Achieving Health and Comfort in High-Rise Residential Buildings by Using Dynamic-Hybrid Air Permeable Ceiling (DHAPC)

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ABSTRACT

Air pollution has become a threat to the vast amount of population in many developing countries around the world. This life-threatening issue is worsening every year, in South-East Asia in particular. Despite the severity of the problem, ongoing major building programs of high-rise residential buildings in urban areas are not addressing it in full. This research explores the use of a 'Dynamic-Hybrid Air Permeable Ceiling' (DHAPC) as a strategy to reduce the amount of airborne particles penetrating internal spaces. This system is also designed to ensure the required constant airflow rate in indoor spaces as well as to control air temperature and humidity. Fieldwork with direct measurements in social housing in Kuala Lumpur was used to establish the exact extent of the problem. The system has been tested carrying out two experiments on physical models using synthetic recycled insulation materials and higher airflow rate. The test has achieved a healthier and more comfortable indoor environment with substantial improvements, including a 98 percent reduction of PM2.5 and PM10 particles, and a 16 percent reduction of air temperature and humidity. This experiment has proven that the DHAPC concept using recycled materials and hybrid ventilation could be the solution to poor indoor quality and indoor discomfort in high-rise residential buildings in urban areas.

INTRODUCTION

Context and Aims of the Research

This paper presents the research carried out in order to address the problem of poor indoor air quality and comfort in high-riser buildings in tropical countries by using an integrated strategy of passive air filtering approach and low-energy ventilation system. Two aims are targeted – to analyze a passive filtering technique that can efficiently reduce heat, humidity and airborne particles and to define an energy-efficient ventilation system that can provide constant and adequate ventilation in indoor spaces in high-rise residential buildings. Air pollution causes one in nine deaths and nine out of ten people worldwide breathe polluted air and the World Health Organization (WHO) has established that around seven million people die every year from exposure to fine particles in polluted air (Osseiran and Lindmeier, 2018). Ambient (outdoor) air pollution alone caused 4.2 million of these deaths and the remaining are from the exposure to smoke from dirty cook stoves and fuels (WHO, 2018a). Also according to WHO, 91 percent of the world's population lives in places where air quality exceeds their guideline limits (WHO, 2018a, WHO, 2018b).

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South-East Asia (SEA) is among the regions with the highest ambient air pollution levels, often exceeding more than five times WHO's limits (Osseiran and Lindmeier, 2018). The inclination of PM2.5 and PM10 increment in SEA is more than five percent over in the five-year (2011 – 2015) period (WHO, 2016). A study on PM2.5 and PM10 concentration in Kuala Lumpur from 2002 to 2011 has revealed that the annual averages were 21 to 35 µg/m3 of PM2.5 and 44 to 56 µg/m3 PM10 (Rahman et al., 2015). These findings suggested that the air pollution in Kuala Lumpur is dominantly caused by the fine particle fraction of PM2.5 and PM10.

The Department of Environment Malaysia (DOE) has monitored in 2015 and 2016 the annual average concentration of PM10 level in urban areas since 2000 and has found that the average level of the particles in urban areas in Malaysia is ranged from 40 to 60 $\mu g/m^3$ (DOE, 2015, DOE, 2016a). Khan et al. (2015) have suggested that the concentration of PM10 in Kuala Lumpur was higher during weekdays (Khan et al., 2015). However, the measurements were only taken outdoors; in order to evaluate the air quality in indoor high-rise residential buildings is indispensable to take measurements inside.

Dynamic Insulation: Precedents

Many researchers have agreed that air pollution could be filtered by using dynamic insulation (Taylor et al., 1998, Imbabi et al., 2002, Imbabi and Peacock, 2003, Elsarrag et al., 2006, Halliday, 1997, Alongi and Mazzarella, 2015, Di Giuseppe et al., 2015), which could also reduce heat and humidity (Mohd Sahabuddin and Gonzalez-Longo, 2019, Craig and Grinham, 2017, Imbabi, 2012). The research so far has been focused on countries with cold and temperate climates. Elsarrag et al. (2006) suggested that dynamic insulation could be also effective in extreme hot-humid climates, but this has not been developed in relevant countries, including Malaysia.

Imbabi (2012) developed a new type of 'parietodynamic' insulation called 'Void Space Dynamic Insulation' (VSDI). This passive-active dynamic insulation system has been designed for all climates which can eliminate the risk of interstitial condensation and over-heating during the summer without the support of a fan to drive the air flow (Imbabi, 2012). The test was conducted using a simulation software where cold winter (20°C/68°F - inside, 0°C/32°F - outside) and hot summer (20ºC/68°F - inside, 40ºC/104ºF - outside) conditions were applied. The system applies a small air inlet located at lower part of the outer wall which allows air to be confined within a co-planar space and distributed bi-directionally and uniformly inside the wall before the air was supplied via a mid-ceiling inlet vent to the indoor space (Imbabi, 2012). However, constant airflow is the key to the success of the dynamic insulation (Etheridge and Zhang, 1998) and it is crucial for the ventilation of buildings in order to achieve air circulation and prevent backflow and air-lock entries in indoor spaces (Lenchek et al., 1987). On the other hand, in tropical countries especially in urban areas, this constant air element is not consistently and reliably available and a mechanism that could provide a constant airflow is indispensable.

On the contrary, the VSDI system has been designed and applied for an isolated room but not for a room in multiple formats, where mostly only one external wall (façade) is available. In addition, the bi-directional airflow system and large areas of the co-planar void will reduce the airflow efficiency. In addition, the mid-ceiling air supply vent at the top was a spotted-type which does not allow for the air flow to be distributed evenly throughout the space. There are also human activities (respiration, cooking, electrical appliances, smoking, etc.) that affect the operative temperature and humidity and contribute in reducing the indoor air quality and comfort (Environmental Health Directorate, 1995). Without active mechanical devices, these internal emissions are impossible to be removed efficiently by natural means and a constant airflow is indispensable in providing health and comfort condition in indoor spaces (Mohd Sahabuddin and Gonzalez-Longo, 2018, Mohd Sahabuddin and Gonzalez-Longo, 2019).

Craig and Grinham (2017) suggested that dynamic insulation studies from the 1960s have shared some common features such as the use of raw insulation materials with additional materials are needed in the building envelope as well as the incorporation of an air-mixing cavity. They also concluded that air filters are needed to improve indoor air quality and should be incorporated into the dynamic insulation system (Craig and Grinham, 2017). Another common feature of the research on dynamic insulation is the implementation of the system in vertical walls (Craig and Grinham, 2017, Elsarrag et al., 2006, Imbabi, 2012), something unpractical considering that occupants tend to place furniture and decorations near or on the walls. This approach might consequently disrupt the performance of the system or otherwise giving restrictions to the occupants on the wall usage. In order to overcome all the issues mentioned above, the dynamic insulation system needs to ensure indoor air quality and comfort as well as allowing for constant air flow (directional airflow). The use of directional airflow concept in housing units is recommended for mitigating the risk of airborne contaminants being released from a high-polluted area (Olmsted, 2008, Jennette, 2014) such as kitchen and bathroom. Our research tries to do this by designing a new dynamic insulation system located in the ceiling compartment, and we have called the system 'Dynamic-Hybrid Air Permeable Ceiling' (DHAPC).

