INVESTIGATION OF INDOOR AIR QUALITY AND THERMAL COMFORT IN MOSQUE BUILDINGS

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INVESTIGATION OF INDOOR AIR QUALITY AND THERMAL COMFORT IN MOSQUE BUILDINGS

by

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LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
ACMV	Air Conditioning and Mechanical Ventilation
ACSUs	Air Conditioning Split Units
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engi-neers
AM	Air Movement
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BRI	Building Related Illnesses
CBE	Center for the Built Environment
CH_2O	Formaldehyde
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DM	Department of Microbiology
DOSH	Department of Occupational Safety and Health
ETS	Environmental Tobacco Smoke
HVAC	Heating, Ventilating, and Air–Conditioning
IAQ	Indoor Air Quality
IARC	International Agency for Research on Cancer
ICOP	Industry Code of Practice
ISO	International Standards Organization
MS	Malaysian Standard
NAAQS	National Ambient Air Quality Standards
NIOSH	National Institute for Occupational Safety and Health
Non-ACSUs	Non - Air Conditioning Split Units
O_3	Ozone
OSHA	Occupational Safety & Health Administration
OTTV	Overall Thermal Transfer Value
PM_{10}	Particulate Matter with an aerodynamic diameter less than 10µm
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied
RH	Relative Humidity

SBS	Sick Building Syndrome
SIRIM	Standard and Industrial Research Institute of Malaysia
T	Temperature
TC	Thermal Comfort
TVOC	Total Volatile Organic Compound
U.S. EPA	United States Environmental Protection Agency
USM	Universiti Sains Malaysia
VOC	Volatile Organic Compound
WHO	World Health Organization
WWR	Window-to-Wall Ratio

PENYIASATAN KUALITI UDARA DALAMAN DAN KESELESAAN TERMA DI DALAM BANGUNAN MASJID

ABSTRAK

Masjid adalah salah satu mercu simbolik kepada masyarakat Islam terutamanya untuk menunaikan solat lima kali sehari dan juga untuk menjalankan aktiviti sosial dan kebudayaan yang lain. Walau bagaimanapun, penggunaan meluas Penyaman Udara Unit Pisah (ACSUs) untuk menyejukkan udara dalaman masjid boleh menimbulkan potensi kesan kesihatan yang kurang baik kepada para pengguna. Oleh itu, kajian secara menyeluruh telah dijalankan untuk mengenalpasti kualiti udara dalaman (IAQ), keselesaan terma (TC), dan bahan pencemar biologi (bakteria dan kulat) di dalam bangunan masjid di Malaysia, dengan keadaan pengudaraan yang berbeza (ACSUs dan bukan ACSUs) di kawasan tanah rendah dan kawasan tanah tinggi. Kajian ini telah dijalankan dari 1200 h hingga 1700 h / 1730 h di 35 buah masjid semasa waktu solat *Zohor-Asar* dan *Jumaat-Asar*. Parameter IAQ yang direkodkan dinilai dengan pematuhan Tataamalan Industri (ICOP) 2010. Manakala undi min ramalan (PMV) dan peratusan orang tidak berpuas hati (PPD) digunakan untuk menilai keselesaan termal dengan menggunakan alat keselesaan termal CBE daripada ASHRAE. Keberkesanan strategi pengudaraan untuk mengurangkan suhu di dalam dewan utama solat dinilai berdasarkan empat kategori: 1) rekabentuk bumbung (Uthmaniyah, Piramid; dan Iran dan Timur Tengah), 2) keadaan pengudaraan (ACSUs dan kipas), 3) nisbah tingkap kepada dinding (WWR) dan 4) peratusan dinding ‘mati’. Seterusnya, tahap pencemar biologi juga dibandingkan dengan had yang telah dicadangkan oleh ICOP dan jenis pencemar biologi telah dikenalpasti dengan menggunakan perisian ID Microgen. Akhir sekali, untuk

meningkatkan IAQ dan keselesaan terma, pergerakan udara luar ke ruang dalaman telah digambarkan dengan menggunakan teknik gambaran aliran asap. Keputusan menunjukkan bahawa kepekatan purata pencemar udara dalaman (TVOC, CH_2O, CO, PM_{10}, dan CO_2) masih di dalam had yang telah dicadangkan oleh ICOP, kecuali purata kepekatan O_3. Purata kepekatan O_3 melebihi had yang telah dicadangkan oleh ICOP pada 0.13 ± 0.02 ppm (masjid ACSUs di kawasan tanah rendah) dan 0.09 ± 0.01 ppm (masjid bukan ACSUs di kawasan tanah rendah) semasa solat *Jumaat-Asar*. Empat daripada enam min pencemar udara dalaman (TVOC, O_3, CO, dan PM_{10}) di masjid ACSUs lebih tinggi berbanding masjid bukan ACSUs semasa solat *Jumaat-Asar*. Selain itu, berdasarkan keputusan yang diperoleh, masjid-masjid di kawasan tanah rendah (ACSUs dan bukan ACSUs) tidak memberikan keselesaan termal yang baik dengan nilai PMV dan PPD yang tertinggi masing-masing adalah 1.64-2.94 dan 55-99% di masjid ACSUs di kawasan tanah rendah berbumbung jenis Piramid. Keputusan yang diperoleh daripada masjid di kawasan tanah rendah menunjukkan bahawa peratusan dinding 'mati' (R^2 = 0.99) mempunyai kesan yang paling tinggi menyumbang kepada suhu udara dalaman yang tinggi di dalam dewan utama solat dan diikuti dengan faktor WWR (R^2 = 0.72). Sementara itu, jenis rekabentuk bumbung atau keadaan pengudaraan tidak mempunyai pengaruh yang ketara terhadap pengurangan suhu udara dalaman yang tinggi. Selain itu, kepekatan bakteria di kawasan tanah rendah yang melebihi garis panduan yang telah ditetapkan oleh ICOP (500 cfu / m^3) di masjid ACSUs (58.8%) lebih tinggi daripada masjid bukan ACSUs (12.5%) manakala tidak di kawasan tanah tinggi. Jenis-jenis bakteria dominan yang terdapat di masjid kawasan tanah rendah ialah *Staphylococcus* spp. dan *Bacillus* spp. manakala untuk kulat adalah *Aspergillus* spp. dan *Aspergillus niger*. Sementara itu, jenis bakteria dominan yang terdapat di masjid kawasan tanah tinggi ialah *Staphylococcus* spp., *Bacillus* spp., dan *Micrococci* spp. manakala bagi kulat ialah *Aspergillus niger* dan *Trichoderma* spp. Oleh itu, panel tingkap dengan dua liang boleh digunapakai untuk membolehkan udara luar memasuki ruang dalaman untuk menghasilkan IAQ dan TC yang lebih baik di dalam bangunan masjid.

