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SMOKE FLOW VISUALISATION TESTING ON WINDOW PANEL AT VARIOUS WIND SPEED AND PORES: A WIND TUNNEL STUDY

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Abstract: The openings at most mosques façades are meant for natural ventilation (i.e. windows and doors) were being shut especially during non-prayer time for security and to avoid rain splatter. The current as-constructed conditions of mosques prayer hall seem to be lack of ventilation with minimum air movement. Most panels that are located near the roof and wall are malfunctioning, hence stack and cross ventilations could not take place. This study aimed to visualize the movement of outdoor-indoor air through the pore of window panels. The testing was carried out in a closed-loop wind tunnel at the Wind Tunnel Laboratory, Science and Engineering Research Centre (SERC), the Universiti Sains Malaysia by using smoke flow visualisation technique. Smoke flow visualisation testing was conducted to evaluate the airflow characteristics of three (3) different pores (Panel A: Panel without pore, Panel B: Panel with the single pore, and Panel C: Panel with double pores) of the window panels 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). Panel C on the window panel with double pores were suggested as it allow 2.4% outdoor air toward indoor compared to Panel A: without pore (0%) and Panel B: with single pore (1.2%). The pores on the window panels should be promoted to induce optimum air movement through the pores, hence allowing better ventilation to reduce indoor air temperature naturally.

Keywords: Air movement, mosque, natural ventilation, smoke flow visualisation and sustainability.

Introduction

Ventilation either of a cross or stack, is a process of supplying air into the indoor space or discharging air from the indoor space in order to control the air contaminant levels, humidity, or temperature (ASHRAE, 2007). Hailos *et al*., (2014) stated that natural or mechanical ventilation is used worldwide to maintain acceptable air quality and to control thermal comfort, and reducing odour associated with human within the building envelope. Natural ventilation is a process that is produced by thermal, wind or diffusion effect through doors, windows, or other intentional openings in the buildings. On the other hand, mechanical ventilation is a ventilation process that is produced by mechanically powered equipment such as fans and air-conditioning system (ASHRAE, 2007). Chen & Zhao (2011) suggested that the outdoor air can be transported into the indoor air space via mechanical ventilation, natural ventilation, and infiltration as shown in Figure 1.

The fresh air could be effectively distributed into buildings by natural ventilation for the occupants' comfort. Natural ventilation uses the natural forces of wind and buoyancy to introduce fresh air into the buildings. There are three benefits of the natural ventilation, which are: 1. the ventilation air can supply oxygen that is needed for human life processes for clear thinking and more focus; 2. the ventilation air that enters the building space can dilute or decrease

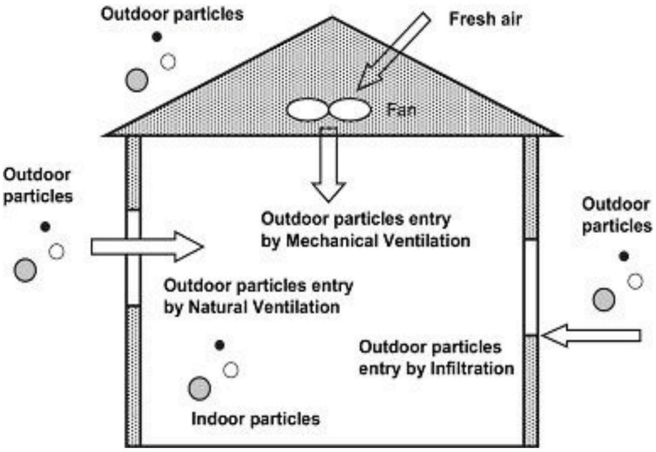

Figure 1: The pathway of outdoor air transported into the indoor air environment (Chen & Zhao, 2011)

indoor air contaminants and; 3. the ventilation air can remove the excessive heat or moisture as it promotes and directs air movement in the building's space (Yang & Clements-Croome, 2013). In naturally ventilated indoor envelops, air exchange depends upon the pressure differential across the building envelop which is further governed by two driving forces which are the stack ventilation and cross ventilation.

Stack ventilation is the thermal buoyancy or the density difference caused by the temperature difference between the indoor space and outdoor environment (Allocca *et al*., 2003). In Malaysia, MS 1525:2014 (MS, 2014) stipulated that stack ventilation is functional to enhance the flow of air movement across space because of the air density differences. Warmed indoor air will rise by the internal load such as people, equipment and lights. It will then, produce a vertical pressure gradient within the enclosed space. The warmer air at the upper levels will discharge if an opening exists near the ceiling. Consequently, the cooler outside air will enter the building through the lower opening. Meanwhile, cross ventilation is the wind pressure differences that cause the movement of air through openings in the opposite walls (Yang & Clements-Croome, 2013). It is functional to enhance the flow of air through a building caused by a wind-generated pressure drop across it (MS, 2014).