METHODOLOGY AND SCOPE

Fieldwork

As one of the tropical countries, Malaysia experiences two major seasons every year – dry and wet. The dry season runs from May to September and wet season occurs from November to Mac (MET, 2019). Due to that reason, two fieldwork studies were conducted by the authors in July 2017 for the dry season and January 2018 for the wet season. The first fieldwork study was conducted on two case studies – the first and second generations of the People's Housing Program (PPR) in Kuala Lumpur. This fieldwork has assessed the indoor comfort condition and suggested that the mean operative temperature and relative humidity for both cases were 29.3°C (84.7ºF) and 70.1%RH respectively (Mohd Sahabuddin and Gonzalez-Longo, 2018). These findings have illustrated that the current comfort condition in the case studies' indoor spaces are poor and need to be improved. Meanwhile, the second fieldwork study that was conducted on the same case studies, evaluating the indoor air quality, has confirmed that two major substances - PM2.5 and PM10, contribute to the poor air quality in indoor and outdoor spaces in Kuala Lumpur. The 24-hour average concentration in these social housing spaces were 44.2 $\mu g/m^3$ (PM2.5) and 53.5 $\mu g/m^3$ (PM10), confirming that the levels of particulate matters in Kuala Lumpur are hazardous and threatening the health of the population. The social housing units are predominantly naturally ventilated; thus, allowing the outside air entering the indoor spaces is obviously permitting also hot and polluted air in (Mohd Sahabuddin and Gonzalez-Longo, 2019).

Physical Model

The experiment intended to use a heater fan to create the Kuala Lumpur's average ambient air temperature and wind movement. Then, joss sticks (a thin stick consisting of a substance that burns slowly and with a fragrant smell, used as incense) were used to fill the air with smoke (PM10 and PM2.5 substances), before the air was channeled into the DHAPC compartment by either using the supply fan or natural buoyancy pressure (from the heater fan). A dynamic insulation membrane was placed in the DHAPC compartment to filter the hot and polluted air which later, the clean air is forced down by the supply fan or sucked-in to the indoor space using an exhaust fan (Fig. 1).

The DHAPC theoretical model concept (Fig. 1) was to reproduce the conditions of room in a high-rise residential building in Kuala Lumpur and be able to measure indoor air quality and comfort levels. The model concept consists of three compartments - the outdoor chamber, the DHAPC compartment and the indoor space. The outdoor chamber reproduces the average outdoor thermal conditions, air quality and wind speed in Kuala Lumpur. The conditions were based on data acquired during the fieldworks conducted in July 2017 and January 2018. The first fieldwork has revealed that the mean air temperature for Kuala Lumpur was 29.3ºC (84.7ºF) with 70.1%RH for relative humidity and 1.1 m/s for average wind speed (Mohd Sahabuddin and Gonzalez-Longo, 2018) and the second fieldwork has found that the PM2.5 and PM10 average in Kuala Lumpur were 44.2 $\mu g/m^3$ and 53.5 $\mu g/m^3$ respectively (Mohd Sahabuddin and Gonzalez-Longo, 2019).

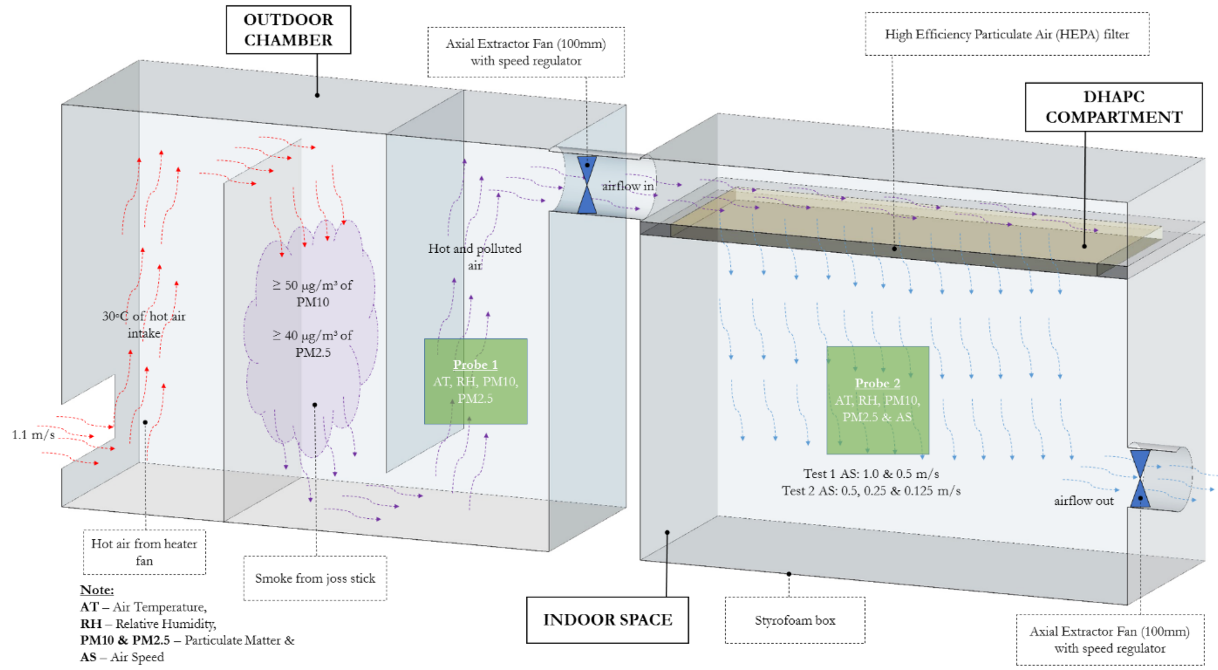

Figure 1. DHAPC theoretical model concept

In order to evaluate the DHAPC concept, a one-fifth scale model of an actual master bedroom in the second generation of People's Housing Program (PPR) building was prepared (Fig. 2). The actual master bedroom's dimension is 4 meters (13.1 feet length) x 3 meters (9.8 feet width) x 3.15 meters (10.3 feet height), thereafter the model measured 0.8 meter (2.6 feet length) x 0.6 meter (1.96 feet width) x 0.63 meter (2.1 feet height) respectively. The model was airtight and made of styrofoam due to its very low rate of thermal conductivity, keeping the indoor space condition at a stable temperature regardless of any external condition (AlQdah and AlGrafi, 2013). Two particle counter instruments were placed, one in the model's outdoor chamber and one in the indoor space compartment, in order to measure the concentration of particles as well as air temperature and humidity levels (Fig. 2).

