Passive Design Strategies with Active System Enhancing Indoor Thermal Environment and Comfort of A Condominium in Bangkok

Parinee Srisuwan[1*], Shoichi Kojima[2]

[1] *Research and Development Department, Kyudenko Corporation, Fukuoka 815-0081, Japan*

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

* Corresponding author e-mail: pan.parinee@gmail.com
27 Feb 2019; Revised 23 Jun 2019; Accepted 27 Jun 2019

Print-ISSN: 2228-9135, Electronic-ISSN: 2258-9194, doi: 10.14456/built.2019.3

Abstract

Urbanization, social change, and the development of housing for foreign expatriates coupled with the extension of a mass transit system, the condominium market in Bangkok have grown rapidly. It has led to an increase in energy consumption in the residential sector since an air conditioning system plays a vital role in maintaining indoor thermal comfort. In this study, the combination of passive design strategies with the active system was proposed regarding the field measurement and the simulation results using EnergyPlus version 8.4. An initial design modification, based on the three-tier design approaches to achieve sustainable building was carried out in order to improve indoor thermal comfort and reduce cooling energy consumption for a high-rise condominium unit in a hot-humid climate of Bangkok. The results showed that utilizing natural ventilation as the main mode of ventilation with the addition of radiant cooling panel used at night could maintain the indoor thermal comfort. Applying natural ventilation during the day could provide a comfortable environment with an indoor velocity of 1.5 m/s. The cooling energy was decreased for the room with natural ventilation applied during daytime and nighttime using a radiant cooling system compared to the room without natural ventilation is applied.

Keywords: high-rise, residential building, urban area, thermal environment, indoor thermal comfort

1. Introduction

Sustainable building is often designed to correspond with the location, outdoor environment, and functional usage of the building in general. The mainstream of sustainable building design is passive and active approaches, dealt with different design strategies but a similar solution in achieving thermal preference and building energy conservation. For passive building, environmental resources are utilized to provide a comfortable indoor environment. Meanwhile, the utilization of mechanical equipment, along with high thermal resistance materials control an indoor environment for active building. However, In the boundaries between being an ideal passive or active building are not obvious for residential building. Natural with mechanical ventilation is applied during the occupied period. Effective design strategies should be studied in order to optimize the benefits of thermal comfort and energy consumption.

In Thailand, the building sector accounts for the highest electricity consumption or 54% of the total consumption (EPPO, 2016). The condominium in Bangkok has possessed the highest supplies among the real estate market (Plus Property, 2016) due to the influences of urbanization, social change, and development of housing for expatriates coupled with an introduction of a mass transit system (Li-Zenn, 2015). The blooming of condominium has led to an increase in building energy consumption since an air conditioning system plays a major role in enhancing occupants comfort condition.

In order to raise awareness of building energy consumption, policy-driven approaches have been launched by the government and the private sectors. According to Ministerial Regulation (2009), the mandatory requirements in the Building Energy Code (BEC) mostly rely on using energy efficient products for three main building systems: building envelope, lighting, and air conditioning system. Meanwhile, in private sector, Thai green building assessment has been released by Thai Green Building Institute (TGBI). The benefits will be provided after achieving the qualification. The barriers of complication in criterion and higher investment cost in energy efficient technology have resulted in a few projects participated in the assessment system. From 2012, only two condominiums out of ten were certified (TGBI, 2019). All of them are categorized in high class to luxury condominium (120,000 to 160,000 THB/m^2) were registered.

This research aims at finding the design modification for the high-rise condominium, which passive with the active system are applied, to optimize the benefits of an occupant thermal comfort and cooling energy consumption. Adaptive thermal comfort was adopted as the assessment criteria. The highest demanded one bedroom condominium unit in Bangkok was selected for thermal comfort evaluation. The study focused on the 33 m^2 occupied area, which is categorized in the main to upper class segment (50,000 to 100,000 THB/m^2). The research flow is illustrated in Figure 1.

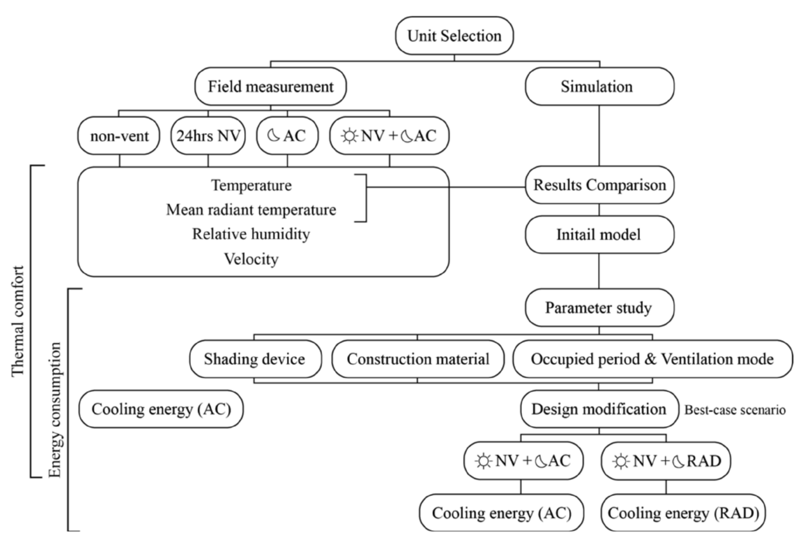


Figure 1. Research flow diagram

The purpose of this study was to extend previous research, conducted by field measurement (Srisuwan & Kojima, 2016; 2017), using simulation program. The combination between passive design strategies with the active system regarding the results from field measurement and computer simulation was proposed with aimed at improving indoor thermal comfort and reducing cooling energy consumption for a high-rise condominium unit in hot-humid climate of Bangkok.

2. Literature review

As the factors that influence indoor thermal environment, passive and active cooling design strategies along with occupant's thermal adaptation are illustrated.