A better natural ventilation can be improved by having a proper opening at the right spot of a building, a proper layout that can regulate the entering of air movement throughout the interior spaces of the building (Wahab *et al*., 2018), and the fresh air may be introduced from a shaded or landscaped space or from over a body of water (Yang & Clements-Croome, 2013). Noman *et al*., (2016) suggested that natural ventilation might help to improve thermal comfort inside mosque buildings because of air movement in and out of these buildings can reduce the temperature within the space. In addition, Heiselberg & Perino (2010) stated that sufficient air exchange rate for indoor air quality and thermal environmental conditions could be provided through natural ventilation. The benefit of the indoor naturally ventilated building is to reduce the operating cost, i.e. electrical cost compared with mechanical ventilation, hence protect the environment. Hence, this study aimed to visualise the movement of outdoor-indoor air through the pore of window panels using smoke flow visualisation technique as an indicator in a closed-loop wind tunnel. Smoke flow visualisation is a standard technique for flow depiction, which is based on a volumetric, particle-based, or image-based representation of the smoke (Von Funck *et al*., 2008).

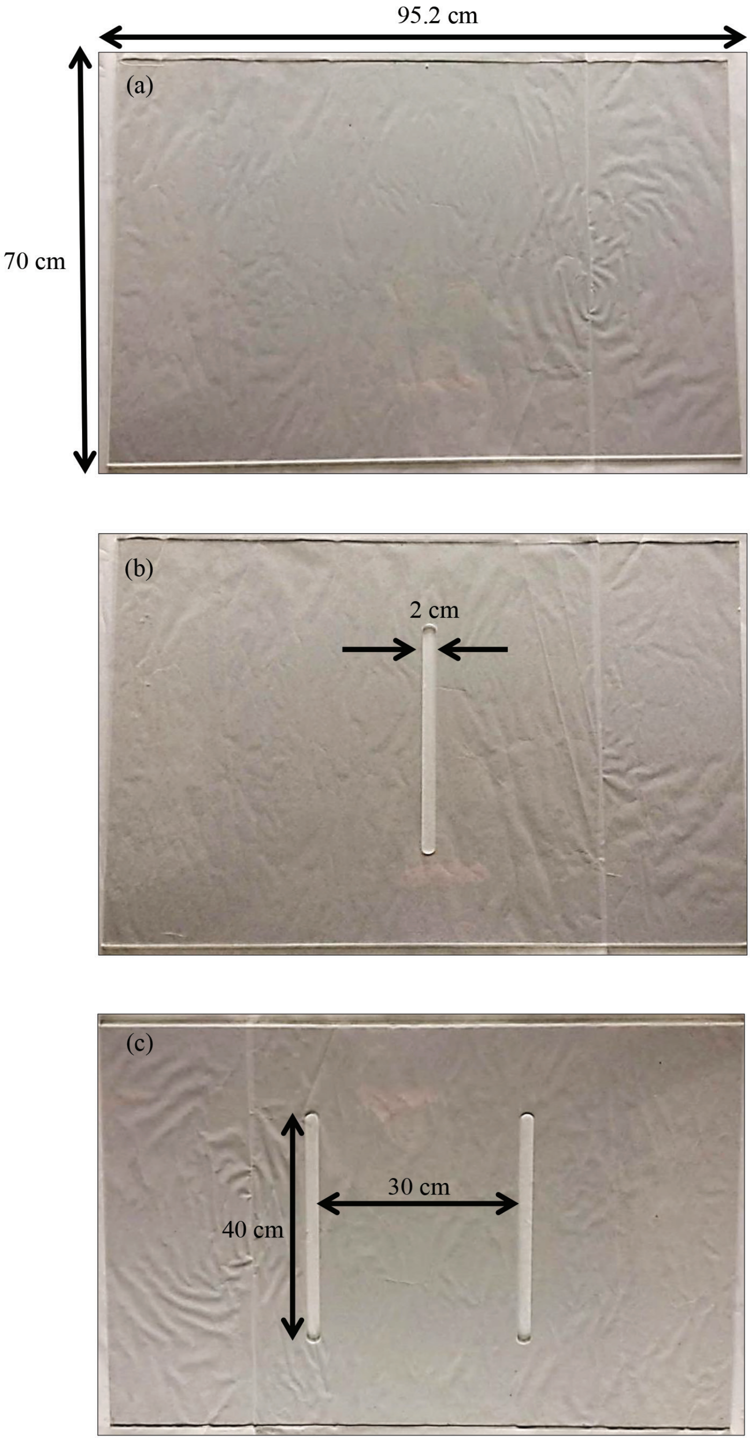

Figure 2: Dimensions of the panels (a) Panel A: panel without pore (b) Panel B: Panel with single pore and (c) Panel C: Panel with double pores (dimension not to scale)

Materials and Methods

Smoke Flow Visualisation Technique

Smoke flow visualisation testing was conducted to evaluate the airflow characteristics of three (3) different pores (Panel A: Panel without pore, Panel B: Panel with the single pore, and Panel C: Panel with double pore) of the window panels. The smoke was tested to flow at different airspeeds (0.5 m/s, 1.0 m/s, 2.0 m/s, 3.0 m/s and 5.0 m/s).

