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Field investigation on indoor thermal environment of a high-rise condominium in hot-humid climate of Bangkok, Thailand

Parinee Srisuwan[a,*] , Kojima Shoichi[a]

[a] *Department of Civil Engineering and Architecture, Graduate School of Science and Engineering, Saga University, Saga 840-8502, Japan*

Abstract

The highest possession of condominium supply among Bangkok's real estate market tends toward dramatic increase in energy consumption of the building sector. Condominium's entrepreneurs have less concerns on green building evaluation due to the barrier of complication in criteria and the investment in energy efficient technology is generally higher per square meter. From the pilot study on indoor thermal environment of a high-rise condominium in the hot-humid climate of Bangkok, Thailand, during May 9th to June 8th, 2015, the highest demanded one bedroom unit was selected. The room conditions during the field measurement were chosen based on the occupancy characteristics towards the use of natural ventilation (NA) and air conditioning system (AC). The results show that by applying natural ventilation during the day while using an air-conditioning system at night is an effective approach for reducing the room's environmental temperature (EnvT). During the daytime with natural ventilation, heat gain and heat loss occur rapidly because the difference between the indoor and the outdoor air temperature is marginal. Dragging EnvT into the comfort zone is possible with an indoor air velocity of 1.5 m/s. In addition, low outdoor air temperature is preferable for natural ventilation since the thermal energy absorbed by internal surfaces increases the cooling load. In a hot-humid climatic region, relative humidity is very high at night. The addition of using air conditioning system at night is likely to provide a comfortable thermal environment.

Keywords: Thermal environment; Field measurement; High-rise condominium; Thermal comfort; Cooling load; Thailand

* Corresponding author. Tel.: +81-806-476-4182.
E-mail address: pan.parinee@gmail.com

1. Introduction

Bangkok, the capital of Thailand, is located between 13º45’ North Latitude and 100º35’ East Longitude. As in a typical hot-humid climatic region, the air temperature and relative humidity (RH) are high for most of the year. The average mean dry bulb temperature ranges from 28.46 ºC to 30.23 ºC and RH is between 70% and 76%. The wind speed is low with its annual average at 1.0 m/s [1]. Since these weather conditions are mostly outside thermal comfort zone, people usually enhance their comfort by using air conditioning (AC) systems, especially during the hottest months around April and May. The peak demand for electricity had recently beaten the record at 29,403 MW as of April 28, 2016 [2].

The total electricity consumption of the country has been on the rising trend. The industrial sector holds 44% of the total consumption followed by the residential, commercial, small general services, and other sectors (e.g. the non-profit sector and agriculture pumping) account for a share of 23%, 19%, 11%, and 3%, respectively [3]. Meanwhile, the residential sector also holds the largest share of 89% of electricity consumers in Thailand. The expansion of real estate market has led to the increasing in electricity consumption by one-third of the total consumption. Condominiums in Bangkok account for the largest share of 63% of the new supply offered for sales [4], which caused the dramatic increase in energy consumption from using air conditioning systems during the occupancy period.

Since the indoor thermal comfort significantly affects the energy usage, thermal environment related to thermal comfort should be determined. In this study, environmental factors in a typical unit of high-rise residential building in Bangkok were investigated through field measurement. The use of an air-conditioning system and windows towards the occupancy characteristic were set during the investigation. The comparative results between thermal comfort and cooling load are also discussed. The significance of the results reported here is limited as the results are based on a specific building configuration and thus, it is difficult to generalise the conclusions.

2. Methodology

The location of a selected condominium is in a very high-density residential area of Thonburi, the outer area of Bangkok, and close to the mass transit line. With the price of 93,000 Baht/m^2, it is in the economy to upper-class segment (50,000-99,999 Baht/m^2), which has the highest shares in condominium market [4]. The field investigations were performed in 33 m^2 of one bedroom unit on the 19^{th} floor (27 floors in total) as shown in Fig. 1. It is a corner room facing south west. The living room has two external walls with 50% of opening facing south (1.6 m^2 operable area) and 20% facing west, which receives high radiative heat gain. One semi-external wall faces north and connects to the public corridor. About 40% of the internal wall that separates the living room and the bedroom is a 6 mm single glassing fixed window. The bedroom has one external wall with 60% of opening facing south (1.1 m^2 operable area).

