Field Investigation on Indoor Thermal Performance of a High-rise Residential Unit in Bangkok

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Abstract

As an alternative solution to support an urbanization in Bangkok, high-rise condominium has dramatically increased the energy consumption. An air conditioning system that enables the unit plays the major role in reaching thermal comfort. A field investigation was conducted on indoor thermal environment of a one bedroom unit (a corner room with single-sided ventilation) during May 9th to June 8th, 2015, summer season. The hypothetical cases were devised to represent the room with different types of ventilation in order to examine the potential of using natural ventilation during the day and also reduce the time of air conditioning usage. The results show that by applying natural ventilation during the day along with air conditioning system during the night can effectively reduce indoor environmental temperature (EnvT). During the day with natural ventilation, indoor air velocity of 1.2 m/s could possibly provide acceptable indoor thermal comfort in some hours. However, thermal energy from high outdoor air temperature that enters room was absorbed within internal surfaces and resulted in the increasing of cooling load at night when air conditioning system was used.

Keywords: High-rise, Residential building, Urban area, Field investigation, Indoor thermal comfort

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1. Introduction

High-rise condominiums are an alternative solution to support the increasing of the density of population per square meter in the cities. From the prediction of the United Nations, Population Division (UNPD), The world's population will increase from 7.3 billion in 2015 to 9.7 billion in 2050 (UNPD, 2015) and 66% of them will be living in urban areas (UNPD, 2014). In Thailand, 50% of the population lived in urban areas with 3% of an average annual growth rate. Meanwhile in rural area, the population growth rate declined by -2.1% (United Nations Statistic Division, 2015; 2016).

Among the real estate market in Bangkok, condominium supply has possessed the highest share of 65%, followed by townhouse and single detached house with a share of 22% and 13% respectively (Plus Property, 2016) due to the urbanization, social change, and the development of housing for foreign expatriates (Li-Zenn, 2015). The blooming of condominium tend towards the increasing in the energy consumption since the air conditioning system plays the major role in enhancing occupants comfort condition.

As a result of hot-humid weather conditions, people experience high air temperature and high humidity for most of the year. The average mean dry bulb temperature ranges from 28˚C to 30˚C and relative humidity ranges from 70% to 76%. Natural wind speed is less than 1 m/s (Meteorological Department, 2013). Thermal comfort condition is difficult to be achieved, thus air conditioning system is used especially in the hottest month as in April and May. The highest peak demand recently set the new record as of 29 GW on May 11th, 2016 (Electricity Generating Authority, 2016). Moreover, 42% of the total electricity consumption is contributed by the residential and commercial sector (Energy Policy and Planning Office, 2015).

In order to reduce the energy used by air conditioning system, the indoor thermal environment should be considered. In this study, one bedroom unit was selected to analyze and investigate the significant issues related to thermal comfort, and also, cooling load from air conditioning processes.

2. Field Investigation and Methodology

The investigation of thermal environment was conducted in one bedroom unit of the upper class segment condominium (80,000 to 100,000 Baht/m^2) which is the highest shared among the condominium market (Plus Property, 2016). The condominium is located in the outer area of Bangkok, very high density residential area, 210 m away from mass transit.

2.1 The Selection of One Bedroom Unit

The selected unit was 33 m^2 one bedroom unit on 19th floor (27-storey high-rise condominium) as shown in Figure 1. It is the corner room facing south-west direction. Two main functions, living room and bedroom, are mostly separated by a 6 mm single glazed fixed window that provides the sense of connection between rooms. Living room consists of two external walls, one is south facing wall with 50% of an opening (1.6 m^2 operable area) and another is west facing wall with 20% of an opening. Semi-external wall facing north is connected to the public corridor which is unconditioned space. For bedroom, there is one external wall with 60% of an opening facing south (1.1 m^2 operable area).

2.2 The Set-up Conditions

In hot and humid region, people usually apply natural ventilation during daytime and use air conditioning system during nighttime (Kubota, Jeong, Toe & Ossen, 2011). The hypothetical cases were devised to represent the room with different types of ventilation in order to examine the potential of using natural ventilation and also reduce the time of air conditioning usage during the day. The set-up conditions (Figure 2) were categorized into 4 cases.

