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# The Influence of Window-to-Wall Ratio (WWR) on Airflow Profile for Improved Indoor Air Quality (IAQ) in a Naturally-Ventilated Workshop in a Hot-Humid Climate

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**ABSTRACT**

Indoor air quality (IAQ) has become a major concern worldwide as indoor air pollution rapidly becomes a public health issue. IAQ plays a pivotal role in occupants' health and comfort and influences their productivity and work efficiency. Many studies have been done on IAQ of common building spaces such as offices, residential buildings, and educational institutions, but the availability of IAQ studies on workshops is limited, considering the significant implications for workers' health and performance. Thus, this paper aims to study the effectiveness of natural ventilation in a workshop based on the influence of different window-to-wall ratios (WWR). Electronic databases are utilized to obtain data, and the findings collected are categorized based on research methodology, issues, and findings. The air movement as part of the physical parameters of IAQ is studied through the application of Computational Fluid Dynamic (CFD) simulation to observe and analyse the airflow pattern and the air velocity of the naturally ventilated workshop with different WWRs. The research outcome underscores the ideal WWR for effective natural ventilation in a workshop is 0.30. However, the study observes that the effectiveness decreases as WWR exceeds 0.50. Further research on the openings' location, inlet, and outlet sizes and application of mechanical ventilation can be conducted to improve the measurement of the IAQ effectiveness in a naturally ventilated workshop.

## 1. Introduction

Indoor Air Quality (IAQ) represents pollutant concentrations and thermal conditions that could adversely impact building occupants' health, comfort, and efficiency [1]. According to the Malaysia Industry Code of Practice (ICOP) on Indoor Air Quality 2010 by DOSH, good indoor air quality (IAQ) is essential for a healthy work environment. Most people worldwide spend 80% - 90% of their time indoors [2]. However, in recent decades, IAQ has been a major concern in developing nations [3].

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Studies have shown that indoor air is more contaminated and polluted than the outdoors [4]. IAQ experts have categorized indoor air pollution as one of the most significant environmental problems [5]. According to Dhungana and Chalise, the indoor air pollutants (IAP) for non-industrial workplaces are 2 to 4 times higher than the outdoors [6]. As for the industrial facilities, the Occupational Safety and Health Administration (OSHA) reported that 30% of the workers are exposed to poor IAQ and work in substandard buildings [7].

The existence of local sources of pollutants, poorly planned and maintained ventilation systems, and building construction or renovation are the causes of poor IAQ [7,8]. According to Surawattanasakul *et al.,* [9], IAQ problems are associated with poorly maintained HVAC systems that result in insufficient ventilation and the inability to remove pollutants to the outdoors. [10] states that poor IAQ due to indoor air pollutants or inadequate ventilation may lead to various short-term and long-term health conditions, sometimes called Sick Building Syndrome (SBS). SBS was recognized by the World Health Organisation (WHO) in 2008 as a condition where a person in a building experiences symptoms and discomfort without having transparent causation [11]. Studies also show that it can be caused by increased indoor chemical pollutant levels and insufficient ventilation per person [12]. SBS does not only cause health implications but also affects work efficiency and productivity [13].

Most of the IAQ research focuses on offices [14,15], residential buildings [15-17], and educational buildings [18]. These studies determined and analysed the major causes of IAQ and ways to rectify IAQ problems [5]. However, research on IAQ for workshops and air distribution for indoor air dilution and removal of pollutant concentrations is also limited. Thus, there is a need for IAQ studies to be conducted in workshops. Workshops usually involve the use of machinery and the production of debris and pollutants. Therefore, different ventilation designs and strategies are needed to achieve optimum IAQ in the workshop. In addition, the manufacturing industry plays a vital role in Malaysia's economic transformation, contributing to job creation and the nation's export revenue [19]. Thus, a healthy working environment and the well-being of workshop occupants are essential to the country's workforce and economic development.

This paper aims to study the airflow profile in a workshop with different window-to-wall ratios (WWR). Besides, this research also aims to suggest a guideline for designing efficient IAQ in a naturally ventilated workshop. This study will be a general guideline to help designers, planners, and architects design a workshop with good IAQ and airflow strategy. The present study is proposed to satisfy the following research objectives

i. To determine the airflow pattern in a naturally ventilated workshop with different window-to-wall ratios (WWR).
ii. To determine the air velocity distribution in a naturally ventilated workshop with different window-to-wall ratios (WWR).
iii. To suggest the optimal window-to-wall ratios (WWR) for effective indoor air distribution in a naturally ventilated workshop.