Monitoring equipment (Table 1) was installed accordingly to the ASHRAE standard 55 [5], see Fig. 2. For the indoor investigation, an air temperature sensor was set up at 1.1 m above the floor. Humidity, wind speed, and globe temperature sensors were set up at 0.6 m above the floor. Moreover, the surface temperature was also measured by temperature sensors attached on indoor wall surfaces, both in the living room and the bedroom. For the outdoor investigation, HOBO outdoor weather station was set up on the balcony to collect micro-climate data. The investigations were conducted from May to June 2015 as it was the hottest period of the year based on the maximum energy consumption resulted from high level of air conditioning usage.

During the 24 hours investigation, the occupancy characteristic was set under 4 cases as follows:

- Case 1: 24 hours without ventilation, all windows were closed (from May 9 to May 13).
- Case 2: 24 hours with natural ventilation, all windows were opened (from May 29 to June 2).
- Case 3: Daytime (6:00 am to 6:00 pm) without ventilation (all windows were closed) and nighttime (6:00 pm to 6:00 am) with an air conditioning system turned on (from June 3 to June 7).
- Case 4: Daytime with natural ventilation (all windows were opened) and nighttime with an air conditioning system turned on (from May 24 to May 28).

Table 1. Monitoring equipment.

Parameter	Indoor weather station	Outdoor weather station
Temperature	Thermo couple type T with GRAPHTEC GL820 data logger	S-THB-M002 Temp & RH sensor with HOBO U30 NRC data logger
Humidity	T&D TR-72 Ui sensor	
Wind speed	AM-14SD Anemometer	S-WSET-A Wind smart sensor set
Globe temperature	Shibata Globe thermometer	-

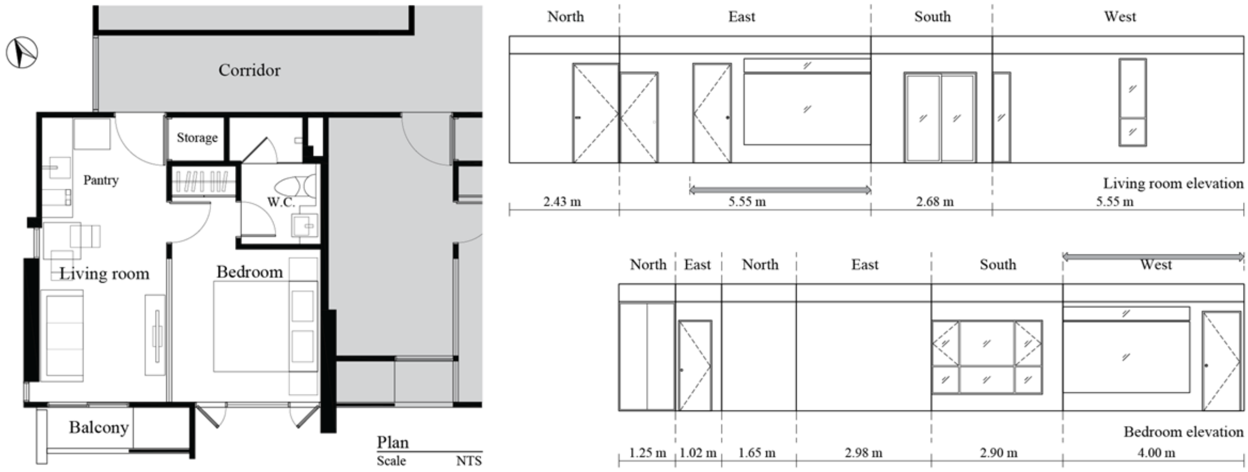

Fig. 1. Floor plan and elevations of the test room.

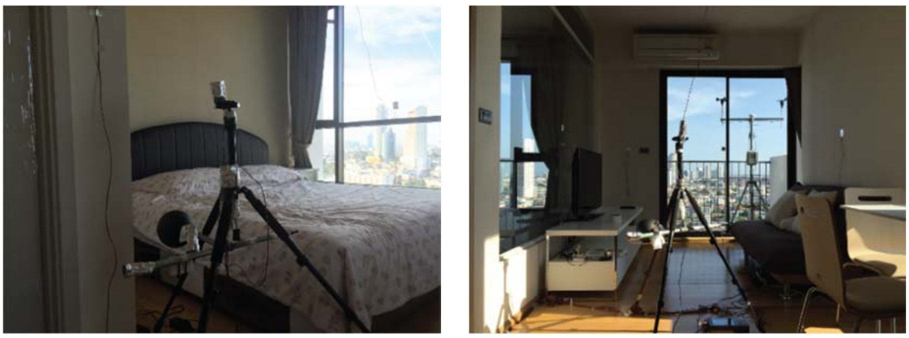

Fig. 2. Installation of monitoring equipment.