- Case 1 represents the rooms without natural ventilation for 24 hours, all windows were closed.
- Case 2 represents the rooms with natural ventilation for 24 hours, all windows were opened.
- Case 3 represents the rooms without ventilation during daytime (6:00 a.m. to 6:00 p.m.) and using air conditioning system at night.
- Case 4 represents the rooms with natural ventilation during daytime (6:00 a.m. to 6:00 p.m.) and using air conditioning system at night.

Figure 1. Floor plan and elevations of the selected unit.

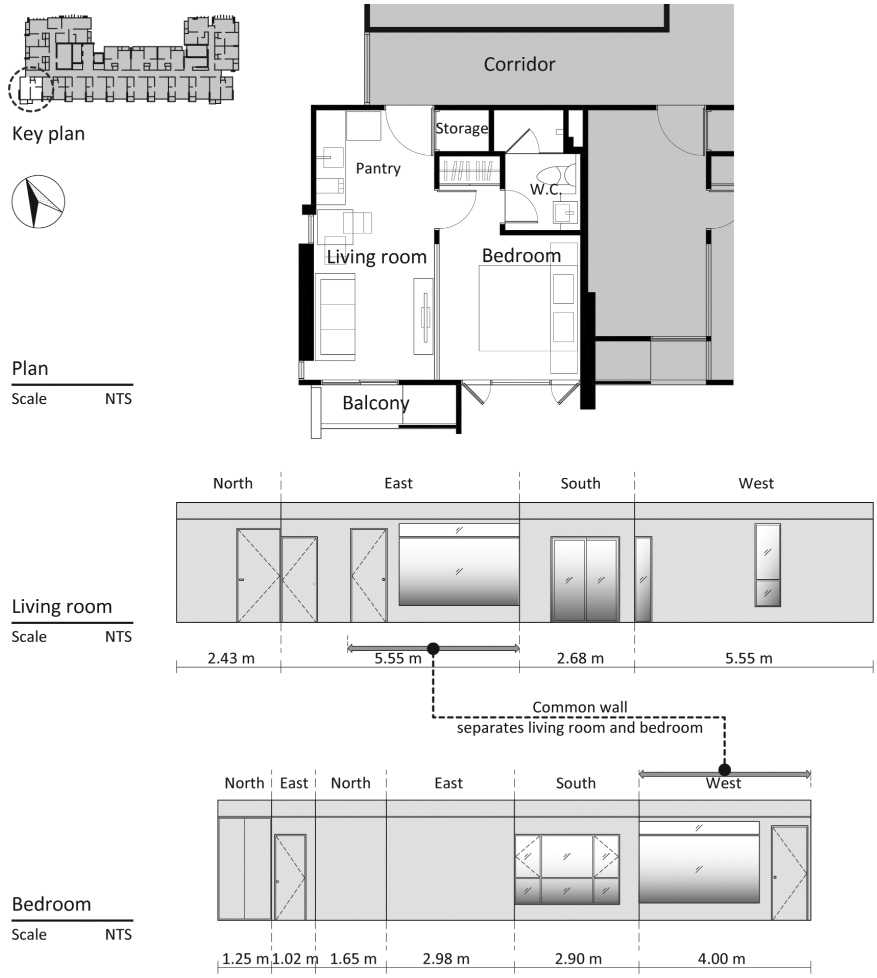
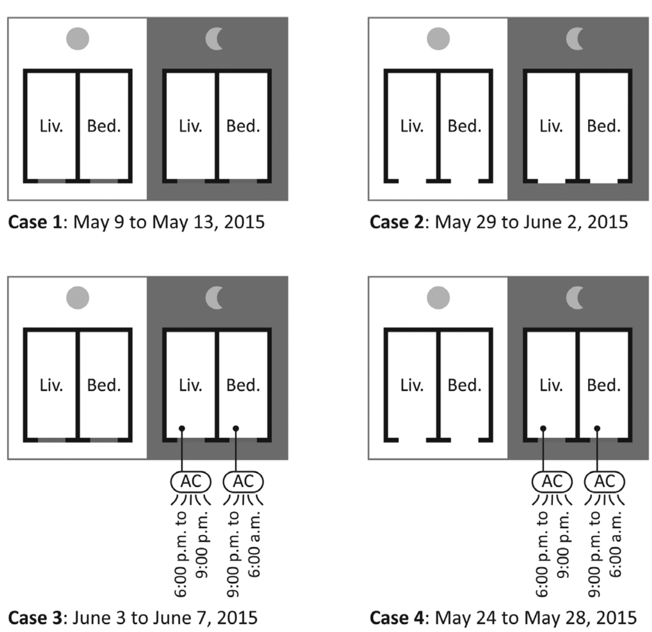