2.1 Adaptation towards thermal comfort

Occupants control their comfort preferences by using various adaptation which can be attributed from three modes of adaptation: behavioral adjustments, physiological adjustments, and psychological adjustments. The evidence reviewed by Brager and De Dear (1998) indicated that behavioral adjustments and expectation have a much greater influence and relevant to thermal adaptation than the slower physiological process of acclimatization. Behavioral adjustments appear to have a significant effect on occupant's thermal adaptation.

The study of Rijai, Humphreys, and Nicol (2015) found that the occupants adapted to a hot and humid environment by increasing the air movement usage through behavioral adaptation such as opening windows and using fans. The proportion of use of the controls increases when the indoor air temperature is higher (hotter) than the outdoor air temperature. The use of controls also helps increase an indoor comfort temperature approximately 3-4˚C under a wind velocity of 1 m/s (Nicol, 2004). However, measurement results indicated low indoor velocity with an average velocity of 0.4 m/s (Srisuwan & Kojima, 2016). Opening windows with using fan are a substantial way to increase indoor comfort temperature.

An air conditioning system plays a significant role in achieving occupant's thermal comfort to some extent as reported in the study on the air conditioning usage in residential buildings in hot-humid climate of Malaysia (Kubota, Jeong, Toe, & Ossen, 2011). The results indicated that people in the hot-humid climate usually operate windows and fan during daytime. Meanwhile, the air conditioning system is operate during nighttime.

2.2 Passive with active cooling design approach

The passive cooling approach is the design method that involves the use of natural phenomena: conduction, convection, and radiation, for indoor cooling purpose without using any electrical or mechanical devices (Cook, 1989; Dimoudi, 1996). In some context, the term "Passive" includes the use of a fan or a pump when those applications could help increase the performance (Givoni, 1994).

Three main cooling strategies of passive cooling can be described as follows (Dimoudi, 1996): 1) prevention of external and internal heat gains in the building, 2) modulation of heat gains by using materials with high thermal storage which provides an attenuation of peaks in internal temperatures, and 3) rejection of heat from the interior of the building to natural heat sink or hybrid cooling. In order to achieve thermal comfort, the three-tier design approach (Lechner, 2015) was adopted in this study.

The first tier is heat avoidance strategies to minimize heat gain in building and also control of internal heat source. However, only heat avoidance is not sufficient enough to provide thermal comfort. Passive cooling strategies should be adopted as a second tier. Passive cooling strategies help reduce the internal temperatures and also expand the comfort zone to higher temperatures. However, the combination of strategies between heat avoidance and passive cooling is still insufficient to maintain thermal comfort in various climatic regions. The third tier of mechanical cooling strategies is required.

In this study, factors influencing the indoor thermal environment in one bedroom unit were analyzed using a computer simulation program, EnergyPlus version 8.4 (U.S. Department of Energy, 2015). A model configuration and results comparison between field measurement and simulation were described in the next section.

3. Model configuration and results comparison

In order to substantiate the simulation program with the field measurement data, model configuration along with results comparison were conducted.

3.1 Model configuration

The preliminary model is configured according to the construction drawing and the outline specification of the selected unit, a corner room facing south west.

3.1.1 General data input (analysis boundary)

The general data input can be mainly categorized into three input objects: a) location, height, and climate, b) surface construction elements and c) thermal zone, surfaces, and shading devices.

The building location was set as located in Bangkok, Thailand. The outdoor weather boundary was set at 60.8 height above ground due to the effect of the height-dependent variable. The local outdoor air temperature is calculated using equation 1.

$$T_Z = T_b + L(H_Z - H_b) \quad \text{(Eq.1)}$$

Where T_z is air temperature at altitude Z; Tb denotes air temperature at the base of layer, L is air temperature gradient, equal to -0.0065 K/m in the troposphere; H_b is the offset equal to zero for the troposphere; H_z is geopotential altitude. The local outdoor wind speed is calculated using equation 2.

$$V_Z = V_{met}\left(\frac{\delta_{met}}{Z_{met}}\right)^{\alpha_{met}}\left(\frac{Z}{\delta}\right)^{\alpha} \quad \text{(Eq.2)}$$

Where Z is altitude or height above ground; V_z denotes wind speed at altitude Z; α is wind speed profile exponent at the site; δ is wind speed profile boundary layer thickness at the site; Z_{met} is height above ground of the wind speed sensor at the meteorological station; V_{met} is wind speed measured at the meteorological station; α_{met} is wind speed profile exponent at the meteorological station; δ_{met} is wind speed profile boundary layer thickness at the meteorological station. From the correlations of height-dependent variable, the terrain filed should be specified. The site's terrain affects the direction of the wind towards the building. The wind speed profile coefficients are different for the different terrain types. According to the field measurement, the terrain type was set as an urban area.

For surface construction elements, construction material layers are defined for walls, floors, ceiling, doors, and windows associated with the number of material layers present in that construction. Material layers are defined based on their thermal properties, which have an effect on the heat balance model. The room surfaces are assumed to have uniform surface temperatures, uniform long and short wave irradiation, and diffuse radiating surfaces and internal heat conduction. The heat balance on the outside surface can be expressed in equation 3.

$$q"_{\alpha sol} + q"_{LWR} + q"_{conv} - q"_{ko} = 0 \quad \text{(Eq.3)}$$

Where $q''_{\alpha sol}$ is absorbed direct and diffuse solar short wavelength radiation heat flux; q''_{LWR} denotes net long wavelength radiation flux exchange with the air and surroundings; q''_{conv} is convective flux exchange with outside air; q''_{ko} is conduction heat flux into the wall. The correlation indicated the effect of three mechanisms of heat transfer: conduction, convection, and radiation. The longwave radiation heat flux can be calculated using equation 4.

