Balancing Comfort and Indoor Air Quality in High-Riser Buildings for Social Housing in Kuala Lumpur: From Regulations to Construction

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SUMMARY

Large cities such as Kuala Lumpur are facing significant environmental challenges concerning air quality and energy efficiency, but their undergoing major construction programs of social housing are not addressing these problems in full. Indoor environmental conditions should be taken into consideration while designing these buildings so that they could achieve indoor comfort and air quality as well as the subsequent reduction in consumption of energy and resources. Increasing pollution levels and dated building standards are two of the key issues to be taken on board to allow for a more appropriate design. Natural ventilation should be promoted but allowing the outside air entering the indoor spaces is obviously permitting also hot and polluted air in. Our research started with a detailed analysis of the existing building regulations in Malaysia and current design practice in social housing in Kuala Lumpur. Two campaigns of fieldwork have been carried out to measure and assess the indoor comfort as well as the external and internal air quality in recently completed high-rise social housing buildings in Kuala Lumpur, part of the large People's Housing Program (PPR). In order to address the findings from the fieldwork and assessment, the 'Dynamic-Hybrid Air Permeable Ceiling' (DHAPC) system, combining dynamic insulation in the ceiling compartment with several ventilation systems, has been developed and tested. The experiments tried to identify the best option for the configuration of the ventilation in the DHAPC considering the indoor space compartments, either fully passive, hybrid or fully mechanical. Several porous materials were tested in the DHAPC compartment, in order to measure the required air temperature, humidity, PM2.5 and PM10 in the indoor space. These experiments suggested that the ventilation configuration of hybrid-positive (F-B) and hybrid negative (B-F) are the best options for reducing polluted air and indoor discomfort, achieving a significant reduction of air temperature, humidity and particles, in particular with lower air speed.

Key words: Indoor Comfort, Indoor Air Quality, Reduced-Scale Model, Hybrid Ventilation, Social Housing, Dynamic-Hybrid Air Permeable Ceiling, Kuala Lumpur

1. INTRODUCTION

Current building regulations and standards, set by public authorities in Malaysia, and green rating tools and standards, created and promoted by private organisations or, have not been able so far to acknowledge in full the current and future local climatic conditions. This is very evident in the case of Kuala Lumpur, where major social housing building programmes have not been able to address the required improvements in occupant's health and comfort and the reduction of the carbon emissions (Mohd Sahabuddin and Gonzalez-Longo, 2015). The Uniform Building By-Law (UBBL, 2013), and in particular clauses 39(1) and 40(1) regulating sizes of openings and light well requirements, were created 33 years ago, based on British building standards, and have not been revised since. They do not take full account of local climate conditions and need to be revised and improved in order to reduce carbon emissions while ensuring occupant's health and comfort (Mohd Sahabuddin and Gonzalez-Longo, 2017).

Likewise, the Malaysian Standard 1525, giving guidance on the effective use of energy in new and existing non-residential buildings (MS1525, 2014) and green rating tools such as the Green Building Index (GBI), GreenRE and MyCREST, have failed to help to devise strategies that could reduce airborne particulate matter and toxic gases as well as to prevent convective, conductive and radiative heat from entering and permeating high-rise residential units in Kuala Lumpur (Mohd Sahabuddin and Gonzalez-Longo, 2017). Clause 39(1) of the UBBL establishes that the minimum size of openings for ventilation purposes in every room for residential in Malaysia should be not less than 10% of the total clear area of the room. However, this sole requirement appears to be inappropriate to provide enough ventilation and filter airborne particulate matter from entering indoor spaces in high-rise residential buildings in urban areas. Similarly, Clause 40(1) of UBBL sets the requirement for a light-well of 15 sqm in buildings higher than 8 stories, which does not provide enough ventilation by natural means in high-rise buildings due to a weaker stack effect and the absence of wind-force ventilation (Mohd Sahabuddin and Gonzalez-Longo, 2017).

As our research has demonstrated, natural ventilation strategies, especially in dense urban areas such as Kuala Lumpur, face huge limitations in providing an adequate ventilation as well as a good air quality in indoor spaces due to the unreliability of wind movement and high air pollution during the dry season (Mohd Sahabuddin and Gonzalez-Longo, 2018). Hence, an integrated strategy of passive and low energy consumption should be further explored by considering the design of the openings and light-wells in more detail. An integrated strategy of passive air filtering technique that can filter air pollution, humidity and heat together with a ventilation system that can create a negative pressure inside a building could be one of the suitable strategies to solve the problems highlighted.