Figure 2. Room's conditions and duration of the investigation.



For case 3 and 4, air conditioning system was turned on during the night: from 6:00 p.m. to 9:00 p.m. for living room, from 9:00 p.m. to 6:00 a.m. for bedroom. Thermostats were set to 25˚C which is the comfort temperature for conditioned space in residential building (Rangsiraksa, 2006). During the investigation, the room was unoccupied and all curtains were drawn open.

2.3 Field Investigation

The experimental set-up refers to ASHRAE standard 55 (2013b). The measuring devices (Table 1 and Figure 3) were placed in the center of the rooms at the level of seated occupants. Temperature sensors were set at 1.1 m above floor and attached to the interior surfaces. Humidity sensors, wind speed sensors, and globe temperature sensors were set at 0.6 m above floor. Moreover, outdoor microclimate data was also investigated by the outdoor weather station placed at the balcony.

The investigation was conducted during May 9th to June 8th, 2015. For each case, the 24 hours data were continuously recorded for 4 days with 1 minute time interval.

3. Results and Discussion

3.1 Comfort zone

People experience comfort sensations under the neutral temperature. The adaptive model of comfort correlations shown in equation 1 was applied (Auliciems, 1981; Auliciems & Szokolay, 2007).

$$T_n = 17.6 + 0.31 \cdot T_{oav} \qquad (1)$$

where T_n is thermal neutralities or neutral temperature (˚C), T_{oav} is the average outdoor air temperature (˚C). The range of comfort zone is between $T_n \pm 2.5$˚C. During the investigation, the average outdoor air temperatures were mostly outside comfort zone (Figure 4 and Table 2). Only 14% of the investigated hours that outdoor air temperatures reached comfort zone especially from midnight to 7:00 a.m.

With the wind speed, the upper temperature limit is extended due to the increasing of convective heat transfer and evaporative heat loss from human skin. The cooling effect of air movement (*dT*) is given by equation 2 (Szokolay, 2008).

$$dT = 6 \cdot V_e - 1.6 \cdot V_e^2 \qquad (2)$$

Where is the cooling effect of air movement (˚C), V_e is the effective air velocity (m/s) which $V_e = V - 0.2$ and V is air velocity (m/s). The expression is valid up to 2 m/s, the applicable maximum indoor wind speed. The extension of upper limit temperatures are shown in Table 2.

Under natural ventilation, the average indoor air velocities were 0.36 m/s during the day and 0.29 m/s during the night. Due to low indoor air velocity, the upper limit of comfort range could be extended approximately 0.9˚C and 0.5˚C for daytime and nighttime respectively.

Figure 3. The placement of measuring devices.

Table 1. List of measuring devices

Parameter	Indoor measuring devices	Range
Temperature	Thermo couple type T with GRAPHTEC GL820 data logger	-200˚C to 200˚C
Humidity	T&D TR-72 Ui sensor	RH 5% to 95%
Air velocity	AM-14SD Anemometer	0.2 m/s to 25.0 m/s
Globe temperature	Shibata Globe thermometer	-5˚C to 95˚C
Parameter	**Outdoor measuring devices**	**Range**
Temperature Humidity	S-THB-M002 Temp & RH sensor with HOBO U30 NRC data logger	40˚C to 75˚C RH 0% to 100%
Air velocity	S-WSET-A Wind smart sensor set	0.0 m/s to 45.0 m/s

