A STUDY OF DOUBLE-LAYERED WALL AND PRISM DEFLECTOR TO IMPROVE NATURAL VENTILATION IN A CONFINED SPACE

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ABSTRACT: Natural ventilating and cooling strategies need to be considered as a substitute to the present air conditioning system. However, the effectiveness of the natural air ventilation in providing cooler environment still needs further investigation. This study proposed a new method, using a double-layered wall and a prism deflector to improve air ventilation in a confined space. Experimental and simulation approaches were used in this study. The results yielded that the double-layered wall and prism deflector configuration can be used to improve air ventilation in the confined space. The significant effect of the prism deflector was dependent on the combination of parameters used. The use of a 45° hole angle inner wall, and a higher prism deflector ratio were able to enhance the air ventilation more effectively.

KEYWORDS: Air Ventilation, Double-Layered Wall, Natural Ventilation

1.0 INTRODUCTION

Passive cooling strategy studies have proven that natural cooling could be an alternative way on cutting down energy consumption rate. The development of passive cooling method can be traced back to the previous generation which implemented a specific building design and took into account various factors such as warm summer temperature, provision of clean air, air movement, heat reclaim, and thermal capacity [1, 2]. Today, passive cooling strategies are studied and compared with the active cooling strategies in terms of energy consumption rate. Several techniques have been used in studying the flow structure of cross-sided ventilation and the results yield that the inlet and outlet ratio for the opening has a huge influence on the cross-sided ventilation [3]. Stack effect is another type of ventilation strategy, which is caused by temperature differences, inherit by the wind [4]. The present wing wall on a single-sided ventilated room is able to boost 40% average air velocity higher inside the room if compared to the outside room average air velocity [5]. The effectiveness of wind wall design in air circulation enhancement is at the optimum stage when incident angle of the wind is at 45° [6]. This statement holds true when the opening is big. However, if the opening is small, the effect of wind incident angle does not contribute remarkable results [7]. A study also finds that dimensional changes like height, width and length of a ventilation passage (such as air gaps) have a direct impact on the ventilation rate [8-10]. Natural ventilation is expected to save 10% of cooling energy and 15% on fan power of annual energy consumptions [11]. In this study we proposed a new method, a double-layered wall and a prism deflector in order to improve air ventilation in a confined space.

2.0 EXPERIMENT

2.1 Experimental Setup

The focus in this experimental study is on investigating the effectiveness of double-layered wall and prism deflector in promoting air ventilation in a confined space. Figure 1 shows the double-layered wall ventilation apparatus which consists of a double-layered wall confined space section, exhaust fan, anemometers, temperature sensor, thermocouple, spotlight as a heat source, flow straightener, and data logger. Wind induced approach was used to draw outside air that acts as natural wind flow into the confined space of the apparatus through the double-layered wall. The test section, which refers to the confined space, was constructed using acrylic glasses to ease observation during the experiment.

Three important parameters of the test section were wall distance (L), hole angle (θ), and the prism deflector ratio (R). The double-layered wall was used to maximize the air ventilation in the confined space. However, the prism deflector was used to direct the surrounding air to the opening of the wall. The prism deflector used in this study was a right-angled triangle prism and the prism deflector ratio referred to a/b ratio. Figure 1(B) illustrates the double-layered wall ventilation apparatus with dimensions. The dimension of the confined space used in this study was 270 mm x 324 mm x 383 mm. Experimental data such as air velocity and air temperature in the confined space were measured by using an anemometer and a temperature sensor, respectively. A thermocouple that was mounted near the heat source was used to measure the roof temperature.