Figure 2. DHAPC actual reduced-scale model

Indoor Air Quality and Comfort Conditions

The DOE has carried out Environmental Quality Reports in 2015 and 2016 and has found out that particulate matter (PM10) was the predominant pollutant that caused unhealthy conditions during the dry season (May until October) in Peninsular Malaysia (DOE, 2015, DOE, 2016a). The reports have also suggested that the daily concentrations of PM10 for Klang Valley (Kuala Lumpur area) were higher than other stations in sub-urban and rural areas (DOE, 2016b). These findings are consistent with the outcomes of our fieldwork (Mohd Sahabuddin and Gonzalez-Longo, 2019).

As a major issue worldwide which needs to be addressed, many organizations have produced guidelines and recommendations to measure and monitor the limits for various types of airborne pollutants. WHO, through its ambient air quality guidelines, has set the PM10 and PM2.5 limits are 20 µg/m^3 and 10 µg/m^3 respectively (WHO, 2006) and DOE has set 40 µg/m^3 and 15 µg/m^3 for the substances (DOE, 2013). Whereas, the CIBSE and ASHRAE have proposed 50 µg/m^3 and 15 µg/m^3 for the PM10 and PM2.5 limits (Table 1). The values are for annual mean concentrations.

Table 1. Comparison of Ambient Air Quality Guidelines and Standard

Parameters	**WHO [1]**		**CIBSE KS17 [2]**		**ASHRAE 62.1 [3]**		**DOE Malaysia [4]**	
	1 year	24 hours	1 year	24 hours	1 year	24 hours	1 year	24 hours
	µg/m^3		µg/m^3		µg/m^3		µg/m^3	
PM10	20	50	50	150	50	150	40	100
PM2.5	10	25	-	-	15	65	15	35

Notes: [1] WHO Ambient Air Quality Guidelines
[2] Indicated exposure limits for selected airborne pollutants
[3] The concentration of interest for selected contaminants
[4] New Malaysia Ambient Air Quality Standard (Department of Environment Malaysia)

We have taken into consideration three fieldwork studies measuring PM10 and PM2.5 in Kuala Lumpur taking into account WHO concentration limits (Table 2). The first study was done by the authors in January 2018, measuring the substances in indoor spaces in the PPR second generation block. Both values surpassed the WHO limits with PM2.5 recorded high concentration. The second fieldwork was a long term study (all year round) done by Rahman et al. (2015) from 2002 to 2011. This study has found that the annual average for PM10 and PM2.5 were 48.4 µg/m^3 and 26.1 µg/m^3 respectively (Rahman et al., 2015). Both values surpassed the annual limit set by the WHO. While the third fieldwork, monitored by the DOE from 2000 to 2015, has found that the annual average for PM10 from 2000 to 2015 in urban areas in Kuala Lumpur was 48.0 µg/m^3 (DOE, 2016a). Similarly, the value surpassed the WHO limits. It is undeniable that both PM10 and PM2.5 concentrations in Kuala Lumpur, either in indoor or outdoor spaces – short or long term, are well above the WHO recommendations.

Table 2. Comparison of fieldwork studies in Kuala Lumpur with WHO concentration limits

Parameters	**Duration**	**Fieldwork Study 2 (2017)**	**Rahman et al. (2002 – 2011)[1]**	**DOE Dataset (2000 – 2015)[2]**	**WHO Limits[3]**
Sampling Location		Indoor	Outdoor	Outdoor	
Mean PM10	(24 hours)	53.5	-	-	50.0
(µg/m^3)	(1 Year)	-	48.4	48.0	20.0
Mean PM2.5	(24 hours)	44.2	-	-	25.0
(µg/m^3)	(1 year)	-	26.1	-	10.0

Notes: [1] Rahman et al. (2015)
[2] Department of Environment (DOE), Malaysia
[3] WHO Ambient Air Quality Guidelines

For indoor comfort conditions, CIBSE Guide A – using the formula '$\vartheta_{com} = 0.33\ \vartheta_{rm} + 18.8$', has proposed the value of 28.4ºC for indoor operative temperature (CIBSE, 2015). The value suggested is in line with several studies done in Malaysia (Tang and Chin, 2013, Mohd Sahabuddin and Gonzalez-Longo, 2015, Gagge et al., 1967, Zain et al., 2007). For relative humidity and air speed, the organization has provided the ranges of 40 to 70%RH and 0.15 to 0.50 m/s respectively (Table 2). Meanwhile ASHRAE 55, has also set different ranges for the comfort criteria. For an acceptable operative temperature in naturally conditioned spaces, the standard has suggested the range (according to Kuala Lumpur's outdoor mean temperature of 27ºC in 2016) of 24ºC to 28.4ºC – 'acceptable operative temperature ranges for naturally conditioned spaces' diagram is referred (ASHRAE, 2010). For the relative humidity and air speed, the standard has set below 65%RH and between 0.15 m/s to 0.80 m/s respectively (ASHRAE, 2010). For the local standard in Malaysia, only Malaysian Standard 1525 – has set the indoor design conditions for the air temperature of 24ºC to 26ºC, relative humidity of 50 to 70%RH and air speed of 0.15 to 0.50 m/s (MS1525, 2014). Unlike CIBSE and ASHRAE standards, these design conditions are set for air conditioned spaces in non-residential buildings (Table 3).

Table 3. Recommended indoor comfort criteria for naturally conditioned spaces

Parameters	CIBSE Guide A:2015	ASHRAE 55-2010	*MS1525:2014
Operative Temperature	28.4ºC (83.1ºF) (1)	24ºC (75.2ºF) – 28.4ºC (83.1ºF) (2)	23ºC (73.4ºF) – 26ºC (78.8ºF) (3)
Relative Humidity	40 – 70%RH	<65%RH	50 – 70%RH
Air Speed	0.15 – 0.50 m/s	0.15–0.80 m/s	0.15 – 0.50 m/s

Notes: [1] Limiting values for the operative temperature to avoid overheating in naturally ventilated buildings
[2] Acceptable operative temperature ranges for naturally conditioned spaces
[3] Recommended design dry bulb temperature for an *air conditioned space for comfort cooling

Table 4 lists the average values of operative temperature (OT) and relative humidity (RH) as gathered in the fieldwork studies and simulation model 1. The average OT and RH for both fieldwork studies done in July (Mohd Sahabuddin and Gonzalez-Longo, 2018) and December were 29.3°C and 70.1%RH respectively. Whereas the simulation model 1 has gathered the full year data for the parameters which are 29.1°C and 66.4%RH. All findings from the two sources surpassed the range limits set by ASHRAE 55.