Dynamic insulation emerged as a concept in the 1960's (Craig and Grinham, 2017) but its origins can be traced back to the middle of the 19th century in Germany (Halliday, 1997). Originally, it was used as a ventilation system for livestock buildings, especially in Northern European countries. It integrates mechanical ventilation techniques: a fan is used to suck fresh air into the room and then the air is warmed by the porous insulation by heat conducting (Craig and Grinham, 2017).

Two recent studies have examined two elements that could successfully pair with dynamic insulation. The elements are infiltration of particles (Di Giuseppe et al., 2015) and the use of natural ventilation strategies to replace fans (Park et al., 2016). Craig and Grinham (2017) suggested that dynamic insulation studies from the 1960s have two common features: first, all of the studies used stock insulation materials with additional materials needed to complete the envelope design, and second, that all of the researches have incorporated an air-mixing cavity to get the final conditions of air in the interior spaces.

Another common feature of the existing research on dynamic insulation is the implementation of the technique on vertical walls. In a normal situation, walls and floors are common locations for occupants to place their furniture, accessories and decorations. If this technique is applied to walls and floors, the performance of the ventilation (air flow rate) will be affected and reduced and the occupants will have restrictions on their indoor spaces. Thus, this research will focus on the implementation of dynamic insulation in the ceiling compartment, the best element for ventilation in a tropical climate due to its hidden location from solar heat radiation. Current conventional construction methods in Malaysia show that spaces between floor soffits and beams are abandoned in the majority of multi-story buildings.

The studies on dynamic insulation and air permeable ceilings are still new in Malaysia, although the idea of using porous structures – taking Malaysian traditional vernacular houses as a reference – has been explored (Mohd Sahabuddin and Gonzalez-Longo, 2015). This research will test a new concept of dynamic insulation, the 'Dynamic-Hybrid Air Permeable Ceiling' (DHAPC). The aim of this experiment is to evaluate several ventilation configurations that can filter particulate matter (PM) of 2.5 (PM2.5) and 10 (PM10) microns, reduce air temperature and humidity as well as allow a constant air movement in the model's indoor compartment.

2. PHYSICAL MODEL

In order to evaluate the DHAPC concept, a one-fifth scale model of an actual master bedroom in one of the buildings from the People's Housing Program (PPR) was prepared. The master bedroom's dimension is 4000mm (length) x 3000mm (width) x 3150mm (height), thereafter the model measured 800mm (length) x 600mm (width) x 630mm (height) respectively (Table 1). It consists of three compartments reproducing the different environments and elements: the outdoor chamber, the DHAPC compartment and the indoor space (Figure I).

The outdoor chamber reproduces the average outdoor thermal conditions, air quality and wind speed in Kuala Lumpur's during the normally dry and wet seasons. The condition ranges selected are based on data acquired during the fieldworks: 29.3°C for air temperature, 70.1%RH for relative humidity, 40.0μg/m^3 for PM2.5, 50.0μg/m^3 for PM10 and 1.1 m/s for average wind speed (Table II) (Mohd Sahabuddin and Gonzalez-Longo, 2018). These values surpassed the recommended limits for air temperature below 28.4°C (ASHRAE, 2010), relative humidity below 70.0%RH (CIBSE, 2015), PM2.5 below 15.0μg/m^3 and PM10 below 40.0μg/m^3 (DOE, 2013).

Table I – Reduced-scale model dimensions in comparison with the actual room.

Parameters	Units	Actual Room	Reduced-Scale Model
Length	mm	4000	800
Width	mm	3000	600
Height	mm	3150	630

Table II – Environmental and air quality conditions for the outdoor chamber.

Parameters	Units	Average Actual Conditions
Air Temperature	^{o}C	29.3
Relative Humidity	%RH	70.1
PM2.5	$\mu g/m^3$	40.0
PM10	$\mu g/m^3$	50.0
Air Speed	m/s	1.1

Figure 1 shows the DHAPC theoretical concept where the test uses indoor air as supply air. The air was heated and speeded-up (1.1 m/s) by a fan heater and filled with smoke from joss sticks (a thin stick consisting of a substance that burns slowly and with a fragrant smell, used as incense), then the air was directed into the DHAPC compartment by either using the supply fan or natural buoyancy pressure from the heater fan. It then will be filtered by the DHAPC membrane before the clean air was forced down or sucked-in to the indoor space using an exhaust fan. The test model was formed with a straight duct equipped with a 'high-efficiency particulate air' (HEPA) filter in the DHAPC compartment, as recommended by the ASHRAE 52.2 and EN779 (ASHRAE, 2007, EN, 2012).