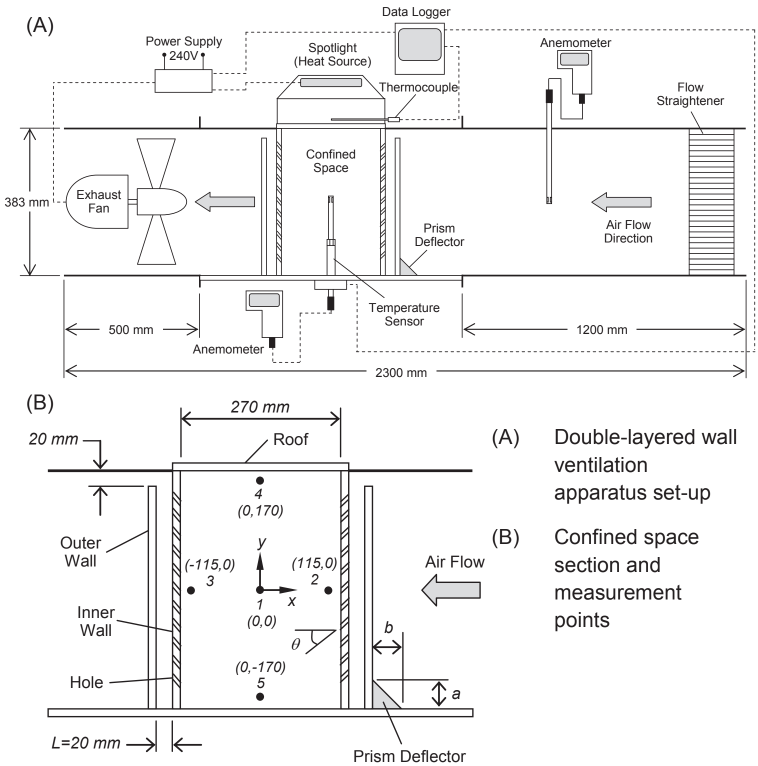

Figure 1: Double-layered wall ventilation apparatus with dimensions

A digital data logger used in this experiment enabled continuous data recording for confined space temperature (T_C), and roof temperature (T_R). TR was measured to make sure that the temperature near the roof area did not exceed 65°C in order to prevent the acrylic glass roof from buckling. The confined space air velocity (V_C) and the inlet air velocity (V_{in}) were measured by using two portable anemometers separately. In order to ensure the uniformity of the airflow, a flow straightener was placed at the inlet section of the apparatus. The heat source was introduced by using a spotlight to simulate the heat from the sun that was transferred into the confined space through the acrylic glass roof.

2.2 Experimental Procedure

The experiment was started with a fixed exhaust fan speed (2,850 RPM). In this study, a fixed 20 mm wall distance, two hole angles, and three prism deflector ratio were used to find out which configuration will give the most effective in enhancing air ventilation in the confined space. Table 1 illustrates the test configurations for experimental and simulation studies.

Table 1: Test configurations for experimental and simulation studies.

CASE	Wall Distance L (mm)	Hole Angle θ (°)	Prism Ratio R (-)	Right-Angled Triangle Dimensions
CASE 1	20	0	0.5	a:38 mm ; b:76 mm
CASE 2	20	0	1.0	a:38 mm ; b:38 mm
CASE 3	20	0	2.0	a:76 mm ; b:38 mm
CASE 4	20	45	0.5	a:38 mm ; b:76 mm
CASE 5	20	45	1.0	a:38 mm ; b:38 mm
CASE 6	20	45	2.0	a:76 mm ; b:38 mm

T_R, T_C and V_C were recorded immediately right after the spotlight was switched on. After that, the confined space was left for five minutes of heating so that the heat produced by the spotlight had enough time to transfer from the heat source section into the confined space. The heating period of five minutes was chosen because it was deemed suitable period to ensure that the temperature near the roof did not exceed 65°C to prevent buckling effect of the roof. As soon as five minutes of heating was completed, the power supply of the spotlight was switched off instantly. The portable anemometer at inlet section was started instantly to record Vin of the inlet section for one minute after the heating process was completed. The measured inlet air was in the range between 0.086 m/s to 0.092 m/s. The confined space was left for 60 minutes with the exhaust fan switched on to cool down the confined space until the temperature was in equilibrium with the room temperature. The time used to measure V_C was 60 minutes. In order to study the air ventilation enhancement for different cases, the data for T_R, T_C and V_C were recorded continuously for 60 minutes for each case.

3.0 SIMULATION

3.1 Simulation Setup

CFD FLUENT 14.0 software was used in this simulation study. FLUENT software uses RANS model and is widely used in ventilation studies. k-ε model was used to simulate the airflow. The 3D model used in this study was a small scale confined space model that fitted into the double-layered wall ventilation apparatus. The basic assumption of the analysis was a steady state flow of incompressible and Newtonian fluids. A fluid model was developed according to the size of the confined space as shown in Figure 1. There was a constant heat flux from the heat source on top of the confined space to represent heat from the roof gained from the sun.