Table 4. Average values of operative temperature (OT) and relative humidity (RH) in fieldwork studies and simulation model 1

PPR 2nd Generation	Mean OT	Mean RH
Fieldwork Study 1 & 2	29.3ºC (84.7ºF)	70.1%RH
Simulation Model 1 (Full Year)	29.1ºC (84.4ºF)	66.4%RH
Selected Limits	<28.4ºC (83.1ºF)[1]	<65.0%RH[1]

Note: [1]ASHRAE 55

The analysis of the results is based on the reduction rate that each of the configurations can achieve. The higher reduction rates provide better indoor air quality and comfort. These reduction rates should achieve several required conditions as follows: PM10 of below 50.0 μg/m^3 and PM2.5 of below 25.0 μg/m^3 (WHO), air temperature of below 28.4ºC (ASHRAE 55), and humidity of below 65.0%RH (ASHRAE 55).

ANALYSES

Experiment 1: Method and Findings

In the first experiment, three types of synthetic materials (Polyester, Polyethylene Terephthalate - PET and Carbon-PET-Polyester) were tested using two different air speeds (0.5 and 1.0 m/s) and three different time interval (5 mins / 10mins / 15 mins). The thicknesses of the materials were 30 mm for Polyester, 40 mm for PET and 50 mm for Carbon-PET-Polyester. The experiment also tested four configurations of ventilation systems which were 'Fully Passive System' (B-B), 'Hybrid-Negative System' (B-F), 'Hybrid-Positive System' (F-B) and 'Fully Mechanical System' (F-F).

This experiment has found that among the three synthetic filtering media, the combination of carbon-PET-polyester with the thickest depth (50 mm) achieved the best performance, significantly reducing humidity and PM2.5 (Mohd Sahabuddin and Gonzalez-Longo, 2019). The main parameter of this achievement is the depth of the filter - a thicker filter could produce better results in which the results are consistent with a study done by Taylor et. al (1998). However, in terms of air speed, a thicker filter may reduce the air movement and this factor should be taken into great consideration when designing a dynamic insulation system.

To achieve indoor comfort for occupants the minimum and constant air movement is mandatory; in this test, the air movement for B-F, F-B and F-F configurations were consistently supplied and controlled using the supply and exhaust fans. However, according to ASHRAE 55 and CIBSE Guide A, the minimum requirement of air movement should be between 0.15 to 0.5 m/s, which is much less than the air speeds used in this test. Thus, the performance of these parameters could be further improved if much lesser air speeds are applied.

In this first experiment, the B-B configuration has achieved significant reduction rates in three parameters (air temperature, PM2.5 and PM10) but not humidity. This technique depends on wind buoyancy pressure which in this test, the pressure comes from the heater fan with 1.1 m/s of air movement (the average air speed in Kuala Lumpur). In an urban area context like Kuala Lumpur where the wind movement is limited and unreliable (Mohd Sahabuddin and Gonzalez-Longo, 2017, Mohd Sahabuddin and Gonzalez-Longo, 2018), this configuration seems not an appropriate option. Although the B-F and F-B configurations have achieved almost similar results in terms of filtering airborne particles; when considering air temperature reduction, B-F configuration performed better than F-B and F-B configuration provided better reduction for humidity. These two combinations are considered the best options among the four systems and should be explored in greater detail in the second experiment.

Different from B-F combination, the F-B configuration which employs in 'clean rooms', uses the driving forces that are mainly from the momentum of supply air – piston ventilation (Awbi, 2002). As a result, F-B configuration has achieved better reduction rate for humidity and airborne particles. In general, this combination is better than B-F configuration. However, the other factors that contribute to indoor discomfort and poor air quality should also be taken into account: without a fan that discharges the air from inside, the contaminated indoor air would inefficiently exhaust from the room. Thus, this F-B configuration should also be tested in further detail in the second experiment.

The F-F configuration may have produced a very significant air flow from the outdoor chamber to the indoor space compartment but the excessive air flow could drag airborne particles pass through the filter membrane and this happened in the first experiment. Only humidity has achieved the best reduction rate using this configuration due to the fact that, when the air continues to flow, the filter membrane effectively creates its own vapor barrier (Halliday, 1997). Table 5 shows the conversion results by using the four systems' percentage rates. Out of four systems, only two configurations complied the three parameters measured. The systems are B-F and F-B configurations which have met the requirement for air temperature, humidity and PM10. It could be deduced that both configurations have great potential to be improved and finally met all the conditions required.

Table 5. Conversion results using B-B, B-F, F-B and F-F reduction rates

Conf.	Parameters	Metric Scale	IES1/FW2 Average	'Carbon-PET-Poly' Reduction Rate (%)	Conversion Results	Compliance
B-B	Air Temperature	ºC (ºF)	29.1 (84.4)	19.4	23.5 (74.3)	√
	Relative Humidity	%RH	66.4	-4.5	69.4	-
	PM2.5	µg/m^3	44.2	45.3	24.2	-
	PM10	µg/m^3	53.5	44.7	29.6	√
B-F	Air Temperature	ºC (ºF)	29.1 (84.4)	16.5	24.3 (75.7)	√
	Relative Humidity	%RH	66.4	2.2	65.0	√
	PM2.5	µg/m^3	44.2	28.6	31.6	-
	PM10	µg/m^3	53.5	32.7	36.0	√
F-B	Air Temperature	ºC (ºF)	29.1 (84.4)	12.4	25.5 (77.9)	√
	Relative Humidity	%RH	66.4	10.9	59.2	√
	PM2.5	µg/m^3	44.2	31.9	30.1	-
	PM10	µg/m^3	53.5	33.5	35.6	√
F-F	Air Temperature	ºC (ºF)	29.1 (84.4)	8.5	26.6 (79.9)	√
	Relative Humidity	%RH	66.4	15.2	56.3	√
	PM2.5	µg/m^3	44.2	17.9	36.3	-
	PM10	µg/m^3	53.5	18.4	43.7	-

Figure 3 shows the tabulation of B-B, B-F, F-B, F-F results on a psychrometric chart where B-F, F-B and F-F configurations fall within the comfort zone. As mentioned earlier, F-F configuration may successful in filtering humidity but not particulate matter and heat. Hence, this research according to the first experiment findings, suggests that only B-F and F-B configurations have a huge potential for reducing polluted air and indoor discomfort in an urban area like Kuala Lumpur. Therefore, B-F and F-B configurations should also be tested in greater detail in the second experiment.