Smoke Flow Visualisation

The experiment was performed in a closed-loop wind tunnel at the Wind Tunnel Laboratory, Science and Engineering Research Centre (SERC), the Universiti Sains Malaysia. There were three types of panels tested in this study i.e. Panel A: Panel without pore (a baseline reference), Panel B: Panel with the single pore, and Panel C: Panel with double pores. All the panels (mimic actual window panel) were made of clear Perspex with a length of 95.2 cm x height of 70 cm as shown in Figure 2. Panel B has the pore at the mid-section of the panel whereas Panel C has the pores at the left and right of the mid-section of the panel. The pore has the size of 2 cm width x 40 cm in height.

The rectangular test section of the wind tunnel was 1 m of width × 0.80 m of height × 1.80 m of length, with a turbulence level of 0.1%. The wind tunnel has the maximum speed of 80 m/s in the test section, and the flow in the test section is driven by an axial fan motor and a diffuser downstream. The wind tunnel control panel was used to control the airflow speed whilst a digital anemometer was used to verify the airflow speed. The illustration of the smoke generator setup is as shown in Figure 3.

The Safex oil in the conical flask was heated up by a power supply at 19 V and 2 A. Then, the Nichrome wire was immersed in the Safex oil, and the hot Nichrome wire caused the Safex oil inside a conical flask to evaporate into white smoke. A motorised air pump was used to pump out the smoke from the conical flask through 21 small tubes of smoke rake inside the test section. Two white halogen lamps were installed at the top and bottom of the test section. The halogen lamps illuminated the smoke lines released from the smoke rake. Meanwhile, the retort stand held the smoke rake arm.

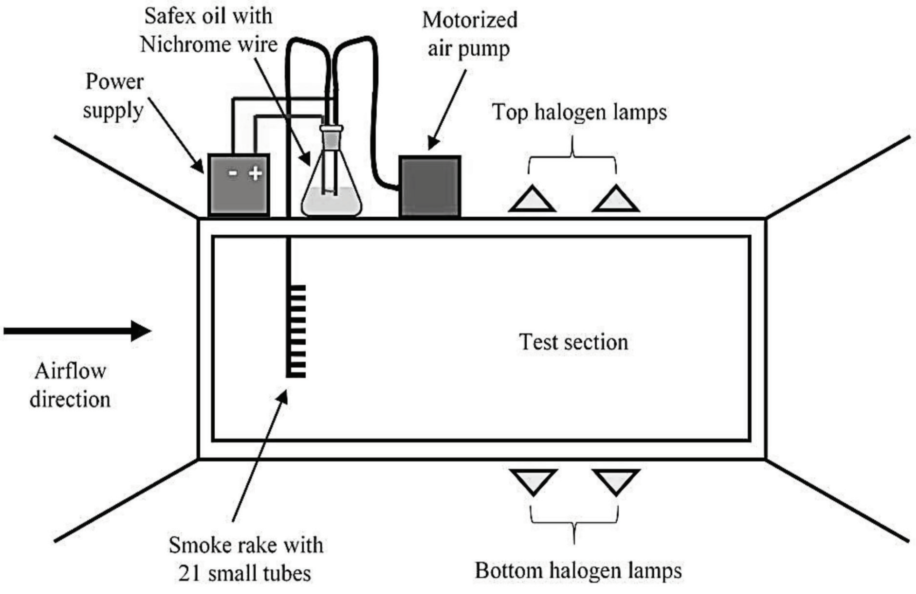

Figure 3: Smoke generation setup (Salleh *et al*., 2018)

Test Section

Figure 4 shows the setup of the panel inside the test section is 24 cm from the smoke rake which was located at the mid-section of the panel. The optimal distance was selected after comparing other location to ensure laminarity of the smoke lines upstream the panel. The black paper was used to cover the interior of the test section except for the test section floor. It captured a better contrasting image of the smoke lines and prevented any reflection caused by the test section window. Two cameras used (Sony 1920 1080i), each was mounted outside and inside of the test section, respectively. The outside camera located at the left side of the test section was used to capture the side view of the airflow pattern. Meanwhile, the inside camera located at the rear side of the test section was used to capture the rear view of the airflow pattern. The airflow patterns were recorded for Panel A, B, and C at five different airflow speeds i.e. 0.5 m/s, 1.0 m/s, 2.0 m/s, 3.0 m/s and 5.0 m/s. Lastly, the airflow characteristics were analysed by capturing the airflow pattern images of the three (3) types of panels.

Results and Discussion

The malfunctioning wall (i.e. closed panels: openings, doors, and windows) could cause the high indoor air temperature as there is no air movement within the main prayer hall. Therefore, the current state of thermal comfort at all monitored mosques needs to be improved by having such openings on panels to lower the indoor air temperature within the main prayer halls. Improvement on the window panels by introducing the pores had been conducted in the wind tunnel. The pores on the window panels allow the occurrences of vertical and horizontal air movement from outdoor towards indoor. Hence, the smoke flow visualisation testing were carried out on three window panels (Panel A: Panel without pore**,** Panel B: Panel with the single pore, and Panel C: Panel with double pore) to visualise the movement of air from outdoor towards indoor.