INVESTIGATION OF INDOOR AIR QUALITY AND THERMAL COMFORT IN MOSQUE BUILDINGS

ABSTRACT

The mosque is a symbolic landmark where the Muslim community mainly prays five times a day and performs other social and cultural activities. However, the widespread use of Air Conditioning Split Units (ACSUs) to cool the indoor air in mosques may pose potential adverse health effects for users. Therefore, a comprehensive investigation was conducted to identify the indoor air quality (IAQ), thermal comfort (TC), and biological contaminants (bacteria and fungi) in the typical mosque buildings in Malaysia, within different ventilation conditions (ACSUs and non-ACSUs) at lowland and highland areas. The study was conducted from 1200 h to 1700/1730 h to assess 35 mosques during *Zohor-Asar* and *Friday-Asar* prayers times. The recorded IAQ parameters were evaluated for their compliance with Malaysia's Industrial Code of Practise (ICOP) 2010, whereas the predicted mean vote (PMV) and percentage of people dissatisfied (PPD) were used to assess thermal comfort by using the ASHRAE's CBE thermal comfort tool. The effectiveness of ventilation strategies in reducing temperature in the main prayer halls were evaluated based on four categories: 1) roof design (Ottoman, Pyramidal, and Iran and Middle East styles), 2) ventilation conditions (ACSUs and fans), 3) window-to-wall ratio (WWR) and 4) percentage of dead walls. Next, the biological contaminant levels were also compared with ICOP's acceptable limits and their types were identified using the ID Microgen software. Lastly, to improve IAQ and thermal comfort, the movement of outdoor air toward indoor were visualized by using the smoke flow visualization technique. The results showed that mean concentrations of indoor air

contaminants (TVOC, CH_2O, CO, PM_{10}, and CO_2) were still within the acceptable limits recommended by ICOP, except for the mean of O_3 concentrations. The mean of O_3 concentrations exceeded the acceptable limit by ICOP at 0.13±0.02 ppm (lowland ACSUs mosques) and 0.09±0.01 ppm (lowland non-ACSUs mosques) during *Friday-Asar* prayers. The mean indoor air contaminants of four out of six (TVOC, O_3, CO, and PM_{10}) at ACSUs mosques during *Friday-Asar* prayers were higher compared to non-ACSUs mosques. Moreover, based on the obtained results, the mosques at lowland (ACSUs and non-ACSUs) did not provide good thermal comfort with the highest PMV and PPD values were 1.64-2.94 and 55-99%, respectively at lowland ACSUs Pyramidal roof style mosques. Results obtained from the lowland mosques showed that the percentage of dead walls (R^2=0.99) had the most effect that contributed to the high indoor air temperatures within the main prayer halls. The next factor was WWR (R^2=0.72). Meanwhile, the type of roof design or ventilation condition had no significant influence on the reduction of high indoor air temperature. Furthermore, the bacteria concentrations at lowland exceeded the guideline set by the ICOP (500 cfu/m^3) in ACSUs mosques (58.8%) were higher than the non-ACSUs mosques (12.5%), whereas, at highland did not. The dominant types of bacteria found in the lowland mosque were *Staphylococcus spp.* and *Bacillus spp*. whereas for fungi was *Aspergillus* spp. and *Aspergillus niger*. Meanwhile, the dominant types of bacteria found in the highland mosque were *Staphylococcus spp.*, *Bacillus spp.*, and *Micrococci spp.* whereas for fungi was *Aspergillus niger* and *Trichoderma* spp. Therefore, window panel with double pores can be implemented to allow outdoor air passing through indoor to improve better IAQ and TC in the mosques buildings.

CHAPTER 1

INTRODUCTION

1.1 Background

Problems with indoor air quality (IAQ) are important risk factors for human health in both low-income and middle- to high-income countries (WHO, 2010). Growing scientific evidence during the last few decades has indicated that the concentrations of certain pollutants in indoor air may be 2–5 times, and occasionally more than 100 times higher, than those in outdoor air (Zock et al., 2002; USEPA, 2017). Besides that, Lee and Chang (2000) also reported that indoor pollutant levels could be higher than the outdoor pollutant levels.

IAQ causes adverse effects mainly when buildings are naturally ventilated, providing a way for outdoor pollutants to infiltrate or enter indoors, where the closing and opening of inlets (doors and windows) are regulated according to occupants' thermal comfort and seasonal variation (Kwok and Chun, 2003; Habil and Taneja, 2011). The factors affecting IAQ include an inadequate ventilation system, indoor contaminant sources, outdoor contaminant sources, less of maintenance, water intrusion and occupant activity (Prihatmanti and Bahauddin, 2014). However, pollutants generated from sources within the indoor environment may lead to higher exposure to indoor air contaminant concentrations in comparison with the outdoors due to the lower air flow in the former. These sources include cleaning procedures, building materials, furniture, furnishing, use of chemical products and general activities.