3.2 Model Geometry

The model was symmetrically cut into half for the analysis purpose. The overall dimension from the side view of the fluid model was 2300.48 mm x 383 mm including the confined space dimension. The width of the whole model was 324 mm. The thickness of the wall was 8 mm and the diameter of holes for the inner wall was 5 mm.

3.3 Parameters

There were three main parameters used in this simulation study; hole angle of the inner wall (θ), distance between outer and inner wall (L) and the prism deflector ratio (R). The value of parameters and configurations used in this study were similar with the experimental study as shown in Table 1.

3.4 Boundary Conditions

All walls of the domain were modelled as adiabatic with no slip condition. The material of the wall was assumed to have a minimum effect on the air flow. The fluid was defined as room air and the air inlet velocity was set at 1.5 m/s. The value was chosen because it was the highest value of wind speed in laboratory. The outlet was set as relative pressure 0 Pa and the outlet was defined as the air flow to the atmosphere. The top wall of the confined space had a temperature of 310 K. The temperature difference between top wall and other walls was only 10 K.

3.5 Multi Point Measurement

Other than the graphical result, the confined space velocity values at different points that were obtained from the simulation were taken for further comparison between cases. The velocity values were taken at various points of the cross section of the confined space model. The designated points are shown in Figure 1(B) and the point locations are measured in milimeter. Point 1 which was located at the centre of the confined space was selected as a reference point (0,0).

4.0 EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Confined Space Air Velocity Comparison

Figure 2 shows the confined space air velocity (V_C) data at the centre of the confined space for various cases. All six cases shown in the figure can be grouped into two categories, which are the 0° hole angle lines categories (CASE 1 to CASE 3) and the 45° hole angle lines categories (CASE 4 to CASE 6). Starting from t = 3 minutes onwards, CASE 1 to CASE 3 achieved higher V_C reading between 0.74 to 0.78 m/s. However, CASE 4 to CASE 6 achieved lower V_C reading between 0.14 to 0.16 m/s. This implies that the 0° hole angle configurations increased the value of V_C five times higher than the 45° hole angle configurations at the centre of the confined space.

From Figure 2, prism deflector ratios of R = 0.5, R = 1.0, and R = 2.0 have similar pattern of air velocity line for each category. All three types of prism deflector ratio for both 0° and 45° holes angle configurations showed almost a similar V_C reading for each category. Thus, a direct comparison via air velocity resulting in differentiating the effectiveness of prism deflector in improving the air ventilation inside the confined space is difficult. The maximum values of V_C in the figure represented only a temporary increase of airflow velocity at the centre of the confined space when the industrial fan was initially switched on.

Because the results obtained in Figure 2 were measured at the centre of the confined space, the results represented the availability of airflow at the centre of the confined space. There was a maximum airflow at the centre of the confined space for 0° hole angle configurations. However, for 45° hole configurations, the airflow at the centre of the confined space was minimum. In order to describe more on the flow pattern in the confined space for each configuration category, an airflow pattern investigation was discussed in the next section.

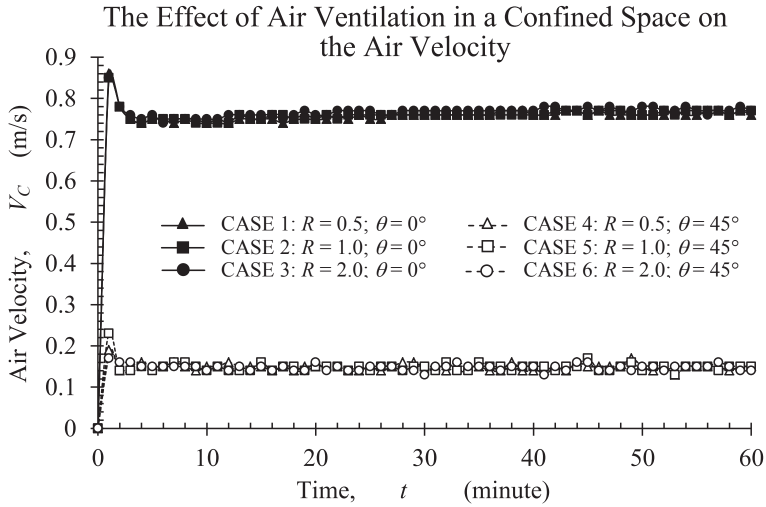

Figure 2: The effect of air ventilation in a confined space on the air velocity for all cases

