DESIGN AND HYGROTHERMAL PERFORMANCE ANALYSIS OF AN INTEGRATED FULL VENTILATION APPROACH FOR RESIDENTIAL HOUSES

GEORGES KHEDARI

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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ENERGY ENGINEERING TECHNOLOGY
DEPARTMENT OF POWER ENGINEERING TECHNOLOGY
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Dissertation Proposal Certificate

The Graduate College, King Mongkut's University of Technology North Bangkok

Title DESIGN AND HYGROTHERMAL PERFORMANCE ANALYSIS OF AN INTEGRATED FULL VENTILATION APPROACH FOR RESIDENTIAL HOUSES

By Georges Khedari

Accepted by the COLLEGE OF INDUSTRIAL TECHNOLOGY, King Mongkut's University of Technology North Bangkok in Partial Fulfillment of the Requirements for the Doctor of Philosophy in Power Engineering Technology

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Major Field	: Energy Engineering Technology King Mongkut's University of Technology North Bangkok
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ABSTRACT

It is well known that proper ventilation can help improve indoor comfort, protect the health of residents, avoid heat and moisture accumulation and save energy. In Thailand, modern houses and residence buildings often do not consider ventilation due to the lack of compulsory regulation and to reduce construction cost. Consequently, excessive heat, moisture, odors and mold growth are observed in indoor spaces that lead to several problems for inhabitants including poor indoor air quality, health risk and contamination. Today, due to modern lifestyle, built-in furniture attract attention as it is modern, easy to make and can be adjustable to each individual space offering architects and interior designers various choices to come up with innovative forms and design. However, materials used such particleboards and wood panels include some chemicals that are harmful to the health of occupants and adsorb air moisture especially unventilated spaces and when air-conditioning is used alternately.

The dissertation objective is to develop an integrated full ventilation approach for houses (IFVH) and residence buildings. The concept is to design and assemble a Built-in Closet (BC) with a proper system of ventilation that can allow to ventilate the indoor space according to the relevant standards, the Built-in Closet and the attic of house simultaneously. To this end, a small prototype of VBC of 1.248 m^3 volume, made from commercial particleboards, was manufactured. Using a small DC fan located at the top, air enters at the bottom, circulates inside through appropriate openings located at different positions, and exits at the top. The VBC was located inside an empty room 52 m^3 volume of a residential house located in Bangkok. Tests were conducted under different conditions and various ventilation scenarios. Results are compared to a standard built-in closet (BC) of the same volume juxtaposed to the VBC. Measured data showed that the temperature inside the VBC is always lower than that of the BC and higher difference is observed during daytime whereas relative humidity difference is less noticeable due to close range of temperatures. The recommended ventilation schedule varied between daytime (20min. ON/10min. OFF) and nighttime (10min. ON/20min. OFF), and the appropriate ventilation rate was found equal to that required to ensure good room air change (0.7 ACH). The corresponding VBC air change is 7.94. The VBC took a short period of about 10 minutes to remove all amount deodorant (2000 mg/m^3 TVOCs) sprayed inside. A variety of design options and alternatives of ventilated built-in closets (VBC) for different standard parts designs such as waldrapps, shelves, etc. are reported and discussed. The thesis outputs will benefit architects, interior designers and engineers to design houses that can offer good and healthy indoor environment for residents, reduce indoor contaminations and save energy.

Keyword : Built-In Closet, Air Quality, Thermal Comfort, Ventilation, Sustainable Built Environment.

______________________________ Advisor

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Georges Khedari

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LIST OF ABBREVIATIONS

BC	Normal Built-In Closet
DT	Temperature Differences
IFVH	Integrated Full Ventilation Approach for Residential Houses
RHBC	Relative Humidity of Built-In Closet
RHRoom	Relative Humidity of the Room
RHVBC	Relative Humidity of Ventilated Built-In Closet
TBC	Temperature of Built-In Closet
TRoom	Temperature of the Room
TVBC	Temperature of Ventilated Built-In Closet
TVOCs	Total Volatile Organic Compounds
VBC	Ventilated Built-In Closet

Chapter 1
Introduction

1.1 Background and Statement of the Problem

It is well known that proper ventilation can help improve indoor comfort, protect the health of residents, and avoid heat and moisture accumulation. However, modern houses and residence buildings in Thailand often do not consider indoor space ventilation seriously due to the lack of compulsory regulation and to reduce construction cost. Ventilation using simple exhaust fans is applied only for limited spaces such kitchen and restrooms located inside residences without windows. Consequently, excessive heat, moisture, odors, and mold growth are observed in indoor spaces that lead to several problems for inhabitants including thermal discomfort, poor indoor air quality, health risk and contamination.

The last three decades saw extensive research effort paid by researchers, architects, and professionals in developing hot humid countries to emphasis the importance of ventilation. Several new architectural design options and systems to ventilate indoor spaces were developed and a significant number of research works are published in specialized literature. By far, solar chimney received special attention as it can induce ventilation and reduce heat gain. Various designs of roof and wall solar chimney configurations were developed including and tested worldwide.

Nowadays, following trends of new lifestyle, built-in furniture attracts attention as it is modern, easy to make and can be adjustable to each individual space offering owners, architects and interior designers. Various choices, methods and options are widely available with innovative forms and design. However, materials used such particleboards and wood panels include some chemicals that are harmful to the health of occupants and adsorb air moisture especially in unventilated spaces and when air-conditioning is used alternately.

The aim of this thesis is to develop an integrated full ventilation concept for houses and residence buildings (IFVH). To do this end, we first focus on the development of a new concept for designing Built-in Closet (BC) with a proper system that can allow to ventilate its inner space. This concept is referred to as Ventilated Built-in Closet (VBC). By integrating this new concept in the inner space such bedrooms, living, dining areas, rooms, etc., it can ensure the integrated full ventilation concept including the built-in closets. Additionally, when VBC is located at the upper floor of houses, it can be used to ventilate attic as well with a greater benefit for residences owners.

1.2 Objectives

The objective of this thesis is to develop an integrated full ventilation concept for houses and residence buildings (IFVH) based on a new concept of Built-in Closet

(BC) with a proper system that can allow to ventilate the inner space. This system is referred to as Ventilated Built-in Closet (VBC). The main objectives are as follows :

1.2.1 To propose design concept of the house full integrated ventilation approach and the VBC

1.2.2 To manufacture and install the built-in close and its various components of the proposed system in a bedroom located in a residential house in Bangkok.

1.2.3 To determine the appropriate ventilation schedule, flowrate and air change (ACH) of VBC.

1.2.4 To conduct hygrothermal performance and air quality analysis of the VBC.

1.2.5 To assess the performance of the IFVH.

1.2.6 To propose design options of VBC and its integration at different locations for practical adaptation inside the residential houses and buildings.

1.3 Scope of the Study

The dissertation will be conducted experimentally by using a full-scale prototype of one unit of a regular type of built-in closet widely used. Field tests will be conducted using a bedroom in a residential house located in Bangkok. The VBC is made of commercial particleboards.

1.4 Expected Benefits

The dissertation outputs will benefit architects, interior designers and engineers from various points of views. These include design guidelines for practical application in houses and buildings, promote innovation, reduce indoor contaminations, offer houses and residences owners good indoor air quality and healthy indoor environment, and save energy. According these advantages, it will open an new era of built-in sustainable environment.

Chapter 2
Literature Review

2.1 Human Thermal Comfort

Today there are several definitions and concepts for human thermal comfort and might be expressed as a state of mind that express satisfaction under prevailing ambient conditions. This sensation is quite difficult to assess as it depends on various parameters such as state of mind, physiological, psychological and environmental conditions, etc. The simple definition widely adopted is that of a person expressing his satisfaction with the thermal environment. Among the different parameters, the most used include dry bulb temperature, relative and air velocity. In tropical countries, where the temperature and humidity are practically high year-round, thermal discomfort is often observed.

2.2 Ventilation

It is well known that proper ventilation can help improve indoor comfort, protect the health of residents, and avoid heat and moisture accumulation. Under Thailand hot and humid climate, Figure 2-1 [1], a ventilation comfort chart was also developed comfort [2] as shown in Figure 2-2. It was shown that ventilation can be adopted to achieve residents' thermal under relatively acceptable ambient conditions.

Unfortunately, and due to the lack of compulsory regulation, modern houses and residence buildings in Thailand often do not consider indoor space ventilation seriously to reduce construction cost. In fact, ventilation using simple exhaust fans is applied only for limited spaces such kitchen and restrooms located inside residences without windows. Consequently, excessive heat, moisture, odors, and mold growth are observed in indoor spaces. Figure 2-3 shows examples of Mold observed at different parts of houses. This obviously can lead to poor indoor air quality that can cause several problems and health risks for inhabitants such as thermal discomfort, allergies, poor indoor air quality, health risk and contamination.

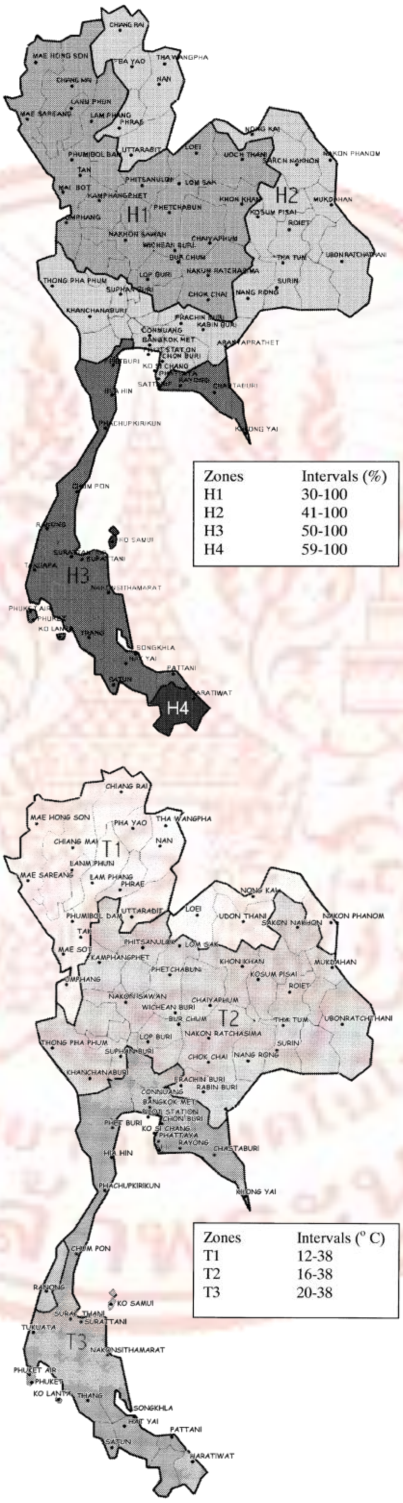


FIGURE 2-1 Thailand climatic zones [1].

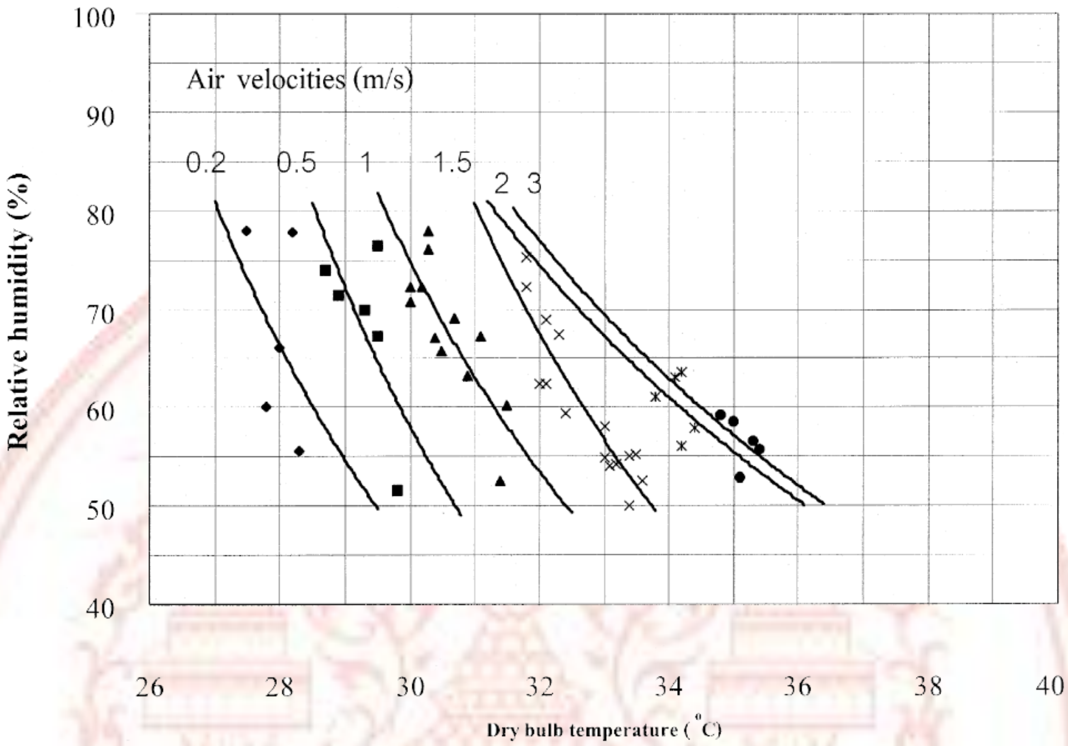


FIGURE 2-2 Thailand ventilation comfort chart [2].

FIGURE 2-3 Examples of mold observed at different parts of houses.

2.3 Furniture and Building

Nowadays, following trends of new lifestyle, built-in furniture attracts attention as it is modern, easy to make and can be adjustable to each individual space offering owners, architects and interior designers. Various choices, methods and options are widely available with innovative forms and design. However, materials used such particleboards and wood panels include some chemicals that are harmful to the health of occupants and adsorb air moisture especially in unventilated spaces and when air-conditioning is used alternately.

2.4 Literature Review

Nowadays, it widely agreed by architects, professionals and engineers that appropriate design of residences and buildings considering traditional wisdom and in harmony with the environment and the climate is crucial to achieve residents' thermal comfort [4-6]. The last three decades saw extensive research effort paid by researchers, architects, and professionals in developing hot humid countries to emphasis the importance of ventilation. Several new architectural design options and systems to ventilate indoor spaces were developed and a significant number of research works are published in specialized literature.

By far, solar chimney received special attention as it can induce ventilation and reduce heat gain. Numerous new architectural design options to ventilate indoor space were proposed and extensively investigated both experimentally and numerically. They include various designs of roof [7-10] and wall [11-14] solar chimney configurations and double skin facades [15-17]. Among these configurations, the BSRC innovative multipurpose bioclimatic roof reported in [8] composed of a combination of concrete tiles and transparent ones not only improved ventilation when compared to simple roof chimney configuration but allowed reasonable indoor daylighting.

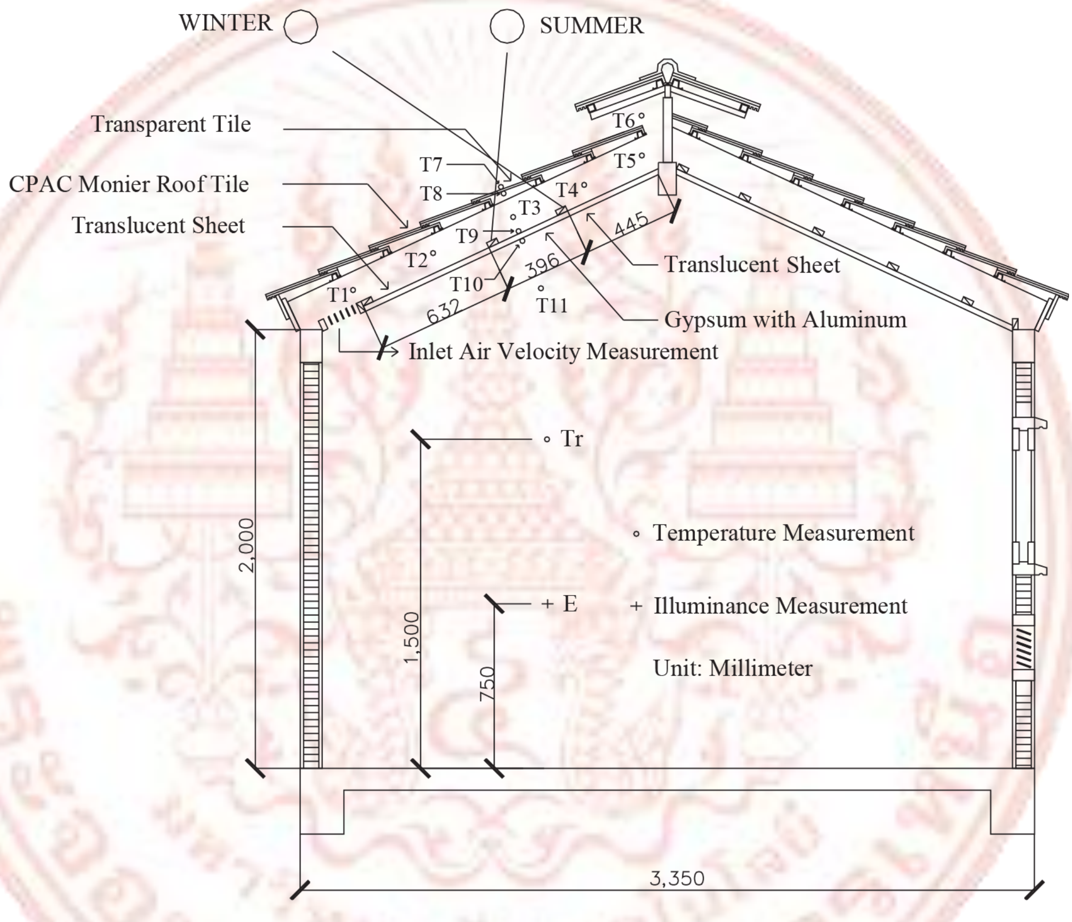


FIGURE 2-4 BSRC Bio-climatic roof [8].

Full–scale investigation of the BSRC bio climatic house that included several building envelope configurations including roof solar collector (RSC), modified Trombe wall (MTW), bio-climatic Roof (BCR) and glazed solar chimney wall (GSCW) was published in [13]. Authors demonstrated that significant improvement of indoor conditions were achieved.