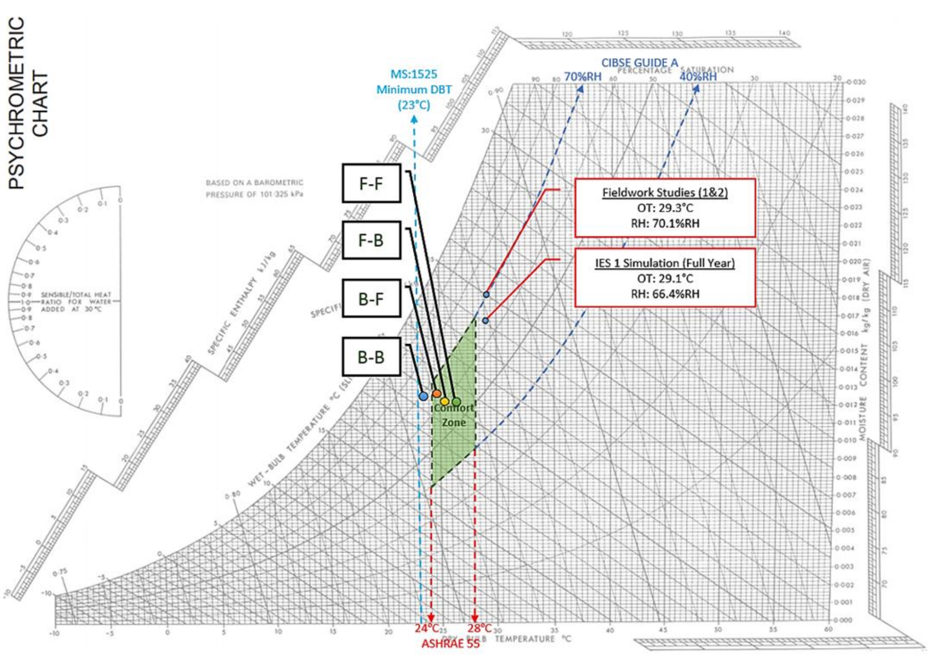

Figure 3. Tabulation of B-B, B-F, F-B, F-F results on Psychrometric Chart.

EXPERIMENT 2: METHOD AND FINDINGS

One of the main objectives of this second experiment is to evaluate the performance of the two ventilation configurations (B-F and F-B) as determined in experiment 1. Using several parameters, this test will also examine the performance of three recycled insulations using different air speeds. These recycled insulations – made from recycled glass, recycled plastic and recycled wool, were tested to filter the airborne particles, heat and moisture. Similarly like the experiment conducted by Olmsted (2008), three different time interval (5 mins/10mins/15 mins) and three different air speed (0.5, 0.25 and 0.125 m/s) were applied in this test. An activated carbon (AC) cartridge was also introduced between the outdoor chamber and the DHAPC compartment inlet (Figure 4).

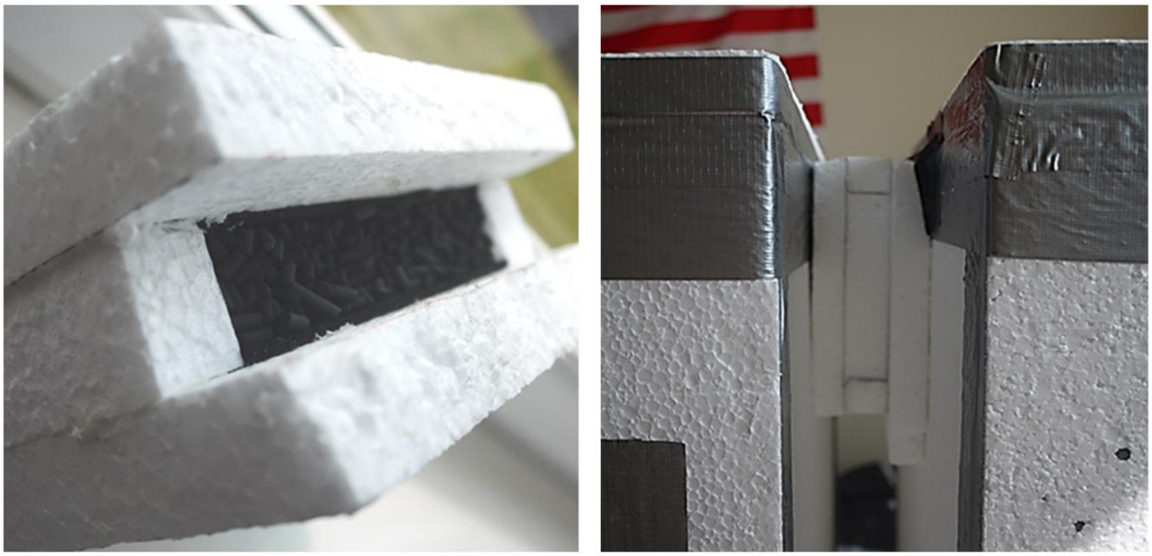

Figure 4. The placement of the activated carbon filter cartridge.

Table 6 shows the technical information of the insulation materials. All of the materials have the same thickness of 100 mm and made from recycled materials. They also shared the same values for thermal conductivity (U-value) and thermal resistance (R-value) which are 0.044 W/m^{2}K and 2.27 m^2 K/W respectively.

Table 6. Technical information of the recycled insulations

Insulation Materials		Thickness	U-Value (W/m^{2}K)	R-Value (m^2 K/W)
1	Recycled Plastic	100mm	0.044	2.27
2	Recycled Wool	100mm	0.044	2.27
3	Recycled Glass	100mm	0.044	2.25

Recycled Plastic

The recycled plastic material has produced encouraging reduction rates for all parameters except humidity. The reduction rates have increased when activated carbon (AC) filter was introduced. Figure 5 shows the experiment results of recycled plastic insulation with and without activated carbon cartridge. The F-B configuration has achieved higher reduction rates compared to B-F configuration (Figure 5). The highest particle reduction rates are performed by the F-B configuration with 81.4 percent (PM2.5) and 79.3 percent (PM10) where the B-F configuration only achieved 54.1 percent for PM2.5 and 54.4 percent for PM10.