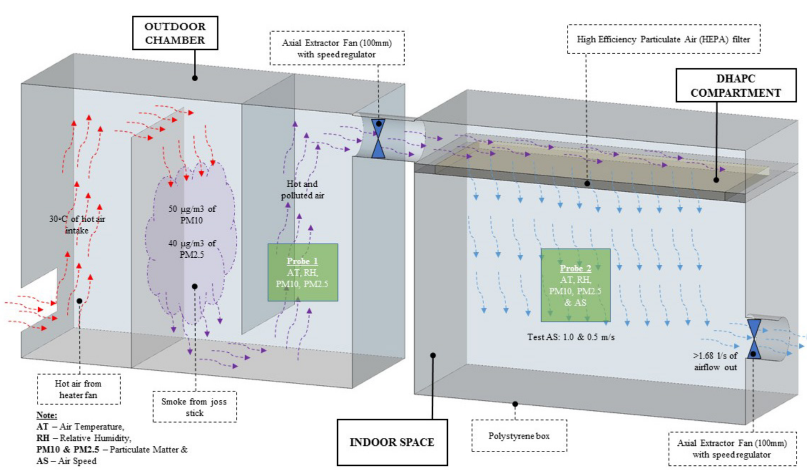

Figure 1 – DHAPC theoretical model concept.

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 external conditions (AlQdah and AlGrafi, 2013). The 25mm thick styrofoam sheet has a U-value of 2.0 W/m2k, the same that a single layer of a 100mm brick wall, the common construction material for social housing in Malaysia. According to ASHRAE 62.1 (ASHRAE, 2016), the design outdoor airflow required in the breathing zone (V_{bz}) of the occupiable space in a zone shall be determined in accordance with Equation 1.

$$V_{bz} = R_p \times P_z + R_a \times A_z \quad (1)$$

Where,

A_z = zone floor area, the net occupiable floor area of the ventilation zone, ft^2 (m^2)
P_z = zone population, the number of people in the ventilation zone during use
R_p = outdoor airflow rate required per person as determined from Table 6.2.2.1 (ASHRAE 62.1-2016)
R_a = outdoor airflow rate required per unit area as determined from Table 6.2.2.1 (ASHRAE 62.1-2016)

From the equation and considering that two people occupy the space, the outdoor airflow required in the breathing zone for the actual room (V_{bz}) is 17.75 m^3/h. As mentioned before, the physical model is one-fifth of the actual room, thus the required airflow for the model is 3.55 m^3/h.

The actual room is also predominantly naturally ventilated but in this study, the model applies passive, hybrid and mechanical ventilation systems (Table III).

Table III – Reduced-scale model details in comparison with the actual room.

Parameters	Units	Actual Room	Reduced-Scale Model
Wall Material	-	Single layer brick wall	styrofoam
Wall Thickness	mm	100	25
U-value	W/m^2k	2.0	2.0
Air Flow (cfm)	m^3/h	17.75	3.55
Ventilation Type	-	Natural	Natural/Hybrid/Mechanical

3. MEASUREMENT PROCEDURE

The experiment followed the recommended procedures outlined in the ASHRAE 52.2 – 'Method of testing general ventilation air-cleaning devices for removal efficiency by particle size' (ASHRAE, 2007) and the European Standard EN779 – 'Particle air filters for general ventilation-determination of filtration performance' (EN, 2012). In terms of particle sizing range, the suggested ranges were between 0.3 to 10μm (ASHRAE 52.2) and 0.2 to 3μm (EN779). However, for this test, only two particle sizes were taken into account: PM2.5 and PM10, as defined from the results of the second fieldwork as the main substances in the ambient outdoor air in Kuala Lumpur.

Two numbers of particle counter instrument were placed in the model's outdoor chamber and indoor space compartments to measure the concentration of particles as well as air temperature and humidity levels (Figure 2). The equipment uses a laser PM2.5 sensor – a new indoor air quality (IAQ) sensor technology built by 'Plantower'. These low-cost instruments are sufficiently accurate and have the potential to identify high pollutant exposures, providing high-density and reliable data (Moreno-Rangel et al., 2018). Another study has found that the low-cost instruments are accurate and reliable in detecting large sources that they appear suitable for measurement based control to reduce exposures to PM2.5 mass in homes (Singer and Delp, 2018).