The configuration of roof skylight combined with solar chimney integrating a combination of reflective aluminum and transparent slots proposed in [7] offered new perspectives for designing naturally based ventilated spaces.

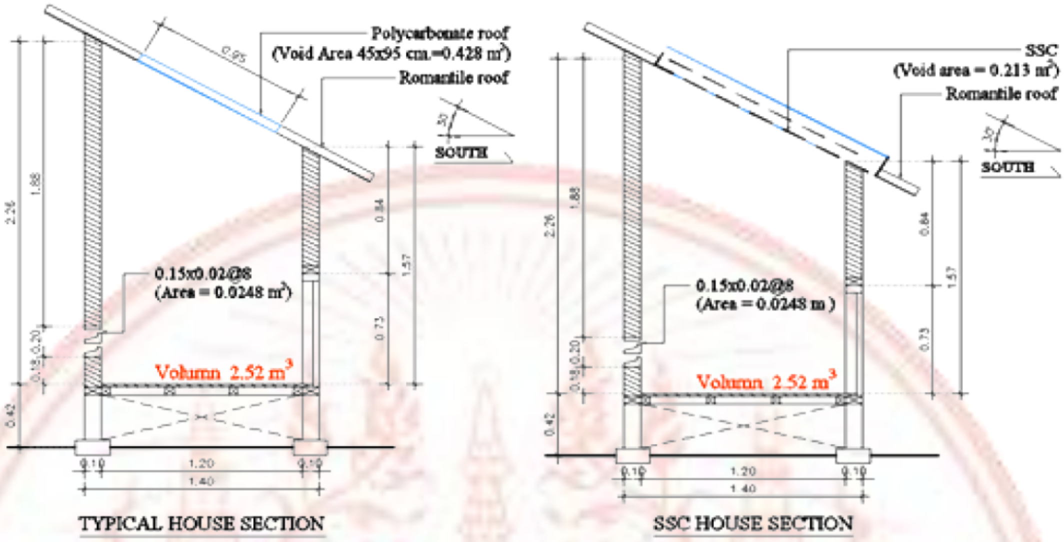
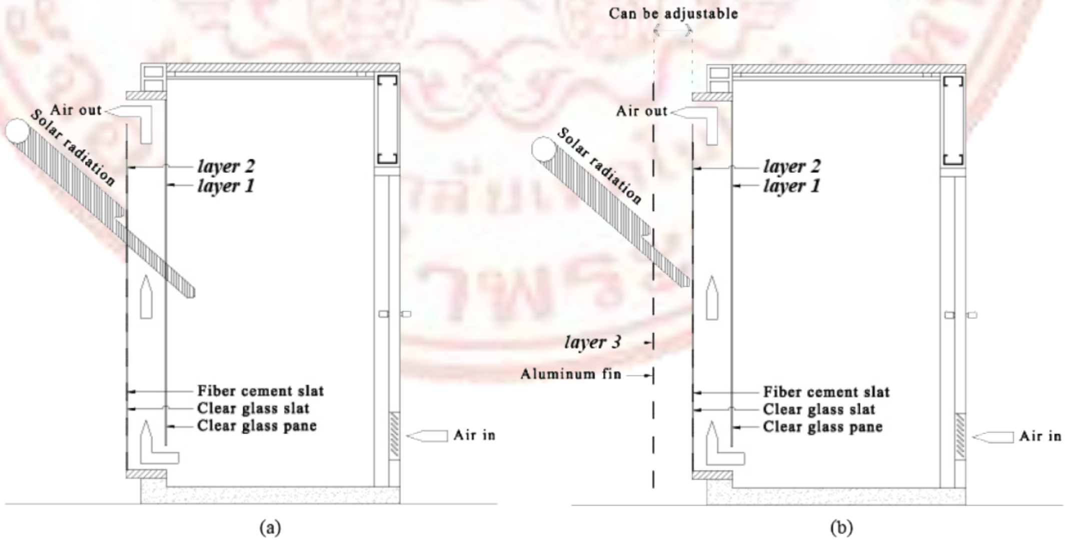
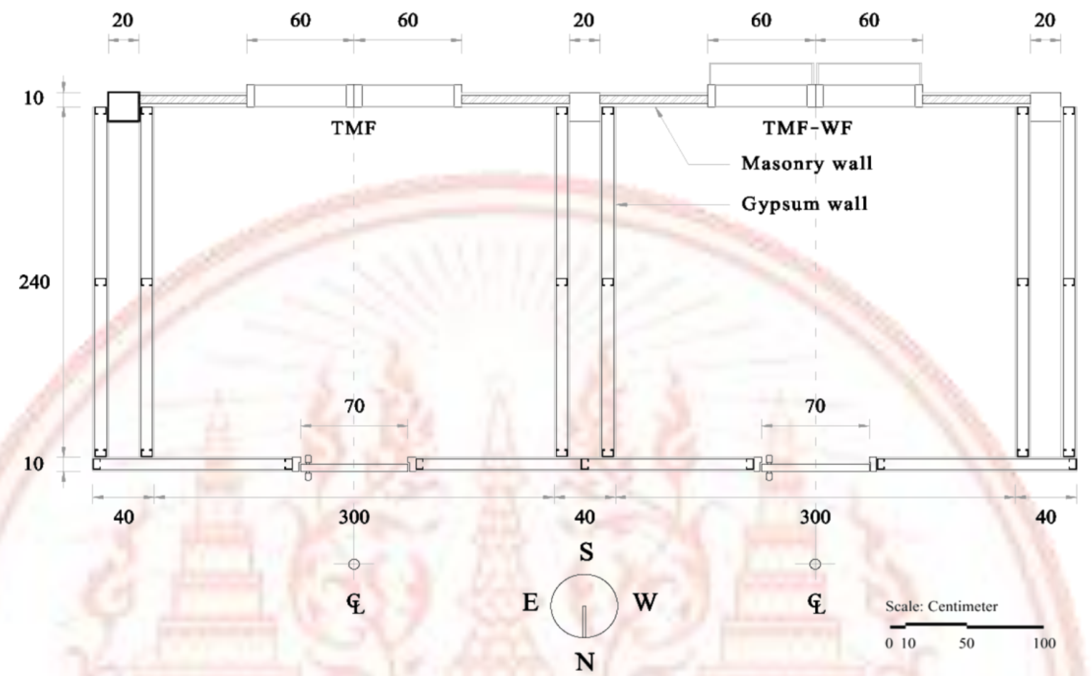
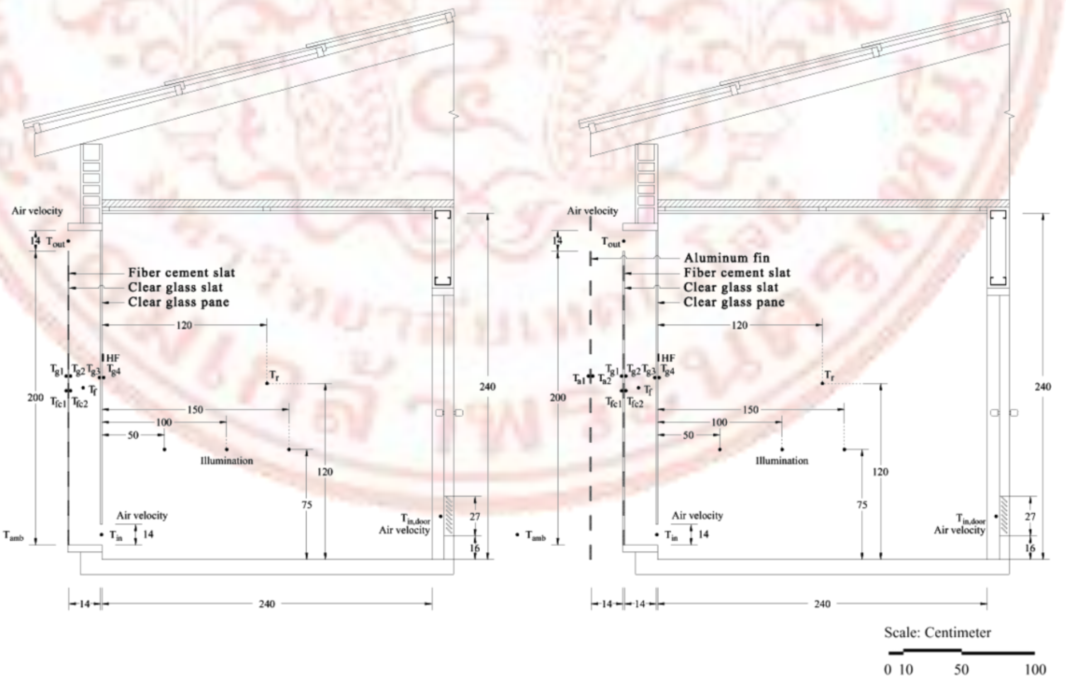


FIGURE 2-5 The configuration of roof skylight combined with solar chimney [7].

The new Modern Thai Façade Wall designed and tested in [11] showed very interesting results for heat gain reduction and enhancing solar-based indoor ventilation. The indoor illumination can be also optimized by varying the distance between the layers for better performance and improved visual feeling.




TMF
TMF-WF
Masonry wall
Gypsum wall
S
E
W
N
Scale: Centimeter


Air velocity
Fiber cement slat
Clear glass slat
Clear glass pane
Aluminum fin
Illumination
Scale: Centimeter

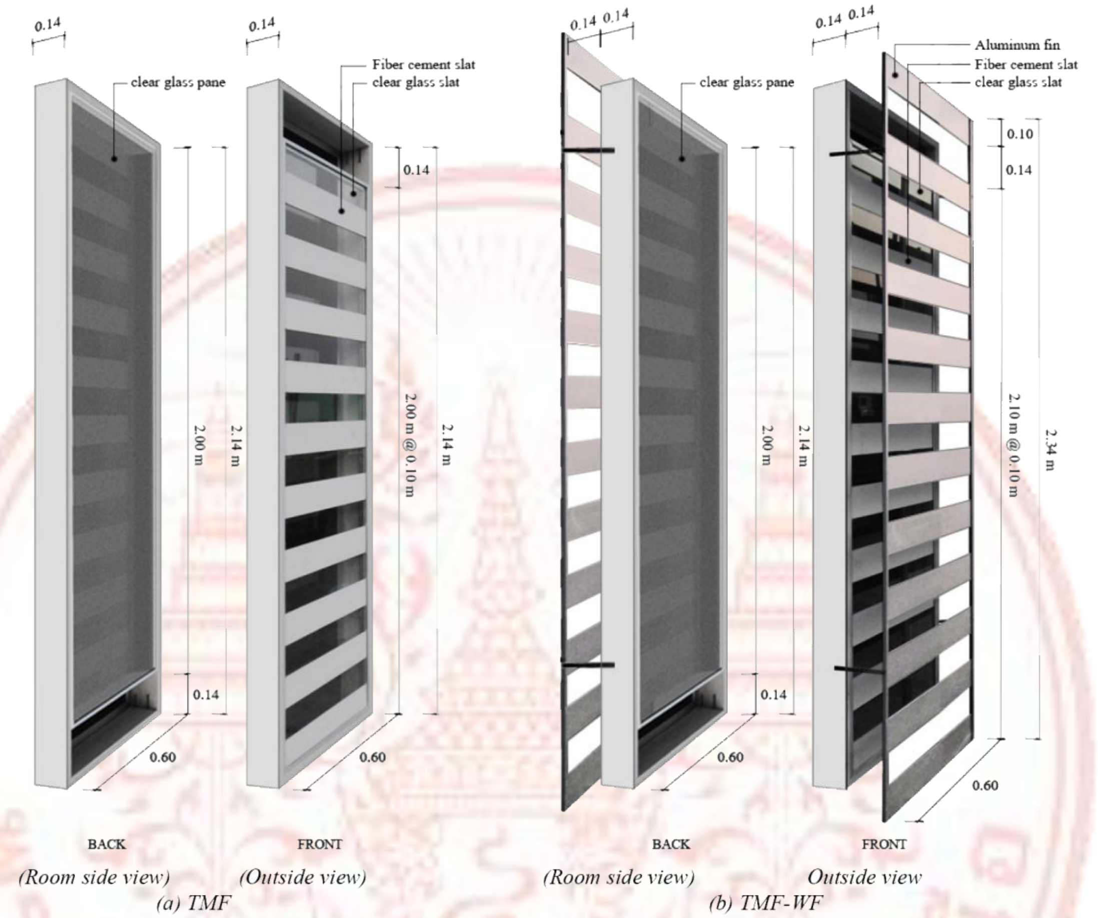


FIGURE 2-6 The configuration of the new modern Thai façade wall [11].

Other researchers addressed the development of roof solar chimney combined with other technologies such as evaporative cooling [18-19], radiant barrier [20-21], cool ceiling [22], earth to air heat exchanger [23], and water spraying [24].

Research outputs published in [25] reported experimental comparison between constant ventilation approach (CAV) and CO_2 based ventilation control approach with respect to energy saving of air conditioning. It was suggested that the proposed CO_2 can help save electrical energy especially when indoor spaces are not occupied continuously and could improve indoor air quality for highly occupied ones. A variable ventilation control strategy was also proposed in [26]. Using an experimental setup shown in Figure 2-7, it was demonstrated that a variable ventilation control strategy is re recommended of constant one as it can achieve acceptable indoor air quality and enhance electricity saving of the air conditioning.

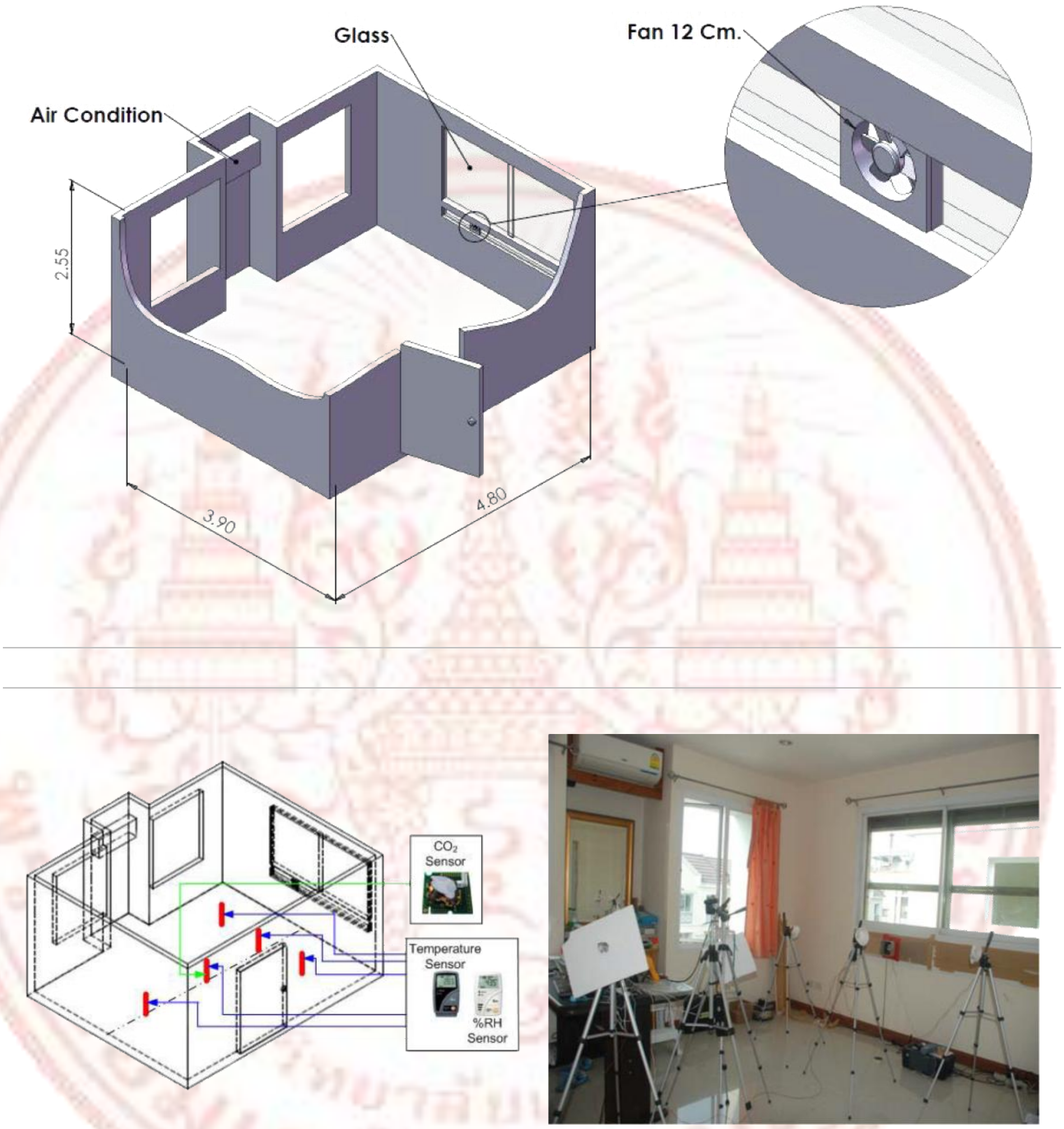


FIGURE 2-7 The experimental setup used for testing variable ventilation control Strategy [26].

With respect to built-in and furniture impact on indoor air quality and occupants, the specialized literature is rather limited and few research works are available. Hyun-Hwa Lee et al. [27] reported a study on the evaluation of the thermal environment for condensation and Mold problem diagnosis around built-in furniture in Korean apartment buildings during summer and winter, Figure 2-8. Authors concluded that the vulnerable areas to the condensation and mold problems in built-in furniture are at the back of furniture, wall side of the building, ceiling etc. In addition, the hot and humid exterior thermal environment influences that of the interior of built-in furniture significantly.