$$q"_{LWR} = \varepsilon\sigma F_{gnd}\left(T_{gnd}^4 - T_{surf}^4\right) + \varepsilon\sigma F_{sky}\left(T_{sky}^4 - T_{surf}^4\right) + \varepsilon\sigma F_{air}\left(T_{air}^4 - T_{surf}^4\right) \quad \text{(Eq.4)}$$

Where ε is longwave emittance of the surface; σ denotes the Stefan-Boltzmann constant; F_{gnd} is view factor of wall surface to ground surface temperature; F_{sky} is view factor of wall surface to sky temperature; F_{air} is view factor of wall surface to air temperature; T_{surf} is outside surface temperature; T_{gnd} is ground surface temperature; T_{sky} is sky temperature; T_{air} is air temperature. The radiation exchange between building exterior surface and outdoor environment of the ground, sky, and air can be determined automatically by input the material properties and assign the layer of construction elements.

The simulation was composed of 5 thermal zones, i.e., living room, bedroom, plenum A (living room), plenum B (bedroom), and storage, see Figure 2.

The observed zones are living room and bedroom. In EnergyPlus, each thermal zone contains two types of surfaces, i.e., heat transfer surface, and heat storage surface. Heat transfer surface is defined when the surface is expected to separate spaces of significantly different temperatures. On the other hand, if the surface separates spaces maintained at the same temperature, heat storage surface is defined. In addition, to compare with the measurement result, 18 years weather data for simulation derived from the international weather for energy calculations (IWEC) was input in the configuration model.

3.1.2 Specific configuration towards occupant thermal adaptations

In EnergyPlus, the opening of windows and doors require airflow rate as the input data. The airflow rate input in the simulation was assumed to be constant according to the measurement results (Srisuwan & Kojima, 2016). The results showed that the different temperature between outdoor and indoor was small or less than 5˚C. Since the effect of single-sided ventilation was poor coupled with the insignificant of building internal resistance, flow caused by thermal forces or stack effect was applied which can be determined by equation 5 (ASHRAE, 2013a).

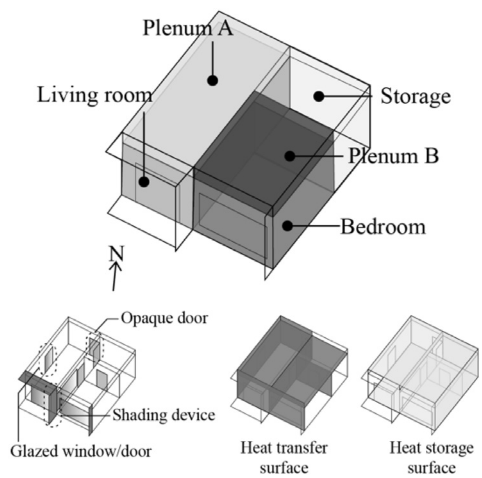


Figure 2. Schematic model of one bedroom unit and type of surfaces

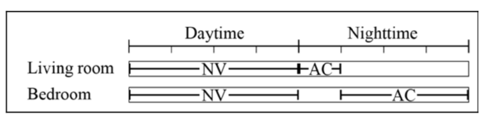


Figure 3. Ventilation schedules

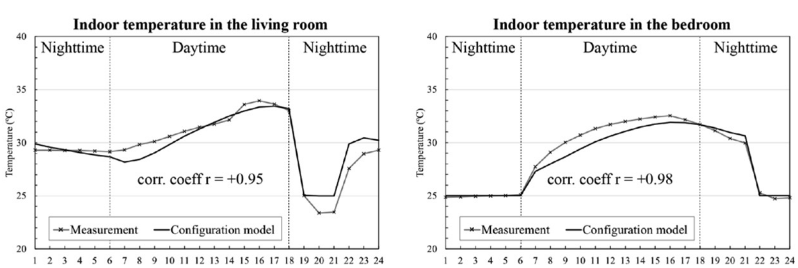


Figure 4. Trend comparison between the configuration model and the measurement result

$$Q = C_D A\sqrt{2g\Delta H_{NPL}(T_i - T_o)/T_i} \quad \text{(Eq.5)}$$

Where Q is airflow rate (m^3/s); C_D denotes discharge coefficient for opening; A is area of inlet openings (m^2); ΔH_{NPL} is height from midpoint of lower opening to neutral pressure level or NPL (m); T_i is indoor temperature (K); T_o is outdoor temperature (K). This equation applies when $T_i>T_o$. If $T_i<T_o$, replace T_i in the denominator with T_o, and replace the term (T_i-T_o) in the numerator with (T_o-T_i). Discharge coefficient can be calculated using equation 6 (ASHRAE, 2013a).

$$C_D = 0.40 + 0.0045 \cdot |T_i - T_o| \quad \text{(Eq.6)}$$

Regarding the calculation, the input airflow rate for the living room was 0.04 m^3/s and 0.02 m^3/s for the bedroom. Natural ventilation schedule started from 6:00 a.m. to 6:00 p.m. For an air conditioning system data input, the ideal loads system was selected to model only the sole conditioning component. According to the system specification, the cooling capacity is 5.2 kW for the living room and 3.6 kW for the bedroom. Airflow rate is 17.6 m3/min for the living room and 9.9 m3/min for the bedroom. Mechanical ventilation schedule for the living room started from 6:00 p.m. to 9:00 p.m. and from 9:00 p.m. to 6:00 a.m. for the bedroom. The diagram showing the ventilation schedule is shown in Figure 3. After completing the model configuration, the simulation was run and the results were compared against the measurement results as described in the next section.

3.2 Results comparison between the configuration model and field measurement

In this study, indoor temperature derived from the configuration model were compared against the measurement result. Trend comparison is illustrated in Figure 4. The results indicated the correspondence with the correlation coefficient of +0.95 for the living room and +0.98 for the bedroom.