Airflow Characteristics

The results of the experiments were discussed in term of the airflow characteristics on the pattern of three (3) different pores (Panel A: Panel

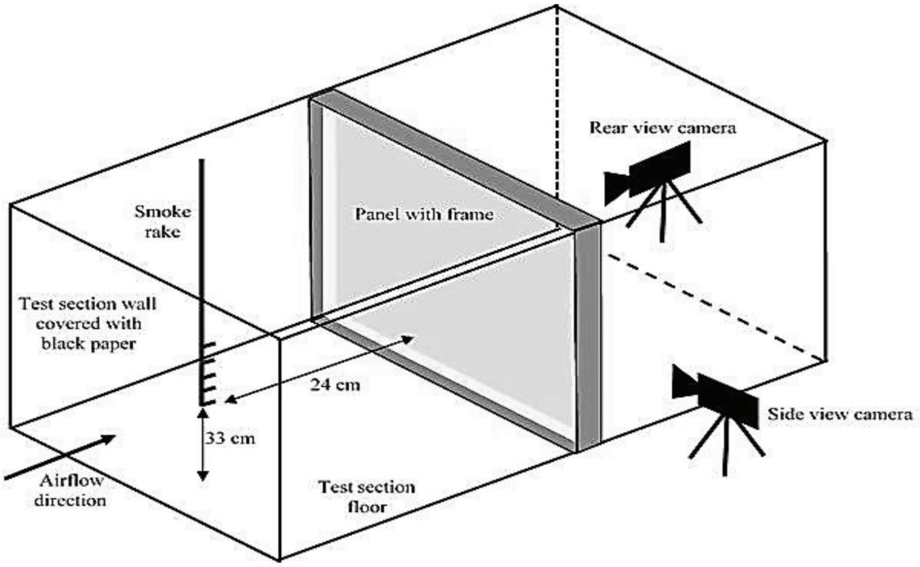

Figure 4: Setup of the panel inside the test section (Salleh *et al*., 2018)

without pore**,** Panel B: Panel with the single pore, and Panel C: Panel with double pore) of the window panels. Panel A was used as the baseline model which represented the malfunctioning wall of the building of the mosque (i.e. when openings, windows, and doors were shut/closed). The airflow characteristics on the pattern before and after it passed through the pores on Panel B and Panel C was compared with Panel A. The summary of airflow characteristics for all the panels at 0.5 m/s, 1.0 m/s, 2.0 m/s, 3.0 m/s, and 5.0 m/s is shown in Table 1.

Table 1: The summary of results for airflow characteristics for all the panels at 0.5 m/s, 1.0 m/s, 2.3 m/s, 3.0 m/s, and 5.0 m/s

Types of Panel	**Panel A: Without Pore**	**Panel B: With Single Pore**	**Panel C: With Double Pore**
0.5 m/s	- The airflow could not pass through the panel - The smoke is circulating the frontal area of the panel as it hits the surface of the panel in the windward side. - The smoke is circulating the frontal area of the panel as it hits the surface of the panel in the windward side. -The motion of vortices in counter-clockwise and clockwise motion recirculation at the top and bottom half of the panel, respectively.	- No recirculation was observed in the windward side of the panel surface. - The smoke in the leeward side of the pore was observed to be turbulent.	- Less turbulent and smaller as compared to the case of Panel A since the airflow can come across the panel through its two pores. - The airflow entered both pores located to the left and right of the mid-section of the panel.
1.0 m/s	- The smoke lines were observed became more laminar and straighter as the airspeed increased - The smoke is circulating the frontal area of the panel as it hits the surface of the panel in the windward side.	- No recirculation was observed in the windward side of the panel surface. - The smoke in the leeward side of the pore was observed to be turbulent.	- The airflow passed through both pores when the smoke lines hit the mid-section.
2.0 m/s	- The smoke lines were observed became more laminar and straighter as the airspeed increased - The smoke is circulating the frontal area of the panel as it hits the surface of the panel in the windward side.	- No recirculation was observed in the windward side of the panel surface. - The smoke in the leeward side of the pore was observed to be turbulent.	- The smoke lines in mostly entered the left pore as it skewed to the left upstream the panel surface.
3.0 m/s	- The smoke lines skewed to the left of the panel surface in the windward side - The smoke is circulating the frontal area of the panel as it hits the surface of the panel in the windward side.	- The smoke lines skewed to the left of the panel surface in the windward side - The smoke in the leeward side of the pore was observed to be turbulent.	- The smoke lines skewed to the left of the panel surface in the windward side - The smoke lines were observed to only pass through the left pore.

5.0 m/s	- The smoke lines skewed to the left of the panel surface in the windward side - The smoke is circulating the frontal area of the panel as it hits the surface of the panel in the windward side.	- The smoke lines skewed to the left of the panel surface in the windward side - The smoke in the leeward side of the pore was observed to be turbulent.	- The smoke lines became more laminar and straighter - The smoke lines were observed to only pass through the left pore.

The images of the side view and rear view for all the panels (Panel A, Panel B, and Panel C) at 0.5 m/s was as shown in Figure 5. Since there was no pore on Panel A, the airflow could not pass through the panel. The smoke line that represented the outdoor airflow had been observed to be failed to permeate, hence creating eddy motion of smokes at frontal area of the panel following contact with the windward panel surface.