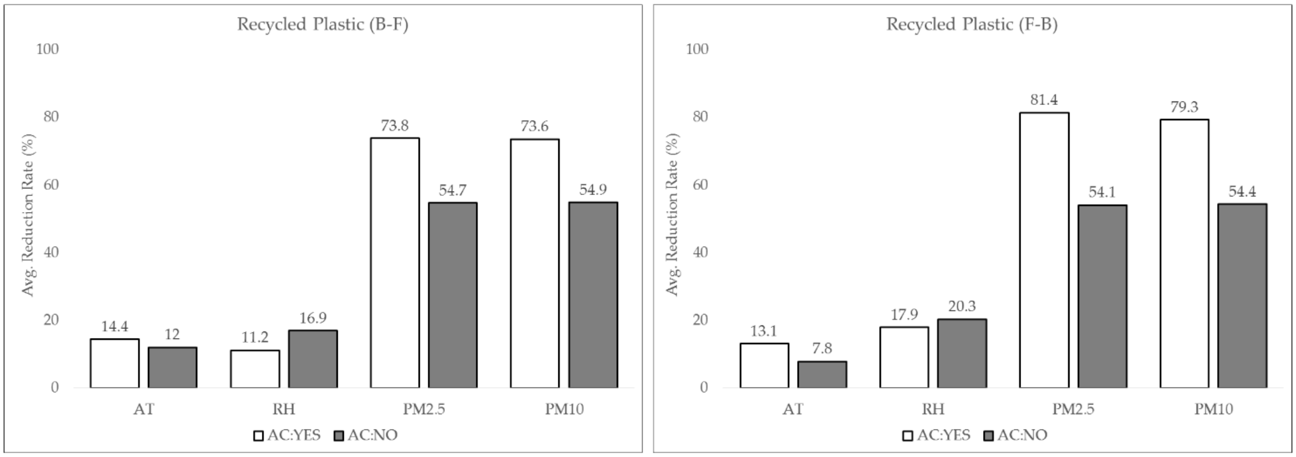

Figure 5. Recycled plastic experiment results with and without activated carbon cartridge

Recycled Wool

Figure 6 shows the mean reduction rates for recycled wool material. Similar to the previous test using recycled plastic material, the F-B configuration has consistently recorded higher reduction rates for filtering airborne particles compared to B-F configuration. The highest rates recorded are 80.1 percent for PM2.5 and 78.4 percent for PM10. Both were using activated carbon (AC) filter. Other remarkable results that this material has produced are the reduction rates for air temperature and relative humidity, especially when applying F-B configuration with AC. The reduction rates are 23.1 percent for air temperature and 24.2 percent for relative humidity.

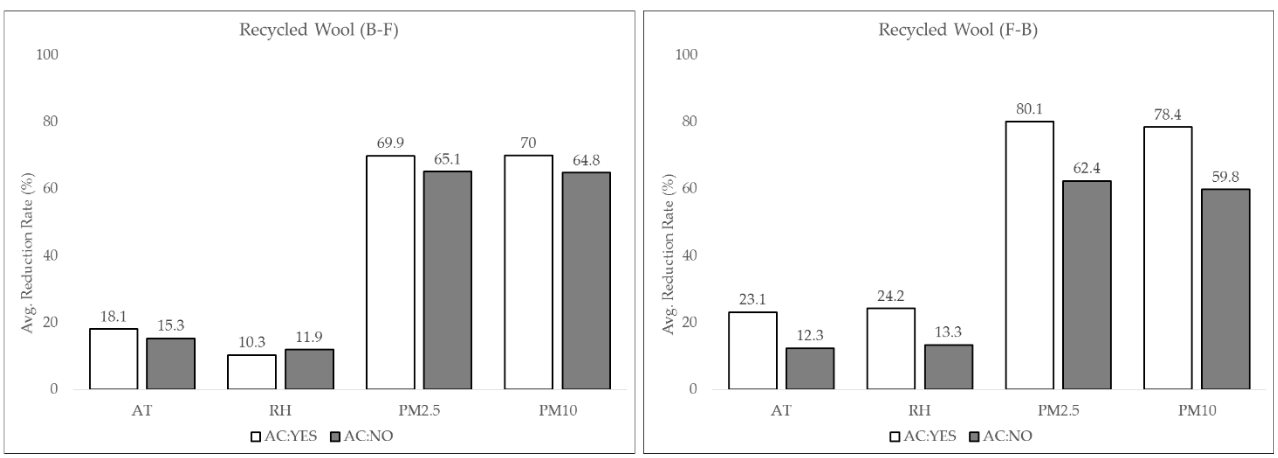

Figure 6. Recycled wool experiment results with and without activated carbon cartridge

Recycled Glass

The recycled glass material has recorded the highest reduction rates for PM2.5 and PM10 among the other materials. Figure 7 shows the material test results which when using activated carbon (AC), the reduction rates are 97.8 percent for both PM2.5 and PM10 while without AC, the rates are 84.6 percent (PM2.5) and 82.4 percent (PM10) respectively (Figure 7). For the B-F system, the rates are approximately 10 to 20 percent lower than the F-B rates - 81.9 percent for PM2.5 and 81.4 for PM10 (with AC); 72.3 percent for PM2.5 and 72.6 percent for PM10 (without AC). In this experiment, in terms of filtering particles, recycled glass material has shown the best performance.

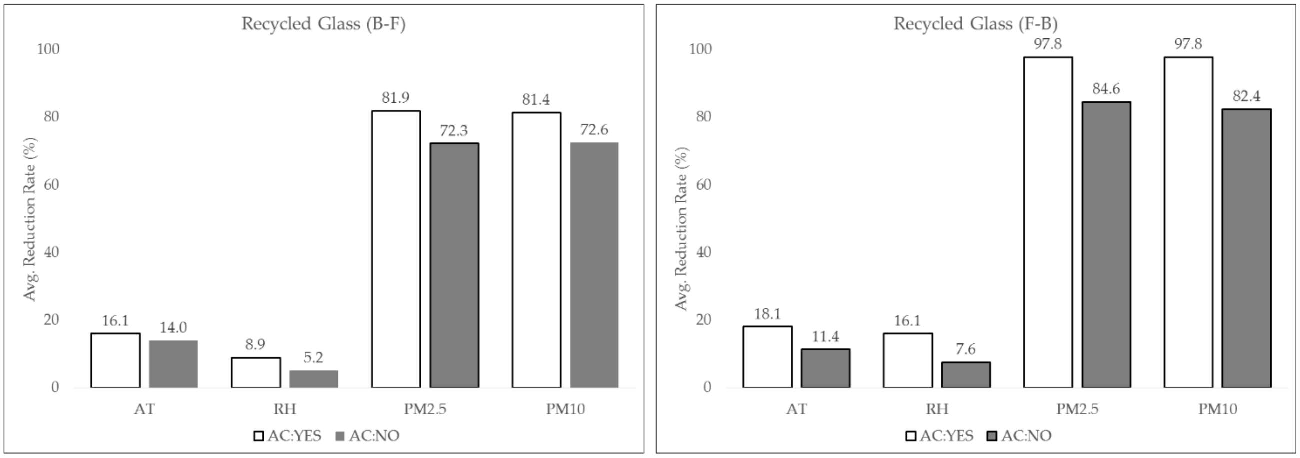

Figure 7. Recycled glass experiment results with and without activated carbon cartridge

DISCUSSION

Figure 8 shows the mean reduction rates for all parameters using B-F configuration combining the results from all materials (recycled plastic, recycled wool and recycled glass). Meaning that these results are averagely calculated regardless of insulation materials and with or without activated carbon filter. It shows that the air temperature and humidity rates are decreasing while the PM2.5 and PM10 rates are increasing. This suggests that lower air speed is better for filtering particles and higher air speed is better for reducing heat and humidity (Figure 8). In this study, improving heath performance is the most important criteria with not neglecting the energy efficiency and comfort conditions of the space. Therefore, the air speed of 0.125 m/s is appropriate and should be used in the DHAPC design.