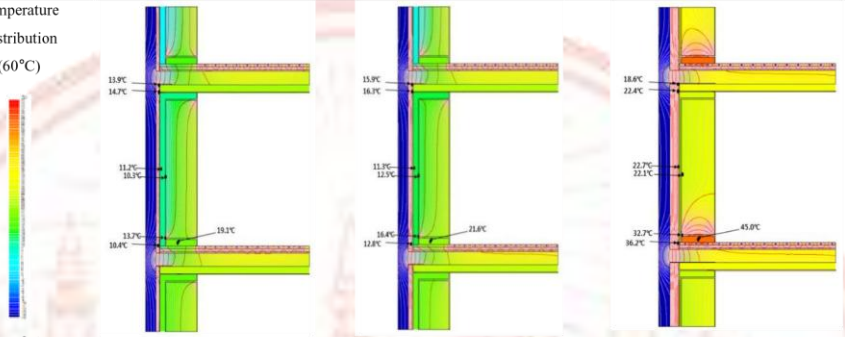
	Apartments A,B,D,G,H,J	Apartment K	New apartment by 2016
Temperature Distribution (60°C) (-15°C)			
U-value of wall (W/m2K)	0.47	0.36	0.21
Minimum Temp. Built-in furniture (°C)	10.3	12.5	22.1
Air Temp. between furniture and wall (°C)	11.2	11.3	22.7

FIGURE 2-8 Thermal analysis results regarding the surface temperature in winter [27].

An investigation of indoor thermal environment in a 3-D furnished and occupied model room with localized heat source and window glazing has been carried out by computational fluid dynamics approach by Kana Horikiri et al. [28]. The model has been used to investigate the effect of furniture arrangement with and without heat generation and occupants in terms of indoor thermal comfort. They found that an existence of non-heat generating furniture in the room and further addition of furniture could induce complicated flow re-circulations and high local air velocities around the edge of the furniture. There was little influence on room temperature and airflow buoyancy strength, compared with that of unfurnished room case. Heat generation from a TV did not have an important influence on the thermal comfort. When the furniture is located too close to the mainstream path from the inlet, it is regarded as obstacle along the flow path, causing the shear flow with high velocity gradients at the edges of the furniture and in the nearby regions, that further leading to re-circulation flows in anti-clockwise direction in the lower space between the window wall and the furniture. The existence of occupants was found to influence thermal sensation as it did increase air temperature for which the occupants will normally feel uncomfortable.

Thus, an increased flow ventilation rate would be required to keep the same thermal comfort level of the room.

By using a simplified two-layer wooden structure of common wooden furniture shown in Figure 2-9, and considering 1 m3 chambre, Yuanzheng Wang et al. [29] reported a study to assess the impact of temperature on the key parameters of VOCs emissions from wooden furniture. They found that with an increase of temperature from 25 ℃ to 35 ℃ that, the diffusion coefficient of VOCs emissions increase by 200% to 2993% significantly.

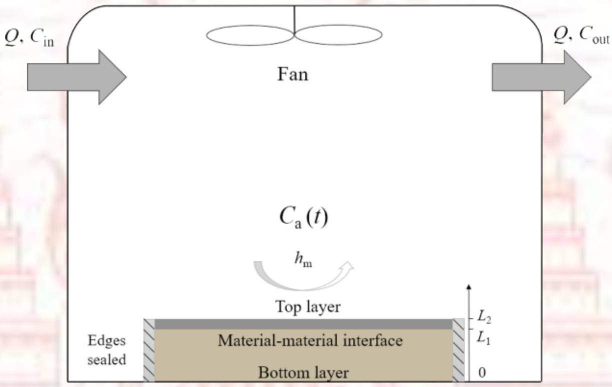


FIGURE 2-9 Schematic of the simplified two-layer wooden structure of common wooden furniture [29].

Experimental evaluation of thermally activated furniture (TAF) panels mounted in front and on the sides of a workspace as space partition panels was published in [30]. It was observed that TAF can be used to achieve personalized thermal comfort and have potential to save energy.

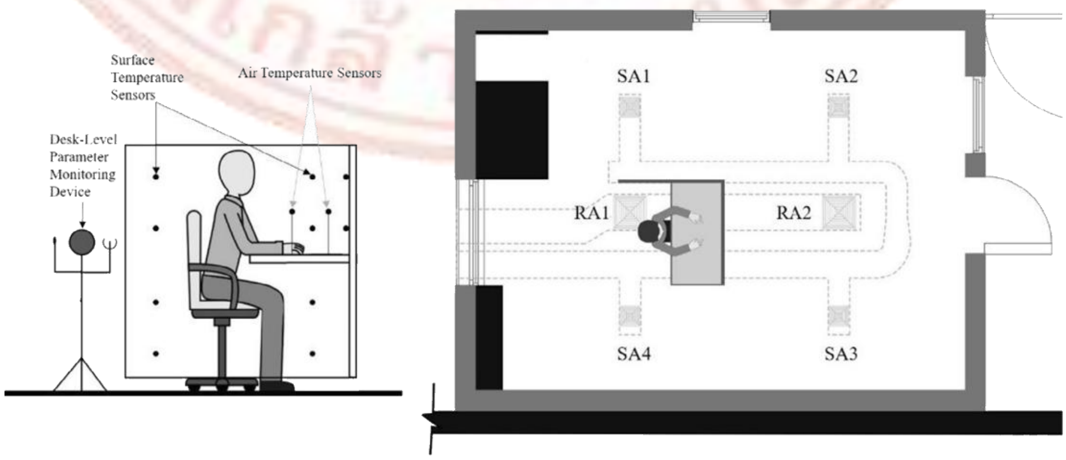


FIGURE 2-10 Experimental setup of thermally activated furniture [30].

A comprehensive review on integration of phase change materials in furniture for building energy storage and influence of internal thermal mass on the indoor thermal dynamics was reported by Hicham Johra et al. in [31].

Chapter 3
Methodology

3.1 Ventilated Built-in Concept Innovation

The new design concept of VBC is that it should allow air to enter at the lower part, circulate inside through various compartments and exit at the top. Figure 3-1 shows a schematic drawing of the proposed VBC design concept. For ventilating the VBC, we use a small DC fan located at the top and consider two small rectangular openings (1.5 cm. x 22 cm.) at the lower part under the front for air inlet, and at the deep part of the two inner shelves as seen in Figure 3-1. When the fan operates, air enters at the bottom, flows through, and exits at the top pulled out to the attic.

To conduct our investigation, we used a commercial particleboard and modified it according to our objective. Such, a small prototype of VBC of 1.248 m^3 volume was built. To assess the VBC performance, a standard built-in closet (non-ventilated) of the same volume was assembled and installed attached to the VBC. The panel separating the VBC and BC was well insulated using insulation foam and sealed using adhesive tape.

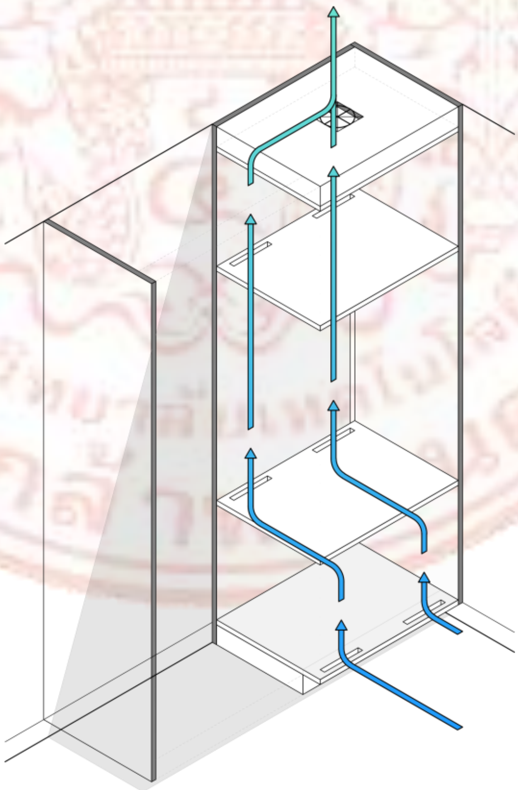


FIGURE 3-1 Schematic drawings of VBC design concept and ventilation contour.

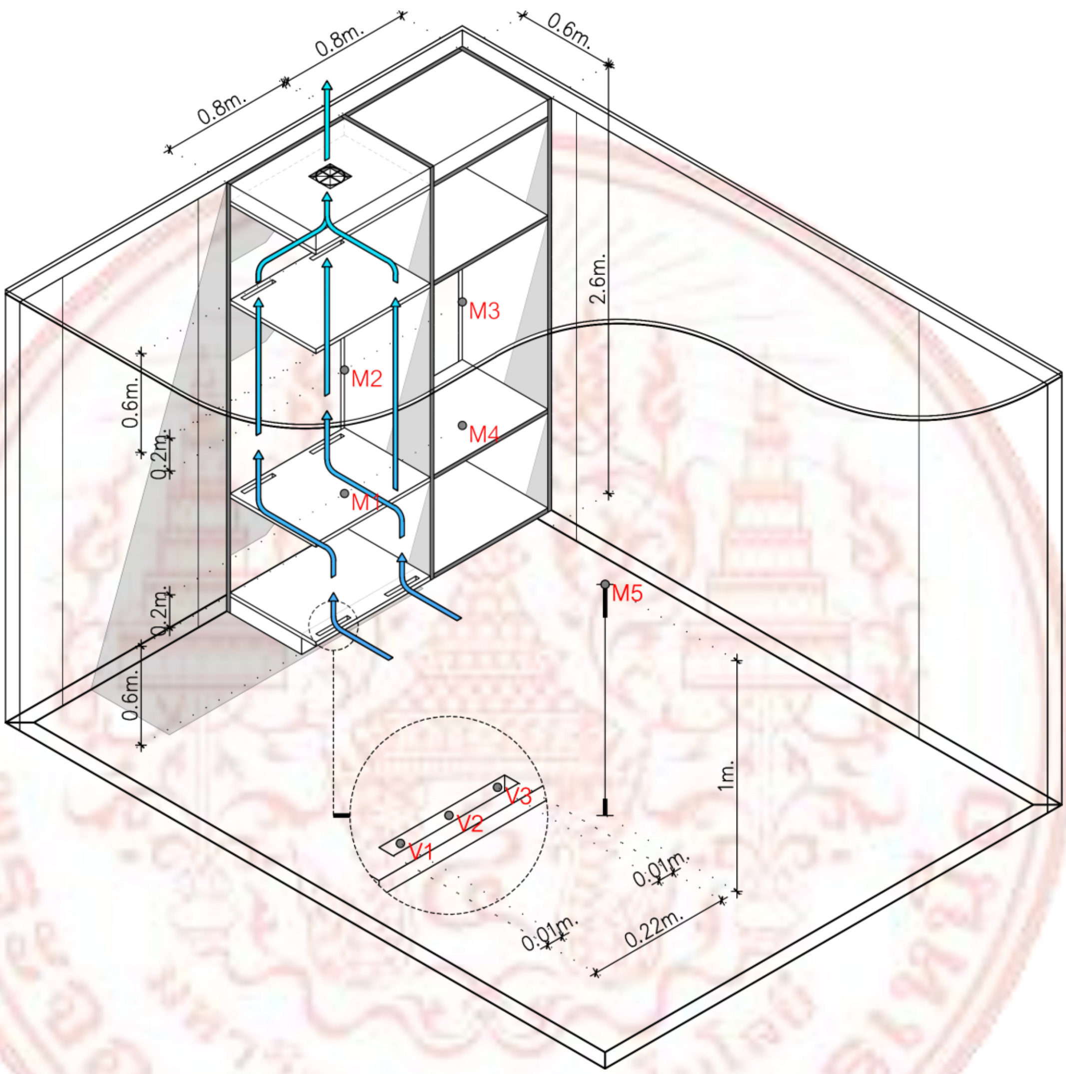


FIGURE 3-2 Schematic drawings of VBC design concept and dimensions.

3.2 The Experimental House

We remind that our objective is to develop an integrated ventilation approach of the residential house including indoor room space and attic. The experimental setup was located inside an empty bedroom 4.0m width, 5.0m length, and 2.6m height ($52m^3$ Volume) of a residential house located in Bangkok. Figure 3-2 shows a photograph of the house used for tests.

FIGURE 3-3 Photograph of the experimental house.

Fgure 3-3 shows the ventilated built-in closet and standard built-in closet installed in the bedroom.

FIGURE 3-4 Photograph of the VBC and BC installed in the bedroom on the 2nd floor.

3.3 Methodology of Experiment

3.3.1 Calculation of ventilation flowrate

According to room dimensions, 4 units of VBC could be installed and we assume that the ventilation rate of the four VBC units should be at least equal to that required for the bedroom where it is located. Based on ASHRAE standard requirement [32]. Table 3-1 shows the minimum calculated required ventilation rate for the bedroom assumed occupied with 2 persons and one unit of VBC.

Therefore, according to Table 3-1, the minimum calculated required ventilation rate of one unit of VBC is therefore 7.94 ACH. This value will be first used to determine the appropriate ventilation schedule, then its effect on VBC performance will be investigated experimentally.

TABLE 3-1 Calculation of VBC required ventilation.

Room	Dimensions	5m. x 4m. x 2.6m.
	Volume	$52m^3$
	Required Ventilation Rate	$39.6\ m^3/h$
	Air Change Rate	0.76 ACH
Ventilated Built-in Closet (VBC)	Dimensions (1 Unit VBC)	0.8m. x 0.6m. x 2.6m.
	Volume (1 Unit VBC)	$1.248\ m^3$
	Total Units	4
	Total Volume	$4.992\ m^3$
	Air Change Rate	7.94 ACH

3.3.2 Testing Conditions

The experimental test schedules and conditions adopted are given in Table 3.2.

TABLE 3-2 The experimental test schedule.

The Experimental Test Schedule	
Dates	**Test condition**
October 2022 - December 2023	Ventilation Scenario
December 2022 – January 2023	VBC Performance Analysis VBC Efficiency
June - July 2024	Air Quality
October 2024	Integrated Full Ventilation Approach for Residential Houses (IFVH)

3.3.3 Ventilation Scenarios

By far, one of the main objectives of ventilation is the identification of an appropriate ventilation schedule appropriate to achieve the objectives set up in this dissertation. Also, ventilation requirements depend on different parameters such as temperature, air moisture, air quality etc. For residents, apart from common and general factors, noise level is an important issue that needs to be considered carefully, especially at bedtime. By considering issues mentioned above, we choose four ventilation schedules varying between ON (min.) and OFF (min.) for daytime and nighttime as outlined in Table 3-3.

TABLE 3-3 The ventilation scenarios.

Daytime Ventilation Scenario ON (min.) : OFF (min.)				
Time (hr.)	05:25	10:20	15:15	20:10
Nighttime Ventilation Scenario ON (min.) : OFF (min.)				
Time (hr.)	05:25	10:20	15:15	20:10

3.3.4 Flowrate

After the determination of appropriate ventilation schedule for operating the fan, the effect of VBC ventilation flowrate is investigated. Table 3-4 shows the three fan voltages considered and the corresponding flowrates and VBC ACH.

TABLE 3-4 Fan voltage, measured inlet air velocity, flow rate and VBC air change rate.

Fan Voltage	**V_{in} (m/s)**	**Flow (m^3/h)**	**VBC ACH**
22V	0.71 ± 0.05	16.87	13.52
20V	0.58 ± 0.04	13.78	11.04
18V	0.43 ± 0.04	10.22	8.19

3.3.5 Instruments

3.3.5.1 WC Fan

We use a commercial DC fan (24V, 0.16A) Sanyo Denkij shown in Figure 3-4.

FIGURE 3-5 Photograph of the DC fan used.

3.3.5.2 Measuring equipment

Temperature and relative humidity were recorded at two positions inside the VBC and BC (Figure 3-1 using air mass online portable measuring equipment shown in Figure 3-5. Measuring ranges and accuracy are 0 to 50 ℃ ± 0.4℃, 5-100 % ± 3%. respectively. The temperature and relative humidity at the room center at 1 m level from floor was measured using testo 177-H1, (-20 to 70 ℃ ±0.4℃, 0-100 % ±2%). Shown in Figure 3-6.

FIGURE 3-6 Photograph of the portable online device used for temperature and relative humidity measurement.

FIGURE 3-7 Photograph of the testo 177-H1 used for room temperature and relative humidity measurement.

The total amount of volatile compounds (TVOCs) was measured inside the VBC using a portable online air quality meter. Shown in Figure 3-7. Measuring ranges and accuracy are: 0-2 mg/m^3 ≤± 10%, -40 to 100 °C ± 0.3°C, 0-99 % ± 3%.

FIGURE 3-8 Photograph of the portable online air quality meter.

Inlet air velocity was measured at three positions at each of the bottom inlet openings as shown in Figure 3-8 using testo 435 hotwire thermal anemometer (measuring range 0-20 m/s, ± 0.2m/s).

FIGURE 3-9 Photograph of the testo 435 hotwire thermal anemometer.

The ventilation schedule was controlled by using an electronic timer. Tests were repeated several times for each condition specified for daytime, nighttime and continuously on different days and under different ambient conditions. In this dissertation, the first part of data analysis focuses on determination of appropriate ventilation strategy, VBC hygrothermal performance, ventilation efficiency and air quality. Then, a full-scale test of the integrated full ventilation approach for residential houses (IFVH) and residences is conducted and analyzed.

Chapter 4
Experimental Results

It is worth mentioning that tests were conducted over several days during several months for the different conditions considered. Although ambient conditions varied from one day to another, subjective analysis and general results could be derived using measured physical parameters considered. Data were recorded continuously, and average data are calculated as appropriate for the different conditions considered.

4.1 Ventilation Scenarios

Tables 4-1 and summarize the hourly average temperature differences between the BC and VBC for the different fan operation scenarios considered during daytime, and nighttime respectively. It can be observed that the early morning hours, the temperature differences are relatively small compared to the other periods. This is obviously due to lower indoor temperature.

Table 4-1 indicates also that increasing the time of operating and reducing that when fan is OFF increases the temperature difference between the BC and VBC for all ventilation schedules considered. However, when it increased from 15 to 20 min., the average daytime temperature difference increase is not very significant as compared to the small periods of operation (5 and 10 min.). Therefore, increasing ventilation period more than 20 min. is not necessary and a 20 : 10 ventilation scenario might be considered appropriate for the daytime period.

TABLE 4-1 Daytime hourly average temperature differences between the BC and VBC for the four ventilation schedules considered.

