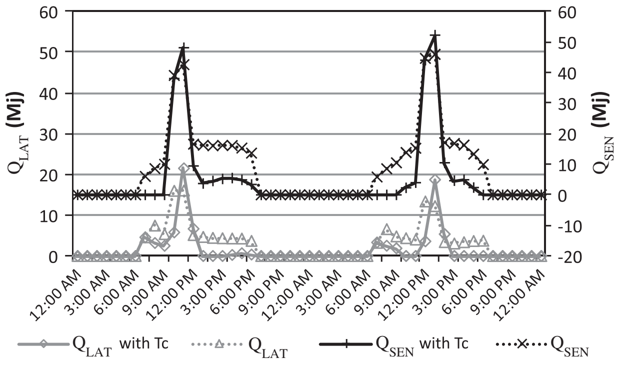

Fig. 10. Hourly cooling load characteristic in the workshop.

7.3. Cooling load in the classroom

Typical intermittent cooling load characteristics of classroom in the building during occupied and unoccupied period are presented in Fig. 12. The figures show the characteristic between current system and proposed technique.

Sensible and latent cooling load were increase significantly during occupied period due to latent heat gain from occupants and more ventilation air needed. From Fig. 12, it can be seen that the occupancy pattern result in intermittent cooling load in this classroom. The cooling load reduction during this period was not much (sometimes even slightly higher) compare to that during unoccupied period. Breakdown of the cooling load for a year is presented in Fig. 13. It is clear that the proposed technique was able to reduce main cooling load component (Q_{ENV} and Q_{LAT}). Using the algorithm, 42.79% of total cooling load reduction for a year can be achieved.

7.4. Cooling load in the office

Typical cooling load characteristics in the office for both current and proposed technique during occupied and unoccupied period are presented in Fig. 14. Sensible and latent cooling load were high during working hours and slightly decrease during break period at 13.00–14.00 p.m. Sensible cooling load using proposed technique was found higher when the office was occupied. This was due to bigger ΔT that should be handled by the AC system. As explained before, during unoccupied and occupied periods, the room temperature set points were as stated in Eqs. (19) and (22), respectively

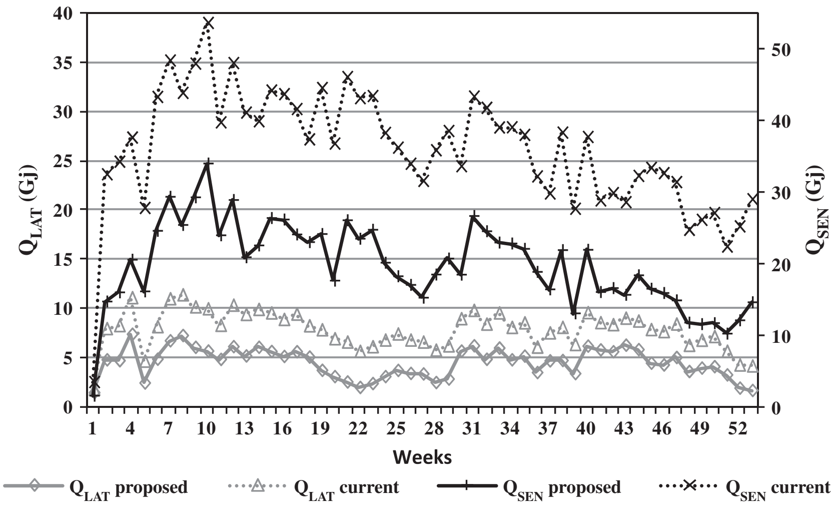

Fig. 9. Weekly average cooling load of the building.

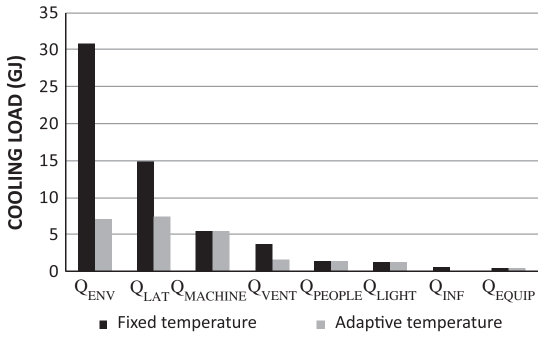

Fig. 11. Breakdown of yearly total cooling load in the workshop.

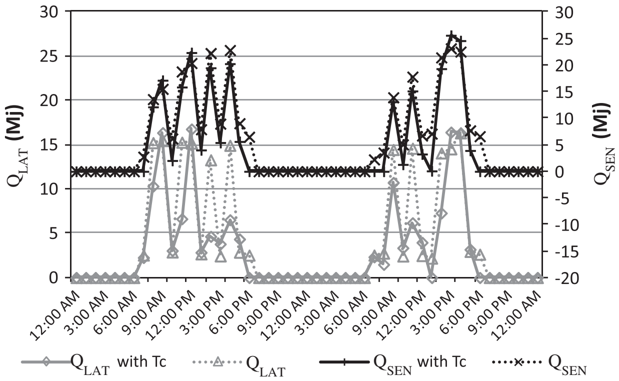

Fig. 12. Hourly cooling load characteristic in the classroom.