The air temperature and relative humidity ranges applied were between 29-33^{o}C and 30-55%RH respectively (Table IV). Two variation of air speeds – 0.5 and 1.0 m/s, were applied in this test to create the positive and negative pressures. These pressures are useful for preventing backflow in the DHAPC compartment and also for preventing air-lock entries in the indoor space compartment (Lenchek et al., 1987).

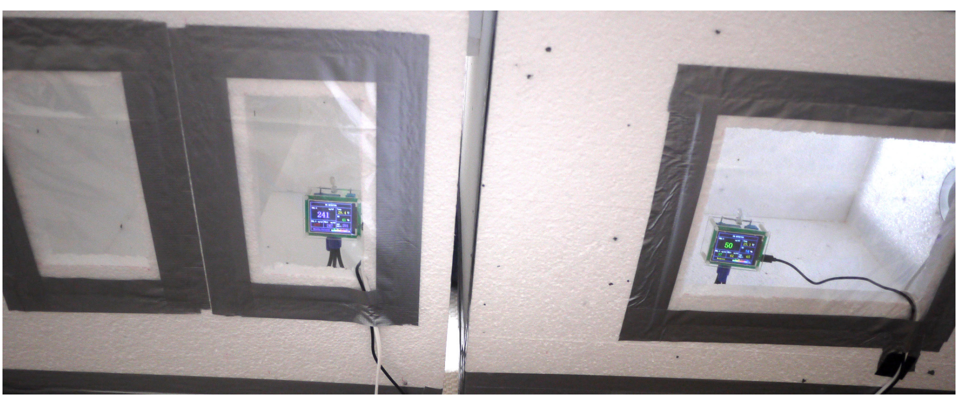

Figure 2 – Positioning of the particle counter instrument in the test model.

Table IV – Comparison of measurement procedures according to ASHARE 52.2, EN779 and DHAPC model

Parameters	ASHRAE 52.2	EN779	DHAPC Model
Particle Sizing Range	0.3~10μm	0.2~3μm	2.5~10μm
Types of Instrument	Optical counter or Aerodynamic particle counter	Optical counter	Laser sensor
Test Duct	Straight/U shape duct, HEPA filter installed	Straight duct, HEPA filter must be installed at the inlet	Straight duct, HEPA filter installed
Inlet Air	Indoor air or return air	Indoor air or outdoor air	Indoor air
Exhaust Air	Exhaust to the outside, indoor, or recirculated	Exhaust to the outside, indoor, or recirculated,	Exhaust to the outside
Temperature	10°C~38°C	n/a	29°C~33°C
Relative Humidity	20%~65%	<75%	30%~55%
Pressure	Positive pressure	Positive pressure or negative pressure	Positive pressure or negative pressure
Air Flow Range	0.22~1.4 m^3/s	0.24~1.5 m^3/s	0.5 and 1.0 m^3/s

Table IV lists the four different ventilation configurations that were used in this experiment to define the best ventilation configuration that can produce high reduction rates for all four parameters selected (air temperature, relative humidity, PM2.5 and PM10).

These configurations were tested using three different filters – Polyester (30mm thickness), Polyethylene Terephthalate as known as PET (40mm thickness) and a combination of Carbon-Charcoal filter with Polyester and PET (50mm thickness). This test used three different time intervals which were 5, 10 and 15 minutes and two different air speeds – 1.0 m/s and 0.5 m/s (Table V).

Table V – Proposed ventilation configurations for the test model.

Ventilation Configuration	Filter Media Selected	Fan Speed Variation	Log Time Intervals
1 Fully Passive Configuration (B-B) 2 Hybrid-Negative Configuration (B-F) 3 Hybrid-Positive Configuration (F-B) 4 Fully Mechanical Configuration (F-F)	Polyester, PET & Carbon-Poly-PET	0.5 m/s & 1.0 m/s	5, 10 & 15 minutes

The analysis of the results is based on the reduction rate that each of the configurations can achieve. The higher reduction rate provides better indoor comfort and air quality. These reduction percentages should achieve several required conditions as mentioned before. The required conditions are: air temperature of below 28.4^{o}C (ASHRAE, 2010), humidity of below 70.0%RH (CIBSE, 2015), PM2.5 of below 15.0 µg/m^3 and PM10 of below 40.0 µg/m^3 (DOE, 2013) (Table VI).