3. Thermal comfort

3.1. Comfort zone

Thermal comfort correlations [6-8] were used to determine the comfort zone. People feel comfort sensation under neutral temperature as shown in the following equation:

$$T_n = 17.6 + 0.31 \cdot T_{Oav} \quad (1)$$

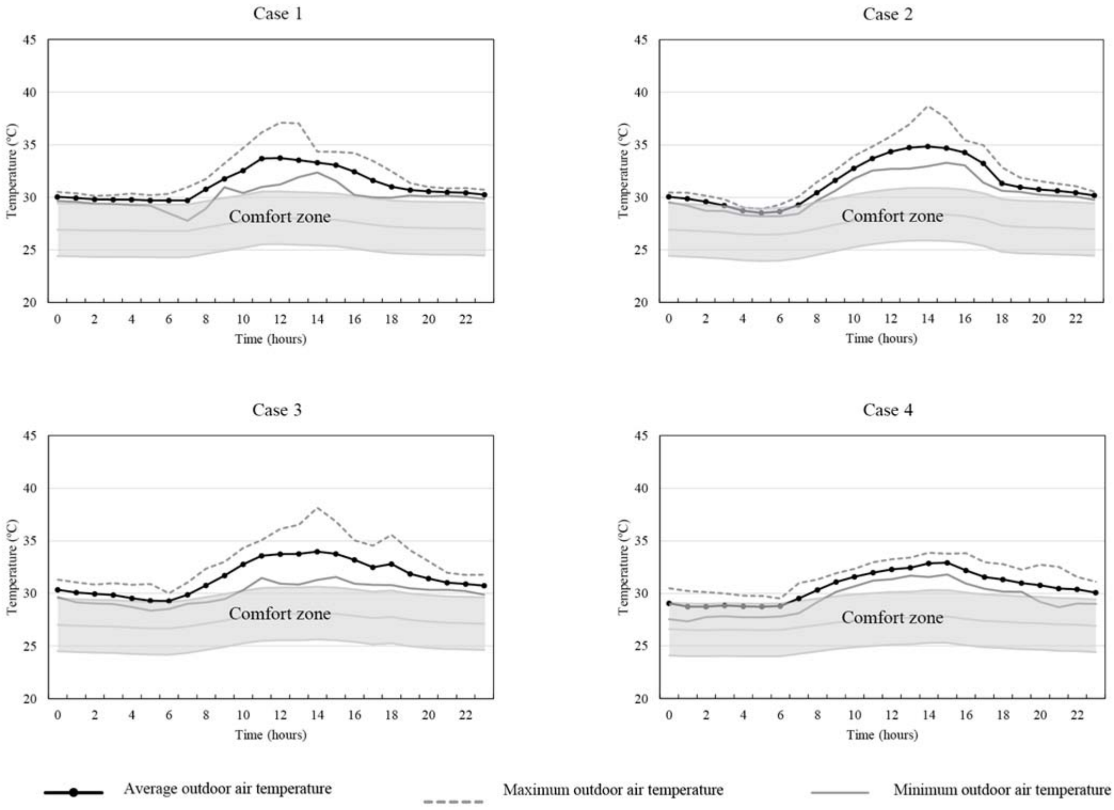

Fig. 3. Average outdoor air temperature and comfort zone

where T_n is thermal neutralities or neutral temperature (ºC); T_{Oav} denotes the average outdoor air temperature (ºC). The range of comfort temperature is in the range of $T_n \pm 2.5$. For tropical climate zone, upper RH limit of 80% [9] and lower absolute humidity (AH) limit of 4 g/kg$_{\text{dry air}}$ [10] are considered as a comfort environment. This combination effect of temperature and humidity is defined by Gagge, Fobelets, and Berglund as standard effective temperature (SET) [11].

In addition, wind speed also has an effect towards the thermal comfort, which can increase convective heat transfer and evaporative heat loss from human body. The extension of upper temperature limit is given by:

$$T_{u(v=x)} = T_n + 2.5 + dT_{(v=x)}$$
$$= T_n + 2.5 + \left(6 \cdot V_e - 1.6 \cdot V_e^2\right) \quad (2)$$

where $T_{u(v=x)}$ is the extension of upper temperature limit at different wind velocity (ºC); V_e denotes effective where $V_e = V - 0.2$ (m/s). This equation is used when indoor wind velocity is less than or equal to 2 m/s, the applicable maximum wind speed for indoor.