	Daytime Ventilation Scenario ON (min.) : OFF (min.)			
Time (hr.)	**05:25**	**10:20**	**15:15**	**20:10**
06:00-07:00	0.49	0.58	0.68	0.71
07:00-08:00	0.51	0.65	0.74	0.81
08:00-09:00	0.50	0.64	0.76	0.85
09:00-10:00	0.54	0.66	0.77	0.79
10:00-11:00	0.60	0.67	0.79	0.77
11:00-12:00	0.59	0.69	0.79	0.80
12:00-13:00	0.63	0.73	0.81	0.82
13:00-14:00	0.62	0.72	0.79	0.78
14:00-15:00	0.65	0.76	0.76	0.76
15:00-16:00	0.64	0.78	0.74	0.79
16:00-17:00	0.63	0.74	0.75	0.81

Daytime Ventilation Scenario ON (min.) : OFF (min.)				
Time (hr.)	**05:25**	**10:20**	**15:15**	**20:10**
17:00-18:00	0.61	0.71	0.77	0.81
Average	**0.58**	**0.69**	**0.76**	**0.79**

At nighttime, Table 2-2 shows that operating the fan at 10(ON) : 20(OFF) scenario is sufficient to give good thermal performance. Reduced ventilation time is also useful that limit noise at bedtime and saving electricity. In the following sections, a 20 : 10 daytime and 10 : 20 nighttime ventilation scenario is adopted.

TABLE 4-2 Nighttime hourly average temperature differences between the BC and VBC for the four ventilation schedules considered.

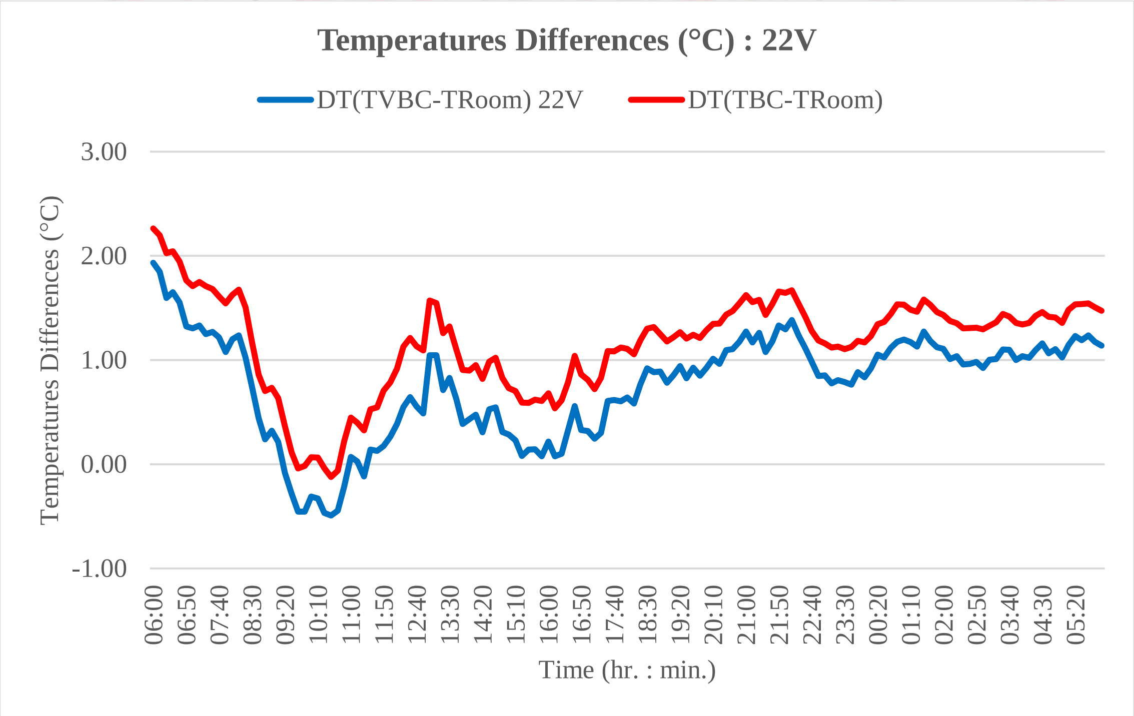
Nighttime Ventilation Scenario ON (min.) : OFF (min.)				
Time (hr.)	**05:25**	**10:20**	**15:15**	**20:10**
18:00-19:00	0.55	0.68	0.70	0.70
19:00-20:00	0.45	0.66	0.68	0.69
20:00-21:00	0.43	0.65	0.64	0.62
21:00-22:00	0.43	0.64	0.63	0.64
22:00-23:00	0.42	0.61	0.61	0.62
23:00-24:00	0.43	0.63	0.61	0.63
00:00-01:00	0.42	0.61	0.61	0.62
01:00-02:00	0.40	0.61	0.62	0.62
02:00-03:00	0.39	0.60	0.64	0.63
03:00-04:00	0.37	0.62	0.61	0.64
04:00-05:00	0.39	0.61	0.62	0.60
05:00-06:00	0.39	0.57	0.61	0.62
Average	0.42	0.62	0.63	0.64

4.2 Temperature and Relative Humidity

Figure 4-1 shows the variations of temperatures differences between the VBC and room DT(TVBC-TRoom) and between the BC and room DT(TBC-TRoom) whereas figure 4-2 shows those of the relative humidity variation of ventilated and non-ventilated built-in closet compared to room relative humidity for the three ventilation rates considered. Data collected are averaged every 10 minutes.

It can be observed that the fluctuation of measured temperatures and relative humidity varied well following the ambient conditions variations.

Under test conditions considered, measured data showed the temperature inside the VBC is always lower than that of the standard BC. Obviously higher temperatures differences are observed during daytime due to high room temperature. The relative humidity difference is less noticeable due to the small difference of temperatures between measured data. Increasing the ventilation rate did not lead to any noticeable performance improvement as the measured temperatures differences decreased.



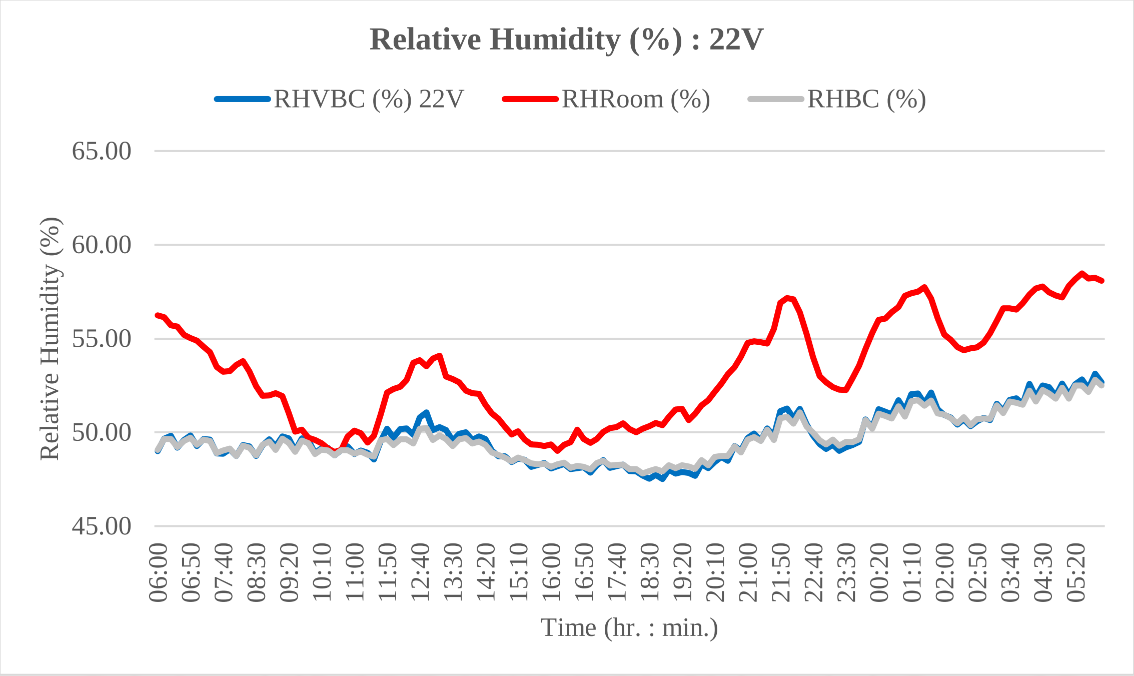
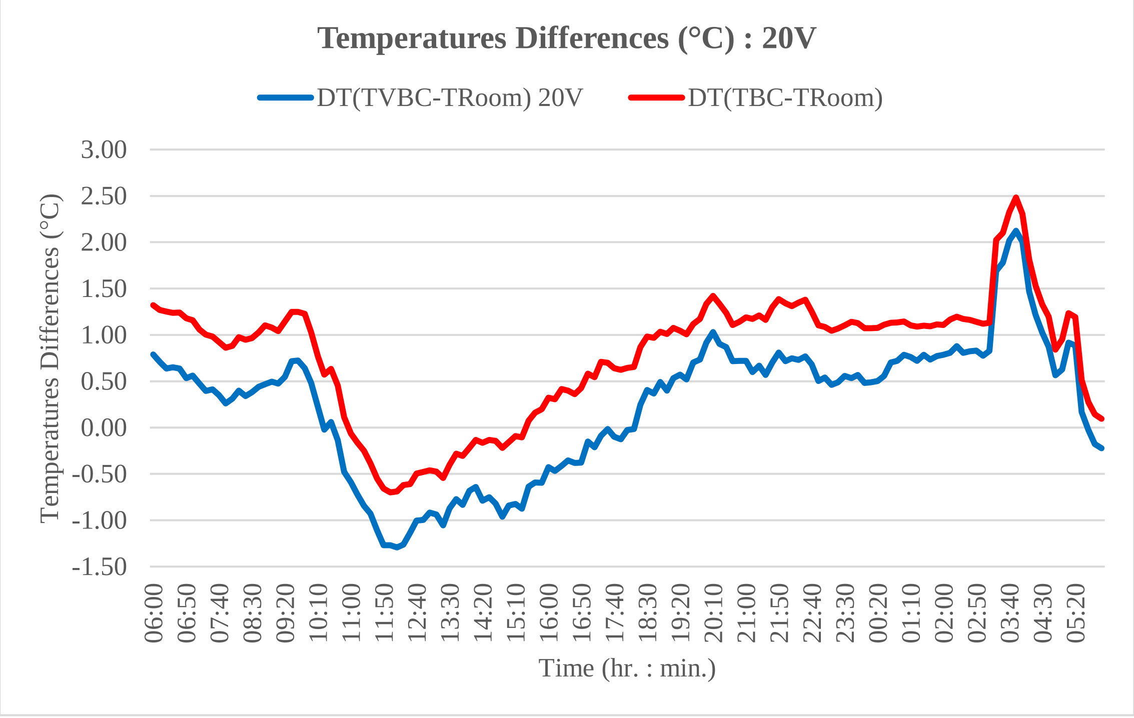


FIGURE 4-1 Hourly variation of temperatures differences between ventilated (VBC) and non-ventilated (BC) built-in closets and room (top) and of relative humidity of VBC and BC compared to room relative humidity at 16.87 m^3/h flowrate (22V).



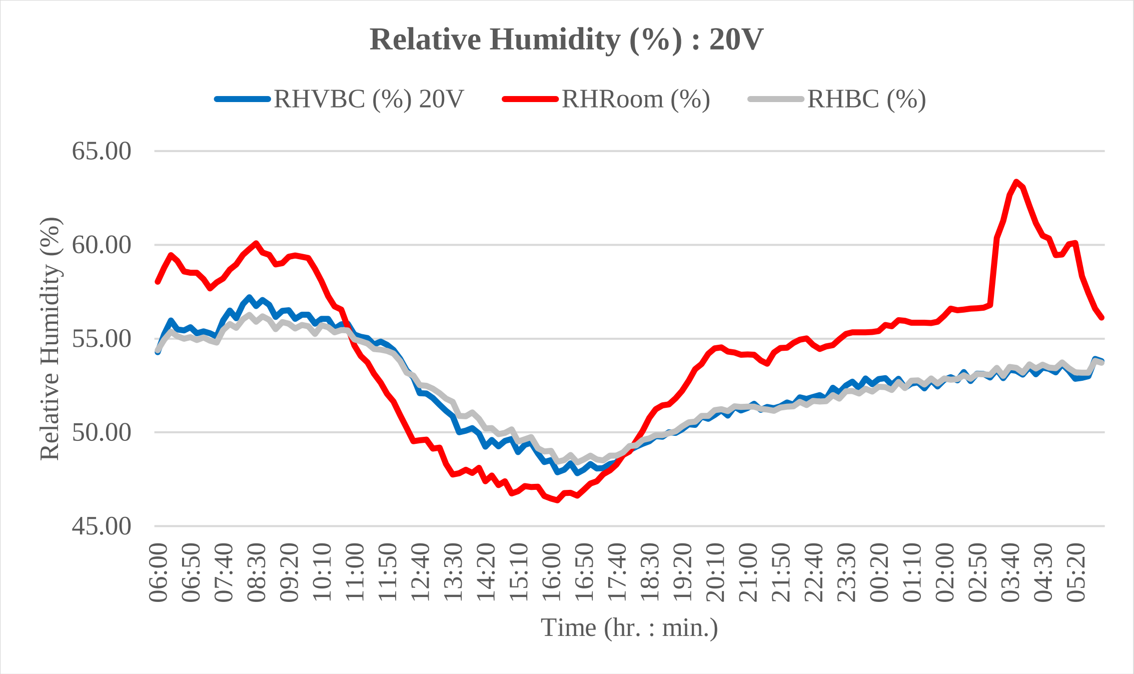
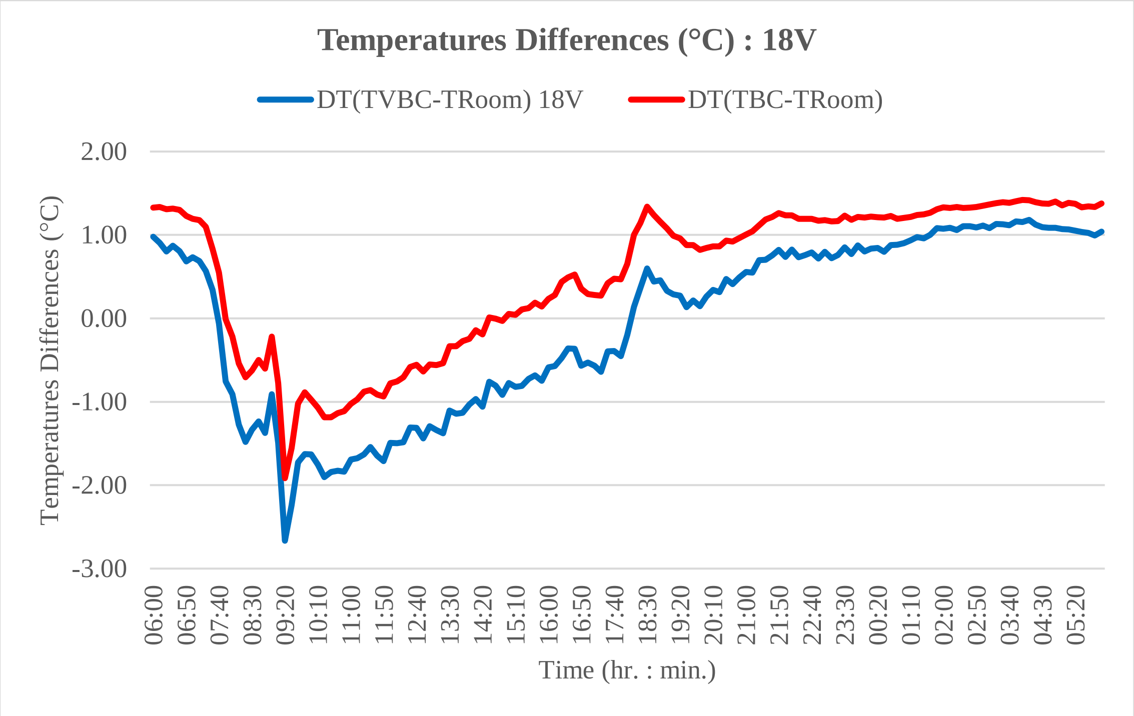


FIGURE 4-2 Hourly variation of temperatures differences between ventilated (VBC) and non-ventilated (BC) built-in closets and room (top) and of relative humidity of VBC and BC compared to room relative humidity at 13.78 m^3/h flowrate (20V).