There was the motion of vortices in counter-clockwise and clockwise motion recirculation at the top and bottom half of the panel, respectively. Meanwhile, there was no recirculation observed in the windward side of the panel surface on Panel B as it has a pore at the mid-section. The smoke lines could be seen before the airflow entered the pore. However, it was hardly seen after it passed through the pore. From the rear view image, it shows that the white fume in the leeward side of the pore was observed to be turbulent.

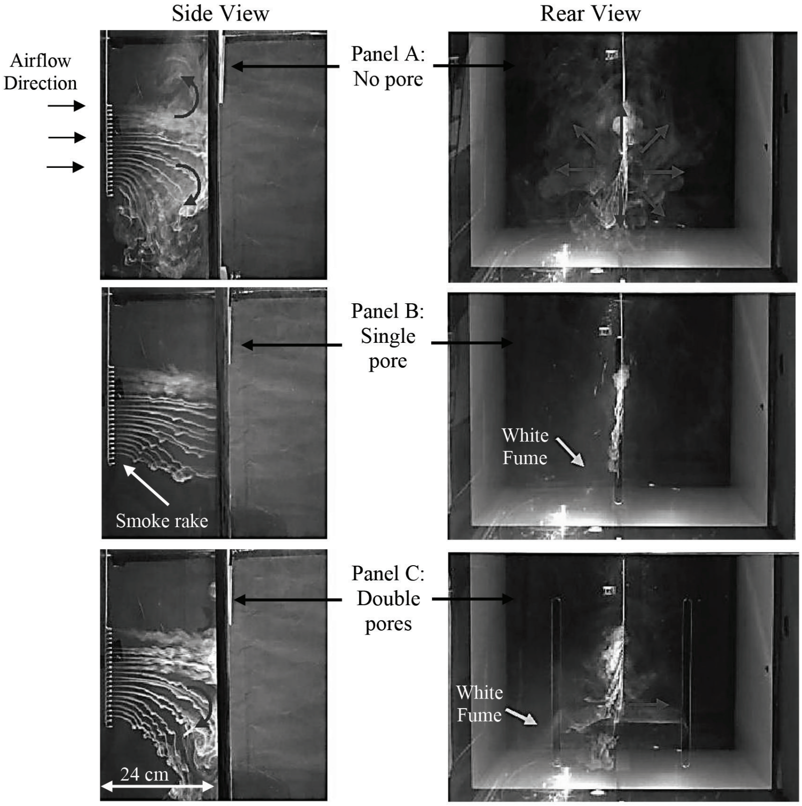

Figure 5: Side and rear views of the airflow characteristics for all panels at 0.5 m/s (dimension not to scale)

The recirculation of airflow in Panel C was observed to be less turbulent and smaller as compared to the case of Panel A since the airflow could come across the panel through its two pores. The airflow could not be observed when it passed through the pores. Based on rear view images, it was found that the airflow permeated through both pores at the left and right of the mid-section of the panel. The airflow characteristics on smoke patterns for 1.0 m/s showed almost similar patterns to that of 0.5 m/s as shown in Figure 6. However, the smoke lines were observed to become more laminar and straighter as the airspeed increased. The airflow patterns in the leeward side of the panel were challenging to capture as the airspeed after passing the pores increased. Rear view images showed that for Panel C, the airflow permeated through both pores as the smoke lines hit the mid-section of the panel.

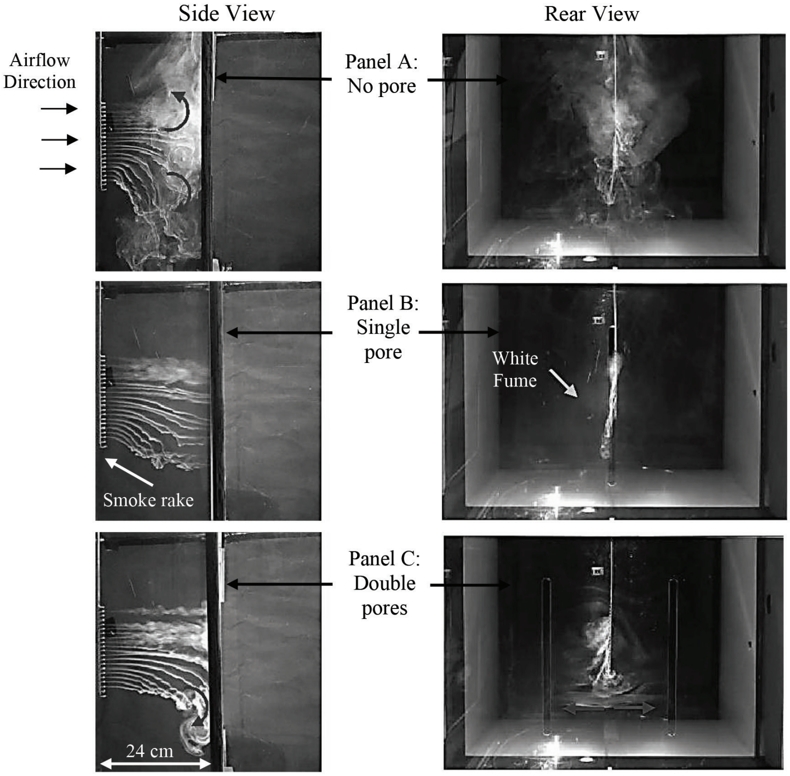

Figure 6: Side and rear views of the airflow characteristics for all panels at 1.0 m/s (dimension not to scale)