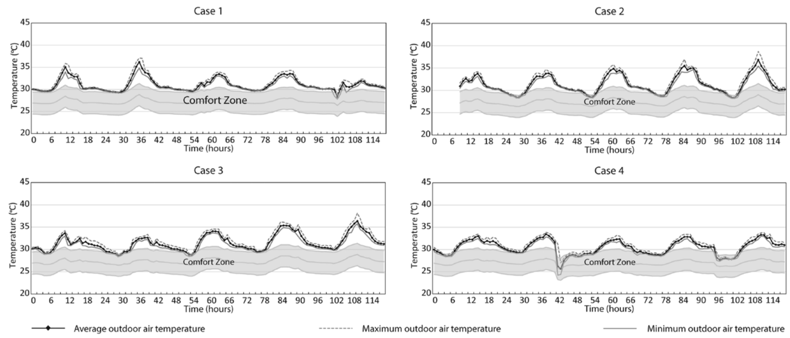


Figure 4. Average outdoor air temperature and comfort zone.

Table 2. Average outdoor air temperature and comfort zone.

	Case	T_{oav} (°C)	T_n (°C)	T_u (°C)	T_l (°C)	$T_{u(v=x)}$ (°C)	$T_{u(v=x)}$ (°C)	V (m/s)	
		Comfort zone							
						Living	Bed	Living	Bed
Daytime	1	32.27	27.60	30.10	25.10	30.47	30.50	0.26	0.27
	2	32.58	27.70	30.20	25.20	30.92	30.52	0.32	0.25
	3	31.13	27.25	29.75	24.75	30.20	30.14	0.28	0.27
	4	31.50	27.37	29.87	24.87	31.27	31.00	0.45	0.40
Nighttime	1	30.33	27.00	29.50	24.50	29.83	30.01	0.26	0.29
	2	30.10	26.93	29.43	24.43	30.18	29.94	0.33	0.29
	3[1]	30.10	26.93	29.43	24.43	29.96	29.53	0.29	0.22
	4[2]	30.26	26.98	29.48	24.48	30.01	29.63	0.29	0.23

Table 3. Environmental temperature in living room.

Living room	Case	MRT (°C)	DBT (°C)	EnvT (°C)	SET (°C)
Daytime	1	34.26	33.66	34.06	35.0
	2	32.64	33.00	32.76	32.8
	3	32.19	31.98	32.12	33.0
	4	32.53	31.80	32.29	33.0
Nighttime[1]	1	31.82	32.16	31.93	33.3
	2	31.18	31.12	31.16	32.5
	3	29.56	29.58	29.56	30.6
	4	28.97	29.18	29.04	29.7

[1]In case 3 and case 4, data during nighttime non-air conditioning hours are shown.

Table 4. Environmental temperature in bedroom.

Bedroom	Case	MRT (°C)	DBT (°C)	EnvT (°C)	SET (°C)
Daytime	1	33.59	33.02	33.40	34.9
	2	32.63	32.48	32.58	33.0
	3	31.22	31.35	31.26	32.3
	4	31.42	31.23	31.36	32.3
Nighttime[1]	1	32.12	31.82	32.02	33.7
	2	31.34	31.08	31.25	32.7
	3	30.59	30.72	30.63	31.4
	4	30.66	30.75	30.69	31.6

[1]In case 3 and case 4, data during nighttime non-air conditioning hours are shown.

In addition, the upper relative humidity (RH) limit of 80% (Szokolay, 2008) and the lower absolute humidity (AH) limit of 4 $g/kg_{dry\ air}$ (Khedari, Yamtraipat, Pratintong & Hirunlabh, 2010) are considered as a range of comfort environment for tropical climate region. The combination effect of temperature and humidity is defined as standard effective temperature or SET (Gagge, Fobelets & Berglund, 1986). In this research paper, SET was obtained from plotting on the psychrometric chart, with SET lines superimposed (Szokolay, 2008).