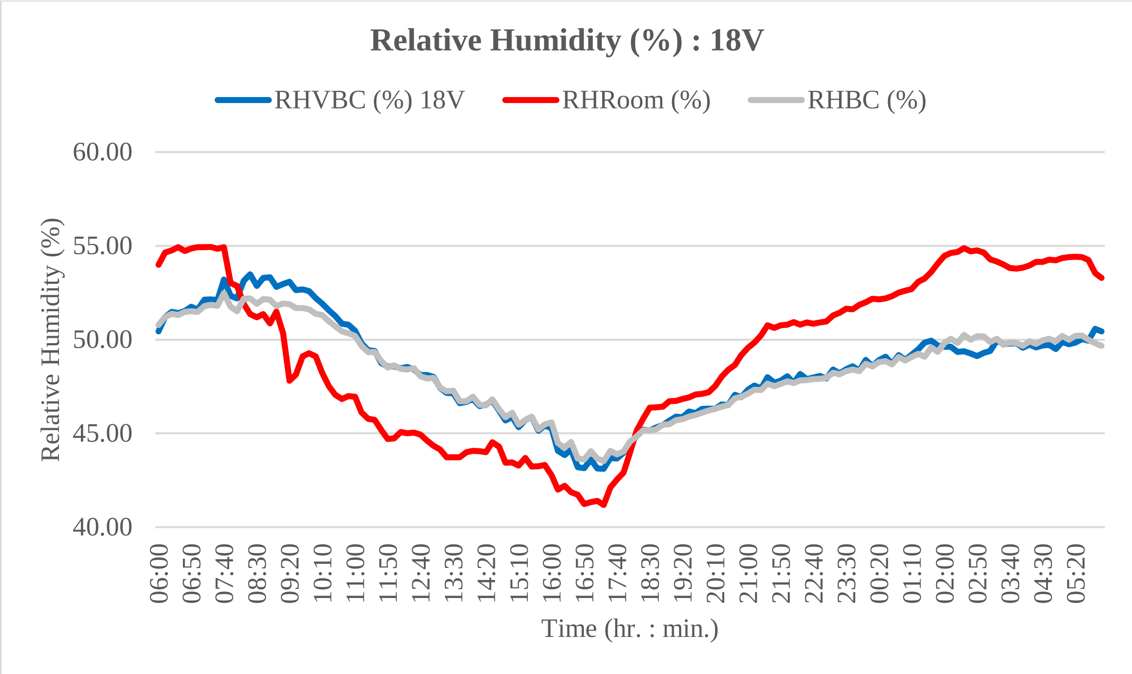
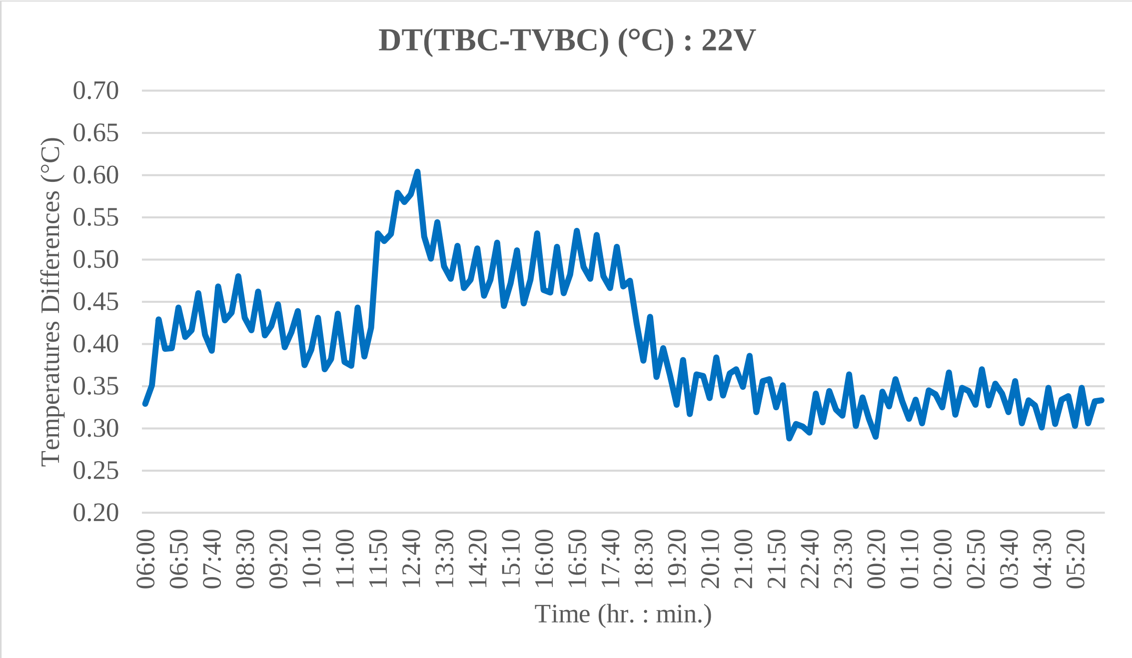
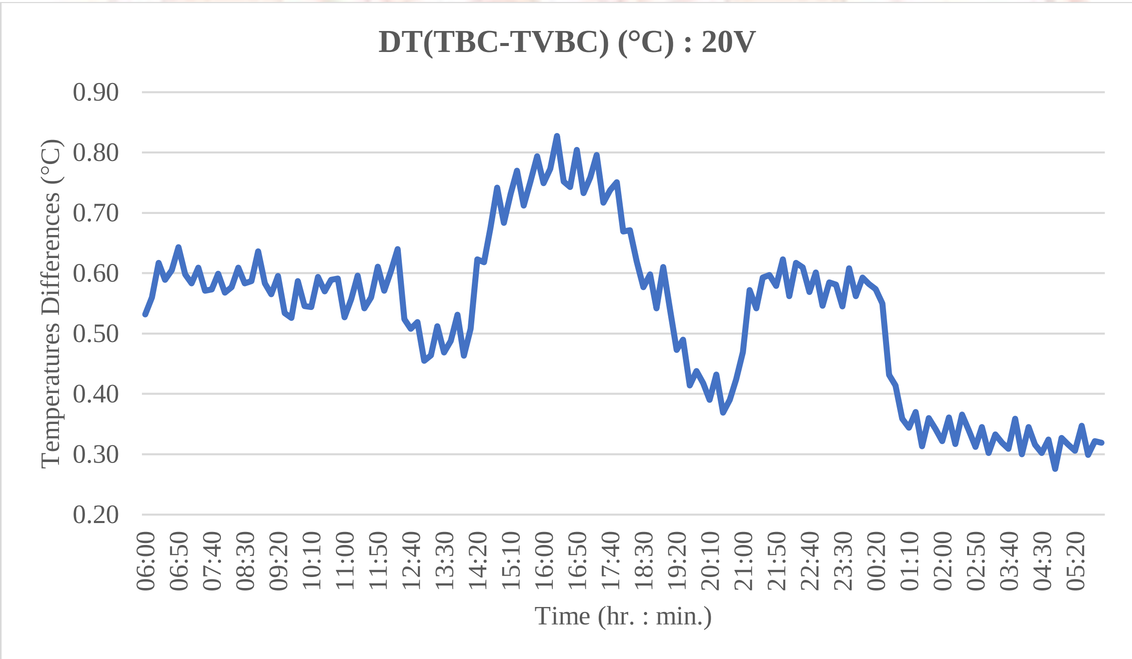


FIGURE 4-3 Hourly variation of temperatures differences between ventilated (VBC) and non-ventilated (BC) built-in closets and room (top) and of relative humidity of VBC and BC compared to room relative humidity at 10.22 m^3/h flowrate (18V).

For better assessment of the ventilation flowrate on the performance of VBC, figure 4.4 illustrates the calculated temperature differences between non-ventilated (BC) and ventilated built-in closet ventilated (VBC) for the three ventilation rates considered.


DT(TBC-TVBC) (°C) : 22V
Temperatures Differences (°C)
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
06:00
06:50
07:40
08:30
09:20
10:10
11:00
11:50
12:40
13:30
14:20
15:10
16:00
16:50
17:40
18:30
19:20
20:10
21:00
21:50
22:40
23:30
00:20
01:10
02:00
02:50
03:40
04:30
05:20
Time (hr. : min.)


DT(TBC-TVBC) (°C) : 20V
Temperatures Differences (°C)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
06:00
06:50
07:40
08:30
09:20
10:10
11:00
11:50
12:40
13:30
14:20
15:10
16:00
16:50
17:40
18:30
19:20
20:10
21:00
21:50
22:40
23:30
00:20
01:10
02:00
02:50
03:40
04:30
05:20
Time (hr. : min.)

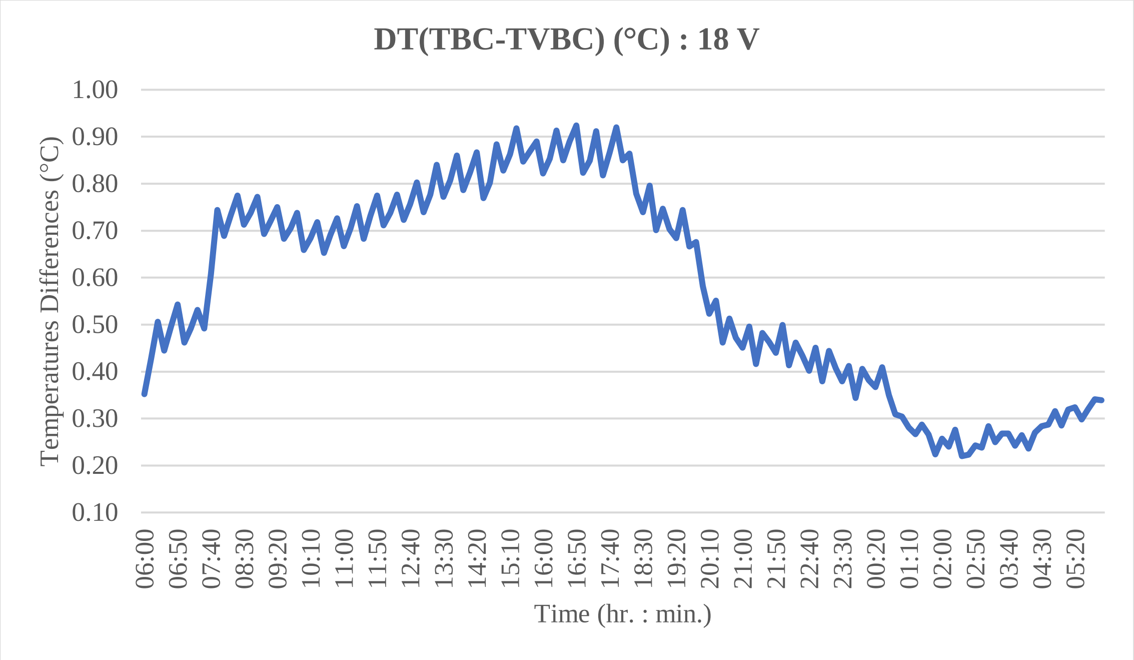
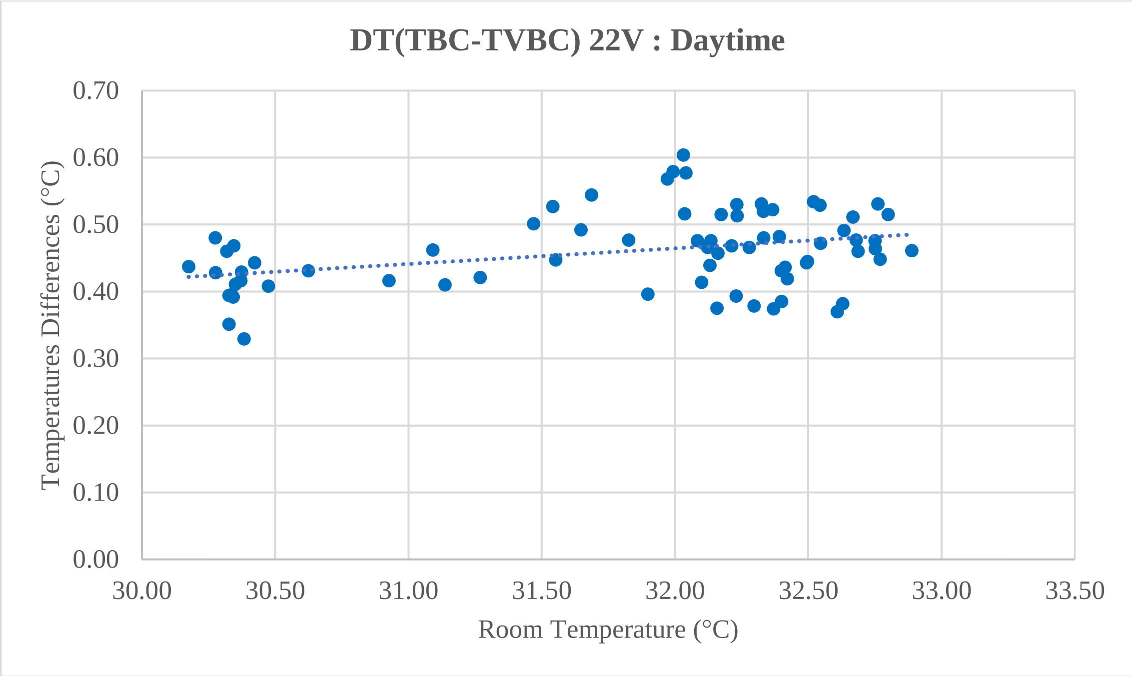


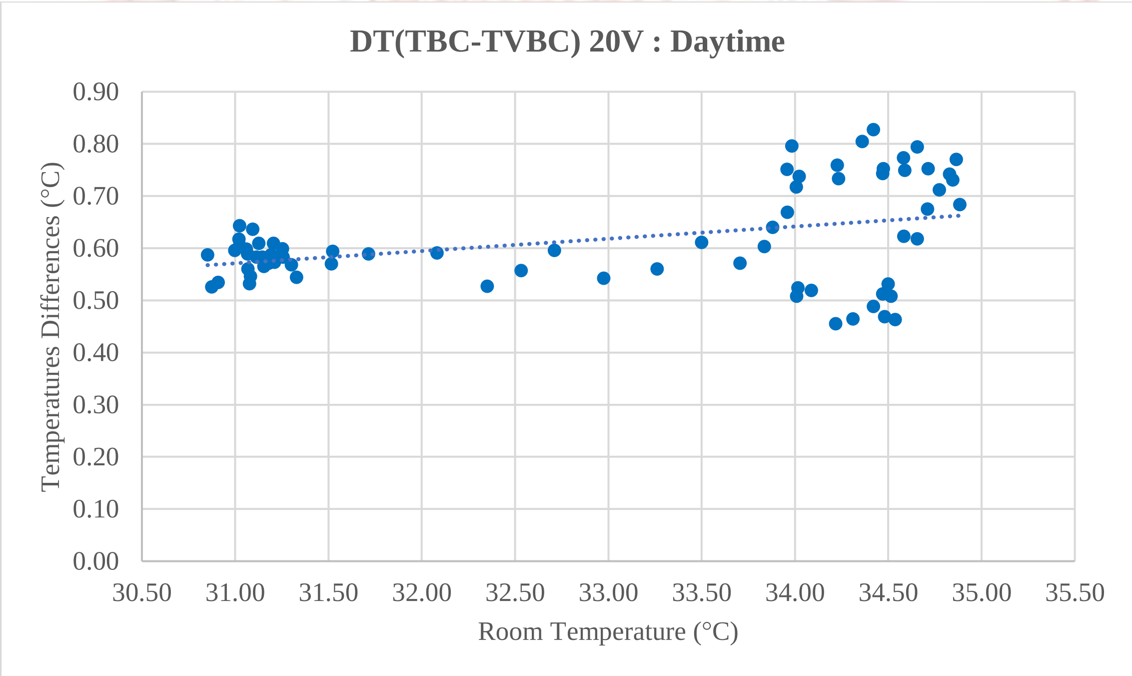
FIGURE 4-4 Variation of temperature differences between non-ventilated (BC) and ventilated built-in closet ventilated (VBC) for the three ventilation rates considered.

These results confirm again that increasing the ventilation rate did not lead to any significant performance improvement as the measured temperatures differences decreased. Therefore, a ventilation rate equal to that required for bedroom ventilation is appropriate and can be adopted by architects and interior designers as a general rule for designing VBC.

4.3 Ventilation Efficiency

To make subjective comparative analysis of the performance of the VBC with field tests conducted under different days and variable ambient conditions, we introduce the ventilation efficiency of the VBC as the calculated temperature difference between non-ventilated and ventilated built-in closet (DT(TBC-TVBC)) determined as a function of room temperature. Figures 4-5 to 4-7 show the scatter of ventilation efficiency of the VBC plotted versus the room temperature for the three different ventilation rates considered during daytime, nighttime and twenty-four hours respectively.


DT(TBC-TVBC) 22V : Daytime
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Temperatures Differences (°C)
30.00
30.50
31.00
31.50
32.00
32.50
33.00
33.50
Room Temperature (°C)


DT(TBC-TVBC) 20V : Daytime
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Temperatures Differences (°C)
30.50
31.00
31.50
32.00
32.50
33.00
33.50
34.00
34.50
35.00
35.50
Room Temperature (°C)