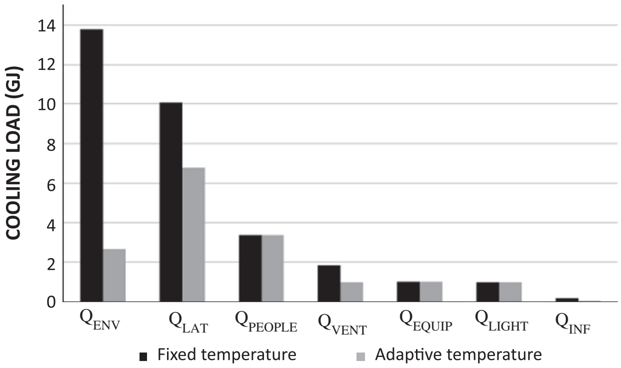

Fig. 13. Breakdown of yearly total cooling load in the classroom.

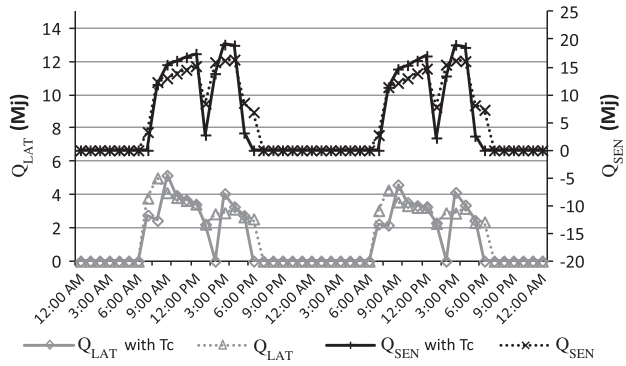

Fig. 14. Hourly cooling load characteristic in the office.

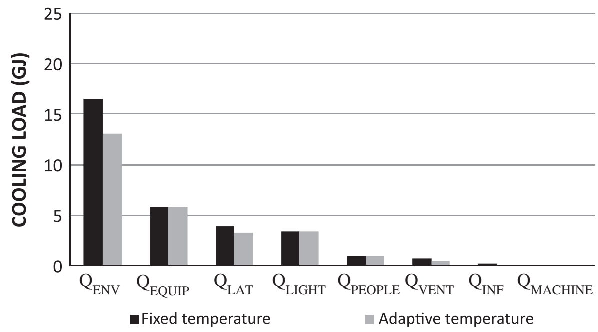

Fig. 15. Breakdown of yearly total cooling load in the office.

while current system always maintain room temperature at 24 °C during HVAC operation hours. Therefore, there was additional sensible heat to decrease room temperature from that in Eq. (19) to that in Eq. (22). The total reduction was found up to 5.4% in a year from the current system. Breakdown of the cooling load for a year is presented in Fig. 15.

It is obvious to highlight that the energy saving from the proposed technique has strong relationship with usage factor of the room. Usage factor is a ratio of room occupied hours to the HVAC operation hours for a year. As the usage factor for workshop, classroom, and office increased (7.55%, 11.8%, and 56.31%, respectively), the cooling load reduction decreased (49.44%, 42.79%, and 5.4%, respectively). It implied that the proposed technique is suitable to be applied to air-conditioned building where the occupancy pattern is low and uncertain while turning off the AC system is practically impossible. In addition, heat gain from building envelope dominated the heat gain for all the three types of room due to very high glazing area (nearly 100%) and the thermal performance. This result is in agreement with other work done by [28–30].

8. Conclusion

Simulations to determine cooling load characteristic for typical workshop, classroom and office in an academic building and energy saving potential using adaptive cooling technique have been presented and discussed.

Building thermal model has been modeled and the validation process proves that the building thermal model was closely matched to behave like the real studied building. 90.8% of the simulated temperature values were found to be within +1.5 °C with the measured values. The difference occurred may be due to climatic difference between building area and outdoor experiment area. 98.33% of the simulated relative humidity values were found to be within +10% compare to measured values. High difference for the indoor relative humidity was due to fact that relative humidity is influenced by the temperature so that the difference on indoor temperature amplified the error of the indoor relative humidity.

Cooling load comparison between current system and proposed technique showed that the technique has potential to reduce cooling load in both occupied and unoccupied period. The reduction was due to application of the adaptive temperature for AC and NV building as indoor temperature set point during occupied and unoccupied periods, respectively, which were higher than the recommended value by ASHRAE (24 °C).

Heat gain from building envelope, latent heat, ventilation rate and infiltration rate were found to be the main reduced cooling load components by the proposed technique. The portion of reduction will be depended on usage factor of the room. It will be higher as the usage factor decreases. It implied that the proposed technique is suitable to be applied to air-conditioned building where the occupancy pattern is low and uncertain while turning off the

Table 5
Mean monthly indoor comfort and outdoor temperature.

Type of rooms	Volume (m^3)	Usage factor (%)	Cooling load reduction		Electricity (RM/kW h)	Saving RM/year
			kW h	%		
Workshop	637.84	7.55	9370.58	49.44	0.38	3561
Classroom	227.8	11.8	4267.11	42.79		1622
Office	321.32	56.31	871.80	5.40		331
The building			305,150	44.66		115,957

AC system is practically impossible. It can also be concluded that the intermittent cooling load for any building with those four heat gain components as major cooling loads can be potentially reduced using the proposed algorithm.

The amount and portion of cooling load reduction using proposed algorithm in a year for the building and the other three types of room are presented in Table 5.

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