3.2 Environmental Temperature

Radiation is also a part of environmental factors related to thermal comfort besides air temperature, air movement, and humidity. Radiation exchange can be measured by mean radiant temperature (MRT), the average temperature of the surrounding surfaces. MRT can be calculated using equation 3 (Szokolay, 2008).

$$MRT = GT \cdot (1 - 2.35\sqrt{V}) - 2.35 \cdot DBT\sqrt{V} \quad (3)$$

Where *GT* is globe temperature (˚C), *V* is air velocity (m/s), *DBT* is dry bulb temperature (˚C). The combination effect between MRT and DBT has resulted in the environmental temperature (EnvT), which is given by equation 4 (Szokolay, 2008).

$$EnvT = \frac{2}{3} \cdot MRT + \frac{1}{3} \cdot DBT \quad (4)$$

In order to compare the environmental temperature of each case, the day that the average outdoor air temperatures conform to other cases was selected. The results are shown in Table 3, Table 4 and Figure 5.

Since the upper limit temperature could not be extended sufficiently, the extension of comfort range under maximum indoor wind speed (2 m/s) was predicted. In all cases, the environmental temperature stayed in comfort zone under varied indoor wind speed. The environmental temperature became closer to comfort zone when natural ventilation and air conditioning system were applied.

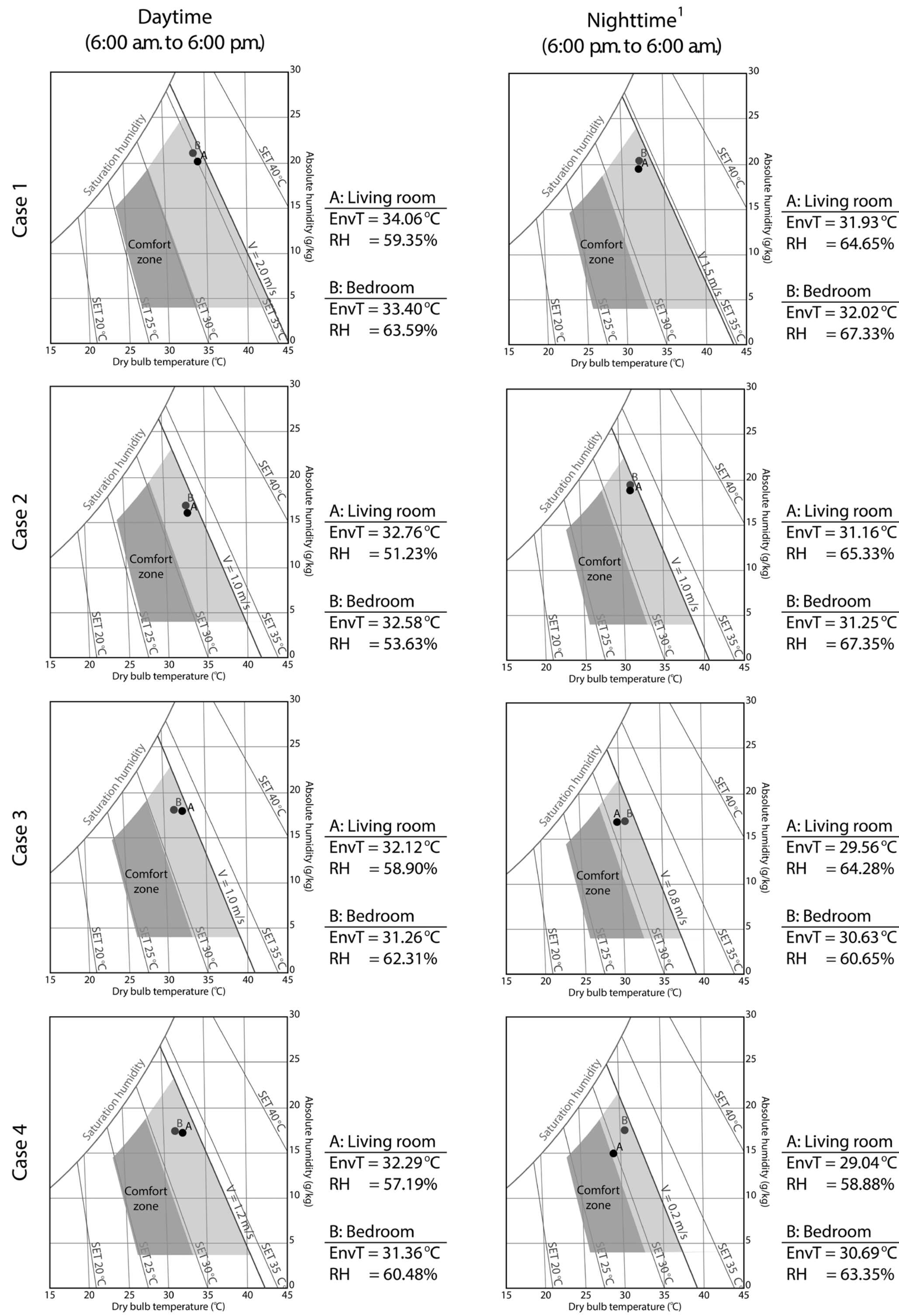


Figure 5. Environmental temperature during daytime and nighttime.

[1]In case 3 and case 4, EnvT and RH during nighttime non-air conditioning hours are shown.

For 24 hours naturally ventilated room, case 2, environmental temperature was lower (cooler) than the room without ventilation (case 1). Naturally ventilated room could provide the comfort environment during daytime with the indoor wind speed of 1.0 m/s while high indoor wind speed (2.0 m/s) was required for non-ventilated room to extend the comfort range. Nighttime with natural ventilation showed a similar tendency as daytime but it might not be able to provide all night comfort environment.

In case 3 and case 4, the air conditioning system were applied at night. The results showed that in case 4, daytime using natural ventilation, the environmental temperature was slightly higher than case 3, daytime non-ventilation. Moreover, the higher indoor wind speed (1.2 m/s) was also required compared to case 3. Daytime natural ventilation in case 4 indicated the lower performance than the result in case 2.

