Improving indoor air quality and thermal comfort in office building by using combination filters

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Abstract. Poor indoor air quality and thermal comfort condition in the workspace affected the occupants’ health and work productivity, especially when adapting the recirculation of air in heating ventilation and air-conditioning (HVAC) system. The recirculation of air was implemented in this study by mixing the circulated returned indoor air with the outdoor fresh air. The aims of this study are to assess the indoor thermal comfort and indoor air quality (IAQ) in the office buildings, equipped with combination filters. The air filtration technique consisting minimum efficiency reporting value (MERV) filter and activated carbon fiber (ACF) filter, located before the fan coil units. The findings of the study show that the technique of mixing recirculation air with the fresh air through the combination filters met the recommended thermal comfort condition in the workspace. Furthermore, the result of the post-occupancy evaluation (POE) and the environmental measurements comply with the ASHRAE 55 standard. In addition, the level of CO2 concentration continued to decrease during the period of the measurement.

1. Introduction
One of the main missions of heating, ventilation and air-conditioning (HVAC) system is ensuring comfort inside buildings. The absence of comfort condition disturbs people and may cause some anxiety and health effects. HVAC system should be provided for controlling thermal comfort through controlling the humidity/dehumidify using humidifier system and controlling of temperature (heating or cooling) using fan coil [1]. According to American Society of Heating, Refrigerating, and Air-Conditioning Engineers ASHRAE-55 standard ASHRAE-55 standard , Thermal comfort is that state of mind that define the fulfillment of the thermal condition [2]. There are many distinctions such as psychologically and physiologically, which make it difficult to please all the occupants; due to the fact that there is a different impact of these variables on people and genders.

There have been many researches that carried out by researchers’ (in various sites and climate characteristics) around the world in order to understand the comfort condition. ASHRAE conducted many studies to investigate the effect of users’ thermal comfort in the tropical and cold climate [2]. There are two essential conditions that must be considered when we talk about the indoor environment such as the indoor air quality (IAQ) and thermal comfort. There are many attributes that have a significant impact on the sensation of thermal comfort that generally consist of air humidity, air
temperature, mean radiant temperature, air velocity, activity levels and human clothing [3]. The main reason of ventilating a building is to ensure that the air circulation is covering all the occupied areas; in order, to eliminate contaminants. The effectiveness of ventilation systems is assessed by many attributes such as the thermal condition, contaminant removal effectiveness; air exchange effectiveness and local air mean age. These features guaranteed the quality of air in each building. In addition, indoor air quality and thermal comfort have a significant impact on the occupants output productivity [4]. According to Niu, thermal comfort could be achieved by varying the conditions of the supplied air [5]. It was also he stated that poor condition of IAQ could cause health problem such as sick building syndrome (SBS) to occupants.

Varied statistical data was gathered from a wide range of field studies and laboratory tests in order to gain an acceptable definition of thermal comfort. The preference of comfort condition varies in individuals. Section 5 of the ASHRAE-55 standard is designed to define the thermal environmental conditions in space, which are required to satisfy a specific percentage of the tenants of space [2]. The poor condition of IAQ was caused by the pollutants indoor. There are many components in the indoor air such as gaseous pollutants and particle pollutants [3]. Previous studies on the indoor thermal condition illustrated that the thermal dissatisfaction was related to higher air movements which did not meet the ASHRAE 55 standard [2]. The climate of Malaysia which is hot and humid has an impact on the indoor thermal comfort due to the effects of the outdoor condition.

From field measurement and thermal sensation votes the findings illustrated a significant reduction in CO₂ concentration while the parameters of thermal comfort slightly improved after the installation of a heat exchanger, although the energy consumption increased by small percent due to the hot and humid fresh air. Furthermore, good IAQ was achieved by the employment of heat exchanger located in the space. This procedure will not increase the energy consumption [6].