Besides that, in a tropical climate, the high solar and terrestrial radiations those reach building envelopes causes discomfort to the occupants (Abdullah et al., 2016). To create an indoor climate in buildings that occupants would find thermally comfortable, building designers refer to thermal comfort standards to aid in their designs (Nicol and Humphreys, 2002). By referring to Hoyt et al. (2017), a comfort zone should be based on six variables, namely, air temperature, air speed, humidity, radiant temperature, occupant's clothing insulation and occupant's activity level as recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)-Standard 55 (ASHRAE, 2017). If temperature and humidity levels in a building are too high or too low, occupants can fall into an uncomfortable zone and feel dissatisfied with the environment, a condition which reduces their productivity. Moreover, poor thermal comfort or thermal discomfort has a negative impact in its own right. If thermal discomfort continues over prolonged periods, it may contribute to serious adverse health effects for individuals, especially the building occupants.

Furthermore, many studies have been carried out on biological contamination levels in different building environments, such as schools and offices (Bornehag et al., 2001; Backman et al., 2014). The results showed that in indoor environments, one of the most reliable and most consistent risk factors for health problems, which include SBS, asthma and allergies and respiratory illnesses, is moisture problems in buildings, known broadly as 'dampness'. Dampness may be caused by the use of multiple Air Conditioning Split Units (ACSUs) for reducing the indoor temperature to reach comfort. Due to this, several chemical and biological agents have been suspected to be the causal agents in the relationship between atopic diseases and dampness in buildings.

For Muslims, mosques represent places of great importance and are unique in their functions and operations. Worshipers or congregators need to feel comfortable, calm and peaceful during their prayers (*solah*) or while performing other religious activities within the main prayer halls of mosques. The main prayer hall of a mosque is an indoor space accessible to Muslims and the public. The hall is occupied at least five times a day because Muslims commonly perform five compulsory prayers (*solah*) daily. However, the prayer times and durations vary corresponding to areas, regions and time zones. The *Subuh* (dawn) prayer time for Malaysia is from 0600–0700 h, the *Zohor* (after midday) prayer is from 1300–1400 h, the *Asar* (afternoon) prayer is from 1630–1730 h, the *Maghrib* (after sunset) prayer is from 1900–2000 h and the *Isha* (evening) prayer is from 2030–2130 h. The main prayer halls of mosques are also fully occupied on Fridays (*Jumaat*) by worshippers as male adult Muslims assemble to listen to sermons and perform the *Jumaat* prayer from around 1300–1430 h. On this holy day, the *Zohor* prayer is replaced by the *Jumaat* prayer and the number of vehicles that transport the worshipers to the mosques increases. Consequently, indoor chemical air contaminants are produced inside and outside mosques could be increased. The indoor conditions of mosques should provide acceptable thermal comfort for worshipers to feel comfortable and calm and leave with a feeling of tranquillity and peace (Abdullah et al., 2016).

Information about IAQ in mosque buildings has been reported by Ocak et al. (2012) in their study in Turkey. The available but limited measurements of ventilation rates and CO_2 concentrations in mosque buildings suggest that based on the current ASHRAE ventilation standard, many mosque buildings are not adequately ventilated.

In Malaysia, there are no specific standards that had been established regarding IAQ and thermal comfort in the mosque buildings. However, Malaysia's Industry Code of Practice (ICOP) was established to ensure that occupants are protected from poor IAQ and thermal comfort that can adversely affect human health, well-being, and productivity (DOSH, 2010). Given that mosques are consistently used by the public, therefore, their IAQ and thermal comfort need to be monitored because it is threatened by various contaminants from indoor and outdoor sources that considerably affect the indoor environment (Elbayoumi et al., 2014).

1.2 Problem Statement

Inadequate ventilation rates and high concentrations of CO_2, $PM_{2.5}$ and biological contaminants have been found in mosque buildings in Turkey and Kingdom of Saudi Arabia (Ocak et al., 2012; Hameed and Habeeballah, 2013). Besides that, some of the studies in Malaysia show that thermal comfort, SBS (Sick Building Syndrome) and displeasure in the buildings have become common issues in buildings (Amin et al., 2015; Shan et al., 2016).

Malaysia is located near the equator and experienced hot and humid climate throughout the year, and buildings may receive greater heat, which increases their thermal loads (Abdullah et al., 2016). The existed mosques that only used fans as active ventilation experienced high temperature inside the mosques during *Zohor-Asar* and *Friday-Asar* prayers. This is because of *Zohor-Asar* and *Friday-Asar* prayers are performed during the hottest times of the day, which are between afternoons to evening. The high temperature inside the mosques could be due to the unavailability of stack ventilation and cross ventilation. Based on MS 1525:2014 (MS, 2014a), stack ventilation is functional to enhance the flow of air movement across space because of the air density differences. The warmer air at the upper levels will discharge if an opening is existing near the ceiling. Then, the cooler outside air will enter the building through the lower opening. However, the existing openings near the ceilings in the mosques were closed thus caused the warmer indoor air temperature at the upper levels cannot be discharged to outdoor.

Moreover, the widespread uses of ACSUs tend to create dampness problems inside the mosques that can increase biological contaminants (bacteria and fungi) growth. Due to this, several chemical and biological agents have been suspected to be the causal agents in the relationship between atopic diseases and dampness in buildings. These biological agents include microbes and their metabolites (Lax et al., 2014), chemical emissions from surface materials that were damaged by moisture (Norbäck et al., 2000), viruses (Hersoug, 2005) and house dust mites (Richardson et al., 2005).

This study is focusing on *qariah/jamek* mosques located in the residential area. There are no specific workers that employed to look after these mosques and these mosques self-sustained. The using of ACSUs is not sustainable because of the high electricity consumption that leads to increased carbon emission (Abdullah et al., 2016). Generally, the expenses for electricity bills and other necessities of the mosques rely on the donation money from the worshippers/congregators. The average cost of electricity per month for an air-conditioned mosque in Malaysia for 2012, was approximately USD 865.00 (Hussin et al., 2015). This will be a challenge to the mosques' management to find more funds for the energy consumption purpose. Besides that, the numbers of worshippers are lesser (10 – 25 persons) during *Zohor* and *Asar* prayers, and the use of ACSUs to cool the indoor air inside the mosques is a waste because it contributed to high electricity consumptions. Therefore, the consumptions of electricity need to be reduced by improving the ventilation strategies for the environment and economic sustainability.