Table VI – Environmental and air quality parameters for the reduced-scale model.

Parameters	Units	Condition Required	Set by
Air Temperature	^{o}C	≤ 28.4	(ASHRAE, 2010)
Relative Humidity	%RH	≤ 70	(CIBSE, 2015)
PM2.5	µg/m^3	≤ 15	(DOE, 2013)
PM10	µg/m^3	≤ 40	(DOE, 2013)

4. RESULTS

4.1 Performance of the Ventilation Configuration

The ventilation configuration that uses a fully passive approach (B-B) achieved a great reduction of air temperature in all selected parameters. However, this technique depends on wind buoyancy pressure which in an urban area like Kuala Lumpur that has huge limitation and unreliability of wind movement (Mohd Sahabuddin and Gonzalez-Longo, 2017), this ventilation configuration may not be a suitable option.

Although B-F and F-B configurations have achieved almost similar results in terms of filtering PM2.5 and PM10 particles, when considering air temperature reduction, B-F configuration performs better than F-B while F-B configuration produces better reduction for humidity (Figure 3). These two combinations are considered the best options and should be explored in greater detail in the future. However, in indoor spaces, there are many factors (human activities and household equipment) that can contribute to indoor discomfort and poor air quality such as cooking, washing, body heat and respiration

(Lenchek et al., 1987). Thus B-F configuration is a better option because it has an active mechanism that can control these factors in indoor spaces. A detailed study on reducing humidity should be carried out to make B-F configuration a more suitable option.

Different from B-F configuration, the F-B configuration which usually being used 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, F-B configuration is better than B-F configuration, however, the 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. Therefore, this F-B configuration should also be tested in greater detail in the future.

The F-F configuration may have produced a very significant air flow from outside to the inside of a house but the excessive air flow could easily drag particles pass through the filter membrane and this happened in these test series. Only humidity has achieved the best reduction rate in this configuration due to the fact that, when the air continues to flow, the filter membrane effectively creates its own vapour barrier (Halliday, 1997).

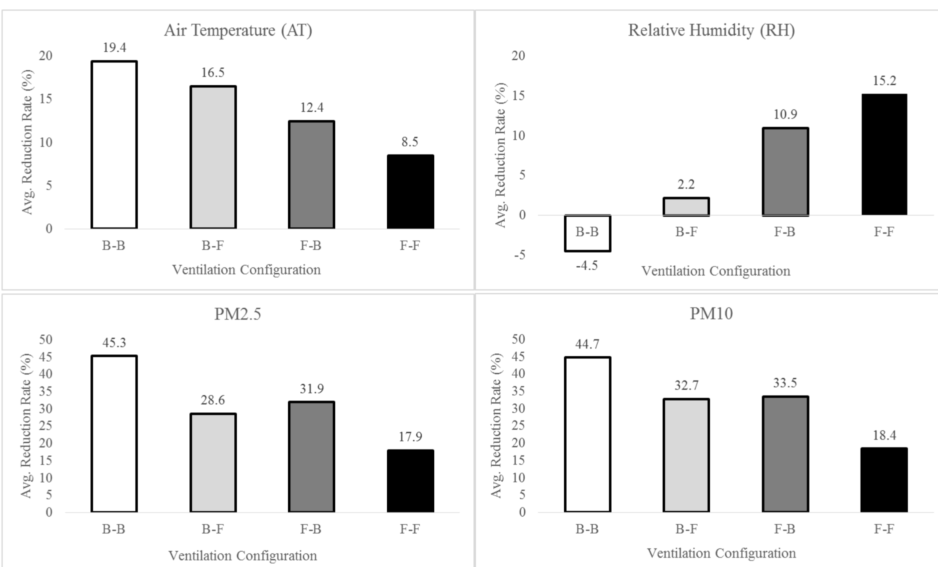

Figure 3 – Results for ventilation configuration performance.

4.2 Performance of Filter Media

Figure 4 shows the results for the filter media performance on all parameters. For air temperature, polyester recorded the best result that can filter 15.2% of heat than PET (13.5%) and carbon-poly-PET (13.9%). For relative humidity and PM2.5, the combina-tion of carbon-polyester-PET has achieved the highest reduction rates – 9% and 36.7% respectively. Carbon charcoal is known as good moisture absorption material and this is consistent with other studies (Fujiwara et al., 2003). Meanwhile, for PM10, PET filter media provides better filtering performance of 41.1%.