Applying natural ventilation during daytime, indoor temperature from the measurement was slightly higher than those from the simulation. The simulation requires a constant airflow rate as the input data for natural ventilation. The airflow rate is controlled by an on-off schedule. As a result, the ventilation in the simulation indicated slightly better performance than in the real situation. This model will be used as the initial settings for the parameter study described in the next section.

4. Parameter study

The parameter study was conducted regarding the three-tier design approach (Lechner, 2015). The simulation was conducted on summer design day (21 April), which has resulted in the highest annual cooling energy consumption. Indoor dry-bulb temperature (DBT) and mean radiant temperature (MRT) obtained from the simulation were used for the theoretical calculation of the environmental temperature or EnvT (Szokolay, 2008). It is the combined effect of air temperature, humidity, and wind speed used to describe the heat exchange between the environmental point in a room and the internal surfaces, which is given by Equation 7.

$$EnvT = \frac{2}{3} \cdot MRT + \frac{1}{3} \cdot DBT \qquad \text{(Eq.7)}$$

The environmental temperature is adopted for evaluating the indoor thermal performance on each parameter. The passive design strategies with an active system for a high-rise condominium unit were described as follows.

4.1 Heat avoidance strategy

The implementation of shading to shade an opening is the most efficient technique for high-rise residential unit in a hot-humid climate. The shading device must not obstruct the pleasant view, which is the significant market value for high-rise condominium (Niu, 2003). Thus, a horizontal overhang and a vertical fin are the best choices for implementing the exterior shading devices.

An implementation of shading devices, depth, along with removing the west-facing window were simulated. The results of the environmental temperature are shown in Table 1. From the parametric study, only removing the west-facing window indicated a great reduction on the environmental temperature. The effect was equivalent to the addition of horizontal overhang or vertical fin at 0.9 m depth. The environmental temperature could be reduced up to 0.6˚C during the day.

For the effect of adding shading devices, the combination between the horizontal overhang and vertical fin indicated the highest performance on the environmental temperature reduction. With a maximum depth of 0.9 m, the environmental temperature was reduced up to 2.8˚C. The effect of adding the horizontal overhang was higher than adding the vertical fin due to high solar elevation angle on the south-facing window.

The effect of the exterior wall construction materials was also studied. A residential unit, unlike the office building, natural ventilation is usually applied during the day in order to reduce the air conditioner usage time. Therefore, the ventilation schedule of applying natural ventilation during the day was included in the simulation. The results are shown in Table 2.

Using concrete 12.5 cm thickness (base case) indicated the most appropriate strategy for the residential unit, which both natural ventilation and air conditioning system are applied. High thermal resistance materials slightly reduced the environmental temperature during daytime, and heat was trapped inside the room. The additional thickness of construction material and insulation also reduce a saleable area and increase the cost investment in building construction. Therefore, concrete 12.5 cm thickness with plastering was preferable.

4.2 Passive cooling strategy

Applying natural ventilation for a difference occupied periods: daytime, nighttime, and all day was studied. Natural ventilation through opening windows and doors was assumed using equation 8 (ASHRAE, 2013).

$$Q = C_v A U \qquad \text{(Eq.8)}$$

Where Q is airflow rate (m^3/s); C_v denotes effectiveness of openings which is assumed to be 0.35 for diagonal winds; *A* is a free area of inlet openings (m^2); U is wind speed (m/s). From the theoretical calculation, the design flow rate in the living room used in the simulation was 2.9 m^3/s and 2.0 m^3/s for the bedroom. The results are shown in Table 3.

From Table 3, applying natural ventilation during the day indicated the highest reduction in the environmental temperature. It could be reduced up to 2.6˚C. Daytime humidity was lower than nighttime. As a result, achieving the comfort condition might be easier compared to high humidity during nighttime. However, applying an electric fan to increase the indoor velocity during the daytime could also help extend the comfort range.

Table 1. Environmental temperature as a result of shading devices implementations

	T_o (°C)	*EnvT* (°C)											
		Base case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11
Living room	33.0	34.9	34.3	v34.8	34.9	34.6	34.5	34.7	34.5	34.4	34.3	34.3	34.2
Bedroom	33.0	34.8	34.5	34.5	34.8	34.5	34.3	34.7	34.6	34.4	34.2	34.2	34.0

Table 2. Environmental temperature as a result of changing wall materials under daytime natural ventilation

	T_o (°C)	*EnvT* (°C)						
		12.5 cm	10 cm	24.5 cm	17.5 cm	22.5 cm	21.5 cm	19 cm
		Base case	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6
Living room	33.0	33.4	33.3	33.1	32.8	32.8	33.0	33.0
Bedroom	33.0	32.1	31.9	32.0	31.7	31.7	31.7	31.7

4.3 Active cooling strategy

When natural ventilation is insufficient to maintain comfort environment at night due to the effect of high humidity, an active cooling system is an alternative. However, a heat stored at the indoor surfaces and high humidity caused by outdoor air from utilizing the natural ventilation will become the cooling load when an air conditioning system is used. Therefore, applying natural ventilation with the addition of an active cooling system in a difference occupied period is studied.

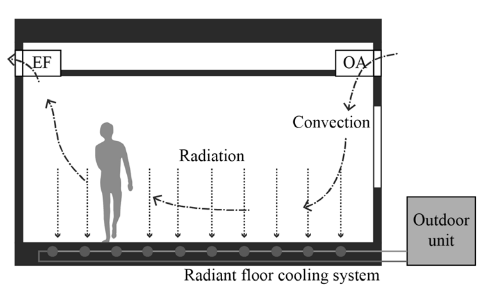


Figure 5. The radiant cooling system diagram

According to the measurement result (Srisuwan &
Kojima, 2016; Srisuwan, 2017), the room's surface temperature was higher than the room temperature. As a result, the heat stored at the indoor surface radiated to the surrounding environment. Since the mean radiant temperature plays a vital role in the environmental temperature reduction compared to the dry-bulb temperature, applying a radiant cooling system to reduce the surface temperature was proposed for studying.