To date, there are no comprehensive studies done on IAQ, thermal comfort and biological contaminants in ACSUs and non-ACSUs mosques in Malaysia. Others studies in mosque buildings focused on the issues separately. Information on the IAQ in terms of ventilation conditions (ACSUs and non-ACSUs), the impact of ventilation strategies on thermal comfort in mosque buildings, and the distribution of biological contaminants levels in the mosque buildings is lacking. Therefore, a comprehensive investigation of indoor air quality, thermal comfort, and biological contaminants in mosque buildings across the representative and typical mosque buildings in Malaysia are needed.

1.3 Objectives

This research was carried out comprehensively on IAQ and thermal comfort in ACSUs and non-ACSUs mosque buildings with three main objectives:

1. To determine the IAQ of representative mosque buildings in Malaysia and evaluate the impact of existing ventilation conditions (i.e. ACSUs and fans) on indoor air quality in the mosque buildings.
2. To evaluate the thermal comfort parameters of representative mosque buildings in Malaysia and evaluate the impact of ventilation strategies on thermal comfort in mosque buildings.
3. To describe and further explain the distribution of biological contaminants levels (i.e. bacteria and fungi) of existing ventilation conditions and estimate the prevalence of biological contaminants within representative mosque buildings.

1.4 Scope of Research

This research was to identify the sources and potential effects of IAQ and thermal comfort in the mosques buildings. The study was conducted from 1200 h to 1700/1730 h to assess 35 mosques during *Zohor-Asar* and *Friday-Asar* prayer times. This is because of the ambient temperature during this time are among the highest during the day time. The mosques building were divided into two types of ventilation conditions, which are ACSUs and non-ACSUs mosques. The collected parameters of IAQ during the sampling consist of chemical air contaminants (i.e. carbon monoxide (CO), formaldehyde (CH_2O), ozone (O_3), respirable particulates (PM_{10}), and total volatile organic compounds (TVOC)) and ventilation performance indicator (i.e. carbon dioxide (CO_2)). The recorded IAQ parameters were assessed for their compliance with ICOP (DOSH, 2010). Then, the ACSUs and non-ACSUs mosques were categorized into three different roof types based on MS 2577:2014 (MS, 2014b) for the ventilation strategy propose. The roof types included Ottoman, Pyramidal; and Iran and Middle East styles. This was to explore the ventilation strategy effects on thermal comfort. Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) were used to assess thermal comfort by using the CBE thermal comfort tool and compared with ASHRAE-Standard 55 (ASHRAE, 2017). The collected parameters for PMV and PPD consist of air temperature, relative humidity, air movement, clothing insulation, and metabolic rate. The interview and observation data did not carried for this study. This study was focusing on the physical measurement sampling on the mosques sites. The effectiveness of ventilation strategies in reducing temperature in the main prayer halls were evaluated based on four categories: 1) roof design styles (Ottoman, Pyramidal, and Iran and the Middle East), 2) ventilation conditions (ACSUs and fans), 3) window-to-wall ratio

(WWR) and 4) percentage of dead walls. Next, the biological contaminant (bacteria and fungi) levels were also compared with ICOP's (DOSH, 2010) acceptable limits in the ACSUs and non-ACSUs mosques and their types were identified using the ID Microgen software. Lastly, to improve IAQ and thermal comfort, the smoke flow visualization test was conducted by using three (3) different window panels (Panel A: Panel without pore, Panel B: Panel with single pore, and Panel C: Panel with double pore) at different air speed (0.5 m/s, 1.0 m/s, 2.0 m/s, 3.0 m/s and 5.0 m/s). This test was carried out to visualize the movement of outdoor air towards indoor space within the main prayer hall.

1.5 Thesis Layout

Chapter 1 presents the overview of this study, including the details about the problem of IAQ and thermal comfort in buildings. Besides that, it also provides the information of the mosques, including the operational time and the problems regarding indoor air faced by the mosques. Then, the problem statement, objectives, and scope of research also include in this chapter.

Chapter 2 provides a literature review that gives the details on the factors influenced IAQ and thermal comfort, the types of the ventilation system and the roof types that can be used as a reference in this study area. It also describes the mosques building and religious practice

Chapter 3 describes the methodology of the study area included the sampling location, sampling methodology, sampling techniques, and data analysis method, as well as the details of all the instruments used for this study. It also includes the compliance level of the relevant standard for IAQ and thermal comfort.

Chapter 4 discusses the results of this study. The first section includes the level of indoor air contaminants and specific physical parameters with the standard compliance level and the impact of existing ventilation conditions on indoor air quality in the mosque buildings. The second section provides the level of thermal comfort with the standard compliance level. It also illustrates the impact of ventilation strategies on thermal comfort in the mosque buildings. The last section presents the distribution and the prevalence of biological contaminants level in the main prayer halls.

Chapter 5 provides the improvement of indoor air quality and thermal comfort by using window panel inside the wind tunnel. Three different window panels (Panel A: Panel without pore, Panel B: Panel with single pore, and Panel C: Panel with double pore) were tested by using smoke flow visualization technique. This test was conducted to visualize the movement of outdoor air towards indoor space within the main prayer hall.

Chapter 6 presents the conclusions of the study area based on the objectives and some recommendations to improve indoor air quality and thermal comfort in the mosque buildings for future studies. The last part of this chapter is ended with the appendices and the list of publications.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the factors that influence the indoor air quality (IAQ) and thermal comfort; and also defines the indoor air contaminants and thermal comfort parameters. In addition, it also describes the effect of ventilation in building, the mosque and religious practice.