In general, among these three filtering media, the combination of carbon-PET-polyester with 50mm thickness has achieved the best performance, reducing humidity and PM2.5. The reduction rates are 9% and 36.7% for humidity and PM2.5 respectively. The main factors of this achievement are the depth of the filter membrane which is the thickest among other materials. A thicker membrane could deposit more particles than less thick membrane (Taylor et al., 1998) and also the structure of filter membrane could affect its performance (Liu et al., 2015). However, in terms of air speed, a thicker filter may produce more pressure drop and eventually reduce the air movement.

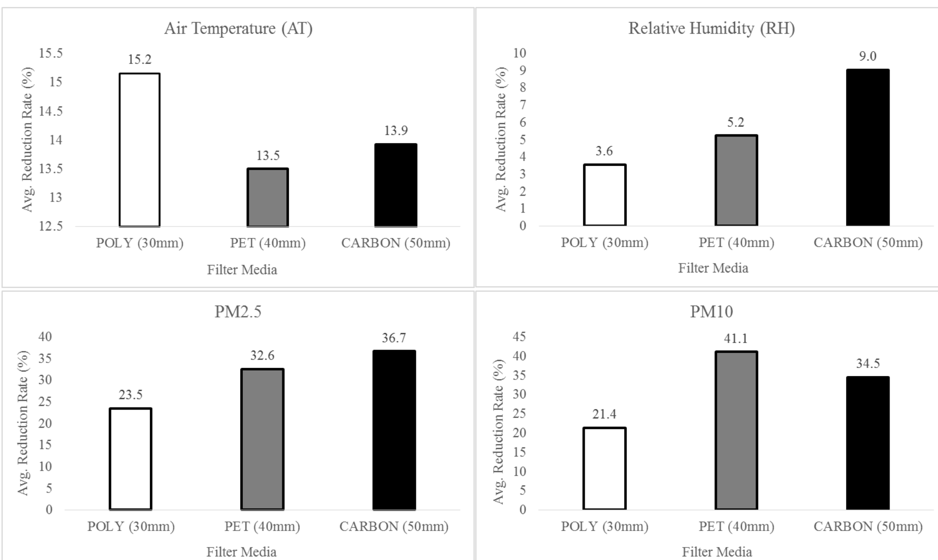

Figure 4 – Results for filter media performance.

4.3 Performance of Air Speeds

Figure 5 shows the performance of two different air speeds in reducing all four parameters. For air temperature, the 0.5m/s of air speed produced 6.4% higher heat reduction than the 1.0m/s of air speed. Whereas for PM reduction, the 0.5m/s air speed recorded 12% and 4.4% more reduction of PM2.5 and PM10 respectively compared to the 1.0m/s air speed. Except for humidity, all of the parameters achieved better results when low air speed is applied in the test, concluding that in dynamic insulation approach, the lower the air speed would produce better results. This is consistent with a study done by Taylor and Imbabi in 1998.

To achieve the right comfort level for the occupants, the minimum requirement of air movement shall be consistently supplied. For this test, the air movement for all ventilation configurations is supplied and controlled using two fans – supply and exhaust. The supply fan is located at the DHAPC compartment while the exhaust fan is at the indoor space compartment. According to the Malaysian Standard 1525, the minimum requirement of air movement in a habitable space should be between 0.15 to 0.5m/s (MS1525, 2014). For this test model (a-fifth size of the actual room) the air speeds used were 0.5 m/s and 1.0m/s, thus, these air speeds are considered high.

Therefore, the results could be further improved when lower air speeds are applied. The implementation of low air speeds of below 0.5m/s should be explored in greater detail in the future.