The airflow patterns at 2.0 m/s for Panel A and Panel B exhibited similar patterns to the previous discussions. The smoke lines in Panel B could not be captured on photos since it was dispersed at a higher speed after it passed through the pore. Figure 7 depicted a rear view image showing a faint white fume in the leeward side of the pore. However, the smoke lines in Panel C mostly entered the left pore as it skewed to the left upstream of the panel surface. The skew motion of the smoke lines was most likely due to the tare effect and interference induced around the smoke rake. In addition, small misalignment of the smoke rake tube exposed could also contribute to this skew behaviour (Salleh *et al*., 2018).

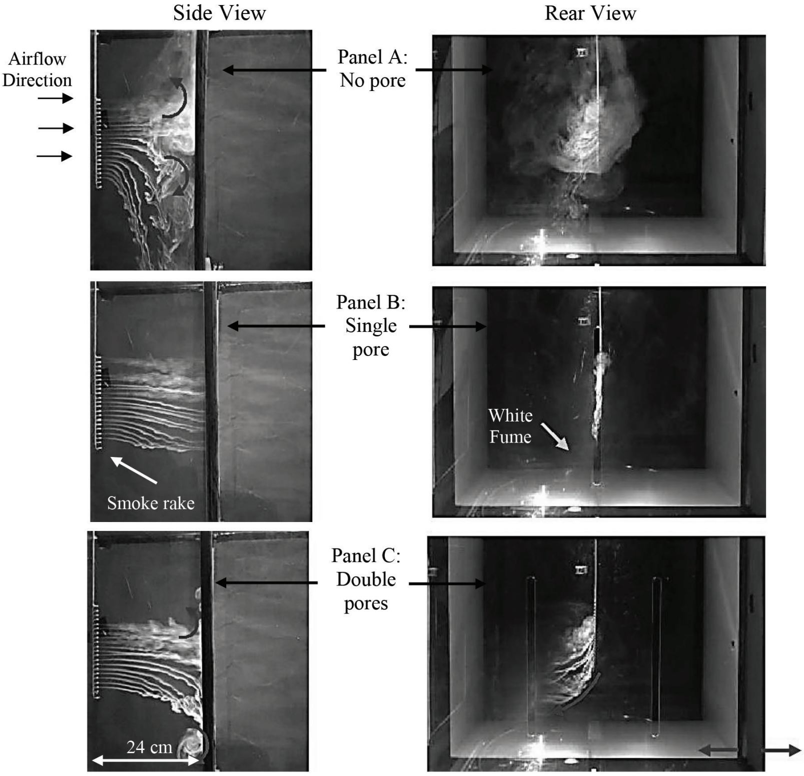

Figure 7: Side and rear views of the airflow characteristics for all panels at 2.0 m/s (dimension not to scale)

Figure 7: Side and rear views of the airflow characteristics for all panels at 2.0 m/s (dimension not to scale)

At 3.0 m/s, it was observed that the skew motion of the smoke lines increased as the airflow speed increased for all panels as shown in Figure 8. The smoke lines skewed to the left of the panel surface in the windward side as shown on Panel A, Panel B, and Panel C. For Panel C, since the smoke lines skewed to the left, the smoke lines were observed to only pass through the left pore. In the leeward side of the pore, similar to the case of Panel B, the smoke lines dispersed into faint white fume that flew at a higher speed.