3.3 Cooling Load

Regarding the results of environmental temperature, nighttime thermal comfort was difficult to be achieved under natural ventilation, therefore, air conditioning system is considering to be used according to its reliability in providing thermal comfort during sleep. However, it is possible to reduce air conditioning usage during the day by enhancing natural ventilation.

Living room, as mainly occupied area with activity level varied from 0.8 Met (reclining) to 3.4 Met (house cleaning), was selected to compare cooling load between daytime non-ventilated room (case 3) and daytime naturally ventilated room (case 4). The calculation method (equation 5 to 8) were derived from ASHRAE (2013a).

In common air conditioning process, heat is extracted from the air to produce cooling. The amount of heat in moist air, the specific enthalpy (h) in kJ/kg$_{\text{dry air}}$, is defined in equation 5.

$$h = 1.006\,t + W(2501 + 1.86\,t) \qquad (5)$$

Where t is the dry bulb temperature (˚C), is the humidity ratio (kg/kg$_{\text{dry air}}$) which can be calculated using equation 6.

$$W = 0.621945\,\frac{p_w}{p - p_w} \qquad (6)$$

Where p_w is partial pressure of water vapor (kPa), p is total pressure which is 101.325 kPa. Partial pressure can be estimated by using relative humidity (ø) data which is given by equation 7.

$$\phi = \frac{p_w}{p_{ws}} \qquad (7)$$

Where p_{ws} is the saturation pressure (Pa) which can be expressed using equation 8.

$$\ln p_{ws} = C_8/T + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln T \qquad (8)$$

Where C_8 is -5.8002206E+03, C_9 is 1.3914993E+00, C_{10} is -4.8640239E-02, C_{11} is 4.1764768E-05, C_{12} is -1.4452093E -08, C_{13} is 6.5459673E+00, T and is absolute temperature (K).

The air enthalpy difference between room air temperature and at the air conditioner outlet were used in the total heat transfer rate calculation. Total heat transfer rate caused by ventilation from air conditioning processes is given by equation 9 (ASHRAE, 2013a).

$$q_t = C_t Q \Delta h \qquad (9)$$

Where q_t is total heat transfer rates (W), C_t is air total heat factor which is 1.2 W/(L·s) per kJ/kg-enthalpy at sea level, is air volumetric flow rate (L/s), Δh is air enthalpy difference across process (kJ/kg). The medium air flow rate of 248 L/s was used in calculation. The results of cooling load, which were converted to megajoules (MJ), are shown in Table 5.