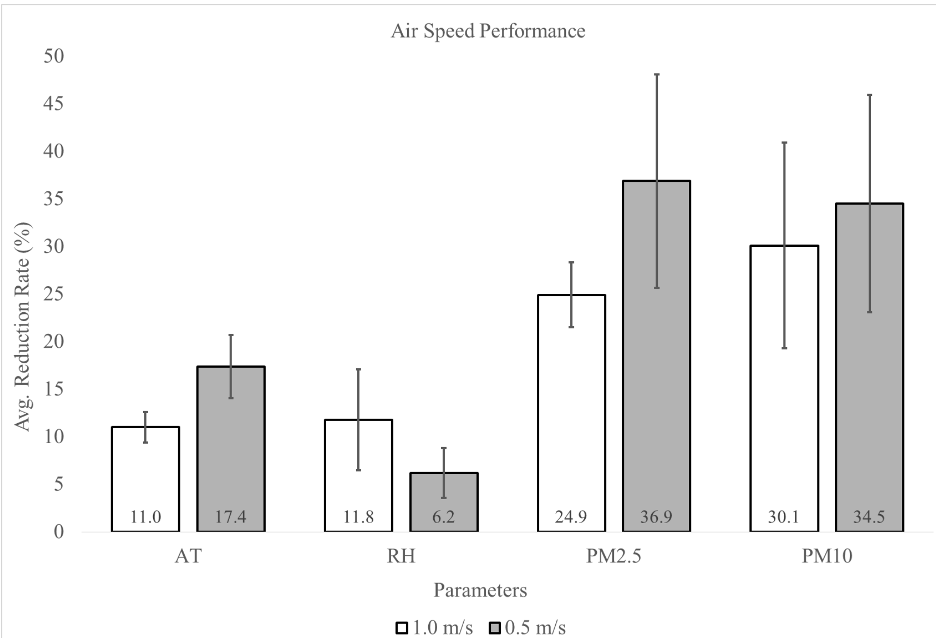

Figure 5 – Results for air speed performance.

5. ANALYSIS AND DISCUSSION

Table VII shows the conversion results by using the four systems' percentage rates. Out of four configurations, only B-F and F-B configurations achieve the best results and comply three parameters – air temperature, humidity and PM10. The B-B configuration complies two parameters – air temperature and PM10; while F-F configuration complies with air temperature and relative humidity only.

Even though the F-B configuration has achieved three requirement parameters, the B-F configuration, however, has recorded better air temperature and PM10 reduction rates. It could be deduced that both B-F and F-B configurations have a great potential to be improved and finally met all the conditions required.

In terms of airborne particles reduction results, three configurations (except F-F configuration) achieved good reduction rate (PM10 below the required condition). However, for PM2.5, none of the configurations has achieved a sufficient reduction rate to lower down the actual average of the substance to the required condition. Thus, another test using different materials and thickness should be conducted in future.

Figure 6 shows the tabulation results of all ventilation configurations on a psychrometric chart. The green zone is labelled as comfort zone as set by ASHRAE 55 and CIBSE Guide A. The B-F, F-B and F-F configurations are tabulated inside the comfort zone. Even though the F-F is tabulated in the comfort zone, its filtering performance does not reach the required standard, whereas the B-F and F-B are located at the upper limit of the zone. Thus, this DHAPC concept needs to be integrated with a low-energy air cooling system to provide more reduction in air temperature and relative humidity.

Table VII – Results using B-B, B-F, F-B and F-F reduction percentage rates

Config.	Parameters	Metric Scale	Actual Average	Rate (%)	Results	Complied
B-B	Air Temperature	°C	29.3	19.4	23.6	√
	Relative Humidity	%RH	70.1	-4.5	73.3	-
	PM2.5	$\mu g/m^3$	40.0	45.3	21.9	-
	PM10	$\mu g/m^3$	50.0	44.7	27.7	√
B-F	Air Temperature	°C	29.3	16.5	24.5	√
	Relative Humidity	%RH	70.1	2.2	68.6	√
	PM2.5	$\mu g/m^3$	40.0	28.6	28.6	-
	PM10	$\mu g/m^3$	50.0	32.7	33.7	√
F-B	Air Temperature	°C	29.3	12.4	25.7	√
	Relative Humidity	%RH	70.1	10.9	62.5	√
	PM2.5	$\mu g/m^3$	40.0	31.9	27.2	-
	PM10	$\mu g/m^3$	50.0	33.5	33.3	√
F-F	Air Temperature	°C	29.3	8.5	26.8	√
	Relative Humidity	%RH	70.1	15.2	59.4	√
	PM2.5	$\mu g/m^3$	40.0	17.9	32.8	-
	PM10	$\mu g/m^3$	50.0	18.4	40.8	-

Note: B-B = Fully Passive, B-F = Hybrid Negative, F-B = Hybrid Positive, F-F = Fully Active