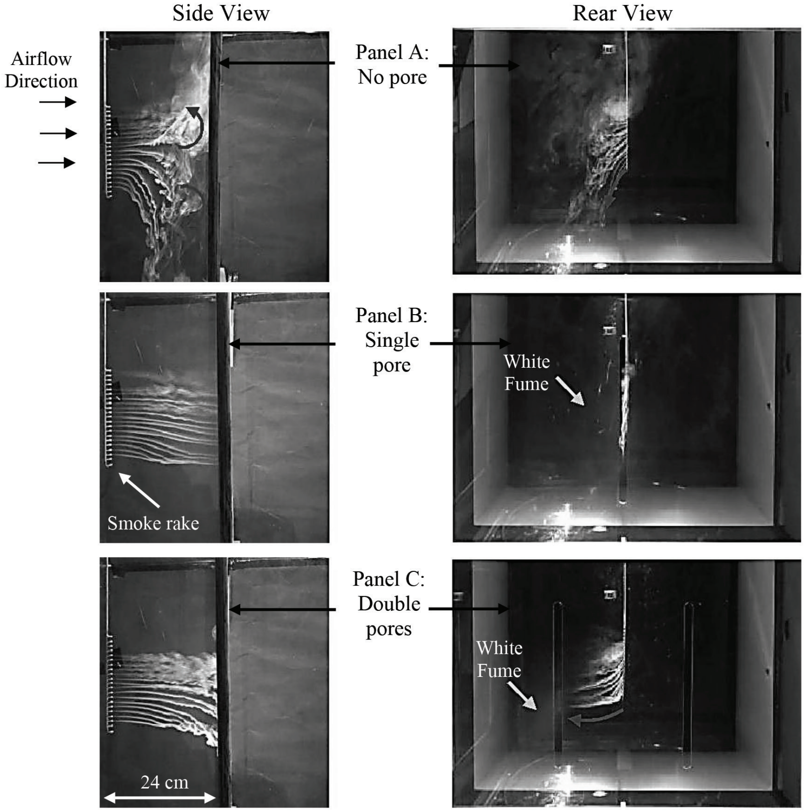

Figure 8: Side and rear views of the airflow characteristics for all panels at 3.0 m/s (dimension not to scale)

Figure 8: Side and rear views of the airflow characteristics for all panels at 3.0 m/s (dimension not to scale)

The smoke lines skewed to the left on Panel A and C at 5.0 m/s as shown in Figure 9. It can be observed that the airflow patterns were almost similar to the case of 3.0 m/s. However, the smoke lines became more laminar and straighter as depicted by the side view images of Panel B and C. It was difficult to observe any white fume in the leeward side of Panel B because it was relatively faint. There was no recirculation of airflow observed upstream of the Panel C based on the side view image, as the airflow mostly passed across the panel through the left pore at high speed as depicted by its rear view image (Salleh *et al*., 2018).

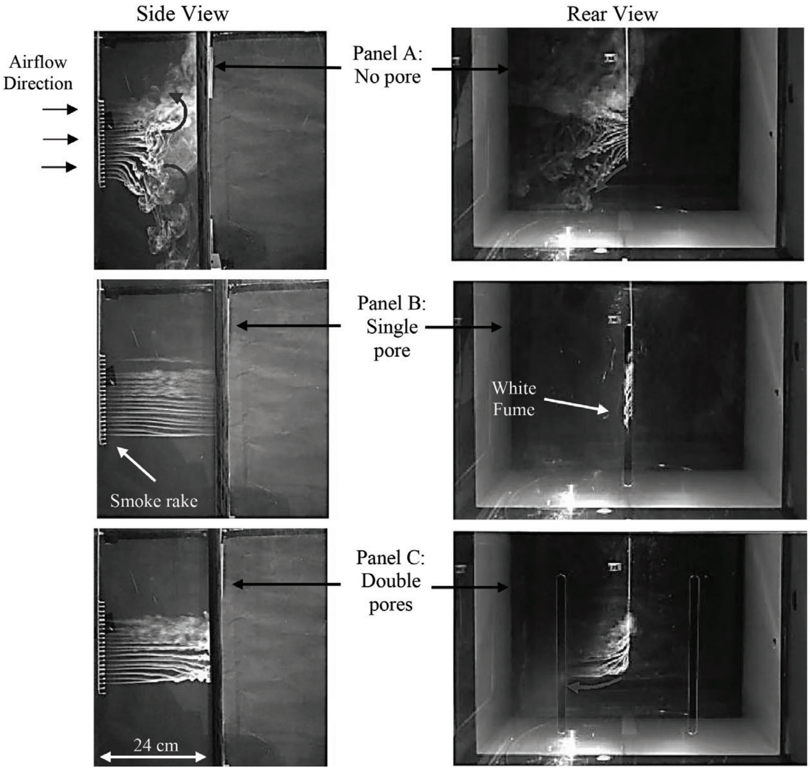

Figure 9: Side and rear views of the airflow characteristics for all panels at 5.0 m/s (dimension not to scale)

Results showed that the panel without pores, which represented the malfunctioning wall of the mosques buildings, resulted in vortices with recirculation of the airflow wake in counter and clockwise directions in the windward side of the panels. In contrast, the presence of the pore on Panel B (single pore) and Panel C (double pores) reduced the recirculation of the airflow wake and eventually diminished the vortices. The airflow for both panels experienced an increment in velocity on the leeward side as it passed through the pores. The pores on the window Panel C could allow 2.4% outdoor air toward indoor compared to Panel A: without pore (0%) and Panel B: with single pore 2%). The window panels with pores have good potential to provide natural ventilation which introduces the fresh outdoor air into indoor.

The pores at the windows panel are proposed to increase the maximum outdoor air that could pass through the pores into indoor. More pores resulted in more ventilation. Perhaps, it could increase the exchange rate of outdoor air entering to indoor and could discharge the warmer indoor air through the openings near the ceiling (introduce to stack ventilation). The high temperature could be reduced to get better thermal comfort in the main prayer hall. Besides that, it could also decrease the indoor air contaminants in the main prayer hall as the air was continuously exchanged from outdoor to indoor. Additionally, it could also help to reduce or avoid the bacteria and fungi growth in the main prayer hall that is due to the bacteria growths which are influenced by high temperature and the dampness areas. The pore at the windows panel perhaps could solve the crucial problems at the main prayer halls of mosques regarding indoor air quality, thermal comfort, and biological contaminants.