Relative humidity in the humid climates may not have a distinct impact on the thermal condition of building occupants. Subsequently, it is accepted that there is a high percent of relative humidity in air-conditioning zones. However, in the non-air conditioned area, there is no need to isolate humidity parameter and air temperature parameter as the two parameters are interrelated when dealing with indoor thermal comfort [7]. According to Lee & Brand [8], there exist a relation between indoor environment, comfort condition, health and the performance of office building users. Whereas, the complaints and symptoms that reported by the users, physical indoor environment measurements and chemical are hard to achieve. The IAQ and the comfort of users’ in traditional office buildings is achieved by a variable procedure such as an air handling unit (AHU) that have a control system for thermostatic and the air box, which collects and mixed air from an AHU and delivers [2]. Wong [4] study the thermal condition in an office area, he mentioned that the thermal comfort should carefully apply due to reason that the office area was occupied by many users’ who need to be satisfied with the environmental condition, which help to enhance the productivity of occupants. However, in tropical climates, the characteristic of the weather (hot and humid) may have a reverse influence on comfort of the occupants.

The adoption of natural ventilation in tropical climate through the openings in the building (door and window) may lead to increasing the percent of the indoor humidity and has a negative impact on the thermal condition. The status of poor IAQ is connected to the amount of relative humidity inside the building and one of many sources of discomfort condition; however, to solve this problem mechanical ventilation system is employed to enhance comfort, which leads to increase in the energy consumption. To control the air temperature and relative humidity, air-conditioning is used to provide more control and improve the IAQ for the users’ [9]. Dear [10], conducted a field study in two high-rise office building that used natural ventilation and mechanical cooling system (air-conditioning); their findings that the employment of natural ventilation makes the indoor condition not complying with ISO standard. It mentioned that the office buildings that used air-conditioning system, did not require much cooling; on the other hand, in the natural ventilated office building the operating temperature was 31.5 °C, which according to the conventional comfort standard, this temperature was higher than the recommended temperature [10], [11]. In residential buildings in Malaysia, thermal
comfort was assessed and the neutrality of occupants’ thermal condition had been conducted by Zain [12]. The result showed that the neutral temperature was 26.19 °C. In this range, the interior space does not need much cooling to maintain thermal comfort for building occupants.

Wan et al [13], conducted thermal comfort study in an office building in southern China, using the principle of effective temperature. The findings showed an increase in the cooling load of air-conditioning and the energy consumption when the indoor air temperature was high. They suggested a solution to this problem by fixing a high relative humidity and lower indoor air temperature, due to the fact that the human body could adapt the higher humidity more than the temperature. By studying the comfort air temperature in an office building for staff and visitors, the result showed that temperature range of 24.5 - 28.2 °C was comfortable as perceived by the office staff; whereas the visitors were more comfortable with the temperature ranging between 24 - 27.8 °C. Comparison between the maximum temperature that was acceptable by both staff and visitors was higher than the recommended temperature based on ASHRAE 55 standard by 2 °C. By highlighting the range of accepted, comfortable temperature in hot and humid climate it could be noticed that the temperature is generally not complying with the comfort zone as that recommended in ASHRAE standard 55-2004 [14]. According to Kwong, Adam, & Sahari [15], it could meet the thermal comfort in natural ventilation residential building if these areas are not exposed to be under the requirement of building safety; but to achieve thermal comfort in these areas the occupants must be able to adjust their comfort condition. However, in an office building in the tropics the operative temperature was listed as 24.2 - 28.3 °C, and between 23.3 – 29.2 °C in other building types; however, the temperature varies in the natural ventilation building; where by the temperature is higher than other building. ASHRAE standard 55 investigated on the impact of the air velocity on thermal condition, the influence of air velocity on thermal comfort is connected with other environmental variables such as radiant temperature, air temperature, and relative humidity.

In ASHRAE standard the use of PMV model is governed by the air velocity not exceeding 0.20 m/s (40 fpm). The air velocity that is more than the suggested range could help to improve the boundaries of the comfort zone in specific situations. In the last decade, the demand for energy has increased significantly in Southern Asian countries. The urgent and decisive demand on air-conditioner use in these countries was a cause for the increase of energy consumption for cooling the building [10]. In hot and humid climate, the non-residential building, especially the commercial buildings, consume the most of the energy as the fact that these buildings are normally provided with a mechanical ventilation and air-conditioning system to improve indoor thermal comfort and indoor air quality. However, this system consumes 30 to 60% of the total energy use among all building services, as in many studies which attempt to identify the best method to save energy [16].