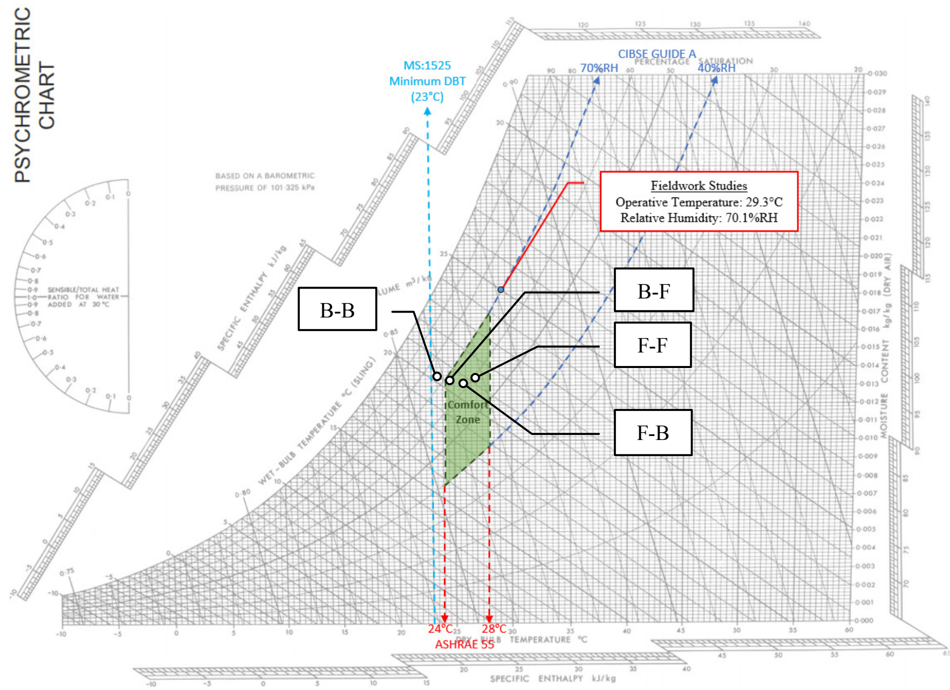

Figure 6 – Tabulation of B-B, B-F, F-B, F-F results on Psychrometric Chart.

CONCLUSIONS

Among the three filtering media, the combination of the carbon-PET-polyester membrane with 50 mm insulation thickness has achieved the best performance especially in reducing humidity and PM2.5. This test has found that the fully passive system (B-B) can provide more reductions in all parameters except humidity. However, this system depends on wind buoyancy pressure which in an urban area like Kuala Lumpur, wind movement is limited and unreliable thereafter this configuration may not be suitable. Meanwhile, the fully mechanical system (F-F) may have produced a very significant of air flow inside the model but this excessive air flow has reduced the particles contact with the filtering membrane in the model. As a result, the reduction rates for PM2.5 and PM10 for this configuration, are lower.

Three out of four parameters (except for humidity) achieved better results when low air speed is applied in the test, concluding that lower air speeds would give better results. In a habitable space, it is important to maintain the minimum airflow requirement as stated in Malaysian Standard 1525. The minimum requirement of air movement is between 0.15 to 0.5m/s, which is for a-fifth size model, the air speeds used (0.5 m/s and 1.0m/s) are considered high and thus the performance of these parameters could be further improved when lower air speeds are introduced.

Hence, this experiment suggests that the B-F and F-B ventilation configurations could have a great potential for reducing polluted air and improving indoor comfort in an urban area like Kuala Lumpur. The F-B configuration has recorded significant reduction rates for air temperature, humidity and PM10 which make this combination is a better option. However, there are other factors that contribute to indoor discomfort and poor air quality such as energy release from human activities and household equipment, therefore these factors (generally produce excessive heat and humidity) should also be taken into account and should be discharged efficiently from the inside of the housing unit. Due to that reason, the B-F configuration would also be an appropriate option. Therefore, the B-F and F-B configurations should be tested in greater detail in the future. With all the findings and arguments, it can be deduced that the DHAPC concept has a great potential to solve the problems of indoor discomfort and air pollution in urban areas.

LIMITATION

This experiment was conducted in local ambient humidity which between 30 to 50%RH. With this small margin, the reduction rates for humidity seem insignificant and the authors believe that the results could be more significant if the realistic Kuala Lumpur's humidity condition of 60 to 90% is applied.

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