In addition, the results also showed that the highest airspeed (5 m/s) contributed to the highest velocity of the smoke passed through the pores compared to the airspeed of 0.5 m/s, 1.0 m/s, 2.0 m/s, 3.0 m/s. This was due to the smoke massflow rate increased with elevated ambient pressure due to the increased air density and the assist of air entrainment strength (Ji *et al.,* 2018). Therefore, the highest airflow also has good potential to promote natural ventilation which contributed more fresh outdoor air into indoor.

The following recommendations should be taken into consideration to improve the reliability of the current results for future works. The window panels need to be resized for better flow dynamics to minimize the blockage effect. Besides that, the camera position needs to be relocated to record the top view smoke lines across the panels for a better capture the airflow pattern as it passes through the pore. In addition, the wake rake needs to be redesigned by adding more small tubes on the smoke rake so that the smoke lines can fully capture the whole window panel.

Ramli (2012) had investigated the re-adaptation of the Malay house into low energy buildings of a modern building in Malaysia in order to maintain the thermal comfort of the building occupants. The results found that there were thermal comfort elements that had been adapted such as building orientation, fenestration design, the application of natural lighting system and natural air ventilation system, and the arrangement of interior spaces. Verma *et al*., (2018) had proven that by using biomass energy, the building could be upgraded into an energy efficient building by using continuous anaerobic digestion and solar photovoltaic modules. The study showed that the potential energy savings and economic benefits could be achieved. In addition, digital architecture and intelligent buildings have successfully led to adequate saving in economic, social, and environmental cost. They have reduced environmental pollution, climate changes, and stress of humans. They have also played a significant role in providing a healthy life to humanity as one of the major components of sustainable development (Loumer, 2015).

In Malaysia, Mohd Ariffin (2018) stated that the consideration of facades design is crucial to reduce the urban temperatures for the tropical climate. The results suggested that the temperature of the building facades on the double skin façade were lower than glass façade. According to Azizi & Torabi (2015), the interaction between the human being and his desired space must be considered in building design. The increased of hard surfaces (concrete and metal) in designing new buildings contributed to the increment of urban temperatures (urban heat island effect) (Victorero *et al*., 2015). They had found that the using of living walls could lower the wall's surface temperature up to 30°C compared red meal wall and grey concrete wall. In addition, Cheng *et al*., (2005) also revealed that the maximum indoor air temperature could be reduced by using the lighter surface colour and thermal mass in the hot humid climate as it can modify the thermo-physical signature of buildings.

Bakhlah & Hassan (2012) stated that there was a small difference between indoor and outdoor temperature and short time lag. In order to protect the indoor environment from outside climatic factors, the wind speed level needs to be induced to increase the air cross ventilation and stack effect. Besides that, the indoor air temperature can also be reduced by the use of efficient active mechanical operation, and the use of shading devises on frontal facades to prevent the entering of low angle solar radiation. There were different effects of ceiling fan direction on the forward direction (counter-clockwise) and reverse direction (clockwise). The forward direction was suggested during summer as it will force the room air down and makes the occupants feel comfortable. Meanwhile, the reverse direction at low speed was suggested during winter as it makes the room air up towards the ceiling and forces the warm air down (Perl, 2013). Thus, having window panels with pores in modern mosque buildings, which allow indoor-outdoor air movement (natural ventilation) could assist in reducing the indoor temperature naturally while lowering the dependency on non-renewable energy and cost.

Conclusion

The current as-constructed conditions of mosques prayer hall seems to be insufficient for ventilation with minimum air movement. This was because most of the openings (i.e. windows and doors) in the mosques were closed especially during non-prayer time for security and rainwater purpose. There was a lack of air movement within the main prayer halls. This study was to visualise the movement of outdoor air into indoor through the pore on the window panel by using the smoke flow visualisation technique. Smoke flow visualisation testing was conducted to evaluate the airflow characteristics of three (3) different pores (Panel A: Panel without pore, Panel B: Panel with the single pore, and Panel C: Panel with double pore) of the window panels 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). The major findings include: 1. Panel C on the window panel with double pores were suggested as it could allow 2.4% outdoor air toward indoor compared to Panel A: without pore (0%) and Panel B: with single pore 2%). From the wind tunnel study results, adding pores to the window panels could promote optimum outdoor-indoor air movement. 2. The highest airspeed (5 m/s) contributed to the highest velocity of the smoke passed through the pores compared to the airspeed of 0.5 m/s, 1.0 m/s, 2.0 m/s, 3.0 m/s. The highest airflow also has good potential to contribute natural ventilation which contributes more fresh outdoor air into indoor. 3. Providing adequate ventilation is one way to promote adequate thermal comfort in the mosque buildings. Perhaps, this could assist in reducing the indoor temperature within the main prayer halls of the mosque buildings. This study increases the basic understanding of the smoke flow characteristics in wind tunnel with different types of window panels at various airspeeds. It also helps us to better understand the movement of outdoor air passing through indoor which could provide better natural ventilation within the main prayer halls.

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