## 2. Literature Review

This paper compiles relevant studies and literature reviews on IAQ and airflow in various building spaces, including workshops. Related methodology and parameters in determining airflow profiles are studied to establish a research framework by acknowledging the critical parameters.

### *2.1 Indoor Air Quality (IAQ) Parameters*

Indoor air quality (IAQ) is defined as air quality within a building's environment. According to [10], IAQ can be assessed through eleven (11) parameters, of which three (3) are physical parameters, six (6) are chemical parameters, and two (2) are biological parameters (shown in Figure 1).

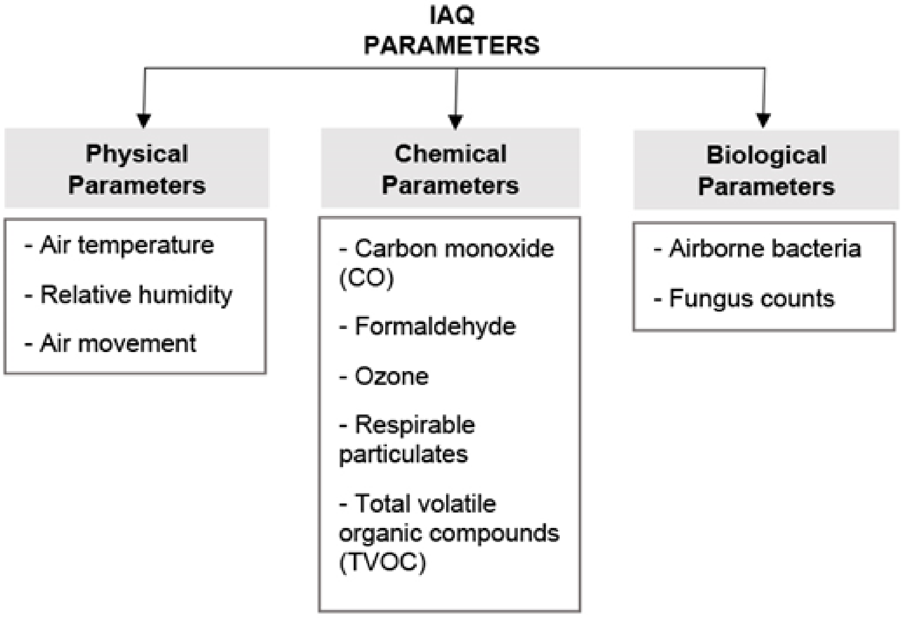


**Fig. 1.** Different parameters in IAQ assessment adopted by ICOP-IAQ (2010)

This paper will focus on IAQ's physical parameters, which is air movement, as shown in Table 1.

**Table 1**
Acceptable range for physical IAQ parameters [20]

| Parameter | Acceptable Range |
|---|---|
| Air temperature | 23 -26 °C |
| Relative humidity | 40 – 70% |
| Air movement | 0.15 – 0.50 m/s |

In general, the studies show that laboratories and workshops in tropical countries require attention for better IAQ and to enhance occupants’ comfort levels. It is observed that dust particles and particulate levels are higher than the recommended threshold limit in naturally ventilated workshops and laboratories. Poor IAQ has caused SBS which affects teaching and learning and reduces the work efficiency of workshops occupants. The studies suggest that the ventilation rate be increased in both naturally and mechanically ventilated workshops and laboratories as summarized in Table 2.

**Table 2**
Summary of previous studies on IAQ in laboratories, workshops, and educational institutions in tropical countries