From the investigations, outdoor air temperature and comfort zone are shown in Fig. 3 and Table 2. The average outdoor air temperatures during the investigation period were mostly outside comfort zone. Since the effect of single-sided ventilation was poor, the outdoor air entered a room with low velocity. The upper limit of comfort range could be extended by only 0.8 ºC under natural ventilation.

Table 2. Average outdoor air temperature and comfort zone.

	Case	T_{Oav}	Comfort zone			
			T_n (ºC)	T_u (ºC)[1]	T_l (ºC)[2]	$T_{u(v=x)}$ (ºC)[3]
Daytime	1	31.95	27.50	30.00	25.00	30.53
(6:00 am to 6:00 pm)	2	32.70	27.74	30.24	25.24	31.05
	3	32.41	27.65	30.15	25.15	30.67
	4	31.46	27.35	29.85	24.85	30.66
Nighttime[1]	1	30.21	26.96	29.46	24.46	29.99
(6:00 pm to 6:00 am)	2	30.01	26.90	29.40	24.40	30.21
	3	30.58	27.08	29.58	24.58	30.11
	4	29.73	26.82	29.32	24.32	29.84

Table 3. Environmental temperature in living room.[4]

Living room	Case	MRT	DBT	EnvT
Daytime	1	33.33	33.05	33.24
(at 12:00 pm)	2	32.79	32.74	32.77
	3	32.27	32.06	32.20
	4	32.50	31.67	32.23
Nighttime	1	31.51	31.77	31.60
(at 12:00 am)	2	31.23	31.20	31.22
	3	29.85	29.81	29.83
	4	29.07	29.08	29.07

Table 4. Environmental temperature in bed room.[4]

Bed room	Case	MRT	DBT	EnvT
Daytime	1	33.24	33.39	33.29
(at 12:00 pm)	2	33.12	33.19	33.14
	3	31.88	32.15	31.97
	4	32.14	31.99	32.09
Nighttime	1	31.86	31.46	31.73
(at 12:00 am)	2	31.43	31.24	31.36
	3	28.35	25.40	27.37
	4	27.75	24.82	26.77

[1]T_u is the upper temperature limit of comfort zone (ºC).

[2]T_l is the lower temperature limit of comfort zone (ºC).

[3]The average indoor velocity was 0.29 m/s without ventilation, and 0.34 m/s under natural ventilation.

[4]In case 3 and 4, an air conditioning system was applied; 6:00 pm to 9:00 pm for the living room, and 9:00 pm to 6:00 am for the bedroom.