The radiant cooling system is defined as a system with a temperature controlled surface that removes sensible heat loads from a space where at least 50% of the heat transfer takes place by radiation. The system is made up of cooling panels installed on the ceiling, wall, or floor which is supplied by the cooling water. In this study, the radiant floor cooling system was selected regarding the closest location to the occupied level. The system diagram is illustrated in Figure 5. The radiant cooling system helps remove sensible heat loads through the heat transfer mode of radiation and convection. It corresponds with the predominant mode of heat dissipation from a human body, which is 40-50% from radiation and 20-26% from convection (Uschwa, 1989 as quoted in Feustel, 1993).

In case of using the air conditioning system, thermostat set-point was set at 25˚C in the simulation. Meanwhile, the cooling water supply for the radiant floor was set at 25˚C in case of using the radiant cooling system. The results are shown in Table 4 and Table 5. The air conditioning system showed greater performance in the environmental temperature reduction compared to the radiant cooling system.

However, in case that natural ventilation is applied along with the air conditioning system (case 2, case 4, and case 6), the cooling energy increased compared to the room without natural ventilation (case 1, case 3, and case 5). Meanwhile, the cooling energy decreased in the room with natural ventilation is applied with the addition of the radiant cooling system compared to the room without natural ventilation.

Table 4. Environmental temperature as a result of applying natural ventilation (NV) with an air conditioning system (AC) in different occupied periods

	Daytime Nighttime Liv AC Bed	Daytime Nighttime Liv AC NV Bed NV	Daytime Nighttime Liv AC Bed AC	Daytime Nighttime Liv NV AC NV Bed NV AC	Daytime Nighttime Liv AC Bed AC	Daytime Nighttime Liv AC NV Bed NV AC
Living room	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Daytime schedule	AC	AC	-	-	AC	AC
Nighttime schedule	-	NV	AC[1]	AC+NV[2]	AC[1]	AC+NV[2]
$EnvT$ (°C)	29.2	29.1	31.2	30.7	29.3	29.2
Cooling energy (J/m²)	322,756	326,985	422,881	443,906	294,562	308,755
Bedroom	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Daytime schedule	-	NV	-	NV	-	NV
Nighttime schedule	-	NV	AC[3]	NV+AC[4]	AC[3]	NV+AC[4]
$EnvT$ (°C)	32.6	32.4	29.2	29.1	29.5	29.7
Cooling energy (J/m²)	-	-	252,334	263,819	204,025	224,282

Note: [1]A/C is applied from 6:00 p.m. to 9:00 p.m. [2]After turning A/C off, N/V is applied from 9:00 p.m. to 6:00 a.m.
[3]A/C is applied from 9:00 p.m. to 6:00 a.m. [4]Before turning A/C on, N/V is applied from 6:00 p.m. to 9:00 p.m.

Table 5. Environmental temperature as a result of applying natural ventilation (NV) with a radiant cooling system (RAD)

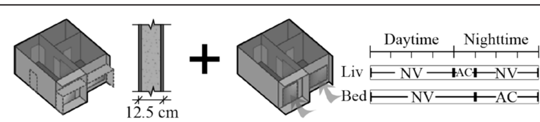
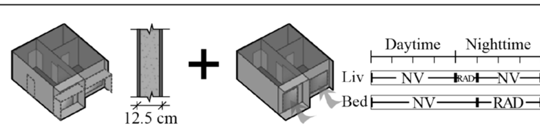
	Daytime Nighttime Liv RAD Bed	Daytime Nighttime Liv RAD NV Bed NV	Daytime Nighttime Liv RAD Bed RAD	Daytime Nighttime Liv NV RAD NV Bed NV RAD	Daytime Nighttime Liv RAD Bed RAD	Daytime Nighttime Liv RAD NV Bed NV RAD
Living room	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Daytime schedule	RAD	RAD	-	-	RAD	RAD
Nighttime schedule	-	NV	RAD[1]	RAD+NV[2]	RAD[1]	RAD+NV[2]
$EnvT$ (°C)	31.9	32.2	31.5	31.0	31.2	31.5
Cooling energy (J/m²)	212,947	165,376	420,251	408,659	191,327	147,669
Bedroom	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Daytime schedule	-	NV	-	NV	-	NV
Nighttime schedule	-	NV	RAD[3]	NV+RAD[4]	RAD[3]	NV+RAD[4]
$EnvT$ (°C)	33.7	33.3	30.9	30.6	31.2	31.3
Cooling energy (J/m²)	-	-	179,740	172,453	164,634	164,475

Note: [1]RAD is applied from 6:00 p.m. to 9:00 p.m. [2]After turning RAD off, N/V is applied from 9:00 p.m. to 6:00 a.m.
[3]RAD is applied from 9:00 p.m. to 6:00 a.m. [4]Before turning RAD on, N/V is applied from 6:00 p.m. to 9:00 p.m.

In the case of using the air conditioning system, air temperature and humidity are controlled in the cooling process. Excessive heat stored in the room's surface, coupled with high humidity which has entered the room through natural ventilation, will be removed. As a result, the cooling load tended to increase. Meanwhile, the radiant cooling system uses the temperature-controlled surface to cool the indoor air indirectly. Therefore, the cooling load was lower when the natural ventilation with the addition of the radiant cooling system is applied.

From the parameter study, the best case from each strategy was integrated. Two alternative options shown in Table 6 were proposed for the evaluation on thermal comfort and cooling energy consumption. According to the heat avoidance strategy, removing the west-facing window and adding the horizontal overhang with a vertical fin of 0.9 m depth were proposed for a design modification. The natural ventilation was applied as the main mode of ventilation. In option 1, the air conditioning system is used during the night. Meanwhile, the radiant cooling system is applied in option 2.