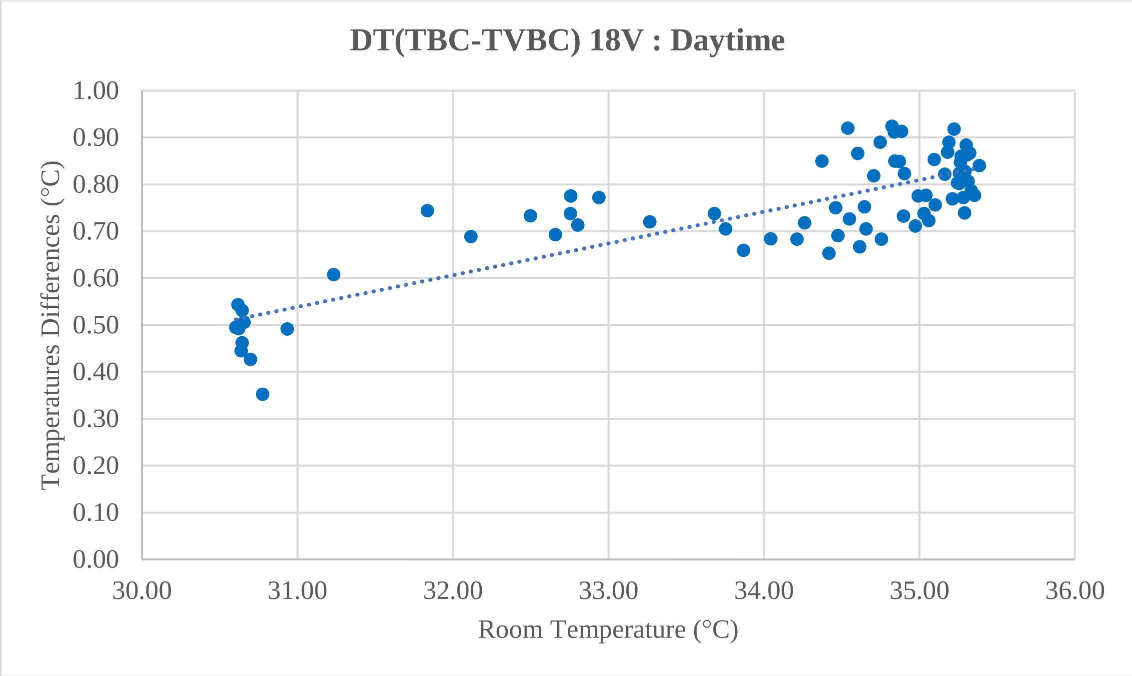
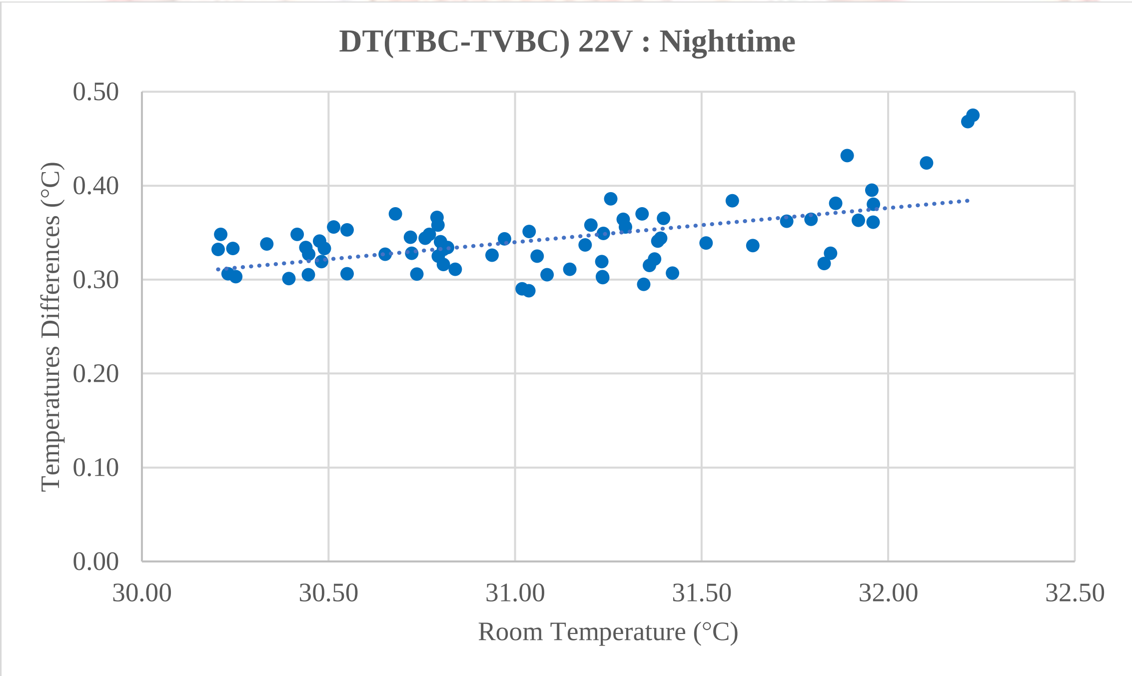
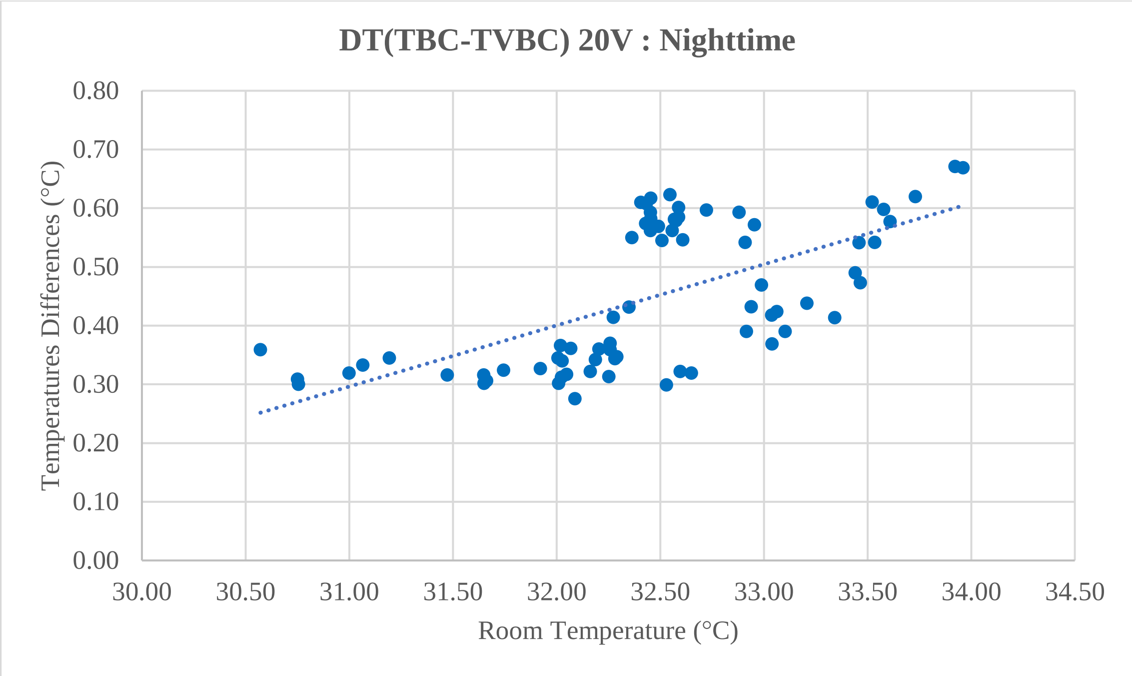


FIGURE 4-5 Scatter of the daytime ventilation efficiency of the VBC plotted versus room temperature for the three ventilation rates (6:00 - 18:00).





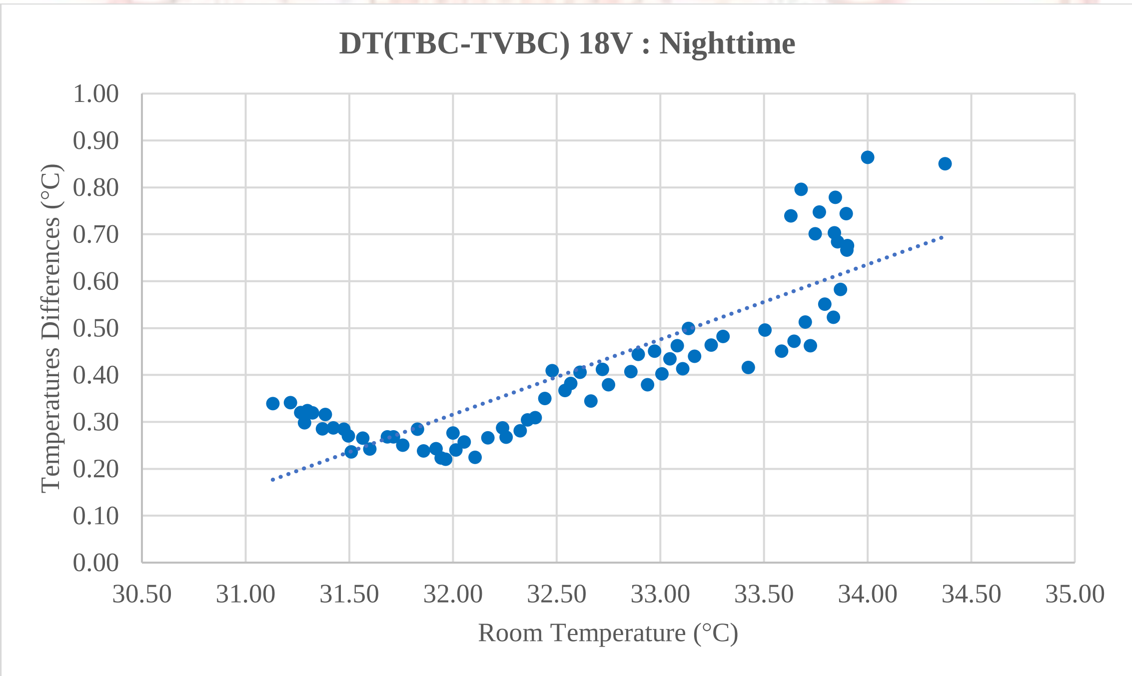
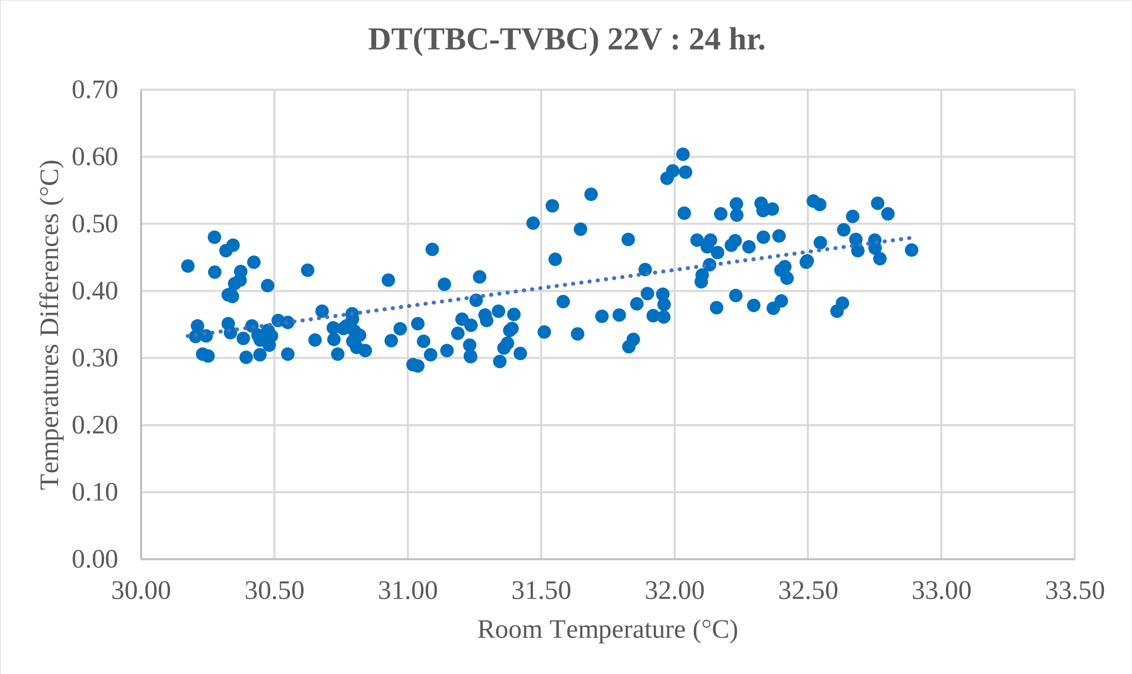
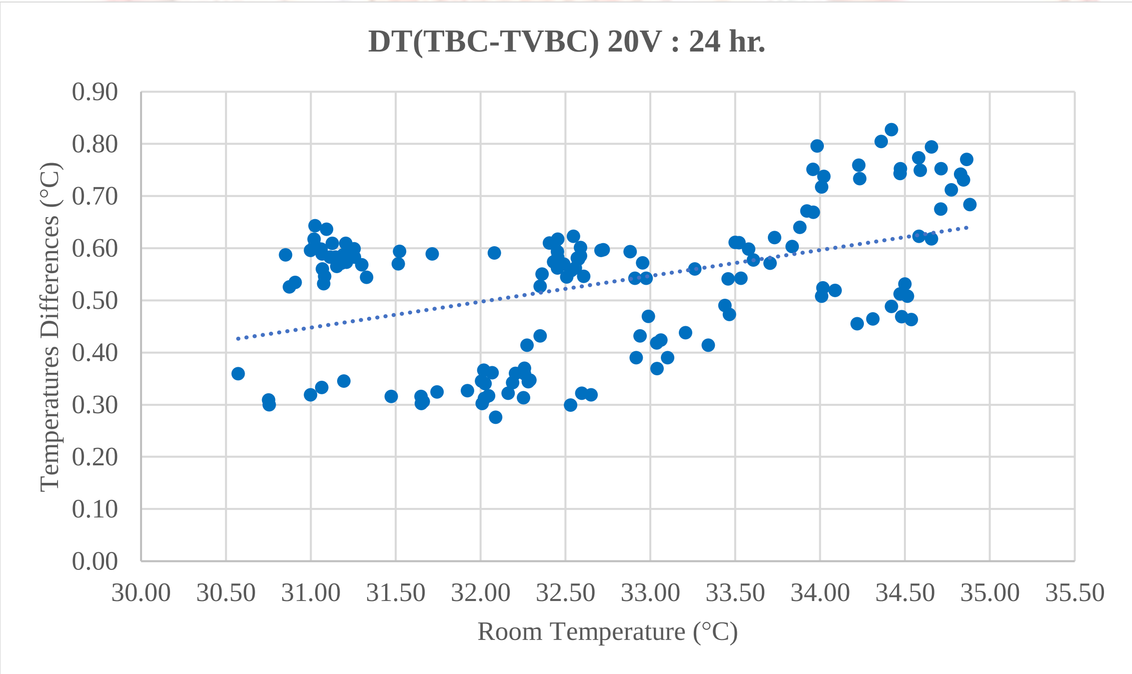


FIGURE 4-6 Scatter of the nighttime ventilation efficiency of the VBC plotted versus room temperature for the three ventilation rates (18:00 - 6:00).


DT(TBC-TVBC) 22V : 24 hr.
Temperatures Differences (°C)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
30.00
30.50
31.00
31.50
32.00
32.50
33.00
33.50
Room Temperature (°C)


DT(TBC-TVBC) 20V : 24 hr.
Temperatures Differences (°C)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
30.00
30.50
31.00
31.50
32.00
32.50
33.00
33.50
34.00
34.50
35.00
35.50
Room Temperature (°C)

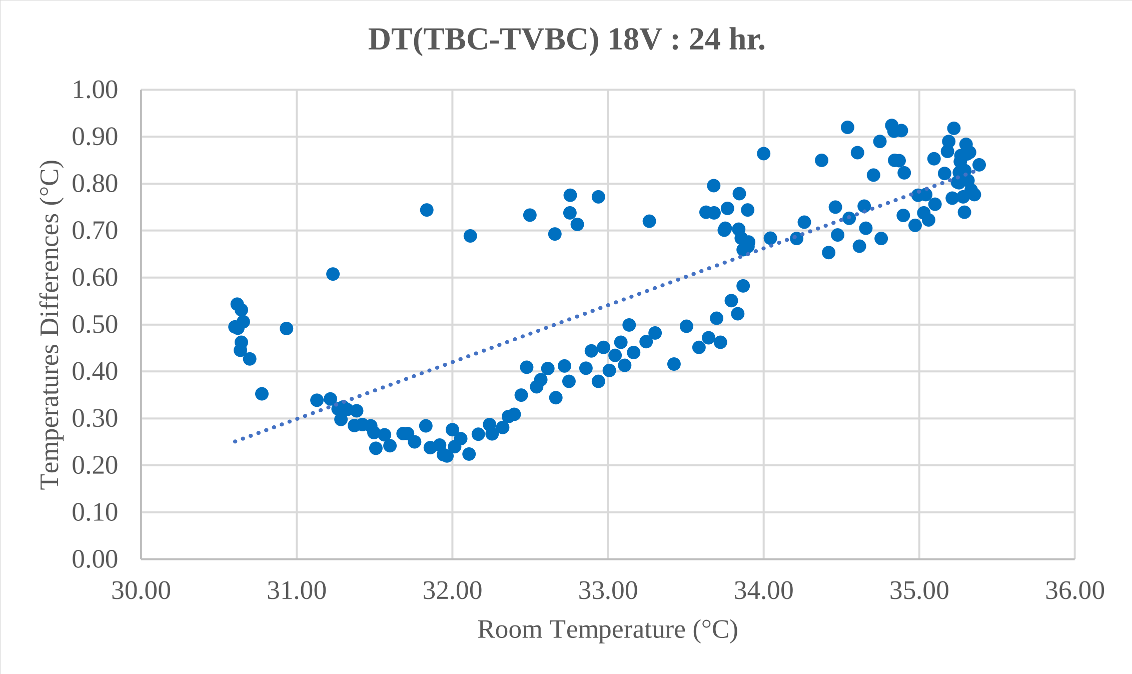


FIGURE 4-7 Scatter of the efficiency of the VBC plotted versus room temperature for the three ventilation rates for 24 hours (06:00 - 06:00).

It can be observed that there is a close dependence on room temperature: the higher the room temperature, the larger is the temperature difference between non-ventilated and ventilated built-in closets. In addition, the lower is the ventilation rate, the better the ventilation efficiency. These constatations confirm that the recommended VBC ventilation rate should be equal to that required of the room or space where it is located. This can be adopted as a rule for designing VBC.

4.4 VBC Fitted with Clothes

In this section, we tested the performance of ventilated built-in closet fitted with clothes, Figure 4-8.

FIGURE 4-8 Photograph of the VBC fitted with clothes.

Figures 4-9 and 4-10 show the temperatures of ventilated (VBC), non-ventilated (BC) built-in closets and room and the relative humidity for two consecutive days at 10.22 m^3/h flowrate respectively. It can be observed that there is a clear difference between the VBC and BC and VBC temperature is always lower than that of the non-ventilated BC. This clearly demonstrates that fitting the VBC as designed with clothes will not reduce ventilation efficiency that validates our proposed concept with promising potential for integration.

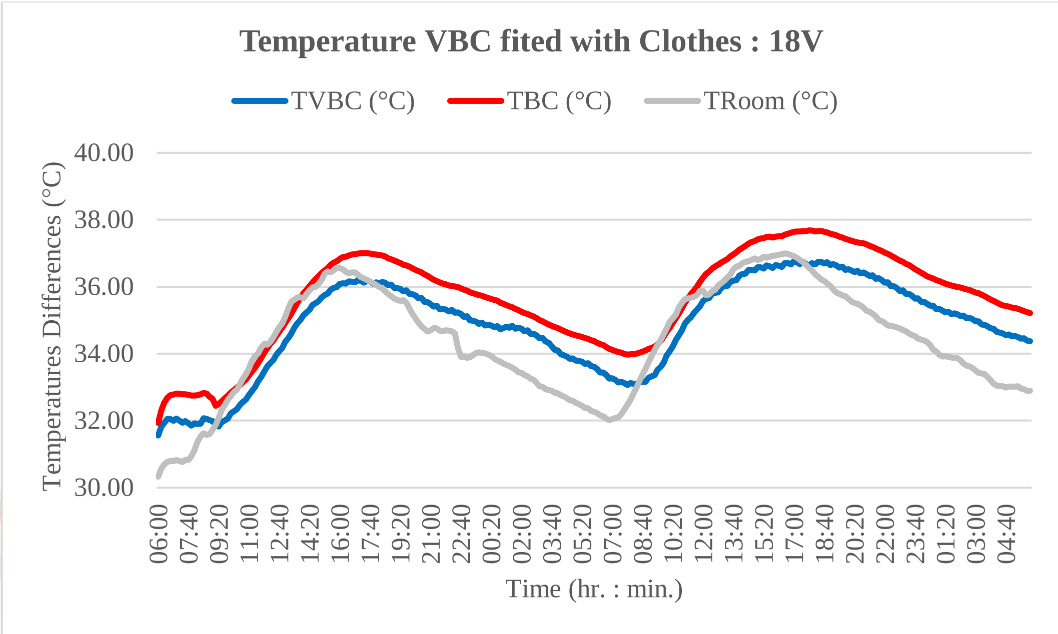


Figure 4-9 Comparison between temperatures of ventilated (VBC), non-ventilated (BC) built-in closets and room differences for two consecutive days at 10.22 m^3/h flowrate.