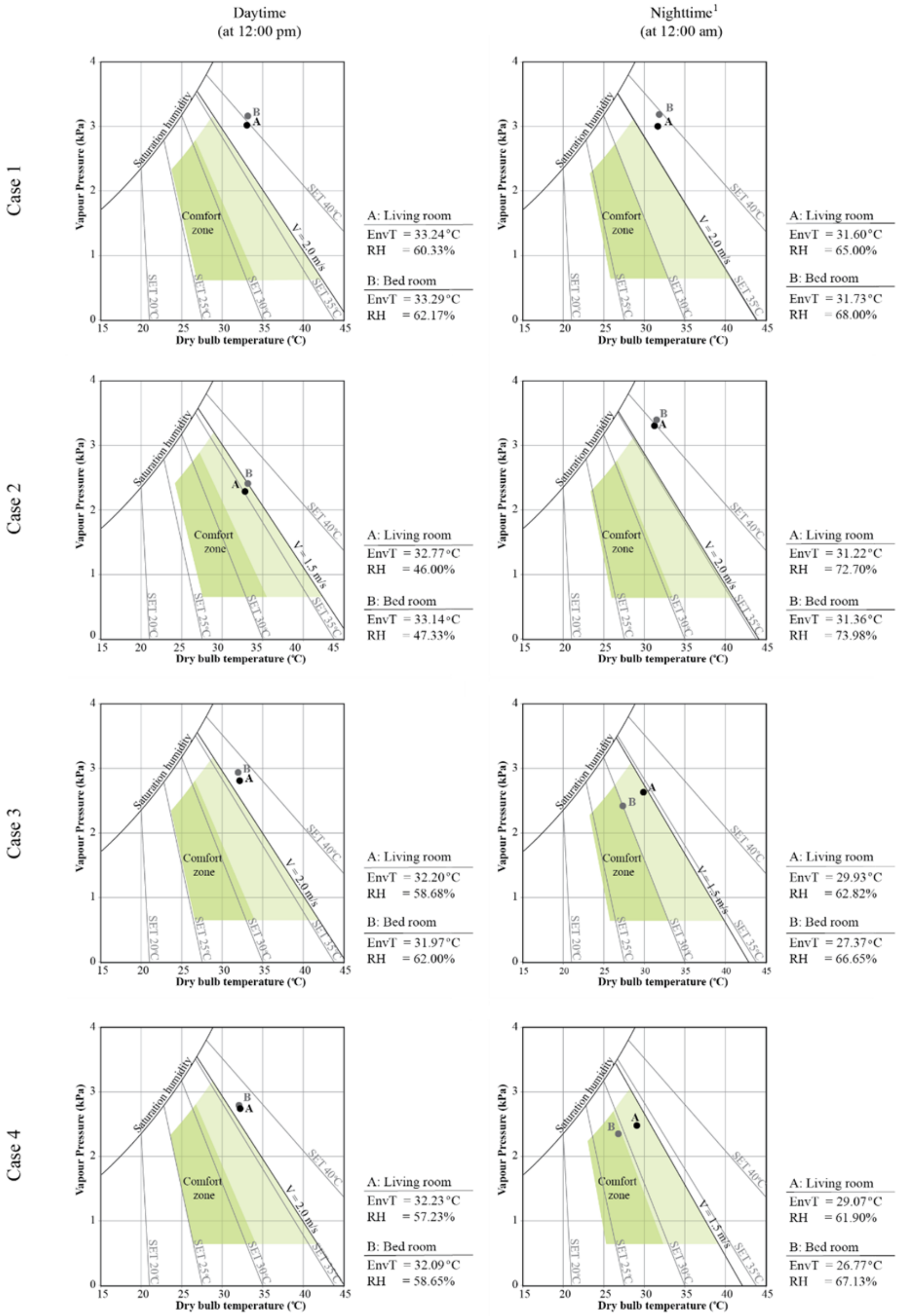

Fig. 4. Environmental temperature during daytime (left) and nighttime (right).

[1]In case 3 and 4, an air conditioning system was applied; 6:00 pm to 9:00 pm for the living room, and 9:00 pm to 6:00 am for the bedroom.

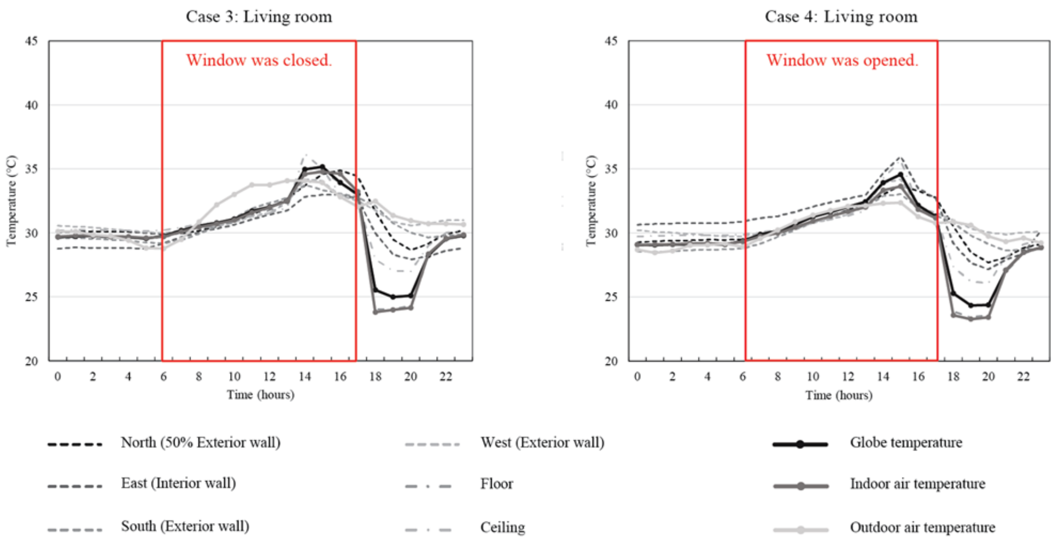

Fig. 5. Internal surfaces temperature in living room.