Table 6. The proposed strategies for evaluation

Option 1	 Heat avoidance + Natural ventilation + AC system
Option 2	 Heat avoidance + Natural ventilation + RAD system

5. Evaluation of thermal comfort and cooling energy consumption

The simulation was conducted on summer design day (21 April) and winter design day (21 December). The results of indoor temperature, mean radiant temperature, and humidity, were once evaluated by the theoretical calculation, which can be described as follows.

5.1 Average outdoor temperature and comfort zone

People experience comfort sensations under the neutral temperature, which can be determined by equation 9 (Auliciem, 1981; Auliciems & Szokolay, 2007).

$$T_n = 17.6 + 0.31 \cdot T_{oav} \qquad \text{(Eq.9)}$$

Where T_n is neutral temperature (˚C); T_{oav} denotes the average outdoor air temperature (˚C). The range of comfort zone is between T_n±2.5˚C. The upper temperature limit can be extended due to an increase in the convective heat transfer and the evaporation heat loss from human skin. The correlation is given by:

$$T_{u(v=x)} = T_n + 2.5 + (6 \cdot V_e - 1.6 \cdot V_e^2) \qquad \text{(Eq.10)}$$

Where $T_{u(v=x)}$ is the extension of upper temperature limit at different wind velocity (˚C); V_e denotes effective velocity where ; $V_e = V - 0.2$; V is wind velocity (m/s).

Besides temperature, the upper relative humidity limit of 80% (Szokolay, 2008) and the lower absolute humidity limit of 4 g/kgdry air (Khedari, Yamtraipat, Pratintong, & Hirunlabh, 2010) are considered as a comfortable environment. The combined effect of temperature and humidity is defined by Gagge, Fobelets, and Berglund (1986) as standard effective temperature (SET).

Outdoor temperature, comfort zone, and an extension of comfort zone under different indoor wind velocities are shown in Figure 6 and Table 7.

Table 7. Average outdoor temperature and comfort zone

	T_{oav}	Comfort zone (21 April)			$T_{u(v=x)}$ (°C)			
	(°C)	T_n (°C)	T_l (°C)	T_u (°C)	V=0.5	V=1.0	V=1.5	V=2.0
Daytime	33.0	27.8	25.3	30.3	32.0	34.1	35.4	35.9
Nighttime	28.9	26.6	24.1	29.1	30.7	32.8	34.2	34.7
	T_{oav}	Comfort zone (21 December)			$T_{u(v=x)}$ (°C)			
	(°C)	T_n (°C)	T_l (°C)	T_u (°C)	V=0.5	V=1.0	V=1.5	V=2.0
Daytime	28.3	26.4	23.9	28.9	30.5	32.6	34.0	34.5
Nighttime	25.8	25.6	23.1	28.1	29.7	31.9	33.2	33.7

The result showed that outdoor temperature on summer design day stayed mostly outside the comfort zone. The high outdoor temperature indicated the most severe scenario of comfort sensations and cooling energy consumption. Meanwhile, on winter design day, outdoor temperature mostly stayed inside the comfort zone. The low temperature indicated a preferred scenario for thermal comfort and cooling energy saving.

The upper limit of the comfort zone was predicted under indoor velocity varied from 0.5 m/s to 2.0 m/s, the applicable range for indoor wind speed used in the warm climatic region. High wind speed of 1.5 m/s and 1.0 m/s could extend the comfort range respectively on summer and winter design day. According to the weather data collected by the Thailand Meteorological Department (2013), outdoor wind speed in Bangkok is low with the annual velocity of 1.0 m/s. The effect of air flow caused by wind only might be insufficient. Therefore, the usage of an electric fan or a ceiling fan could maintain comfort sensation for residents.

5.2 Environmental temperature and thermal comfort

This study evaluated an indoor thermal performance during daytime and nighttime. The maximum environmental temperature can be shown in Table 8 and Table 9. During daytime when natural ventilation is applied, the maximum indoor temperature occurred around 4:00 p.m. to 5:00 p.m. Similarly, the maximum outdoor temperature also occurred at 4:00 p.m.

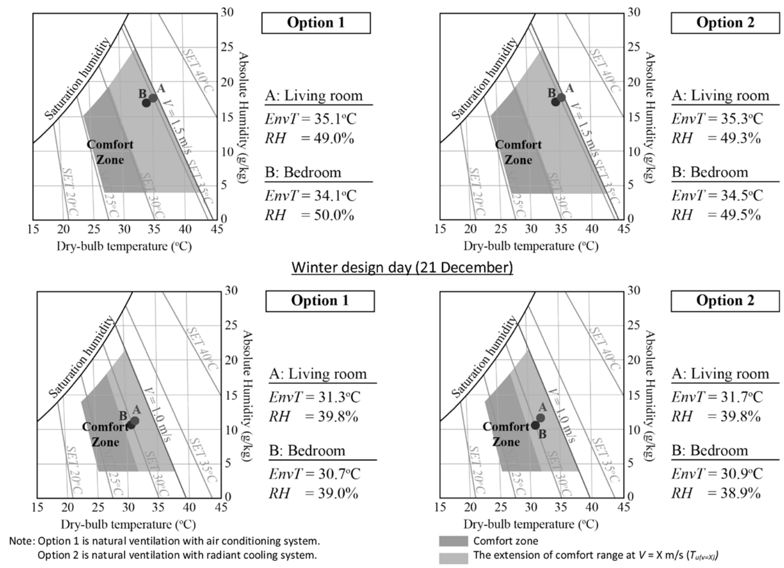


Figure 7. Daytime maximum environmental temperature and thermal comforta

Similarly, the maximum outdoor temperature also occurred at 4:00 p.m. This behavior indicated the effect of concrete wall 12.5 thickness. Using low heat capacity material allows heat to pass through rapidly without time lag. Moreover, applying natural ventilation during daytime also allow heat to enter indoor space directly. The low outdoor temperature during winter design day resulted in low indoor air temperature. Therefore, the low outdoor temperature is preferable for the utilizing of natural ventilation. Thermal comfort was evaluated under the maximum environmental temperature. The results are shown in Figure 7.