| Literature Review | Methodology | IAQ Parameter | Issues | Findings |
|---|---|---|---|---|
| Azlan *et al.,* [21] | Field measurement and Questionnaire Survey | IAQ, SBS, Higher Educational Building | To determine the relationship between IAQ and SBS in higher educational building. | Poor IAQ and SBS symptoms among occupants may impact the teaching and learning. |
| Kim *et al.,* [22] | Computational fluid dynamic (CFD) simulation | Ventilation control, Artificial intelligence, Particulate matter (PM), IAQ, Airflow pattern, Airborne hazardous material | Control of airflow patterns remain problematic due to location of inlets and outlets, and the distributions of the indoor pollutants. | AI model predicted an efficient ventilation condition within a prediction accuracy of 91% based on the distribution of the airborne materials. Removal time up to 63.65% can be achieved by the controlled strategy compared to conventional ventilation system. |
| Nilandita *et al.,* [23] | Field Measurement | IAQ, Thermal comfort, Laboratory | Ventilation system for large space area with internal heat source. | The ventilation system positions and the installed position of equipment inside the workshop have significant effect on suction force which results in the accumulated heat and transport air pollution within the workshop room. |
| Wiriyasart & Naphone [24] | Computational fluid dynamic (CFD) simulation | Ventilation system, thermal distribution, workshop | IAQ and thermal comfort in the laboratory are essential as they can affect work and health of the researchers and staffs. | The analysis on $CO_2$ concentration, relative humidity (%RH), temperature ($^oC$) has shown that the IAQ does not exceed the threshold limit set by ASHRAE and Health Ministry Regulation. Installation of fan and air filter improve IAQ through control humidity. |
| Kwong *et al.,* [5] | Field measurement and Questionnaire Survey | IAQ, workshops, laboratories, indoor air pollutants, sick building syndrome (SBS) | Prevalence of SBS symptoms among occupants of air-conditioned laboratories and naturally ventilated workshops. | Indoor air pollutants (IAP) level in air-conditioned laboratories is higher than threshold limit.<br>Total particulate levels are higher in naturally ventilated workshop.<br>SBS are reported in both air-conditioned labs and naturally ventilated workshops.<br>Increase of ventilation rate would reduce IAP's concentration in air. |

### *2.2 Ventilation and Airflow*

Ventilation is a system where the internal air is continuously replaced by relatively fresh air from the outdoors through vents, windows, doors and etc. [25]. Air movement or circulation within an enclosed space in any ventilation system is therefore vital to ensure the temperature and humidity to be maintained within the acceptable range that allows adequate evaporation of perspiration from the skin [26]. According to a study by [26], poorly ventilated spaces that lack air currents, increase in relative humidity and temperature prevent normal evaporation of perspiration and heat loss from the surface of the skin, thus affecting thermal comfort of occupants. The three (3) fundamental elements of ventilation are summarised in Figure 2.

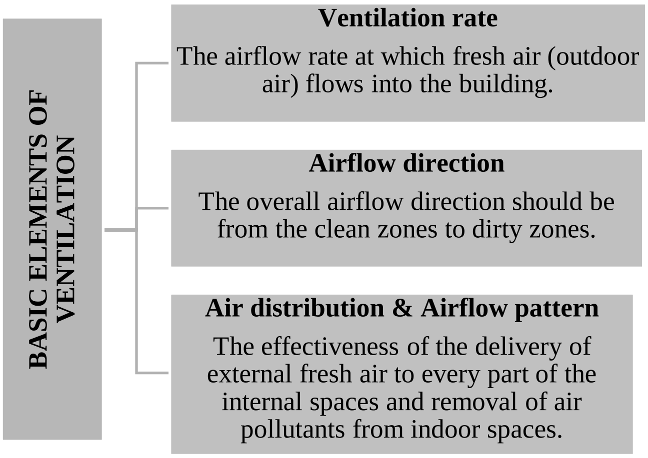


**Fig. 2.** Fundamental elements of ventilation [26]

### *2.2.1 Natural ventilation*

One of the most fundamental techniques to enhance air movement is through the implementation of natural ventilation strategies, where the cooling effect of ambient air is utilised to achieve indoor thermal comfort [27,28]. Thus, lessening the necessity for mechanical space conditioning [29]. The study by [29] states that natural ventilation relies on natural forces such as wind from surrounding the building and buoyancy forces that developed due to the temperature gradient within a building. The types of natural ventilation can be summarised in Figure 3.