2.2 Factors Influencing Indoor Air Quality

Indoor air quality can be defined as air quality within and around buildings and structures, and it concerns the health and comfort of building occupants (USEPA, 2018). The factors that influence poor indoor air quality include the sources from outdoor air contaminants, lack in the ventilation system and the existence of indoor contaminant sources (Fernández et al., 2013). There are, however, pollutants that are generated from sources within the indoor environment, such as cleaning, construction materials, furniture, furnishings, the use of chemical products and general activities which may lead to an increased exposure compared to that outdoor concentrations. Tobaccos smoking are the main sources of indoor air contaminants that were influenced by the heating and combustion appliances, building site and used materials, excess water in building structures and ambient air.

2.2.1 Sources of Outdoor Air Contaminants to Indoor

Some investigations have reported in the absence of a strong indoor source; the indoor concentrations were closely following the corresponding outdoor concentrations (Matson, 2005; Koponen, 2001). For example, a study conducted by Diapouli et al., (2011) revealed that a result from regression analysis showed that the sources of indoor black carbons mainly came from the outdoor origin. Indoor contaminants may originate from a variety of sources, including the infiltration of outdoor pollutants, from the dust as a mixture of organic matter such as soil, particulate matter, and shed skin cell (Layton and Beamer, 2009). Many factors are influencing the outdoor particles toward indoor particles based on the previous researchers, as shown in Table 2.1.

Table 2.1 Factors influencing the outdoor particles toward indoor particles

Factors	**Details**	**References**
Contaminants sources	Type, concentrations, position, distance, size	Milner et al., 2004 Chen & Zhao, 2011
Individual building	The size, shape, orientation, the cracks in building envelopes, position, window opening percentage	Milner et al., 2004 Chen & Zhao, 2011 Azimi et al., 2018 Yang et al., 2015a
Atmospheric conditions at the time	-	Milner et al., 2004
The distribution of buildings in relation to each other	-	Milner et al., 2004
Surrounding topography	-	Milner et al., 2004
The air exchange rates between indoor and outdoor in the building	-	Chen & Zhao, 2011
Wind speed	The high wind speed can decrease the indoor particle concentration	Jin et al., 2016

2.2.2 Existence of Indoor Sources

According to Klepeis et al., (2001) people tend to spend their time indoor (87 % on average a day) and therefore they are exposed to indoor air contaminants several times higher than outdoor air contaminants (Molloy et al., 2012). The sources of indoor contaminants may originate from smoking, cooking, building and furniture materials, consumer products, organic fibers and human disturbance (Layton and Beamer, 2009; Chao and Cheng, 2002; Lee et al., 2002).

Malaysia's Industry Code of Practice (ICOP) had divided the indoor air contaminants into three categories, which are chemical air contaminants, a ventilation performance indicator, and biological contaminants (DOSH, 2010). Chemical air contaminants consist of carbon monoxide (CO), formaldehyde (CH_2O), ozone (O_3), respirable particulates, and total volatile organic compounds (TVOC) (DOSH, 2010). Ventilation performance indicator consists of carbon dioxide (CO_2) whereas biological contaminants consist of total bacterial counts and total fungal counts (DOSH, 2010). The details of indoor air contaminants are discussed in the following sections.

2.3 Chemical Indoor Air Contaminants

2.3.1 Carbon Monoxide

CO is a colourless and odourless gas, and it can be dangerous to humans. Fernández et al., (2013) reported that the common sources of CO emission might originate from the portable heaters that use kerosene, wood-burning fireplaces, automobile exhaust, and tobacco smoke. The CO concentrations in the mosque buildings could be contributed by the automobile exhaust. The automobile exhaust emissions could intrude indoor environment through openings (NIOSH, 2016). CO concentrations can contribute to health issues to the occupants, especially towards children. Currie et al., (2009) reported that 3.8% increase of CO concentrations in absenteeism of school children and other health issued when the mean CO concentration is 2.73 ppm (range = 0.65–6.23 ppm). In addition, Evans et al., (2014) revealed that the risk of asthma in urban children could be worsening by high CO concentrations from traffic pollution.

2.3.2 Formaldehyde

CH_2O is a hazardous pollutant because it can be detrimental towards health (Plaisance et al., 2014) affecting the eyes, nose, and respiratory system. CH_2O is listed as a human carcinogen that is highly associated with nasopharyngeal carcinoma and probably leukaemia. The possible sources of indoor CH_2O also could be from solvent usage, industrial, biomass burning, fossil fuel combustion, biogenic emissions building, furniture materials, wood-based materials, flooring materials, insulation materials, coatings materials, indoor chemistry and indoor combustion (Parrish et al., 2012; Salthammer et al., 2010; Shinohara et al., 2009). Therefore, as CH_2O can potentially contribute health effect on human adversely, it needs to be monitored in an indoor environment.

2.3.3 Ozone

The formation of O_3 is mainly by photochemical reactions of nitrogen oxides (NO_X) and volatile organic compounds (VOCs) (Ismail et al., 2016) in the presence of ultraviolet light from the sun (Fisk, 2015). O_3 is a secondary pollutant that has adverse effects on human health and the environment (Chang et al., 2019; Kampa and Castanas, 2008). O_3 is a secondary pollutant that can be influenced by precursor availability, local meteorology, seasonal variability (Lin et al., 2015; Awang et al., 2018), local sources and hemispheric background concentrations through transboundary transport (Ryoo et al., 2017).

The consequences of the increment of the ozone level were associated with human health inside the buildings as people in the developed countries spent about 90% of their time indoors (Fisk, 2015). The ozone level inside the buildings needs to be monitored as it can react chemically with the building furnishings and buildings materials; and it also can produce new air contaminants (Weschler, 2006). A study by Salonen et al., (2018) found that a broad range average of ozone concentrations in the school and office environments were 0.8–114 μg/m^3 and from 0 to 96.8 μg/m^3, respectively which is exceeded the permissible value of 100 μg/m^3 by WHO. Besides that, the indoor ozone levels could be associated with various building characteristics including the carpeting, air conditioning, window fans, air cleaners, and window openings; and also the age of a building (Salonen et al., 2018).