Cooling load in case 4, daytime naturally ventilated room, was higher than case 3, daytime non-ventilated room.

4. Discussion

4.1 The extension of thermal comfort range

As in the hot-humid climatic region, people experience high air temperature and high humidity for most of the year. The investigation was conducted during the extremely high outdoor air temperature in May to the beginning of the rainy season in June. In daytime, the average dry bulb temperature ranged from 30.76˚C to 33.45˚C and relative humidity was between 52% and 75%.

In nighttime, the air temperature was lower but humidity was higher. The average dry bulb temperature ranged from 28.57˚C to 31.23˚C with 66% to 77% relative humidity. The outdoor air velocity was low with the average velocity of 0.41 m/s.

In order to extend thermal comfort range, indoor air velocity is needed to elevate the upper limit temperature. Compare to non-ventilated room, air velocity in naturally ventilated room were slightly higher and lower in some cases. Thus, it had resulted in less extension of comfort range. The indoor air velocity was very low due to the following effects: the effect of single-sided ventilation, low outdoor air velocity, and less window operable area (12% of the total living room area and 11% of the total bedroom area). Therefore, the greater extension of comfort range can be achieved by increasing indoor air velocity with ceiling fan and also the wind-driven natural ventilation design strategy.

4.2 Indoor air and mean radiant temperature contribute to environmental temperature

Environmental temperature (EnvT) is the combination effect between MRT and DBT. But the effect of MRT is twice as significant as the DBT. The comparison between outdoor air temperature (T_o), indoor air temperature (T_i), and MRT are shown in Figure 6.

As mentioned previously, the average outdoor air temperatures conform to the other case was selected. It appears that the selected of daytime outdoor air temperature in case 2 is slightly higher than case 1. But with the effect of natural ventilation, the environmental temperature could be reduced up to 1.3˚C and stayed in comfort zone under low indoor wind speed (under 2.0 m/s and 1.0 m/s for case 1 and case 2, respectively).

Table 5. Cooling load from air conditioning processes.

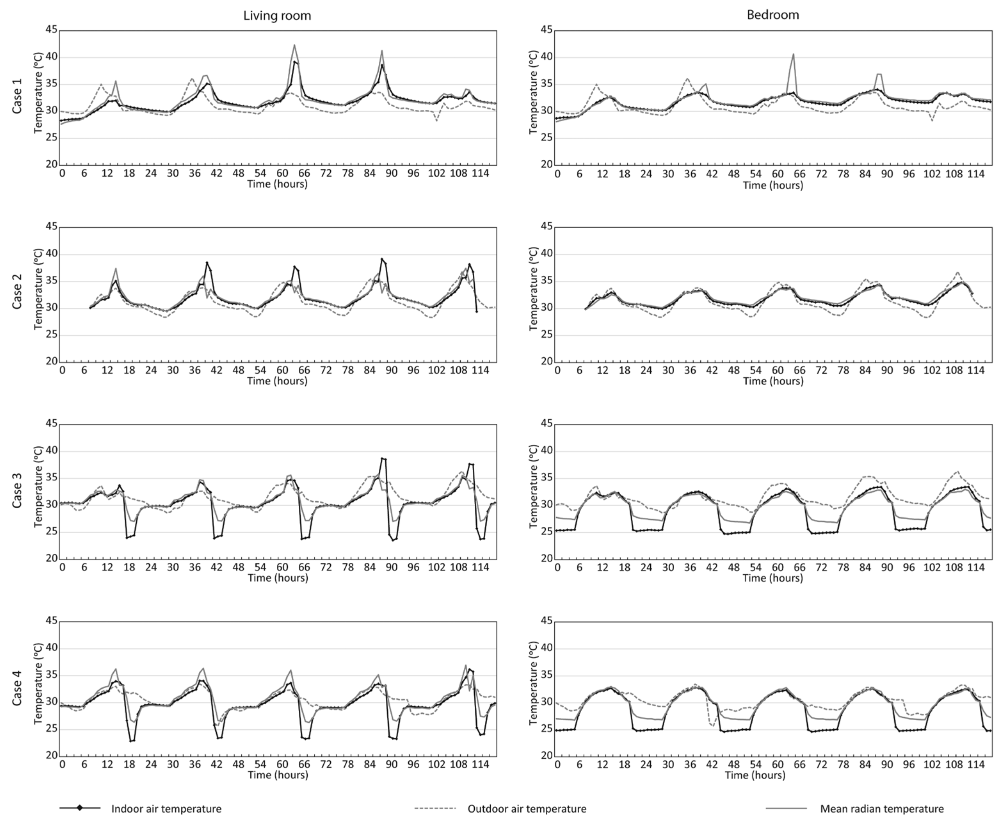
Case 3	**Cooling load (MJ)**	**Case 4**	**Cooling load (MJ)**
June 3rd, 2015	49,727	May 24th, 2015	63,131
June 4th, 2015	50,663	May 25th, 2015	45,270
June 5th, 2015	51,730	May 26th, 2015	60,078
June 6th, 2015	49,101	May 27th, 2015	58,109
June 7th, 2015	46,006	May 28th, 2015	51,320
Average	49,446	Average	55,582