Many experts in the field of building construction such as operators, air-conditioner manufacturers and building engineers in hot and humid climate adopted the idea that the low operating air temperature of the cooling system (air-conditioning) is essential in providing a thermally comfort conditioned space for building users’. Consequently, this leads to waste of valuable energy and raising the cost of maintenance and operating in buildings. Previous studies that focused on thermal comfort in commercial buildings recommended that the setup of upper air-conditioning temperature, could achieve thermal comfort of users’; whereas, the high air speed may adjust the cooling condition to gain less energy consumption without the increase in the expenses. On the other hand, the studies on thermal comfort focus on the impact on several aspects on the thermal condition such as physical condition, educational level, age and gender of occupants; in addition, more investigation are needed on the non-thermal parameters that influence the sensation of thermal comfort [16].

The objectives of this study are to assess the effectiveness of indoor thermal comfort in the office buildings, and to control the concentration of CO₂ by using suitable ventilation and air filtration system. Xu et al [17], studied the concentration of CO₂ and TVOC in a residential building, using the HEPAiRx. The results showed a reduction of about 210 mg/m³ and 710 ppm of both CO₂ and TVOC concentration levels respectively; thus, lower CO₂ concentration can be achieved by controlling the fresh air and recirculation air. On the other hand, in a tropical climate the fresh air intake will increase
temperature and relative humidity of the supply air, which led to increasing the energy consumption due to the reason that the fresh air needs to be cool to the design supply condition.

2. Methods
The study is carried out using the environmental control chamber that is able to simulate a typical office environment. The chamber dimension is (5 m x 5 m x 2.8 m), A schematic diagram of the chamber setup is shown in Figure 1. Figure 2 show the layout of sensors measurement and occupants position inside the chamber, the walls and the ceiling were of polyurethane insulation board of 10 cm thickness, the design of the joint, the groove and the tongue that made from stainless steel metal (5 mm) and located in the chamber on both sides. The chamber was equipped with HVAC system, a compressor (10 HP), an outdoor condenser and fan coil unit in the mixing room, which is located on the top of the chamber roof. The supply air duct located at the roof of the chamber. The main air supply duct links the fan coil unit to the chamber. The main supply duct was distributed in two main branches to provide air through ceiling diffusers (0.4 m x 0.4 m); moreover, there are two holes (0.55 m x 0.45 m) provided on the return air duct suspended on the top of the ceiling connecting the chamber and mixing box. A filter box (0.6 m x 0.3 m) was designed to house the new filters and to ensure good mixing of the air passage and cleaning through the filter before entering the fan coil unit.

The outdoor fresh air intake was in the mixing room through the flexible duct, exhaust fan, and damper. The damper was connected by a flexible duct to warrant that sufficient supply of outdoor fresh air compatible to ASHRAE standard 62 [18]. Another damper was also connected to the exhaust fan at the top of the ceiling to control the exhaust air.

The air flow through the system was adjusted to 560 CFM (951 m³/h) to achieve a face velocity 1 m/s through any diffusers, with air changes rate about 3 h⁻¹ (typical air change rate for an office building) as suggested by ASHRAE standard 62. The chamber environmental condition was adjusted between 23 °C to 26 °C and 78% for RH, which is the indoor environmental condition that suggested in Malaysia by the studies of [19, 20]. The control of the air temperature and relative humidity by using AHU system, through temperature and relative humidity monitoring system to adjusting the temperature.