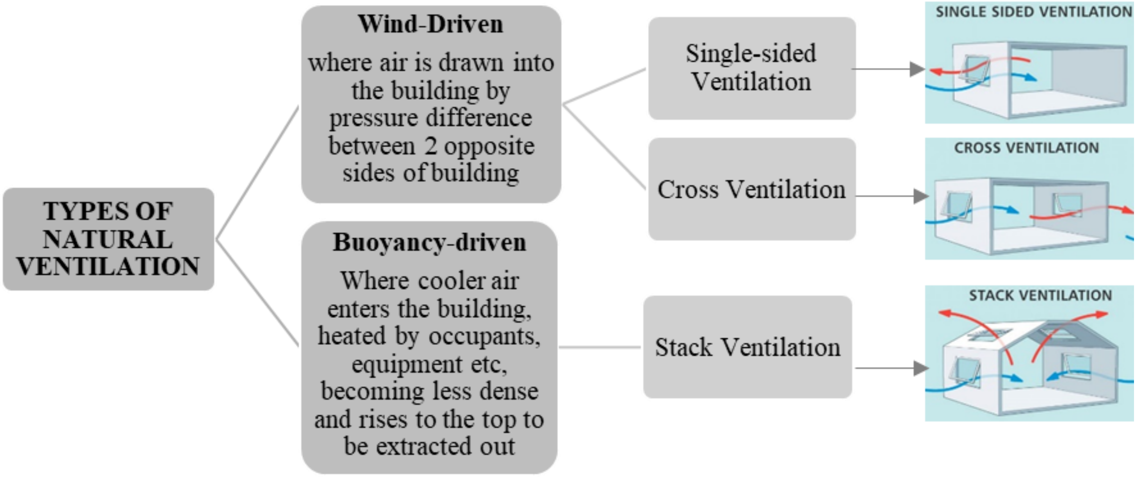


**Fig. 3.** Types of natural ventilation

### *2.2.2 Airflow profile & air velocity*

Airflow is one of the fundamental elements in building ventilation. It comprises of the airflow pattern, distribution, and air velocity. Air velocity is the speed at which a cubic meter of air flows through a specific point. Table 3 shows the local and international standards for indoor air velocity.

**Table 3**
Local and International Standards for Indoor Air Velocity

| | Malaysia Guideline (DOSH, 2010) | MS1525: 2007 | ASHRAE Standard |
|---|---|---|---|
| Air Velocity | 0.15-0.50 | 0.15-0.50 | 0.8 |

It has a significant influence on air renewal rate and airflow profile. Airflow profile has been considered very substantial to the assessment of air quality exposed to the occupant's sensation (Table 4) and comfort level due to air movement [30]. Sekhar and Willem [30] also suggest that airflow pattern due to air supply volume, air inlet and outlet devices arrangement, space layout, and the presence of heat sources, has critical impacts on the distribution and dilution of air pollutants. Detailed information of indoor airflow, particles' concentration, and maintaining a sufficient air exchange rate is therefore essential in maintaining a healthy IAQ.

**Table 4**
Occupants Sensation on Various Air Speed (MS 1525; 2019)

| Air Speed (m/s) | Mechanical Effect | Occupant Sensation |
|---|---|---|
| ≤0.25 | Smoke (from a cigarette) indicates movement | Unnoticed, except at low temperatures |
| 0.25-0.5 | Flame from a candle flicker | Feels fresh at a comfortable temperature but draughty at cool temperatures |
| 0.5-1.0 | Loose papers may be moved or equivalent to walking speed | Generally pleasant when comfortable or warm, but causing constant awareness of air movement |
| 1.0-1.5 | Too fast for deskwork with loose papers | Acceptable in warm conditions but can be from slightly to annoyingly draughty |
| >1.5 | Equivalent to a fast-walking speed | Acceptable only in very hot and humid conditions when no other relief is available. Requires corrective measures if comfort and productivity are to be maintained |

### *2.2.3 Local mean age (LMA) of air*

Local mean age (LMA) of air is a relative indicator used to measure the ventilation effectiveness. It is the representation of time required by all fresh air molecules to move from the supply inlet to an arbitrary point [31]. LMA is the identifying index of IAQ. The younger the LMA, the better the IAQ. According to Jahanbin and Giovanni [31], LMA is used to determine the efficiency of air change in a room.

## *2.3 Building Orientation, Wind Angles and Natural Ventilation*

According to study by Al-Tamimi *et al.,* [32] building orientation with regard to solar radiation and wind is a significant design consideration. The provision of effective cross ventilation under the local wind direction is the main factor that affects building orientation in hot humid regions [33]. Apart from external wind velocity, architectural parameters such as building position and orientation, roof shape, balcony configuration, window types and locations, partition, and furniture arrangement also largely influence the air movement inside the building [32]. The wind direction and wind angles towards the building influence air velocity within the building and indoor air circulation. Table 5 provides a summary on the relationship between building orientation, wind angles (Figure 4) and window design factors on IAQ.