4.2 Overall Temperature Difference and Overall Cooling Rate

Figure 3 presents the overall cooling rate $(dTC/dt)_{\text{Overall}}$ which is defined as the overall temperature difference between the initial temperature ($T_{C,0}$) and the final temperature ($T_{C,1}$) of the confined space in that each case is divided by 60 minutes. The effectiveness of cooling by comparing different prism deflector ratio can be observed using the figure. Among the six cases, R = 2.0 for 45° hole angle configuration (CASE 6) recorded the highest overall temperature difference. The difference in terms of overall temperature difference among all cases were small which is approximately between 0.11°C to 0.2°C. Due to the small difference, the results from the experiment were still insufficient to satisfactorily prove which prism deflector ratio within each category has the most effect in improving air ventilation in the confined space.

A generalised conclusion can be made based on the overall cooling rate results. The best configurations in both 0° and 45° hole angle configurations that manage to show good overall cooling capability were CASE 1 (0.068°C/min) and CASE 6 (0.080°C/min), respectively. Among all the cases, CASE 6 had the highest overall cooling rate.

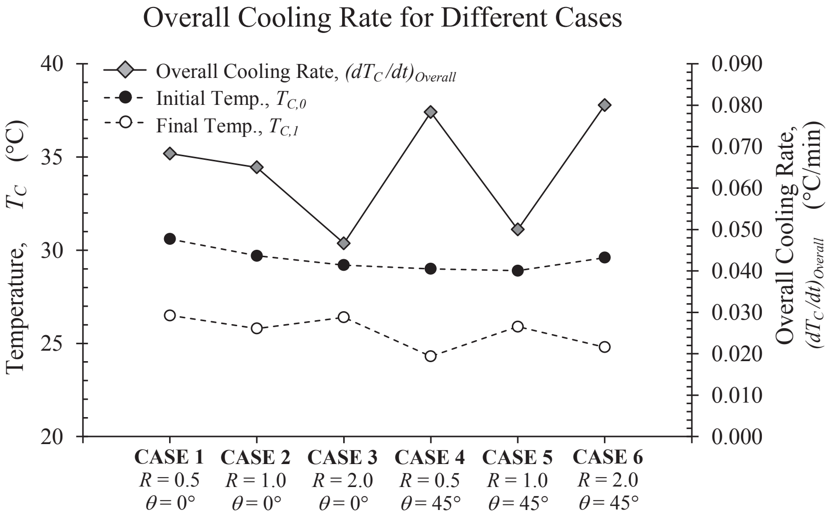

Figure 3: Overall cooling rate for all cases

In order to determine the best configuration in this study, consideration was given based on temperature difference and overall cooling rate. A general conclusion for the best configuration was made according to the configuration that fulfilled the good performance criteria for both aspects. The best configuration in this study was CASE 6 followed by CASE 4, CASE 1, CASE 2, CASE 5, and CASE 3. In terms of category, configurations that used the 45° hole angle inner wall showed the better result in enhancing the air ventilation in the confined space.

5.0 SIMULATION RESULTS AND DISCUSSIONS

5.1 Flow Pattern

Figure 4 shows the airflow pattern results for 0° and 45° hole angle configurations. Generally, two types of airflows were observed for all cases. The first one was a double air circulation flow in the confined space for the 0° hole angle configuration. The second type was a single air circulation flow in the confined space for the 45° hole angle configuration.