3.2. Environmental temperature

Similar to air temperature, humidity and wind speed, Mean radiant temperature (MRT) affects the thermal comfort. It is the result of an average internal surface temperature. When MRT is lower than indoor air temperature, radiation is emitted to the surrounding surfaces, which were cooler. In addition, a composite of MRT and indoor air temperature resulted in environmental temperature (EnvT), which is used to describe the heat exchange between the environmental point in a room and the internal surfaces [9]:

$$EnvT = \frac{2}{3} \cdot MRT + \frac{1}{3} \cdot DBT \qquad (3)$$

where EnvT is the environmental temperature (ºC), MRT is mean radiant temperature (ºC) and DBT is dry bulb temperature (ºC). Comfort sensation increases when EnvT is lower than the human skin temperature. The results are shown in Table 3, Table 4, and Fig. 4.

Since the upper limit of comfort range could be extended by only 0.8 ºC as mentioned in the previously, EnvT of every cases were out of comfort zone but gradually got closer when natural ventilation and air conditioning system were applied. Therefore, the extension of upper limit temperature at the highest wind velocity was predicted. The 24 hours naturally ventilated room in case 2 was cooler than those without ventilation exhibited in case 1. EnvT was reduced and within comfort zone when high indoor air velocity of 1.5 m/s was applied. Similar to case 4, daytime naturally ventilated room (windows were closed during the night), EnvT was closer to comfort zone compared to case 3, daytime without ventilation.

Moreover, natural ventilation showed high effectiveness in temperature reduction when it was a naturally ventilated room (case 2). This was because of it lost heat faster than the room without ventilation (case 1). On the other hand, when room’s ventilation was mixed with air conditioning system (case 3 and case 4), EnvT during daytime had a small reduction when natural ventilation was applied (case 4). Room air temperature rose up close to outdoor air temperature simultaneously after the window was opened (see Fig. 5). Internal surface temperature gained excessive heat from outdoor air and insufficient convection from low indoor air velocity contributed towards poor cooling load.

Table 5. Cooling load from air conditioning processes.

Case	Cooling load (MJ)					
	Day 1	Day 2	Day 3	Day 4	Day 5	Average
Case 3	62,277	63,450	64,786	61,493	57,617	61,925
Case 4	79,064	56,696	75, 241	72,775	64, 273	69,610

4. Cooling load

Based on thermal comfort analysis, EnvT at night lay outside comfort zone even though the maximum of applicable indoor air velocity (2 m/s) is applied. Therefore, an air conditioning system is considered for use to provide comfort. On the contrary, there is the possibility to reduce air conditioning energy consumption during the day by applying natural ventilation. In this section, the total heat transfer rate caused by ventilation from the air conditioning system in the living room, as mainly occupied area, is compared between case 3 and case 4. The basic heat transfer rate is given by:

$$q_t = C_t Q \Delta h \tag{4}$$

where q_t is the total heat transfer rates (W); C_t is the air total heat factor, W/(L·s) per kJ/kg enthalpy; Q is the air volumetric flow rate (L/s); Δh denotes the air enthalpy difference across process (kJ/kg) [12]. The results of cooling load from air conditioning processes (at medium air flow rate of 526 CFM) are shown in Table 5.

From Table 5, cooling load of the room using natural ventilation during the day, case 4, was slightly higher than the room without ventilation shown in case 3. For the room that natural ventilation and air conditioning system were applied, internal surfaces gained heat from outdoor air and therefore, the thermal energy stored in internal mass resulted in an increasing of the cooling load. However, other load components must be studied in order to increase the validity.

5. Conclusion

In this study, thermal environments in one bedroom unit of high-rise condominium were investigated based on the occupancy characteristics towards the using of natural ventilation and air conditioning system. The results showed that naturally ventilated room with high air velocity (1.5 m/s) could enhance thermal comfort in some hours during the day. But in existing condition, the single-sided ventilation was insufficient for natural ventilation. The average indoor wind speed was only 0.34 m/s. The upper limit of comfort range could be extended by only 0.8 ºC. During nighttime, as in typical hot-humid climatic region, relative humidity was very high. Only 24 hours of natural ventilation might not be able to provide a comfortable thermal environment. In addition, lower temperature of outdoor air was preferred for natural ventilation in order to reduce cooling load due to thermal energy absorbed within the internal surfaces.

Therefore, the integrative between passive design strategies with the addition of active system could be an alternative solution in order to reduce energy consumption from using air conditioning system and balance with occupancy thermal comfort. However, this investigation was based on field data from one specific building. Further comparison with simulation data is needed to increase the validity and the understanding of thermal performance in high-rise condominium.

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