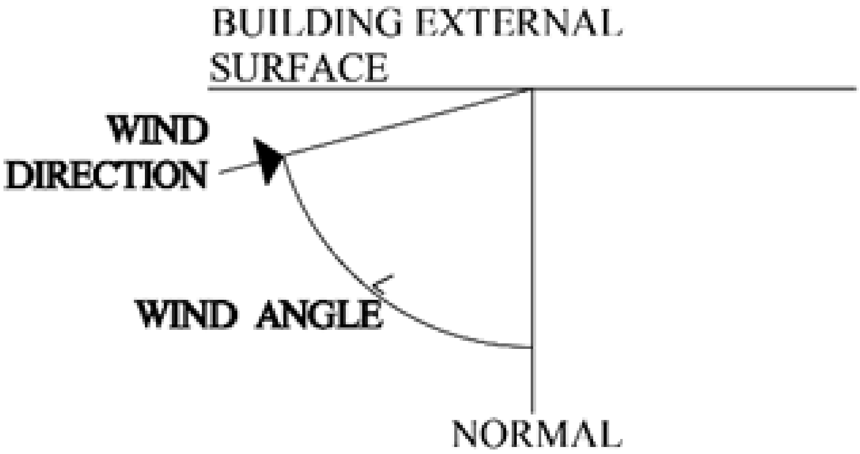


**Fig. 4.** Fundamental elements of ventilation and definition of wind angle

### *2.4 Window-to-Wall Ratio (WWR) and Natural Ventilation*

Windows play vital role in natural ventilation of a building. Operable windows have control over normal airflow in the building [34]. According to Masood *et al.,* [34], window factors like its position, shape, area, slope, wind direction, and quantity are the variables that affect the occupants' comfort level within a building. Among all the other building envelopes, window has the highest thermal permeability, thus having the highest proportional distribution of heat loss and gain compare with other envelop elements [35].

Window-to-wall ratio (WWR) is described as the ratio of the area of clear glass to the area of the wall from floor to floor outside [22].

**Table 5**
Summary of literature studies on building orientation, wind angles and window factors on natural ventilation

| Literature Studies | Climatic Condition | Methodology | Issues | Findings |
|---|---|---|---|---|
| Alsehail & Almhafdy [36] | N/A | Comparative Analysis | Window to wall ratio (WWR) and window orientation (WO) and their effect on thermal performance. | -Recommendations for WWR are low (10%-22%) in dry weather (hot and cold)<br>- In northern direction, WWR is greater than Southwest direction, an undesirable direction due to high solar heat gain. |

| | | | | |
|---|---|---|---|---|
| He *et al.,* [37] | Active House, China | Experimental measurement & Numerical simulation | Artificial and natural ventilation strategies were evaluated and compared quantitatively. | Artificial and natural ventilation enhancement strategies using mechanical ventilation and roof window systems were demonstrated to be significant.<br>The ventilation efficiency enhanced by roof window is 1.62 times higher than mechanical ventilation system at some conditions.<br>Roof window design and opening door is crucial for the generation of dominant air flow.<br>The study suggests that indoor space geometry, local climate condition and heating strategy |
| Albuquerque *et al.,* [38] | - | Field measurement | Impact of typical window geometries on single openable window on natural ventilation flows driven by wind shear parallel to the building facade. | Combination between window geometry and wind direction where the windows direct the wind into the room, the flow is increased by 4 times larger. |
| Aini & Nadia [39] | Settlement, Indonesia | CFD Simulation | Performance of building ventilation of grid patterns of the hillside. | Best natural ventilation was created in opening that is parallel to wind.<br>Building oriented against the wind deflects airflow.<br>Topography, building orientation in relation wind, opening dimension and position are the factors that influence ventilation performance. |
| Masood *et al.,* [34] | - | Computer Simulation | Determine the impact of window factors (WWR, window shapes and window orientation) on air speed and air quality inside architectural spaces. | - ANSYS CFD software can evaluate air flow around and inside buildings.<br>- Circular shape window openings, increased outlet area, location of windows at opposite walls increases air flow rate.<br>- Building orientation parallel to the main airflow has lower airflow rate. |
| Nie *et al.,* [40] | Residential, China | Numerical simulation through CFD and DesignBuilder | To study the ventilation effectiveness of a residential unit that consists of multiple rooms. | 5 kinds of window-opening behaviours were compared. It is concluded that best building orientation for ventilation is West. However, the best orientation for building energy consumption is south. The air inlet should be located in the north wall. |
| Bangalee *et al.,* [25] | - | Comparative analysis ad CFD simulation | A 1-storey full scale building was considered to carry out a comparative study of 3 different cases of wind-driven natural (WDN) cross ventilation with the help of CFD. | - Ventilation rate increases when the number of windows increases<br>- Ventilation can be faster if the windows are located at mid-wall and corner area.<br>- The closer the windows, the higher the ventilation rate. |

| | | | | |
|---|---|---|---|---|
| Yu *et al.,* [41] | Office Building, China | Computer simulation | Existing research only considers single factor that is WWR when investigating building energy consumption. | The study provide reference for public buildings in setting the building orientation and window-to-wall ratio (WWR). |
| Al-Tamimi *et al.,* [32] | Dormitory, Malaysia | Field measurement | Effect of building orientation relative to solar absorbance of exterior wall, varied area ratio of glazed window to wall and the effect of natural ventilation on the thermal performance for residential building in tropical region. | East windows have more significant effect on increasing indoor air temperature than west windows, for both ventilated and non-ventilated rooms. |