The chamber study was conducted in two cases. The first case involved in recording the environmental condition; daily in two months, simulating typical work hours from 8:00 am to 4:00 pm with four occupants in the chamber. A MERV 13 pre-filter and ACF filter (0.6 x 0.3 x 0.025) m³
placed in a filter box before the fan coil unit. Thermal environmental parameters were measured and recorded. The second case involved the measuring of \((\text{CO}_2)\) gas concentrations in the chamber. The temperature and relative humidity were recorded using four sensors (KIMO 100) that connected to the computer device using temperature and relative humidity monitoring system. Whereas, air velocity was measured using VelociCalc plus model 8324/8384 the instrument sat at three heights points, the first one at 0.5 m above the floor that represented the occupant seated at the knee height, while 1.1 m high represented the occupant level at sitting condition, and the last point is 1.6 m at standing level [2]. The measurement of \(\text{CO}_2\) concentration was recorded using an IAQCalc device model 8760/8762 at four locations in the chamber, the measurement at any location was repeated three times to ensure. The air temperature and relative humidity were recorded every 5 minutes interval using the chamber monitors / sensors.

Another assessment tool used to determine the occupant’s comfort condition in the experimental space is the post-occupancy evaluation (POE) survey. The occupants were asked in the evaluation to assess their perception of the indoor condition. The survey questionnaire designed based on (ASHRAE standard 55, MM 040 NA offices and Industry Code of Practice on Indoor Air Quality 2010) [2, 20] and divided into two sections. The first section consists of general information such as gender, age, nationality, activity, clothing value (CLO value) and the thermal sensation; while, the second section consists of the perception on environment satisfaction rating of air temperature, the time of dissatisfaction and the source of dissatisfaction, and occupants’ additional comments related to their satisfaction of the chamber environment condition.

### 3. Results and discussion

The measurement was carried out from January 25 to March 25, 2016. The outdoor air temperature was between 24 °C in the morning and 32 °C (at the peak during the experimental period); whereas, the relative humidity was in the range of 87 ± 7%. The thermal comfort condition in the chamber was assessed by environmental measurement and POE questionnaire; the results of the experiment were compared with ASHRAE 55 standard. The \(\text{CO}_2\) concentration in the chamber log within recommended level that would not affected the users’ health. The environmental variables (air temperature, mean radiant temperature, relative humidity and air velocity) are amongst the variables / parameters that affect thermal comfort in the space.

#### 3.1. Results from Measurement

**3.1.1. Environmental Assessment**

Figure 3 shows the fluctuating of temperature and relative humidity on a working day (8 hours). From Figure 3 it is noticed that the temperature varies between 23.2 °C to 25.1 °C. In this study the temperature was controlled by adjusting the thermostat range for controlling the temperature to 25 °C. According to [21], the indoor and outdoor climates both have influences on human adaptability; furthermore, the occupants’ activity had affected the internal heat load and hence increasing the temperature.

The study also cited that the outdoor relative humidity was fluctuating between 78 to 95% average humidity in Malaysia during the northeast season. In the chamber, the relative humidity fluctuated between 69 to 89% and the average was 80%. Study on the perception of thermal comfort in air-conditioning building in Thailand by [22], focused on two non- measurable factors such as adaptation and educational level. The study showed that the air temperature settings of 26 °C and 50 – 60% relative humidity result in a thermally comfortable condition to the building users / occupants.
The air movement in the chamber ranged between 0.13 to 0.2 m/s, (measurement conducted at three levels and six points in the chamber. According to Malaysian standard 2007 had recommended the indoor air velocity be within the range of 0.15-0.5 m/s [23]. Another assessment tool used to evaluate air velocity through using predicted percentage dissatisfied (PPD) and predicted mean vote (PMV) indices. Figure 4 presents the PMV and PPD plot in the chamber on a comfort chart. A comfort chart is a tool that used to define building’s comfort condition according to ASHRAE. It is noticed that the PMV value was (-0.08), which indicate that overall thermal sensation inside the chamber was slightly cool. However, questionnaire study by participants voted that the general condition inside the chamber was neutral.

**Figure 3.** Air temperature and relative humidity variation in office (with four occupants)

**Figure 4.** CBE Thermal Comfort Tool
3.1.2. Air Quality Assessment
The concentration of CO₂ as in Figure 5, recorded high level of 650 ppm when the chamber was occupied by four persons, and observed that the decrease of concentration as passage of the time. From Figure 5 it is noticed that the concentration of CO₂ dropped to 620 ppm after 20 minutes, and to 595 after 60 minutes. Furthermore, the CO₂ concentration depend on the ratio of fresh air to recirculation air; according to study of Lee [24], explained that the effect of the makeup air ratio to recirculation air ratio and evaluated the optimum ratio of fresh air and recirculated air for acceptable indoor air quality and energy consumption. In this study it was controlled by air damper to ensure the ratio of 0.2; this ratio complied with ASHRAE standard 55 for air change rate in office building.