2.3.4 Particulate Matter

PM is one of the indicators that can determine air quality both indoors and outdoors (Szigeti et al., 2017) and is the most hazardous pollutant that can affect more people. These health effects vary from small respiratory symptoms and it increases in morbidity and mortality rates depending on the duration of exposure and the concentration of pollutants (Jedrychowski et al., 2013). There are many different physical characteristics and chemical components of particulate matter that can contribute adverse health effects to human (Szigeti et al., 2017). According to USEPA (2004), due to the extensive range of particle sizes, PM is classified into three categories which are coarse PM with aero-diameter 2.5 μm to 10 μm, fine PM with aero-diameter less than 2.5 μm and ultrafine particle with aero-diameter less than 0.1 μm.

Furthermore, Thatcher and Layton (1995), Ferro et al., (2004) and Fromme et al., (2007) concluded in their studies that resuspension was influenced by particle size, occupants' activities and the types of floor materials. Ocak et al., (2012) monitored particle number and $PM_{2.5}$ concentrations in a mosque building. The sampling was conducted in nine (9) days with three different campaigns (before, during, and after prayer) under three (3) different vacuuming schedule which is in the morning of the prayer, a day before and a week before prayer. The results showed that the lowest concentrations were vacuuming carpet a day before prayer and also suggested that a preventive cleaning strategy is needed for better ventilation. Besides that, Chatoutsidou et al., (2015) reported that in the office environment, the sources of particles with an aerodynamic diameter larger than one (1) μm is from the resuspension of settled dust and particle emission from photocopiers and printers.

2.3.5 Total Volatile Organic Compounds

Total Volatile Organic (TVOC) is also one indicator of indoor air quality (Mølhave et al., 1997). TVOC is a diverse group of carbon-containing compounds, including aldehydes, ethers, esters, acid, alcohols, and ketones. According to USEPA (2017), the sources of volatile organic compounds (VOCs) included paints, paint strippers, and other solvents, wood preservatives, aerosol sprays, cleansers and disinfectants, moth repellents and air fresheners, stored fuels and automotive products, dry-cleaned clothing and pesticide. TVOC concentrations can also be affected by temperature, humidity, seasons and other environmental factors (Jo and Sohn, 2009).

Besides that, as mentioned by Jokl (2000), VOC could be produced by building materials and fittings, especially carpets and other floor covering materials. In developed countries, most people might expose to a high of TVOC concentrations because they spend most of their time indoors (Tang et al., 2005). Sensory irritation, drowsiness, and headaches to cancer are the effects of both acute and chronic if people exposure TVOC concentrations in prolonged time (Plaisance et al., 2014).

In addition, a study conducted by Dewangan et al., (2013) showed that benzene has the highest emission factor among selected volatile organic compounds in all four different religious places in India. Moreover, high VOC concentrations found in a 2012 Hajj that were influenced by gasoline evaporation, vehicular exhaust, air conditioners, and liquefied petroleum gas (Simpson et al., 2014).

2.3.6 Carbon Dioxide

According to Lin and Deng (2003), the indoor CO_2 level is one of the indicators that are usually used to measure IAQ. CO_2 concentrations around or above 1000 parts per million (ppm) were classified as toxicity values (Guais et al., 2011). The exposure of carbon dioxide can typically change the acid or base of the body balance, cellular metabolism, and lung. Besides that, it can also cause the disruption of the heart and central nervous system functions in the body. Al-Dabbous et al., (2013) found that high CO_2 concentration peaks at every regular prayer. The highest CO_2 concentration peak has been detected on *Friday* at high noon prayer, and this period represents the maximum occupancy in the mosque building. The study suggested that regulating fresh air intake is needed during prayer times to avoid a high build-up of CO_2 concentrations because high CO_2 concentration peaks have been found every regular prayer. Besides that, another study by Mumovic et al. (2009) and Ponsoni and Raddi (2010) suggested that CO_2 concentrations levels inside the building can be controlled by increasing the ventilation rate and the sources of fresh air.

2.3.7 Biological Contaminant

Many studies have been carried out on biological contaminants (bacteria and fungi) levels in different building environments, such as schools, offices, restaurants and industrial processes (Bornehag et al. 2001; Meklin et al. 2002; Mendell et al. 2014; Kousar et al. 2013; Backman et al. 2014; Nahar and Mahyudin, 2018). Bacteria are single-celled organisms ranging size from 0.8-5 microns in diameter, whereas fungi are plant-like organisms that do not contain chlorophyll (NIOSH, 2016). The results showed that in indoor environments, one of the strongest and most consistent risk factors for health problems, which include sick building syndrome (SBS), asthma and allergies; and respiratory illnesses, are moisture problems in buildings, known broadly as 'dampness'. A study by Zock et al., (2002) in the dampness home found that the highest indoor mould growth has a bad influence on adult asthma. The dampness could be contributed from the operations of ACSUs in mosques.

There are many factors that can contribute to bacteria and fungi such as from anthropogenic sources (Després et al., 2012), human activity (Adams et al., 2015), topography, microenvironmental conditions, building materials (Hyvärinen et al., 2002) and amount of dust in the air (Alananbeh et al., 2017). According to Khan and Karuppayil (2011), bacteria can be introduced into the air via talking, sneezing, coughing, skin-shedding microorganisms, walking, and toilet flushing, whereas fungal spores can be released into the air through food stuff, ventilation ducts, and carpets.