## 3. Methodology

### *3.1 CFD Simulation*

For the present study, the Computational Fluid Dynamic (CFD) simulation is used to achieve the research aims and objectives of this paper. The Autodesk Computer Fluid Dynamic (CFD) 2023 Ultimate software is used to stimulate the airflow pattern, air velocity, and local mean age (LMA) of the naturally ventilated workshop with different window-to-wall ratios (WWR) and different wind angles towards its external wall. The air velocity and LMA values at each specific points labelled as A, B, C, D, E, and F (shown in Figure 5 and 6) were collected and tabulated.

Two sets of CFD simulations were undertaken to assess the impact of WWR and wind angles on airflow profile for efficiency of IAQ in a workshop, one on the case study, and one on the cross-ventilation design scenarios. The WWR of inlet openings are manipulated to 0.25, 0.30, 0.50, and 0.75 while the outlet openings remain constant in the investigation. A 3D model of the workshop is created using Autodesk Revit 2022 software and is then imported into Autodesk CFD 2023 Ultimate for further simulation study. The boundary conditions as shown in Table 5 were identified and computed to perform a simulation on the case study model. Simulations were then performed on another set of study models. The impact of WWR and wind angles on the effectiveness of air circulation in the workshop was then identified through a comparative study of results obtained through airflow pattern, air velocity, and LMA in the simulation.

The case study selected for this research is the Woodworking Workshop at the main campus of Universiti Sains Malaysia (USM) in Penang. The layout of the workshop, orientation, entrance, and windows locations, machinery equipment, and local dominant wind direction are studied and computed. Figure 6 and 7 is the details of the case study workshop. The workshop is 10m wide, 15m deep and has a ceiling height of 2.7m.