Table 8. Maximum environmental temperature and standard effective temperature on summer design day

		Living room				Bedroom			
		MRT	DBT	$EnvT$	SET	MRT	DBT	$EnvT$	SET
		(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
Daytime	Option 1	34.9	35.3	35.1	35.0	33.6	35.2	34.1	34.1
	Option 2	35.4	35.3	35.3	35.1	34.2	35.2	34.5	34.4
Nighttime	Option 1	31.2	29.5	30.6	33.2	32.5	31.8	32.3	33.5
	Option 2	30.9	29.5	30.4	32.8	33.1	31.9	32.7	33.8

Table 9. Maximum environmental temperature and standard effective temperature on winter design day

		Living room				Bedroom			
		MRT	DBT	$EnvT$	SET	MRT	DBT	$EnvT$	SET
		(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
Daytime	Option 1	31.3	31.3	31.3	30.4	30.1	31.7	30.7	29.8
	Option 2	31.8	31.4	31.7	30.8	30.5	31.7	30.9	29.9
Nighttime	Option 1	28.8	27.3	28.3	28.4	29.4	29.2	29.3	29.1
	Option 2	28.7	27.3	28.2	28.4	29.8	29.3	29.6	29.4

From Figure 7, the environmental temperature could be dragged into the comfort zone under high wind velocity of 1.5 m/s during summer design day and 1.0 m/s during winter design day. In order to maintain indoor air motion, an electric fan should be used.

On summer design day, the standard effective temperature was almost equivalent to the environmental temperature due to the effect of humidity. Under the condition of 50% relative humidity, people feel equal to the temperature of the surrounding environment.

Regarding the simulation result, daytime humidity was lower than 50%. Thus, people could feel colder than the actual temperature around 1.0˚C. Applying natural ventilation during daytime was preferable to nighttime due to lower humidity.

For nighttime, the utilization of active system was set at 3 hours (6:00 p.m. to 9:00 p.m.) for the living room, and at 9 hours (9:00 p.m. to 6:00 a.m.) for the bedroom. Under the setpoint temperature at 25˚C, the air conditioning system in option 1 indicated better performance in space cooling. The environmental temperature was lower than the room with the radiant cooling system. However, the mean radiant temperature was higher than the air temperature (dry-bulb temperature). As a result, heat from the room's surface radiated to the room's air. In option 2, applying the radiant cooling system could reduce mean radiant temperature to be lower than the air temperature. As a result, heat from occupants and room's air radiated to the cooler surface.

The hours of applying natural ventilation could be extended from daytime to nighttime occupancy on winter design day. The comfortable environment could be achieved under low wind velocity of 0.5 m/s, see Figure 8.

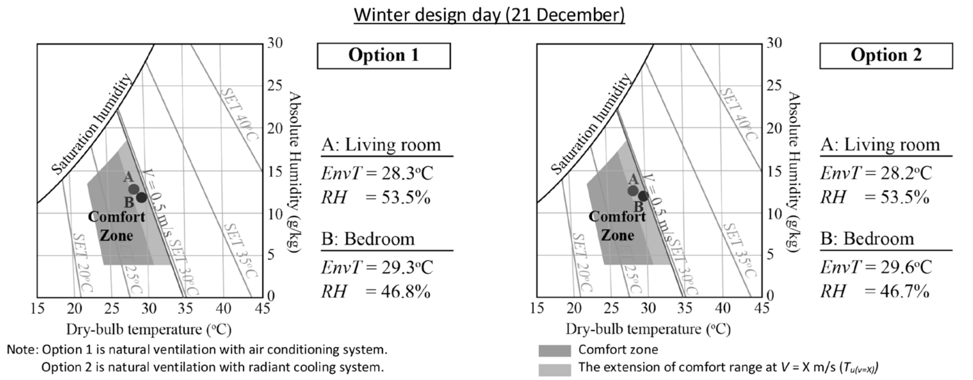


Figure 8. Nighttime maximum environmental temperature and thermal comfort on winter design day

5.3 Cooling energy consumption

Cooling energy consumed by the active system can be shown in Table10. The result showed that the radiant cooling system indicated lower cooling energy consumption under the same setpoint temperature at 25˚C. Average cooling energy per area was lower than cooling energy used in the air conditioning system approximately 20% reduction for the living room and 36% reduction for the bedroom on summer design day. On winter design day, the result showed that half of the cooling energy consumed during summer design day was reduced. When the radiant cooling system is utilized, the room with low heat gain, the bedroom, indicated a greater reduction in cooling energy consumption than the room with high heat gain, the living room.

6. Conclusions and further study

This study aims at finding the design modification for the high-rise condominium which passive with the active system are implemented to optimize the benefits of an occupant thermal comfort and cooling energy consumption. According to the three-tier design approach: 1) heat avoidance strategy, 2) Passive cooling strategy, and 3) Active cooling strategy, the combination between passive design strategies with the active system regarding the results from field measurement and computer simulation was proposed.

For the design modification, removing the west-facing window and adding the horizontal overhang with a vertical fin of 0.9 m depth should be considered to avoid heat from entering the room. The indoor temperature could be reduced up to 2.8˚C.