Besides that, the climatological surroundings and cleanliness can change the bacteria and fungi, and the levels of the bacteria and fungi are very variable. Fungi and bacteria need nutrient to support their life; therefore the accumulation of organic material such as in wood, paper, paint, and carpets can be nutrient for bacteria and fungi (Fernández et al., 2013). Table 2.2 presents the summary of previous researches on the genus of bacteria and fungi species.

Table 2.2 Genus of bacteria and fungi from previous studies

No.	Description	Genus of Bacterial	Genus of Fungal	Authors
1.	To evaluate bacterial and fungal aerosol concentrations at the holy mosque (Al-Masjid Al-Haram)	*Bacillus*, *Micrococcus*, and *Staphylococcus* genus were the predominant Gram-positive bacteria and *Pseudomonas, Klebsiella* and *Escherichia coli* were the predominant Gram-negative bacteria.	*Aspergillus niger*, *A.flavus*, and *Fusarium* were the common fungal types. *Cladosporium* and *Penicillium* were found in low percentages.	Mashat (2015)
2.	To estimate the numbers of fungi and bacteria inside and outside Al-Haram Al-Nabawi and to find whether new bacterial and fungal species have emerged compared to previous studies.	The most discovered genes were *Staphylococcus, Micrococcus, Bacillus,* and *Dermacoccus* accounting for 32.47%, 18.18%, 12.85%, and 11.23% of the total count, respectively.	*Aspergillus* species had the highest percentage (78%) and the other fungal species identified are *Alternariatriticinia*, *Emericellanidulans*, *Estriatastriata*, *Mucorcircinelloides, Peniciliumchrysogenum, Pminioluteumminioluteum, Rhizopusarrhizus, Rhizopusoryzae,* and *Syncephalastrumracemosum* had less than (5%) frequency.	Alananbeh et al., (2017)
3.	To gain more insight into the variability of airborne bacteria, fungi, and actinomycetes at the main directions of the holy mosque, to determine its microbial air quality and give site-specific information.	*Staphylococci* (4.2-26%), and *Bacillus* (5.5- 30.9%) were the dominant Gram-positive bacteria. Gammaproteobacteria (*Pseudomonas*) constituted 8.75% of the total isolates.	*Aspergillus* represented by *Aspergillusfumigatus, Aspergillusniger, and Aspergillusflavus. Aspergillusniger* (14.27 %-46.9%) and *Fusarium* (6.90% - 13.62%) were the common fungal isolates. The highest fungal diversity was found in the south direction, among which *Epicoccum, Mucor, Trichophyton, Chaetomium, Cladosporium, Alternaria,* and *Emericella* were detected.	Hameed and Habeeballah (2013)
5.	To determine the bacteriological quality of water and carpets of mosques in Elkhomes city in Libya.	(27.3%) were positive for *Escherichia coli*, (22.7%) for *Klebsiella spp*. and (34.1%) for other enteric bacteria for water samples whereas (12%) were positive for *E. coli*, (66%) for *Klebsiella spp*. and (60%) for *Staphylococcus spp.* for dust samples of carpets.	-	Mohamed Ali et al., (2014)
6.	To investigate the dust loading and culturable microorganisms contamination characteristics of Heating, Ventilating, And Air–Conditioning (HVAC) systems in 24 office buildings.	The predominant culturable bacteria were *Micrococcus*, *Bacillus*, *Staphylococcus*, and *Pseudomonas.*	The predominant culturable fungi were *Penicillium*, *Aspergillus*, *Cladosporium*, and *Alternaria*	Liu et al., (2015)

2.4 The Acceptable Limits of IAQ Parameters by International/National Agencies

Table 2.3 shows the comparative study by previous researchers of indoor air quality standards and guideline for international agencies. As defined by various international agencies, standards and guidelines are employed by the researchers to evaluate an acceptable indoor air quality of air in indoor (Abdul-Wahab et al., 2015).

Table 2.3 Indoor air quality standards and guidelines from international /national (Chithra and Shiva Nagendra, 2018; DOSH, 2010)

Pollutants	NAAQS/U.S.EPA	OSHA	NIOSH	ACGIH	WHO	DOSH
CO_2	-	5,000 ppm (8 h) 30,000 ppm (15 min)	5,000 ppm (8 h) 30,000 ppm (15 min)	5,000 ppm (8 h) 30,000 ppm (15 min)	-	1000 ppm (8 h)
CO	9 ppm (8 h) 35ppm (1 h)	35 ppm (8 h)	35 ppm (8 h)	25 ppm (8 h)	90 (15 min) 50 (30 min) 25 (1 h) 10 (8 h)	10 ppm (8 h)
NO_2	100 ppb (1h) 53 ppb (Annual)	1 ppm (15 min)	1 ppm (15 min)	3 ppm (8 h) 5 ppm (1 min)	200 μg/m^3 (1 h) 40 μg/m^3 (Annual)	-
SO_2	75 ppb (1 h, Primary) 0.5 ppm (3 h, Secondary)	2 ppm (8 h) 5 ppm (15 min)	2 ppm (8 h) 5 ppm (15 min)	2 ppm (8 h) 5 ppm (15 min)	500 μg/m^3 (10 min) 20 μg/m^3 (24 h)	-
O_3	0.075 ppm (8 h)	0.1 ppm (8 h) 0.3 ppm (15 min)	0.1 ppm (8 h)	-	100 μg/m^3 (8 h)	0.05 ppm (8 h)
$PM_{2.5}$	35 μg/m^3 (24 h) 12 μg/m^3 (Annual, Primary) 15 μg/m^3 (Annual, Secondary)	5 mg/m^3 (8 h, respirable fraction)	-	3 mg/m^3 (8 h)	25 μg/m^3 (24 h) 20 μg/m^3 (Annual)	-
PM_{10}	150 μg/m^3 (24 h)	-	-	10 mg/m^3 (8 h)	50 μg/m^3 (24 h) 20 μg/m^3 (Annual)	-
Respirable particulates						150 μg/m^3 (8 h)
HCHO	-	0.75 ppm (8 h) 2 ppm (15 min)	0.016 ppm (8 h) 0.1 ppm (15 min)	0.3 ppm (8 h)	-	1000 ppm (8 h)
Lead	0.15 μg/m^3 (3 months)	0.05 mg/m^3 (8 h)	0.1 mg/m^3 (10 h)	0.05 mg/m^3 (8 h)	0.5 μg/m^3 (Annual)	-
Bioaerosol	-	-	1,000 CFU/m^3 (total bioaerosol)	1,000 CFU/m^3 (total bioaerosol) 500 CFU/m^3 (total bacteria)	-	1,000 CFU/m^3 (total fungal counts) 500 CFU/m^3 (total bacteria counts)