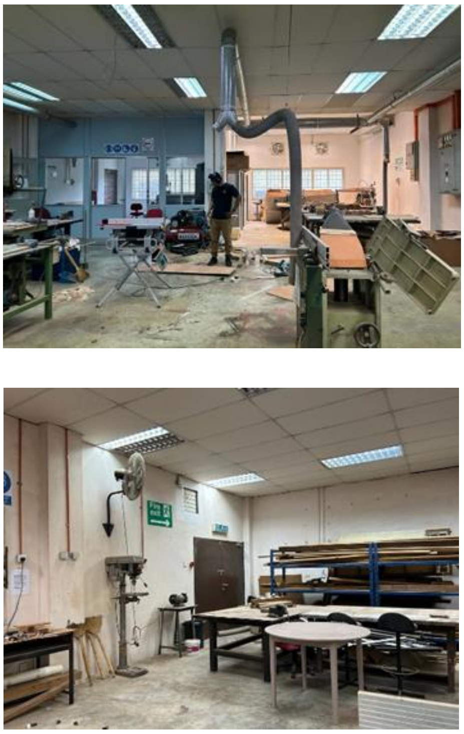


**Fig. 5.** Woodworking Workshop at the School of Housing, Building & Planning, USM

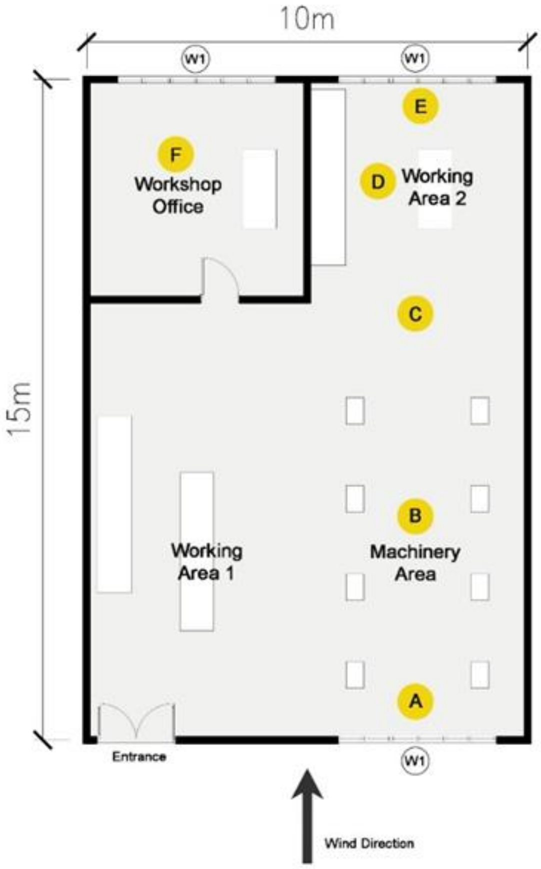


**Fig. 6.** Plan layout of the workshop

The specifications and settings of boundary conditions are crucial to the performance of CFD simulations [42]. The indoor boundary condition of this study is set up in accordance with the ICOP-IAQ 2010 as shown in Table 6. The average value for each aspect was taken from the recommended range and was computed into the CFD model. The indoor air temperature was set at 24°C. Besides, the indoor relative humidity was set at 50%. These values were kept constants for all the study scenarios.

The outdoor boundary conditions were taken from Malaysia Meteorology Department on the meteorology parameters of Penang and a study produced by [43]. The data is shown in Table 6.

**Table 6**
Summary of literature studies on building orientation, wind angles and window factors on natural ventilation

| Indoor Boundary Conditions | |
|---|---|
| Indoor Air Temperature | 24°C |
| Relative Humidity | 50% |
| Outdoor Boundary Conditions | |
| Mean Daily Dry Bulb Temperature | 28°C |
| Mean Daily Relative Humidity | 80 % |
| Mean Daily Average Wind Speed | 2.0 m/s |