![Figure 5. CO₂ concentrations in chamber with four occupants](image)

3.2. Results from Questionnaire
The thermal comfort, including air velocity, was evaluated by questionnaires and the measurement of physical parameters compared with ASHRAE 55 standard. The questionnaires were conducted on occupants inside the chamber. The results of questionnaire analysis are shown in Figures 6 (A, B and c), on the basis of temperature and thermal comfort, the participants rated/voted as cool (30%), as slightly cool (35%), Neutral (19%), slightly warm and cold (4%). The overall thermal sensation is shown in Figure 6B; the percentage of occupants comfortable (38%), comfortably warm, (4%) much too cool (2%), too cool (10%) and comfortably cool (40%). Whereas, the indoor thermal comfort for satisfied occupants with temperature in the test chamber as shows in Figure 6C; consisting of satisfied (48%) followed by normal (19%), quite dissatisfied (15%), very satisfied (10%) and quite satisfied (4%). However, the POE asked the participants to vote their satisfaction with the indoor air temperature, the composition of participants were local Malaysian students and international students as in Figure 7B. The final findings on the perception of indoor air temperature by nationality noticed that more than 45% of local Malaysian participants feel comfortably cool, whereas almost 50 percent of international occupants voted as comfortable as shown in Figure 7A. Daghigh [10] stated that Malaysian subject feel comfortable with the indoor air temperature not greater than 28 °C. Lastly, the participants were asked to describe the source cause of discomfort in the chamber, consisting of 6 parameters such as humidity, air movement, incoming solar and incoming noise; the most distinct cause of discomfort was due to the air movement. Whereby, more than 58% of participants voted that the air movement was normal, while 27% complaining that the air movement was high and 16% of
occupants considered that the air movement was too low. The results were compared with ASHRAE 55 standard. The environmental parameters and the level of CO₂ were in agreement with the results of the study of F.-J. Wang [7].

![Figure 6A. Occupants votes on air temperature](image)

![Figure 6B. Occupants votes on comfort sensation](image)

![Figure 6C. Occupant’s sensation acceptability](image)

![Figure 7A. Occupants votes on comfort sensation](image)

![Figure 7B. Occapant test subject by nationality](image)
4. Conclusions
This study investigated the indoor thermal comfort in an office building in tropical climates, besides improving the indoor air quality by controlling the concentration of CO₂ by using ventilation and filtration system (combination filters). The environmental parameters (air temperature, relative humidity, air velocity, PMV, PPD, and CO₂) were measured and compared with ASHRAE standard 55-2004. Occupants’ perception on the thermal environment and air quality were carried out.

The PMV value was recorded as (-0.08), which indicating that the indoor environment inside the chamber was slightly cool. This result was experienced when the outdoor air temperature was recorded low. According to ASHRAE standard 55, the range of PMV value that recommended for the office building is between (-0.5 to 0.5) and percentage of the PPD value less than 10%. Based on this suggestion the results for PMV and PPD values in the chamber were within the recommended values of ASHRAE standard 55-2004.

Results from measurement showed good agreement for thermal comfort even when using the combination filter. The acceptability of the thermal comfort as recommended in ASHRAE standard. However, the air temperature achieved in the chamber was 24 °C, whereas the relative humidity ranged between 69 to 89%. Furthermore, the air movement was between 0.13 to 0.2 m/s, which was in the range of ASHRAE standard recommendation.

The CO₂ concentration decreased during the measurement period, the results showed that that average of CO₂ concentration varied during the working hours; which were high, when the participants were doing some activities. A recommendation for future work is to find the balance among improving indoor air quality, thermal comfort and energy consumption in offices building in tropical climates.

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