Moreover, natural ventilation also showed the significant effect on the reduction of mean radiant temperature (MRT). MRT of case 2 was lower than case 1. Comparison of results between mean radiant temperature and dry bulb temperature (DBT) showed that in case 2, MRT was lower than DBT. In warm climates, MRT is about as twice significant as DBT which effects on the environmental temperature. As a result, EnvT of case 2 was lower than case 1. Therefore, naturally ventilated room (case 2) shows higher performance in reducing EnvT compared to non-ventilated room (case 1).

Refer to Figure 5, during nighttime, the environmental temperature of all cases were lower compared to daytime but relative humidity was very high; thus, the environmental temperature couldn't be drawn into comfort zone. Only natural ventilation might not be able to provide comfortable thermal environment at night.

When air conditioning system was used at night (case 3 daytime non-ventilation and case 4 daytime natural ventilation), in contrast with case 1 and case 2, the tendency of indoor air temperature and mean radiant temperature were different. During the day, the average indoor air temperature of case 4 rose up close to outdoor air temperature simultaneously after windows were opened. Heat from outdoor air was absorbed within the internal surfaces and resulted in higher mean radiant temperature. As a result, the

Figure 6. Average outdoor air temperature, indoor air temperature, and mean radiant temperature.



environmental temperature of case 4 shows small decline compared to case 3 but has similar tendency as case 2. In addition, the heat stored within the internal surfaces also had an effect on the increasing of cooling load. However, in order to increase the validity, other load components are needed for further studies.

5. Conclusions

Environmental factors contributed to thermal comfort are the key factor which has resulted in energy consumption by air conditioning usage. This study aims at investigating thermal environment in one bedroom unit of high-rise condominium in urban area of Bangkok, Thailand. The hypothetical cases were devised based on the occupancy characteristics towards the use of natural ventilation and air conditioning system.

The results show that naturally ventilated room has the possibility to provide comfort in some hour during daytime under the air velocity of 1.2 m/s. But from the investigation, the average air velocity was low due to the following effects: single-sided ventilation, low outdoor air velocity, and less ratio of operable window area to floor area. The upper limit of comfort range could be extended by 0.9˚C for living room and 0.5˚C for bedroom with average indoor air velocity of 0.36 m/s and 0.29 m/s respectively.

For nighttime, humidity is the significant factor beside air temperature that has resulted in the reduction of environmental temperature. Indoor humidity was very high with the average value between 54% to 72% relative humidity. As a result, nighttime using natural ventilation could not be effective in providing comfortable indoor environment.

In addition, daytime natural ventilation had resulted in an increasing of cooling load at night due to the heat stored within the internal surfaces.

The present study has some limitation as it was carried out on the different days and the filed data based on one specific unit configuration. Similar research and/or computer simulation which include the effect of user and the electricity consumption should be conducted in order to increase the validity and also provide a better understanding of indoor thermal environment contributed to thermal comfort.

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