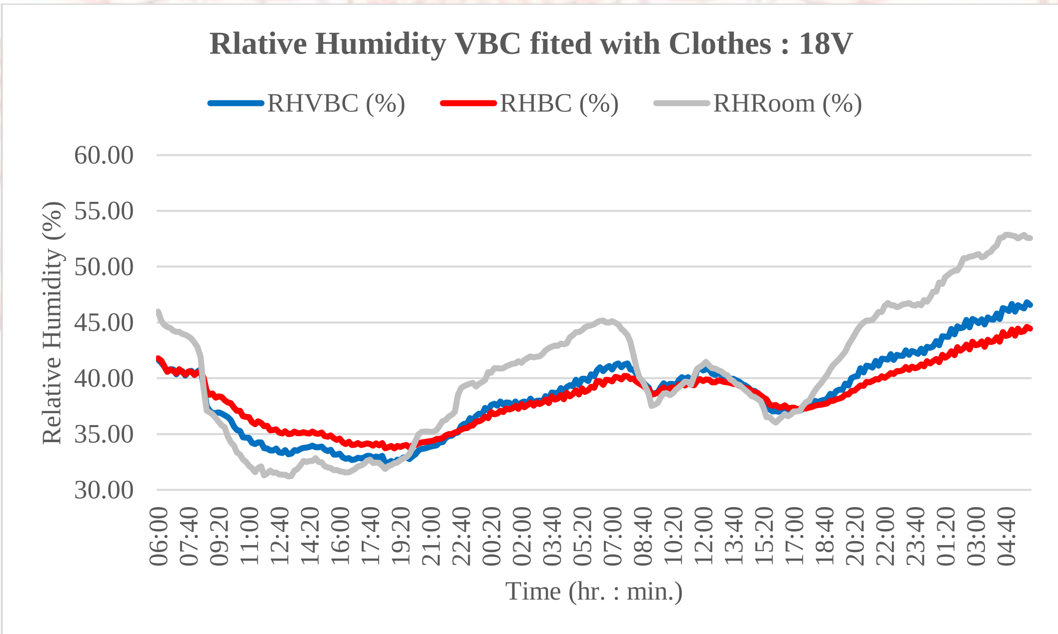


Figure 4-10 Comparison between relative humidity of ventilated (VBC), non-ventilated (BC) built-in closets and room for two consecutive days at 10.22 m^3/h flowrate.

4.5 Air Quality

To demonstrate the benefit of proposed VBC to remove Odors and chemicals form inside the BC and consequently from the indoor space, we conducted a simple test by spraying deodorant inside the built-in and varied the operation of ventilation fan between OFF and ON periodically. Figure 4-11 shows the variations of the total volatile compounds TVOCs measured inside the VBC for two cycles of fan operation. At the beginning, the fan was switched off for 25 minutes to reach saturation, then it was activated. It can be observed that it took a short period about 10 minutes to remove all amount of the TVOCs. Then another amount of deodorant was sprayed again into the BC at the 70th minute and switching OFF the fan. Ten minutes later, we reoperated the fan and the TVOCs was removed again very quickly. Therefore, it is well demonstrated that the VBC concept can ensure fast removal of dirty and polluted air and can help to achieve good indoor air quality continuously.

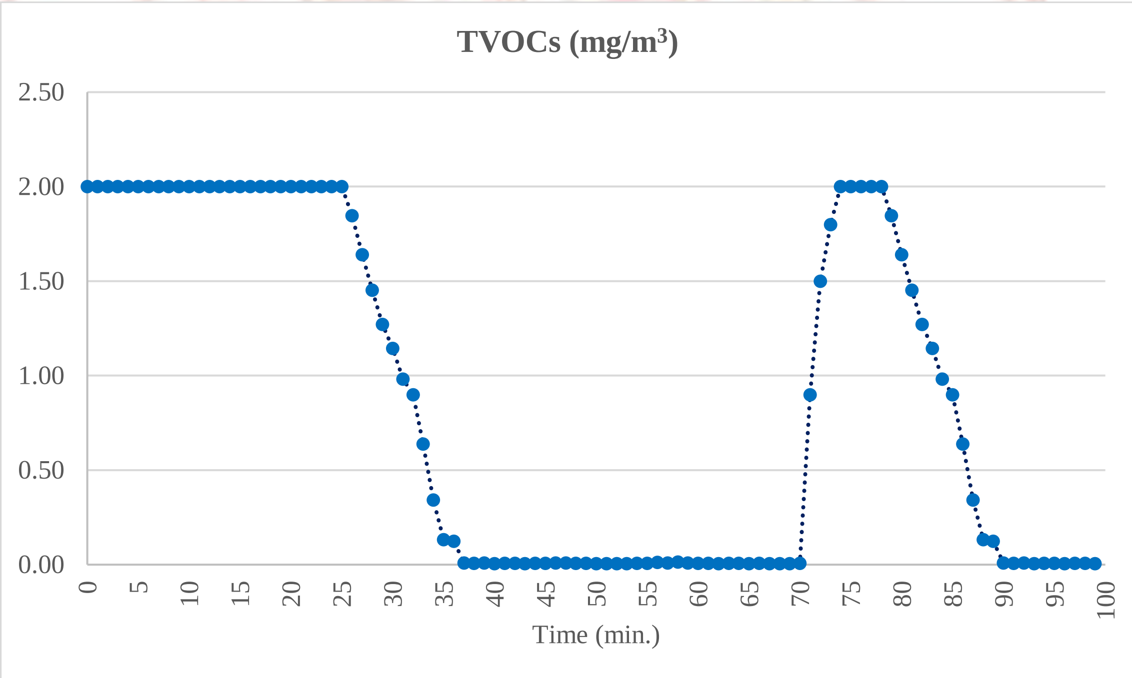


Figure 4-11 The variations of TVOCs versus time of the VBC with two cycles of fan switched OFF and ON.

4.6 IFVH Approach

We remind that the main objective of this thesis is to develop an integrated full ventilation approach for houses and residence buildings referred to as (IFVH). The concept proposed is to consider the use of Built-in Closet (BC) with a proper system of ventilation that can allow to fully ventilate the indoor space of homes and buildings to ensure good air quality and improve human thermal comfort. In this section, we conducted simple field investigation of our IFVH concept using two adjacent rooms with relatively similar conditions. The two rooms were located on the 2nd floor of the house used in the experiment. The ventilation rate was adjusted equal to that as specified earlier for the tested room (0.76 ACH, Table 3-1) with the recommended variable operation schedule as determined in the previous section. During tests, all windows on the second floor were closed.

Figure 4-12 shows the hourly variations of temperatures of room with IFVH, and normal house compared to ambient temperature whereas figure 4-12 show those of the relative humidity. It is observed that the measured data varied well according to the variations of the prevailing ambient conditions; and the temperature of IFVH room is practically always lower than that of the normal room. In addition, and even though the difference of relative humidity is not very noticeable due to the small differences between measured temperatures, as already discussed in the previous section, the IFVH room relative humidity followed better the ambient conditions due to air admitted into the ventilated room as result of VBC fan operation.

Therefore, this simple field test conducted with limited number of parameters well demonstrated that the IFVH integrating VBC concept can improve indoor conditions significantly, help to achieve good indoor air quality et ensure fast removal of dirty and polluted air continuously.

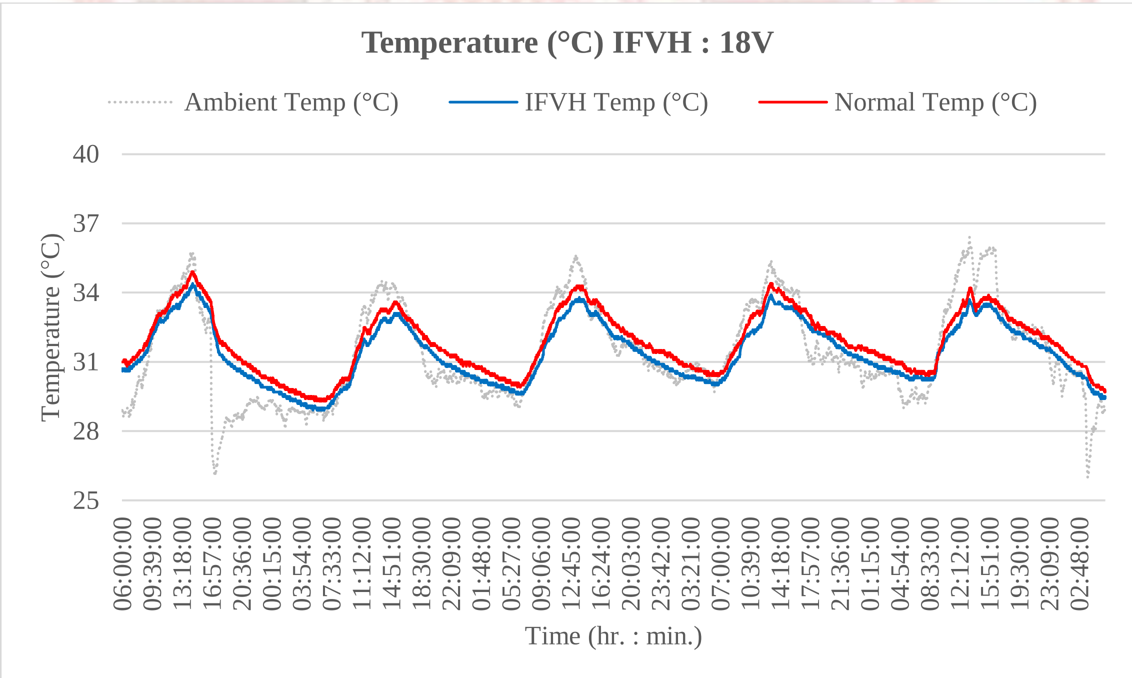


Figure 4-12 Five consecutive days variation of temperatures of room with IFVH and normal room compared to ambient temperature (18^{th} – 23^{rd} /10/2024).

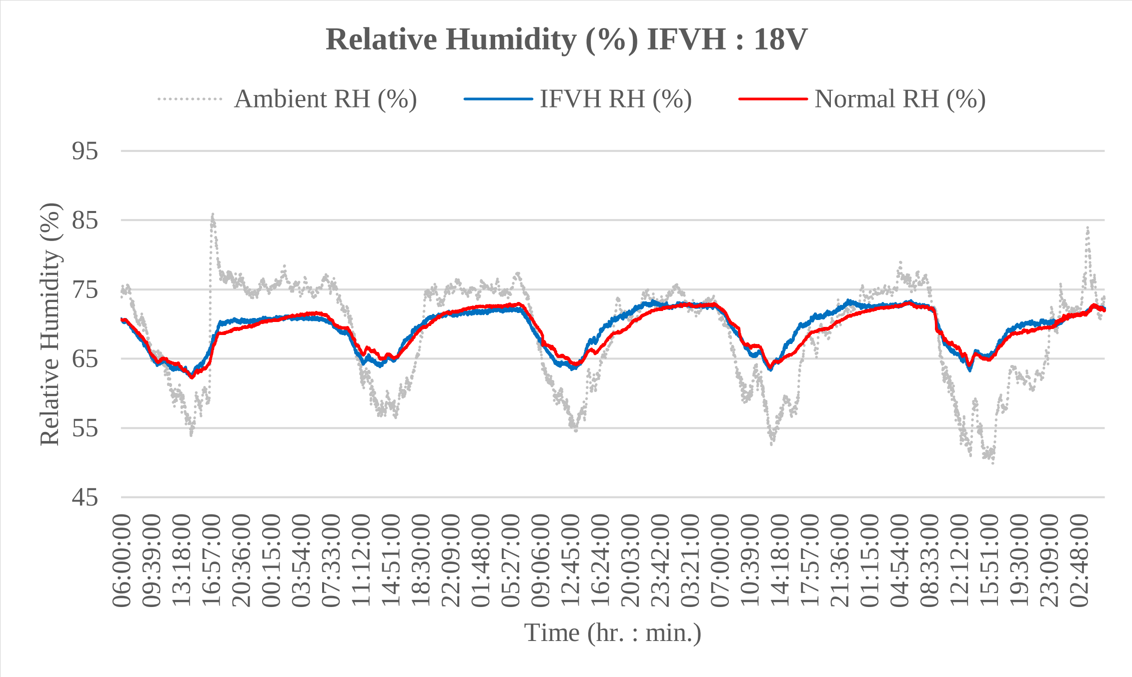


Figure 4-13 Five consecutive days variation of relative humidity of room with IFVH and normal room compared to ambient temperature (18th - 23rd /10/2024).

4.7 Built-In Design Option

To assist architects, professionals, and built-in designers integrating the VBC and IFVH concepts developed, this section is devoted to give insights for practical application.

By considering the basic design of built-in closets, figure 4-13 illustrates a schematic standard design of VBC and Table 4-3 shows three sample of VBC configurations and locations that can be applied for several design options and purposes of VBC for different standard parts such as waldrapps, drawers, shelves, etc. The ventilation concept is the same for all options: Air is admitted at the lower part, circulates throughout all compartments of the BC, and exits at opening(s) properly located either at the top, the side or the rear of BC., Table 4-3.

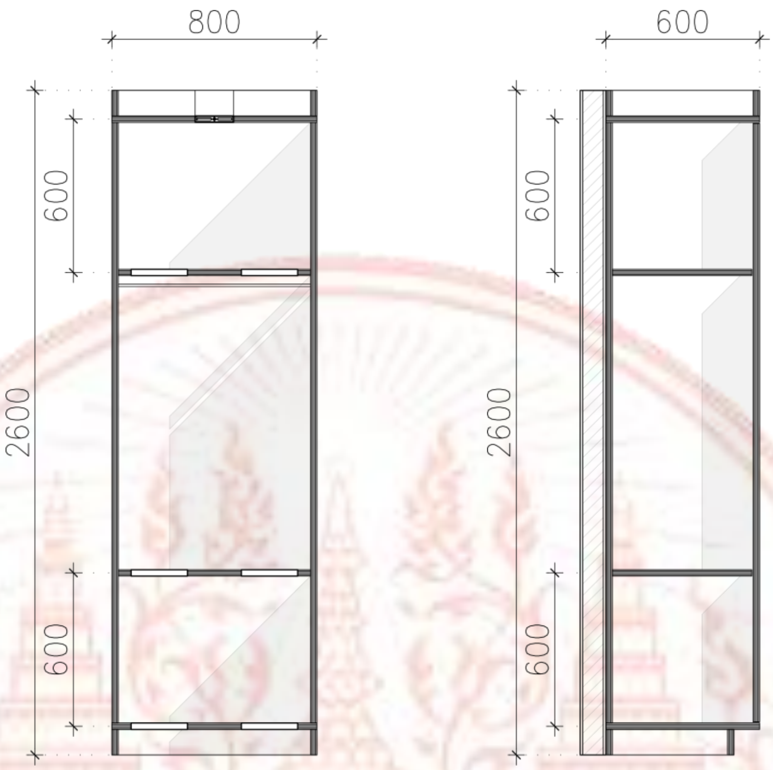
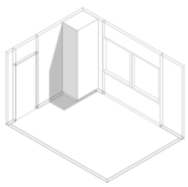
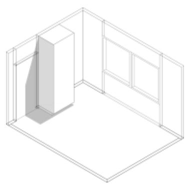
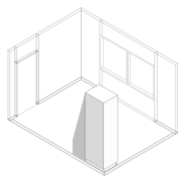
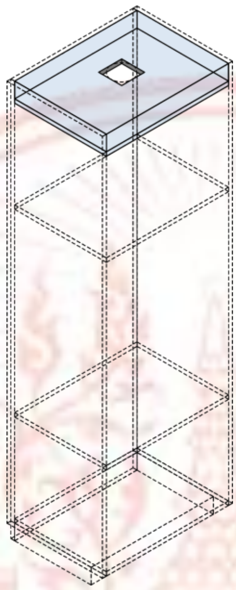
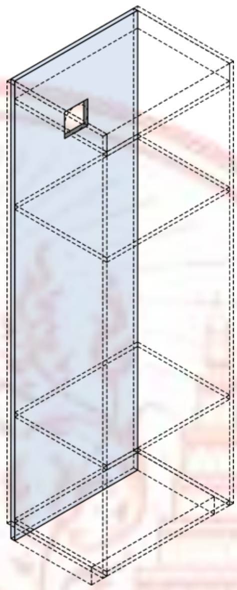
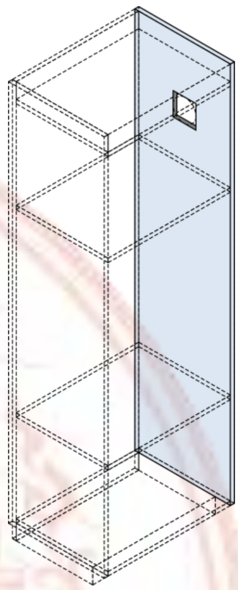


Figure 4-14 Basic schematic standard drawings of ventilated built-in closets.

Table 4-3 Design alternatives and configurations of ventilated built-in closets.

Built-in Closet Alternatives		
Configuration 1 Corner - Inner wall	**Configuration 2** Middle - Inner wall	**Configuration 3** Corner - Outer wall
		
		

Fan Installation			
Configuration	**Position**		
	Top	Back	Side
			
Con.1	✓	✓	✓
Con.2	✓	✓	
Con.3	✓		

Figures 4-15 to 4-18 illustrate 3-D schematic drawings for VBC integrated in residence building that can be used as design guidelines to consider and assist professionals implementing their projects. As seen in the drawings, several ventilations patterns are possible depending on the house design and owner expectations. Air circulation can be considered in various ways with propoer locations of inlet and outlet openings.