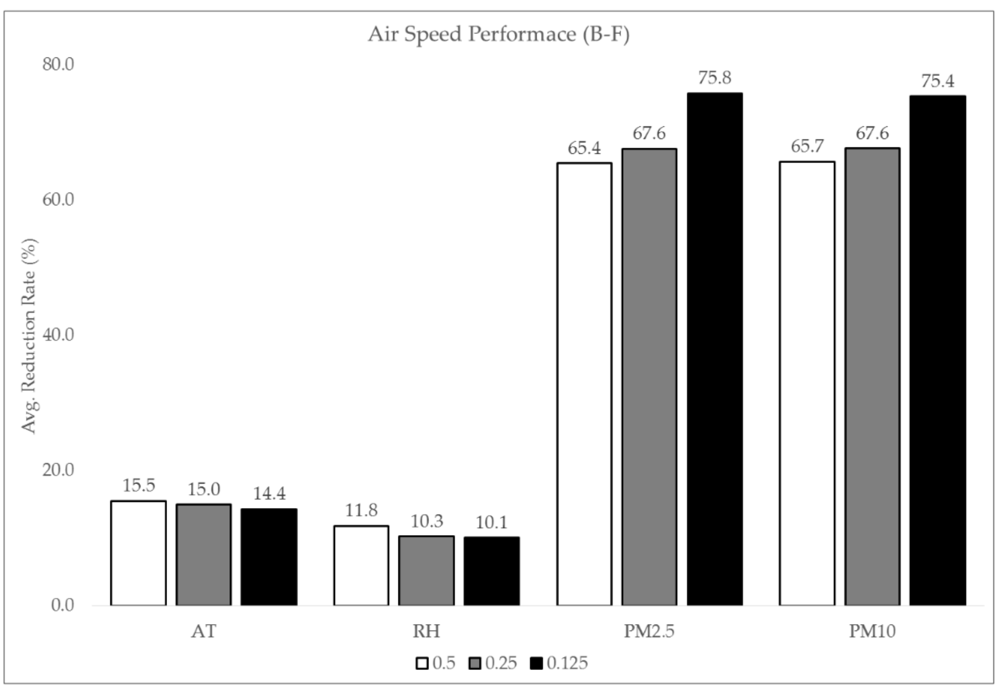

Figure 8. Results for B-F configuration with the different air speed performance

Figure 9 shows the reduction rates performance for F-B configuration regardless of insulation materials, with or without activated carbon filter. Similar to the B-F results, for air temperature and relative humidity, the results are descending from 0.5 m/s to 0.125 m/s. It suggests that the mean reduction rates of air temperature and humidity are inefficient when slower air speed was applied. However, for airborne particles (PM2.5 and PM10), the reduction rates are better when slower air speed was implemented (Figure 9). The highest reduction rates for PM2.5 and PM10 are 82.0 percent and 80.1 percent respectively. On that factor, the reduction rates achieve by the 0.125 m/s of air speed are chosen to generate the final conversion values in this study.

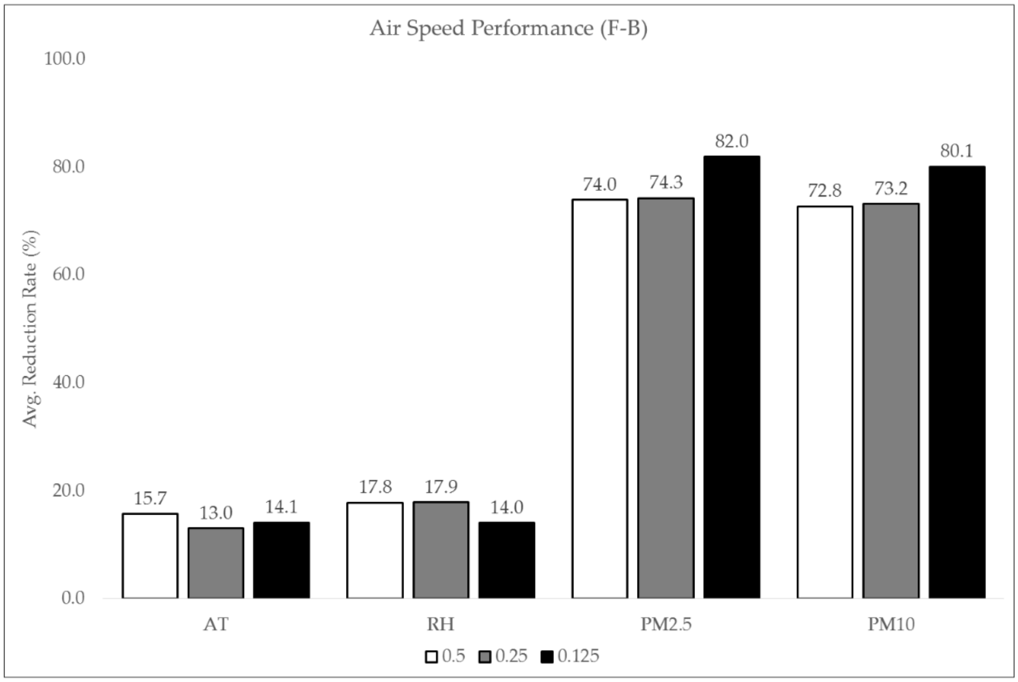

Figure 9. Results for F-B configuration with the different air speed performance

From the findings above, it can be deduced that the air speed of 0.125 m/s is scientifically proven can produce better results than the other air speeds. Table 7 shows the conversion results for all four parameters using the reduction rates of the 0.125 m/s results. Both systems, F-B and B-F using recycled insulation materials, with or without activated carbon (AC) can comply with the environmental and air quality limits explained earlier.

Table 7. Conversion results using the averages of 0.125 m/s reduction rates

Conf.	Parameters	Metric Scale	IES1/FW2 Average	Reduction Rate (%) For 0.125 m/s	Conversion Results	Compliance
B-F (I)	Air Temperature	ºC (ºF)	29.1 (84.4)	14.4	24.9 (76.8)	√
	Relative Humidity	%RH	66.4	10.1	59.7	√
	PM2.5	µg/m^3	44.2	75.8	10.7	√
	PM10	µg/m^3	53.5	75.4	13.2	√
F-B (I)	Air Temperature	ºC (ºF)	29.1 (84.4)	14.1	25.0 (77.0)	√
	Relative Humidity	%RH	66.4	14.0	57.1	√
	PM2.5	µg/m^3	44.2	82.0	7.9	√
	PM10	µg/m^3	53.5	80.1	10.6	√

This study has found that recycled glass material could produce the best reduction rates for filtering airborne particles as well as reducing heat and humidity. As stated in Table 8 below, the best conversion results are achieved by using recycled glass with F-B configuration. The F-B (II) conversion results are considered the best result achieved in this experiment with all values are within the lower threshold of the required limits.