For CASE 1 to CASE 3, similar double air circulation flow pattern was observed among the cases as shown by Figure 4(A) to Figure 4(C), respectively. The reason for the air circulation occurring was due to the airflow being trapped in the confined space. The airflow could not exit through the small holes of the inner wall at the opposite side which resulted in a poor air ventilation for these cases. In this case, horizontal airflow direction was more dominant at the middle of the confined space. The air flow was directed to the hole at the opposite inner wall, flowing out directly from the confined space. However, the air that hit the wall surface without holes flowed upward or downward depending on the air velocity at the middle of the confined space.

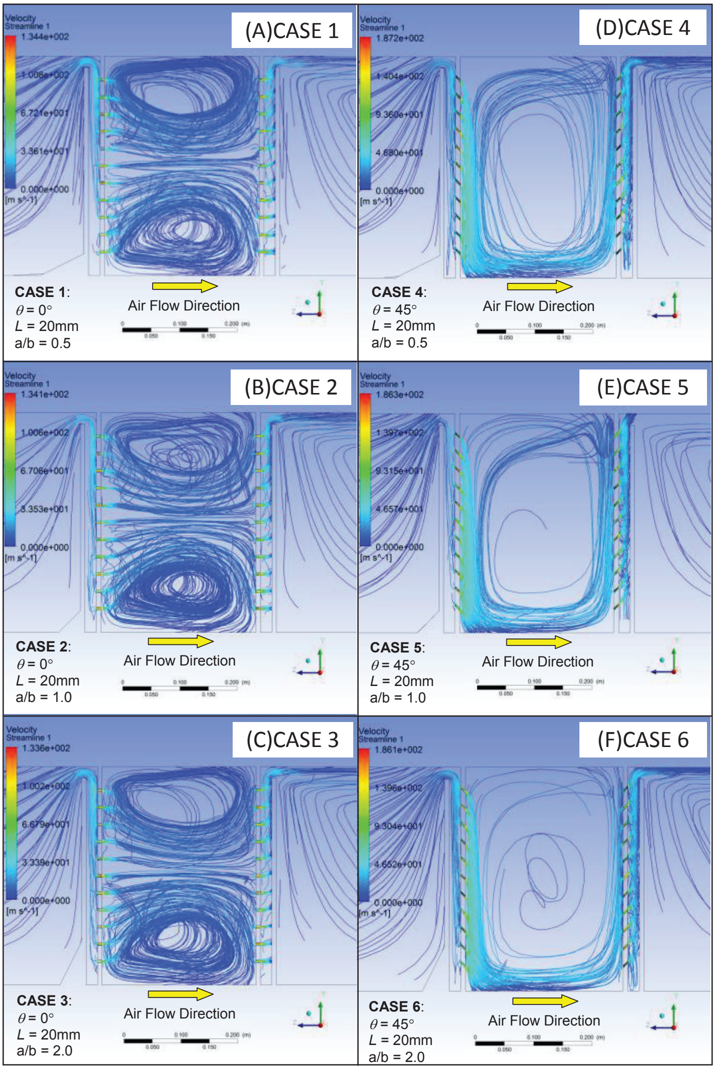

Figure 4: Air flow pattern and air velocity distribution comparison for 0° and 45° hole angle configurations.

The airflow at the upper part of the confined space was forced to flow upward and form a counter clockwise air circulation flow at the top. However, the airflow at the lower part of the confined space was forced to flow downward causing the second air circulation flew in a clockwise direction. Although prism deflector ratio for CASE 1 to CASE 3 seemed to give no significant effect in flow pattern for the 0° hole angle configuration, there were fluctuations of airflow distribution intensity for both upper and bottom air circulation when the prism deflector ratio increased.

The other type of flow pattern was a single air circulation flow pattern, where the airflow circulated from the bottom to the upper part of the confined space (refer to Figure 4 (D) to Figure 4(F) for CASE 4 to CASE 6, respectively). The airflow was directed by the 45° hole angle of the inner walls. The 45° hole angle at the first inner wall was directed to the bottom. Thus, the airflow tended to flow to the bottom part of the confined space. Then the air flowed upward approaching the opposite inner wall. The airflow direction was aligned with the holes angle of the opposite inner wall which was directed upward. Hence, the air was easily ventilated in order to flow out from the confined space. However, the air that flew directly to the wall surface without hole deflected upward and formed a single air circulation flow in a counter clockwise direction. If compared to the 0° hole angle configuration, the 45° hole angle configuration obtained less air being trapped in the confined space. This means that 45° hole angle configuration ventilates air better than the 0° hole angle configuration.