Table 10. Cooling energy consumed by the active system

	Cooling energy per area (J/m^2)			
	Summer design day (21 April)		Winter design day (21 December)	
	Living room	Bedroom	Living room	Bedroom
Option 1	459,962	240,662	253,448	97,228
Option 2	369,719	153,071	233,187	66,591

The natural ventilation should be utilized as the main mode of ventilation. The results indicated that applying natural ventilation during daytime could extend the comfort range and enhance the occupant comfort sensation under high wind velocity of 1.5 m/s. The hours of using natural ventilation could be extended from daytime to nighttime occupancy due to the influences of low temperature and humidity in winter. Nighttime thermal comfort could be provided under the wind velocity of 0.5 m/s.

When only natural ventilation is insufficient to maintain comfort environment during nighttime due to high humidity, an active cooling system is an alternative to control the indoor environment. Under the setpoint temperature at 25˚C, the conventional air conditioning system indicated the greater performance in space cooling compared to the radiant cooling system. However, the room's surface temperature was higher than the air temperature and resulted in high environmental temperature. On the other hand, applying radiant cooling system could reduce surface temperature to be lower than the air temperature. As a result, heat from occupants and indoor environment could radiate to the colder surface.

Moreover, the room with natural ventilation is applied with the addition of the radiant cooling system indicated that the cooling energy was decreased compared to the room without natural ventilation. Meanwhile, the cooling energy increased in the room that natural ventilation was applied along with the air conditioning system. However, the equivalent performance between an air conditioning system and a radiant cooling system should be further investigated in order to achieve more accurate results. Based on the recommendation, modifications of high-rise condominium in hot-humid climate can be further improved.

References

American Society of Heating, Refrigerating and Air-conditioning Engineers [ASHRAE]. (2013). *ASHRAE handbook: Fundamentals*. Atlanta, GA: Author.

Auliciems, A. (1981). Towards a psychophysiological model of thermal perception. International Journal of Biometeorology, 25(2), 109-122.

Auliciems, A. & Szokolay, S.V. (2007). Thermal comfort (2nd ed.). Retrieved from http://www.researchgate.net/publication/234169993_THERMAL_COMFORT

Brager, G. S. & De Dear, R.J. (1998). Thermal adaptation in the built environment: a literature review. *Energy and Building, 27*(1998), 82-96.

Cook, J. (1989). *Passive cooling*. London, England: The MIT Press.

Dimoudi, A. (1996). Passive cooling of buildings, Passive Cooling of Buildings [Santamouris, M. & Asimakopoulos, D. (eds.). James & James (Science Publishers) Ltd., London, 35-55.

Energy Policy and Planning Office, Ministry of Energy. (2016). *Energy statistics of Thailand 2016*. Retrieved from http://www.eppo.go.th/index.php/th/eppo-intranet/item/11342-energy-statistics-2559

Feustel, H.E. (1993). *Hydronic radiant cooling: Overview and preliminary performance assessment*. Lawrence Berkeley Laboratory Report No. 33194.

Gagge, A. P., Fobelets, A.P., & Berglund, L.G. (1986). A standard predictive index of human response to the thermal environment, *ASHRAE Transac, 92*(2B), 709-731.

Givoni, B. (1994). *Passive and low energy cooling of buildings*. New York, NY: John Wiley & Sons, Inc.

Khedari, J., Yamtraipat, N., Pratintong, N. & Hirunlabh, J. (2010). Thailand ventilation comfort chart. *Energy and Buildings, 32*(3), 245-249.

Kubota, T., Jeong, S., Toe, D. H. C., & Ossen, D. R. (2011). Energy consumption and air-conditioning usage in residential buildings of Malaysia. *Journal of International Development and Cooperation, 17*(3), 61-69.

Lechner, N. (2015). *Heating, cooling, lighting: Sustainable design methods for architects*. Hoboken, NJ: John Wiley & Sons, Inc.

Li-Zenn Publishing. (2015). *New design condominium Thailand*. Bangkok, Thailand: Author.

Niu, J. (2003). Some significant environmental issues in high-rise residential building design in urban areas. *Energy and Building, 36*(2004), 1259-1263.

Plus Property. (2016). *Plus property focus: Half-year research paper, July-December 2015*. Retrieved from http://www.plus.co.th/News-and-Articles/Plus-Property-Focus-Half-year-research-paper-July---December-2015.

Rijai, H.B., Humphreys, M., & Nicol, F. (2015). Adaptive thermal comfort in Japanese houses during the summer season: Behavioral adaptation and the effect of humidity. *Buildings, 5*(2015), 1037-1054.

Srisuwan, P. (2017). *Title of Passive design strategies with active system enhancing indoor thermal comfort of a high-rise condominium in hot-humid climate of Bangkok*. (Unpublished doctoral dissertation). Graduate School of Science and Engineering, Saga University, Saga, Japan.

Srisuwan, P., & Kojima, S. (2016). Field investigation on indoor thermal performance of a high-rise residential unit in Bangkok. *International Journal of Building, Urban, Interior and Landscape Technology, 7*(September - October), 13-22.

Srisuwan, P., & Kojima, S. (2017). Field investigation on indoor thermal environment of a high-rise condominium in hot-humid climate of Bangkok, Thailand. *Procedia Engineering, 180*, 1754-1762.

Szokolay, S.V. (2008). *Introduction to architectural science: the basis of sustainable design* (2nd ed.). Woburn, MA: Architectural Press.

Thailand, Meteorological Department. (2013). *Bangkok's weather data*, 2004-2013 [computer file].

Thailand, Ministerial Regulation (2009). *Prescribing type or size of building and standard, criteria and procedure in designing building for energy conservation B.E. 2552*. Retrieved from http://www2.dede.go.th.

Thai Green Building Institute. (2019). *Project.* Retrieved from http://www.tgbi.or.th/project

U.S. Department of Energy. (2015). *EnergyPlus version 8.7 documentation: Engineering reference*. Retrieved from https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v8.7.0/EngineeringReference.pdf