2.5 Factors Influencing Thermal Comfort

Thermal comfort can be defined as a condition of mind which expresses satisfaction with the thermal surroundings (ASHRAE, 2017). There are six primary variables to determine the acceptable thermal comfort which include i) air temperature, ii) relative humidity iii) air movement, iv) radiant temperature, v) metabolic rate, and vi) clothing insulation (ASHRAE, 2017).

According to Ormandy and Ezratty (2012), thermal comfort also depends on the age, health status, gender, and the adaption to the local environment and climate of the individual. The occupant can be dissatisfied with the environment, uncomfortable and less effective in their task if the temperature and relative humidity levels in the building are too high or too low. Besides that, design factors could also influence the indoor conditions of mosques, thus thermal comfort. Those design factors include the façade and heat gains into the building.

2.5.1 Temperature

In a tropical climate, the high solar and terrestrial radiations that reach building envelopes cause discomfort to the occupants (Abdullah et al., 2016). The indoor air temperature corresponds toward outdoor air temperature in a naturally ventilated building. According to Irsyad et al., (2017), thermal load consists of solar radiation energy which passes through the outside wall surface and continues to the inside wall surface via conduction. This will cause a high temperature inside the building that due to the thermal load from sunshine from the outdoor environment through building materials.

However, the heat in the buildings can be reduced. A study performed by Liu et al., (2017) found that heat transfer can be reduced from the outside to the inside by the moisture transfer in the buildings. The cool air may introduce from a shaded or landscaped space or from over a body of water (Yang and Clements-Croome, 2013). Furthermore, Varzaneh et al., (2014) reported that the climatic problem in the mosque buildings could be solved by the double-shelled dome. The external dome can play an important role to protect the internal dome from the heat of the sun's energy, thus can reduce the temperature inside the building of the mosque. In addition, Cheng et al., (2005) also revealed that the indoor air temperature could be reduced by using the lighter surface colour and thermal mass.

2.5.2 Relative Humidity

The relative humidity is generally shown in percent (%) and it is defined as the ratio between the measured (actual) water vapour pressure of water in the air and the maximum quantity of saturated water vapour pressure contained by the air at a known temperature (Finucane, 2006). People experienced thermal discomfort if the relative humidity higher than 70 % as the recommended acceptable limit by ICOP for relative humidity is between 40 – 70 % (DOSH, 2010).

There are two factors that need to be considered about relative humidity, which are air temperature and the water vapour content in the air. Relative humidity needs to be adjusted in the acceptable limit to be comfortable so that the problems associated with the dehydrated air can be solved in indoor space. The water evaporation is fast when the air temperature has a high value and the relative humidity has a low value (Enescu, 2017).

2.5.3 Air Movement

According to Tong et al., (2016), one of the main factors that strongly affect the indoor air concentration was the wind direction. The ambient wind condition is the main factors that need to be considered at the early design stage for a new building planning beside than the distance of the building from the roadway. The recommended acceptable limit by ICOP for air movement is between 0.15 – 0.5 m/s (DOSH, 2010).

In naturally ventilated buildings, the natural wind is required to assist in providing good thermal comfort for the occupants. When the temperature and humidity are relatively more difficult to control, indoor air circulation (wind) inside the buildings plays an important role by creating direct physiological cooling (Elbayoumi et al., 2015). Besides that, Mishra and Ramgopal (2013) found that one of the factors that enhance heat loss from the human body is by increasing the air movement in the warm and humid surrounding for adequate ventilation. The more air movement can help for better thermal comfort with an internal pleasant sensation (Chow et al., 2010).

2.5.4 Mean Radiant Temperature

Mean radiant temperature is defined as the temperature of a uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual enclosure surroundings (ASHRAE, 2017; Torres and Martin, 2008). The mean radiant temperature is taken in the steady-state condition of the weighted mean temperature at different surfaces and can be expressed in the Eq. (2.1) (Enescu, 2017).

$$T_{MR} = (\sum_{i=1}^{n} T_i \cdot S_i) \cdot (\sum_{i=1}^{n} S_i)^{-1} \quad (2.1)$$

Where,

T_{MR} The mean radiant temperature;

T_i The temperature of surface *i* (computed or measured);

S_i The area of surface *i*;

n The number of data points.

Walikewitz et al., (2015) had conducted a study in four rooms in a building and found that the mean radiant temperature is equal to the air temperature. The difference between the mean radiant temperature and air temperature is insignificant under moderate outdoor conditions.

2.5.5 Clothing Insulation Value and Metabolic Rate

One of the most significant indicators use in thermal comfort is the clothing insulation, which is adopted by the International Standards Organization (ISO-1995) and by ASHRAE-2005 (Al-ajmi et al., 2006). According to ISO 9920:1995 clothing insulation (I_{cl}) can be interpreted as thermal insulation (resistance to dry heat loss from the body) of a clothing ensemble and is expressed in square meter degrees Celsius per watt (m^2.° C/W), which is the insulation from the skin to the clothing surface. The dry heat loss from the body through convection, radiation and conduction, then takes place from the skin surface through the clothing to the clothing surface (1 clo = 0.155 m^2.°C/W). The equation for clothing is shown as in Eq. (2.2) (ISO, 1995).