From the 45° hole angle configuration results, the effect of prism deflector ratio can be identified. The ratio affects the air velocity distribution intensity that circulates at the centre of the confined space. Higher prism deflector ratio will produce greater air velocity distribution intensity at the centre of the confined space. This is because, as shown in Figure 4(F), the airflow at the inlet tends to attach to the surface of the prism deflector if the ratio is higher as in CASE 6. The prism deflector helps to direct the airflow entering the outer wall opening. This probably gives some effect on the airflow pattern in the confined space. However, by comparing the airflow pattern for CASE 4, CASE 5 and CASE 6 as shown in Figure 4, CASE 5 exhibit a greater area of minimum airflow at the centre area of the confined space as shown in Figure 4(E). It shows that a greater amount of air is being trapped in the confined space for CASE 5 compared to CASE 4 and CASE 6. Thus, lower cooling rate for CASE 5 is obtained in the experimental result as shown in Figure 3 compared to CASE 4 and CASE 6. Figure 4 shows that the single air circulation flow pattern (CASE 4 to CASE 6) which is for 45° hole angle configuration has more effective air ventilation with less air being trapped in the confined space compared to the double air circulation flow pattern (CASE 1 to CASE 3) for 0° hole angle configuration.

5.2 Multi Point Air Velocity Measurements

Air velocity values were taken at measurement points of 1, 2, 3, 4 and 5. Among these points, point 2 and point 3 were the most important points. These points represented the air velocity at inlet and outlet of the confined space, respectively. The points represented how effective the air was ventilated from the confined space. Figure 5 shows the air velocity variation at different measurement points for comparison among cases.

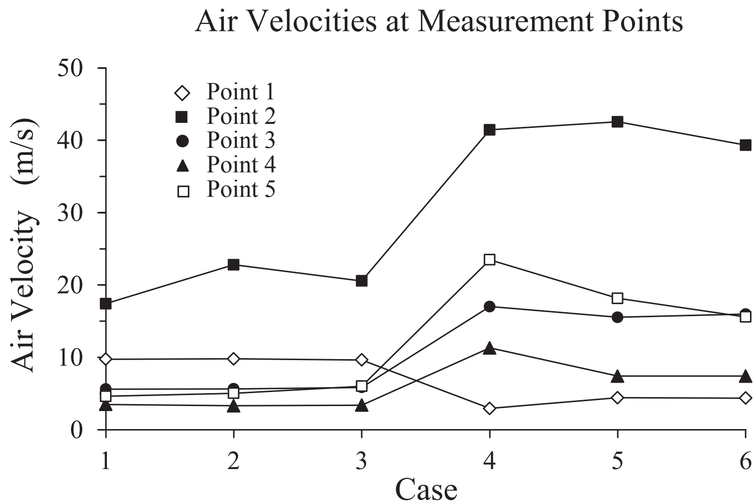

Figure 5: Air velocities at measurement points for all cases.

All the cases for 0° hole angle configurations showed that at each measurement point, the air velocity values were not changing significantly except for point 2, which was located very close to the 0°hole angle inner wall. At that point, the air velocity was the highest for each case which was approximately in the range between 17 m/s to 23 m/s. At points 3, 4 and 5, all cases in the 0° hole angle category recorded a low air velocity, which is approximately 5 m/s with approximately 50% reduction of air velocity compared to the air velocity value at point 1. The higher air velocity at point 1 compared to point 3, 4 and 5 is due to the domination of horizontal airflow at the middle of the confined space as discussed earlier for double air circulation flow pattern. The different configurations of 0° hole angle cases only give obvious effect on air velocity at point 2. In terms of air velocity at inlet (point 2) and outlet (point 3) in the confined space, CASE 1 obtained the lowest air velocities at point 2 for the 0° hole angle configuration. However, for the configuration that obtained the highest air velocity, CASE 2 recorded the highest at these points. Both CASE 1 and CASE 2 obtained almost similar value of air velocity at point 3.