Table 8. Conversion results using recycled glass (with AC) reduction rates

Conf.	Parameters	Metric Scale	IES1/FW2 Average	Reduction Rate (%) for Recycled Glass	Conversion Results	Compliance
B-F (II)	Air Temperature	ºC (ºF)	29.1 (84.4)	16.1	24.4 (75.9)	√
	Relative Humidity	%RH	66.4	8.9	60.5	√
	PM2.5	µg/m^3	44.2	81.9	8.0	√
	PM10	µg/m^3	53.5	81.4	9.9	√
F-B (II)	Air Temperature	ºC (ºF)	29.1 (84.4)	18.1	23.8 (74.8)	√
	Relative Humidity	%RH	66.4	16.1	55.7	√
	PM2.5	µg/m^3	44.2	97.8	1.0	√
	PM10	µg/m^3	53.5	97.8	1.2	√

Figure 10 shows the tabulation of the conversion results using 0.125 m/s and recycled glass reduction rates. Both results using 0.125 m/s reduction rates located in the comfort zone suggested by the CIBSE and ASHRAE. Meanwhile, the results using recycled glass reduction rates are located between the comfort zone and the minimum dry-bulb temperature as suggested by the Malaysian Standard 1525 (MS1525, 2014). When compared to the fieldwork studies and IES simulation results, the conversion results are significantly improved, both in health and comfort aspects.

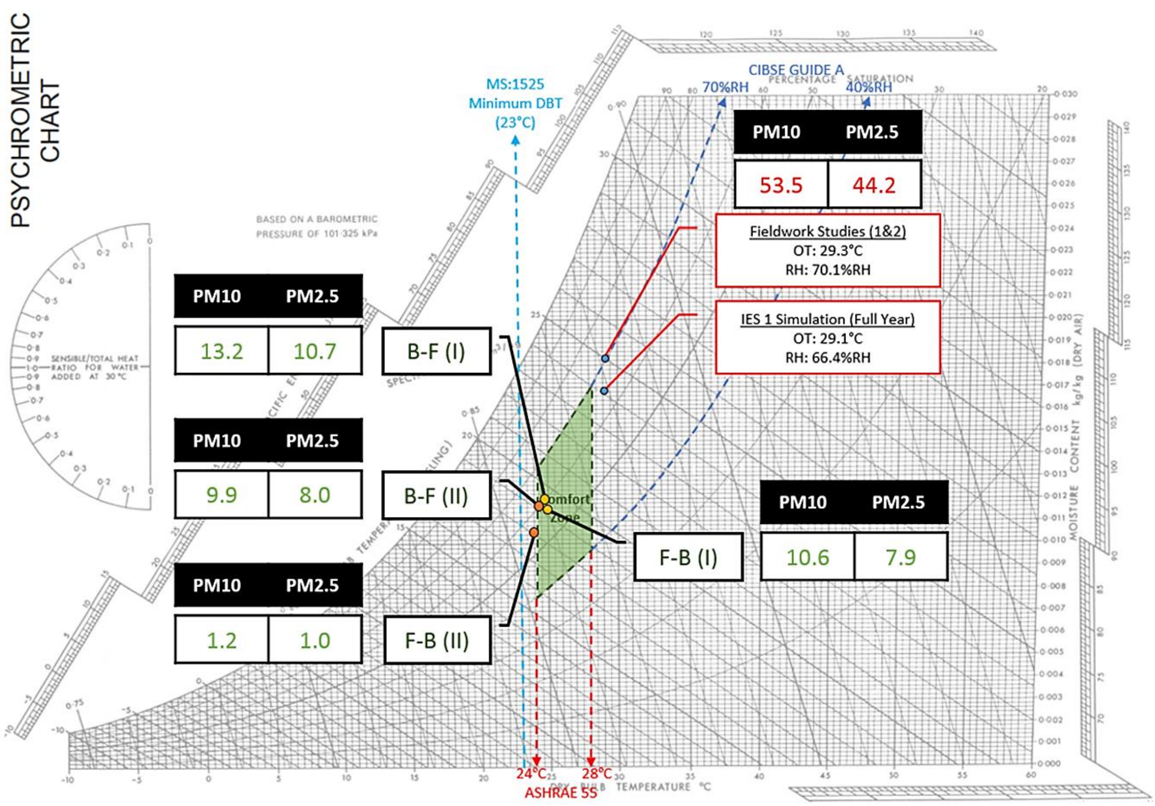

Figure 10. Tabulation of B-F and F-B results on Psychrometric Chart.

CONCLUSIONS

This study suggests that the ventilation configuration of B-F (hybrid-negative) and F-B (hybrid-positive) could be considered as the right options for reducing polluted air and indoor discomfort in urban areas. Both systems, F-B and B-F, can successfully achieve the environmental and air quality standards and with assisted by the right air speed and activated carbon filter, the reduction rates could be significantly improved.

Through this study, the activated carbon cartridge could add up another 10 to 30 percent improvement of airborne particle reduction. This has been proved by the second experiment explained in this paper. The lower air speed, 0.125 m/s particularly, has not only achieved and fulfilled the required air movement requirement but also could efficiently provide indoor comfort and air quality for the occupants. Recycled glass material as dynamic insulation has also produced remarkable results in reducing airborne particles as well as heat and humidity. The second experiment concludes that recycled materials are very suitable to become air filter materials and taking into account of current waste dumps all around the world, this initiative could generate another useful purpose for waste dumps as air filter product.

By considering the current design of high-rise social housing in tropical countries that emphasizes natural ventilation method, this experiment has found that the integrated strategy of DHAPC system using recycled glass material with hybrid ventilation and air speed of 0.125 m/s could be one of the best problem solving of indoor discomfort and poor indoor air quality in the future. A detailed study should be conducted to investigate and further reduce the indoor air supply by using a low-energy air cooling technique. In the second experiment, the activated carbon cartridge and recycled glass material recorded a significant effect on reducing particulate matter, hence, they should be studied in greater detail with other air pollution substances such as gases from diesel and petrol engines.

LIMITATION

These experiments were conducted in the UK local ambient humidity which between 50 to 30%RH. With this limited margin, the reduction rates for humidity seem insignificant and the author believes that the results could be more significant if the more realistic Kuala Lumpur's humidity condition of 70 to 90% is applied.

ACKNOWLEDGMENTS

The authors would like to thank the Commonwealth Scholarship Commission (CSC) for funding the study in which Mohd Firrdhaus Mohd Sahabuddin is a Commonwealth scholar, funded by the UK government.

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