It is our hope that these ideas and illustrations offer new perspectives for sustainable built environment and business development in the near future.

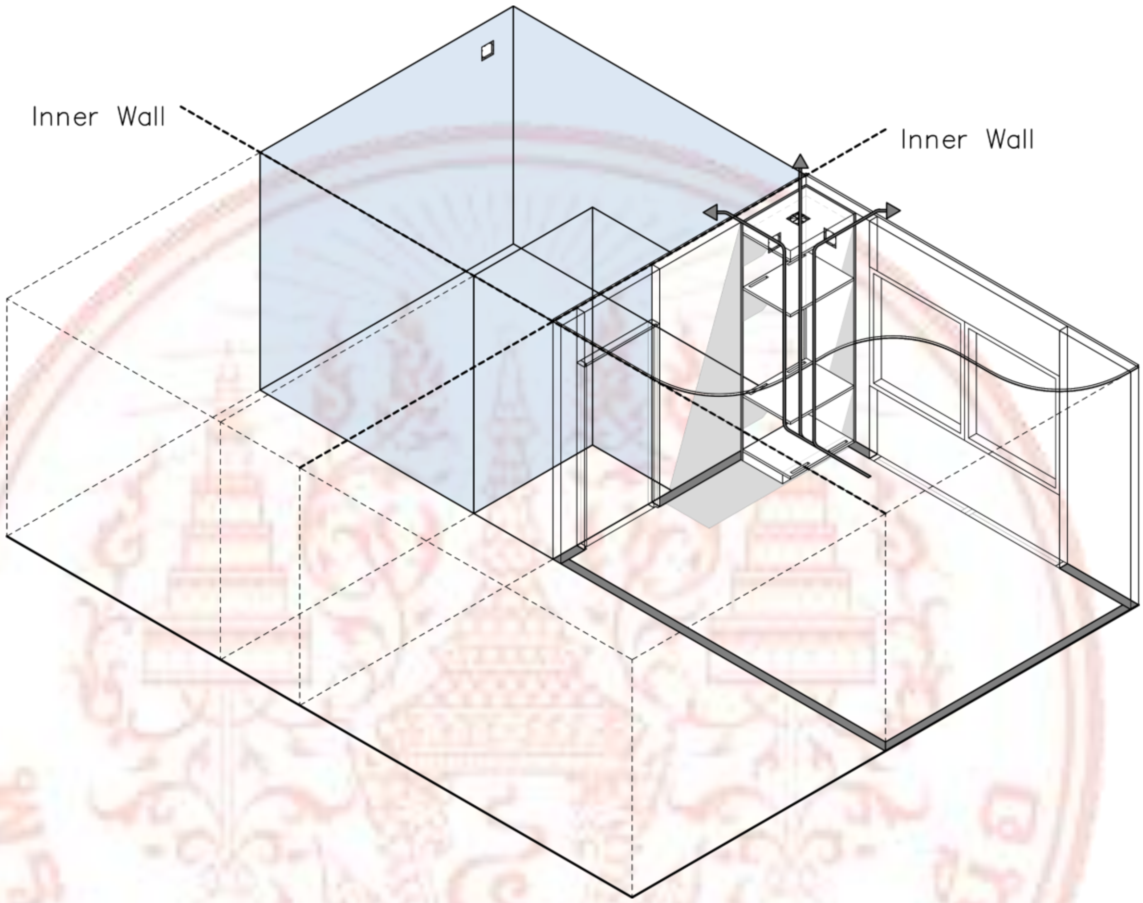


Figure 4-15 Design option for VBC located at the middle - outer wall of residence perimeter part adjacent to another room with different internal - external ventilation patterns.

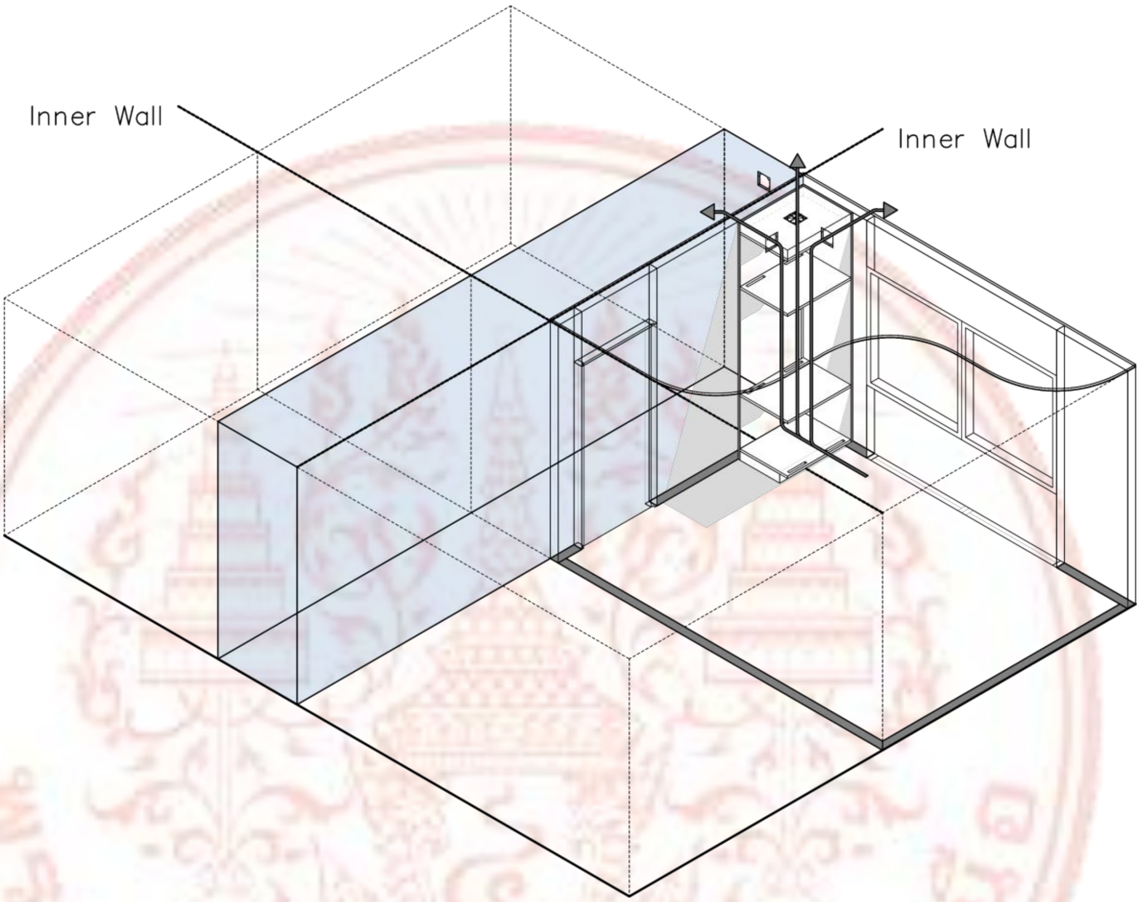


Figure 4-16 Design option for VBC located at the middle - outer wall of residence perimeter part adjacent to a corridor with different internal - external ventilation patterns.

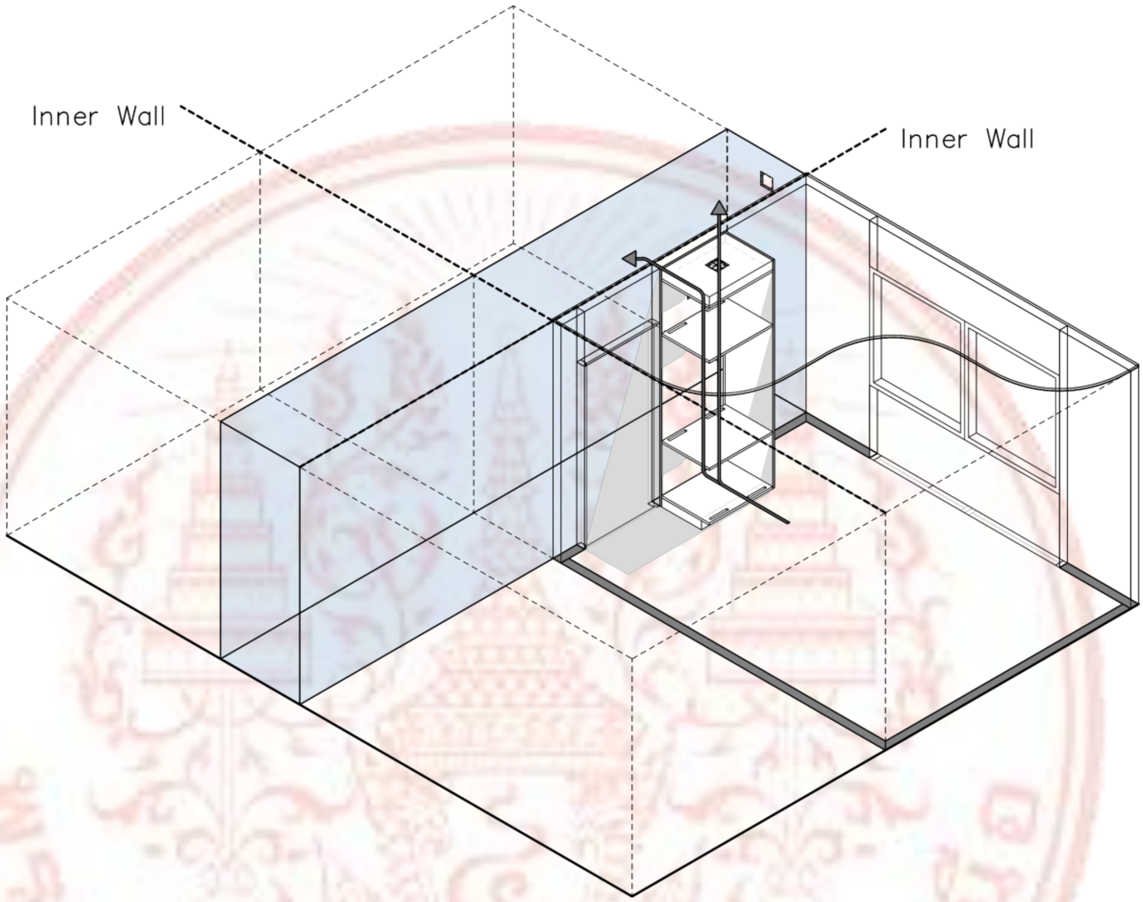


Figure 4-17 Design option for VBC located at the middle - inner wall of residence perimeter part adjacent to a corridor with different internal - external ventilation patterns.

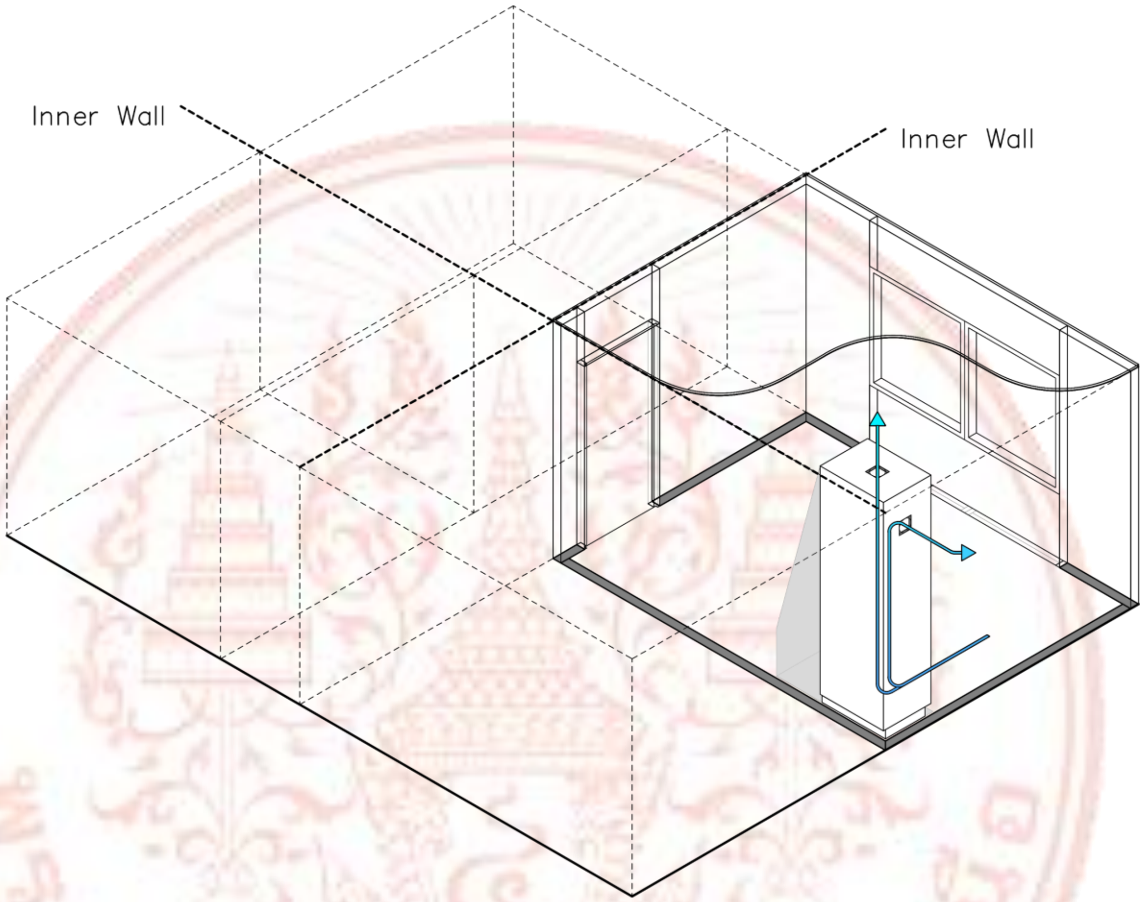


Figure 4-18 Design option for VBC located at the middle inner corner of room at outer wall of residence perimeter part with external ventilation patterns.

Chapter 5
Conclusion and Recommendation

5.1 Conclusion

It is widely recognized that ventilation can help improve indoor comfort, protect the health of residents, avoid heat and moisture accumulation and save energy. However, modern houses and residence buildings in Thailand often do not consider ventilation seriously. This is because there are no compulsory regulations and to reduce construction cost as well. Consequently, excessive heat, moisture, odors and mold growth are observed in indoor spaces that lead to several problems for inhabitants leading to poor indoor air quality, health risk and contamination. Today, due to the modern lifestyle, built-in furniture attracts great attention as it is modern, easy to make and can be adjustable to each individual space offering architects and interior designers various choices to come up with innovative forms and design. However, materials used such particleboards and wood panels include some chemicals that are harmful to the health of occupants and adsorb air moisture especially unventilated spaces and when air-conditioning is used alternately. This enhances the growth of mold and bad odors which might lead to residents' allergies and health problems.

The dissertation objective is to develop a new integrated concept to ensure full ventilation for houses and residence buildings. This concept is referred to as : Integrated Full Ventilation Approach for Residential Houses (IFVH). The main idea is to design and assemble a Built-in Closet (BC) with a proper system of ventilation that can allow to ventilate the indoor space according to the relevant standards, the Built-in Closet and the attic of house or space between floors simultaneously. To this end, a small prototype of VBC of 1.248 m^3 volume, made from commercial particleboards, was manufactured. Using a small DC fan located at the top, air enters at the bottom, circulates inside through appropriate openings located at different positions, and exits at the top. The VBC was located inside an empty room 52 m^3 volume of a residential house located in Bangkok. Extensive field tests were conducted for different conditions, ambient conditions, ventilation flowrate and various ventilation scenarios. Results are compared to a standard built-in closet (BC) of the same volume juxtaposed to the VBC. Measured data showed that the temperature inside the VBC is always lower than that of the BC and higher difference is observed during daytime whereas relative humidity difference is less noticeable due to close range of temperatures. The recommended ventilation schedule varied between daytime (20min. ON / 10min. OFF) and nighttime (10min. ON / 20min. OFF), and the appropriate ventilation rate was found equal to that required to ensure good room air change (0.7 ACH). The corresponding VBC air change is 7.94. The VBC took a short period of about 10 minutes to remove all amount deodorant (2000 mg/m^3 TVOCs) sprayed inside. Finally, a variety of design options and alternatives of ventilated built-in closets

(VBC) for a wide range of applications and for different standard parts designs such as waldrapps, shelves, etc. are reported and discussed.

The dissertation outputs will benefit architects, interior designers and engineers to design houses that can offer good and healthy indoor environment for residents, reduce indoor contaminations and save energy. Due to their advantages, the VBC and IFVH proposed here are expected to receive attention and attract professionals to integrate into their projects. In addition, VBC and IFVH will offer new perspective for new era of sustainable built environment with promising potential for sustainable business development.

5.2 Recommendations

It is recommended that a full-scale long-term testing of a house integrating the VBC and IFVH concepts proposed in the dissertation be conducted to confirm the outlined advantages and test performances for all ambient conditions. This would help finalize all results and develop necessary and appropriate accessories needed to ensure good performance, maintenance, and replacement. Cost-effective analysis is also encouraged and assessment of electrical energy saving of the air conditioning of homes and residences integration our proposed system is of major importance that would help enlarge benefits and reduce electricity bill burden of houses owners especially these days with increased electricity tariff.

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This is Mendeley biography

APPENDIX

List of publications derived from the thesis

1 Georges Khedari, Preeda Chantawong, Thana Ananacha. (2024). "Initial In-Depth Analysis of Performance of Ventilated Built-in Closet". In The 9th International Conference on Sustainable Energy and Green Architecture : Circular economy and creative sustainability. Bangkok, (44-47)

2 Georges Khedari, Preeda Chantawong, Thana Ananacha. (2024). "Design Options and Alternatives of Ventilated Built-In Closets". In The 9th International Conference on Sustainable Energy and Green Architecture : Circular economy and creative sustainability. Bangkok, (48-51)

3 Georges Khedari, Preeda Chantawong, Thana Ananacha. (2024). "Enhancing Indoor Air Quality and Thermal Comfort with a Ventilated Built-In Closet Design". International Journal of Heat and Technology. 42(6) : 1963-1968

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