Figure 5 also shows the air velocity measurement at various point for 45° hole angle cases. For all cases in the 45° hole angle configurations, the air velocities had significant changes except for points 1 and 4. It seems that different configurations for the 45° hole angle cases affect the air velocity at the measurement points more. If compared to the results obtained for the 0° hole angle category, different configurations in the 45° hole angle configuration affect the air velocities at point 2, 3, and 5. The air velocity values at these points are higher compared to the 0° hole angle cases, where the air velocities are between 7 m/s and 42 m/s for the 45° hole angle cases. However, for the 0° hole angle cases, at the same points the air velocity range is between 3 m/s and 23 m/s. The increment of air velocities for 45° hole angle cases is almost doubled compared to 0° hole angle cases at these points. The air velocities at point 3, 4 and 5 obtained in this result are not constant compared to the results at the same points for 0° hole angle configuration. Among these three points, point 5 has the highest value of air velocity because the airflow is directed by the 45° hole angle at the first inner wall to the bottom area where the point 5 is located. For 45° hole angle cases, point 2 remains the point with the highest air velocity for all cases which is in the range of 39 m/s to 43 m/s. Point 1 for 45° hole angle configuration obtained the lowest air velocity with approximately 50% reduction compared to the air velocity at the same point for the 0° hole angle category. The lower air velocity at point 1 for the 45° hole angle configuration is due to a single air circulation flow pattern that has minimum air flow at the middle of the confined space where point 1 is located. Among all measurement points in Figure 5, point 1 obtained the lowest air velocity for all cases in the 45° hole angle configuration.

In terms of air velocity at inlet (point 2) and outlet (point 3) of the confined space, CASE 6 and CASE 5 obtained the lowest air velocities at point 2 and 3 for 45° hole angle configuration, respectively. However for the configuration that obtained the highest air velocity, CASE 5 gets the highest for point 2 and CASE 4 is the highest for point 3.

From the result, it can be concluded that the 45° hole angle inner walls are able to enhance the air velocity at the inlet and outlet of the confined space. Hence, it enhances the air ventilation in the confined space compared to the 0° hole angle inner walls. However, in this study, the manipulation of prism deflector ratio does affect the air velocity to be increased or decreased depending on the parameter combinations. Thus, the results obtained in this study show the effect of the prism deflector ratio in improving air ventilation in a confined space. Although the significance of prism deflector ratio cannot be identified, the results show that the higher ratio of prism deflector tends to enhance the air velocity in the confined space. The prism deflector with higher ratio is able to direct the airflow effectively into the confined space.

6.0 CONCLUSIONS

In conclusion, air ventilation in a confined space is enhanced by using double-layered wall configurations. CASE 4 and CASE 6 are found to be effective in improving air circulation and ventilation in a confined space. Among each category, CASE 1 and CASE 6 have the highest overall cooling rate for 0° and 45° hole angle configurations, respectively. However the best configuration among all cases is CASE 6 which fulfils most of the aspects in improving air ventilation in this experimental study.

From the simulation results, it is observed that the 45° hole angle cases would give better air ventilation compared to 0° holes angle cases, where higher air velocities are recorded at most of the measurement points. The prism deflector ratio does affect the air velocity in this study. Prism deflector ratio of 1.0 gives a significant effect compared to prism deflector ratios of 0.5 and 2.0. The best configuration according to the air velocities at point 2 and 3 for 0° and 45° hole angle cases are CASE 2 and CASE 5, respectively. For the overall results, CASE 5 with the 45° hole angle, wall distance of 20 mm and prism deflector ratio of 1.0 is the best configuration. However, the difference in term of air velocity at point 2 for CASE 5 and CASE 6 is only 7.6%. Thus, CASE 6 can also be considered as comparable to CASE 5 in this simulation study. Generally, the usage of 45° hole angle inner walls and a higher prism deflector ratio are able to enhance air ventilation effectively. Thus, the double-layered wall configuration improves air ventilation in a confined space.

ACKNOWLEDGMENTS

The research for this paper was financially supported by University Teknikal Malaysia Melaka (UTeM) through the short term grant (PJP/2011/FKM(5A)/S00858). The authors are thankful to Faculty of Mechanical Engineering (UTeM) for providing the necessary facilities for the preparation of the paper.

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