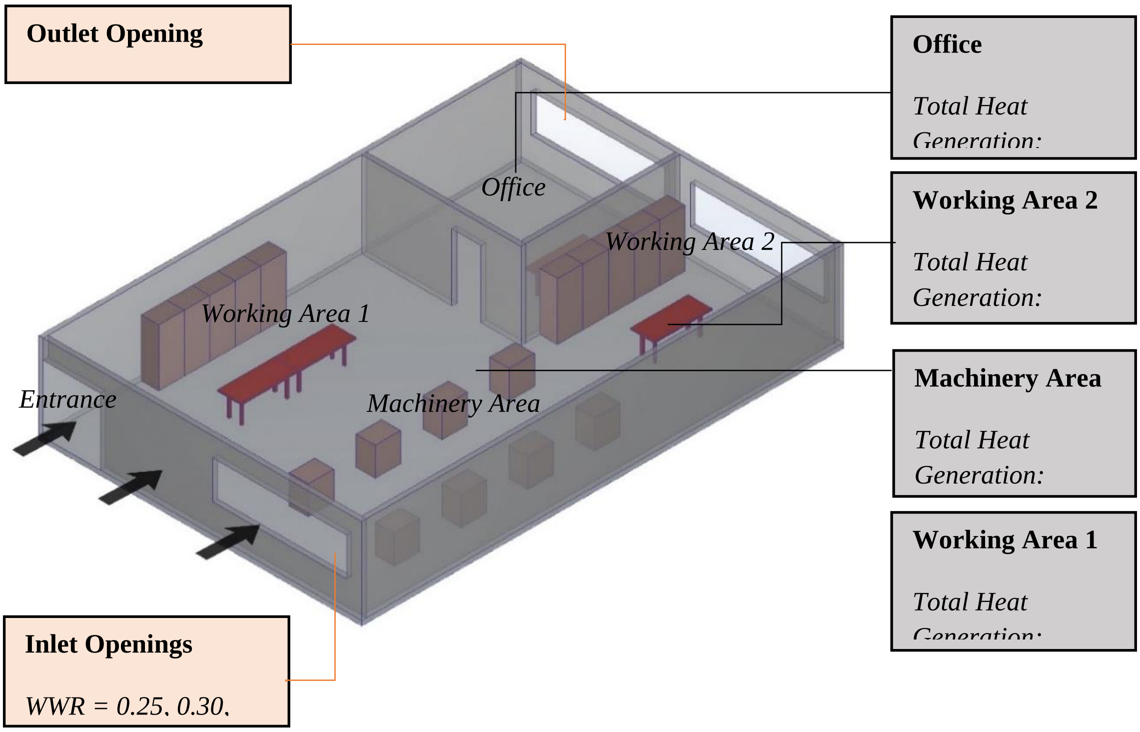


**Fig. 7.** Schematic diagram of CFD model and computational settings

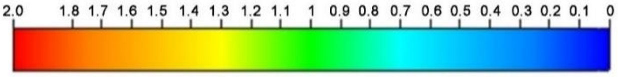
## 4. Results and Discussion

### *4.1 Analysis of Airflow Pattern and Air Velocity Distribution*

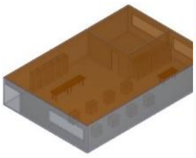
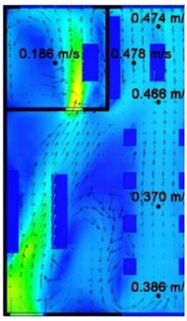
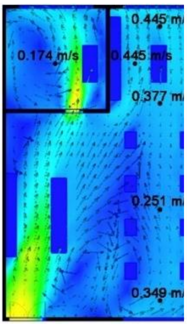
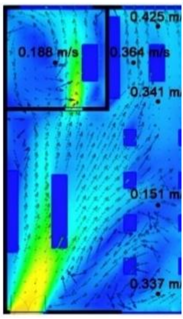
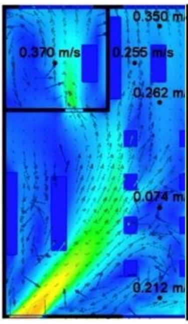
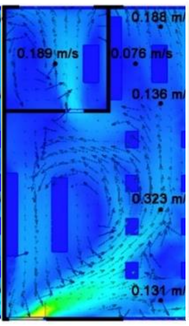
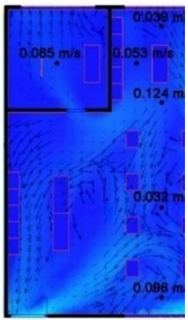
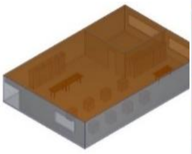
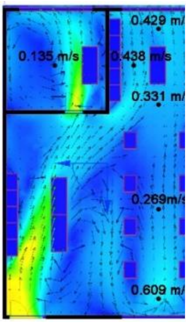
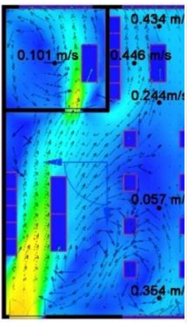
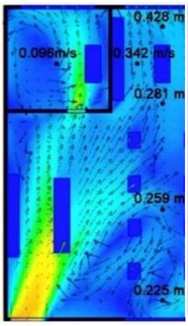
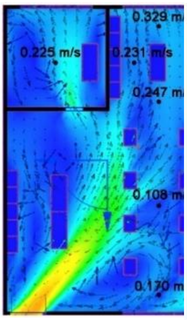
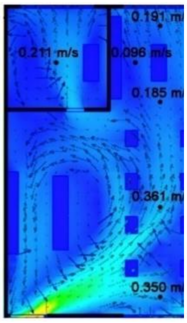
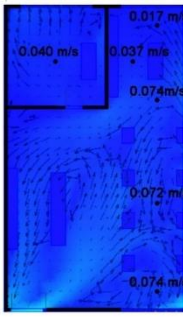
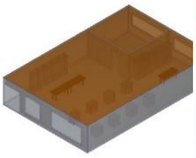
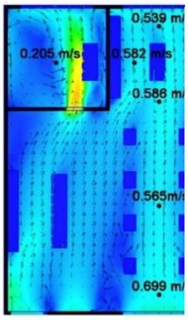
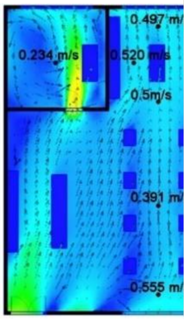
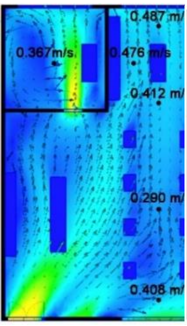
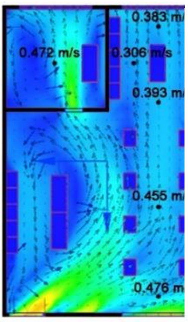
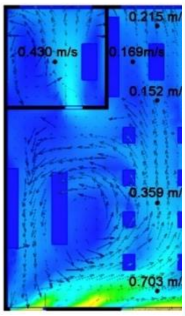
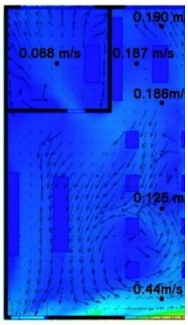
This section presents the analysis of the CFD simulation. The CFD simulation results of air flow pattern and air velocity distribution based on different wind angles (0,15,30,45,60,75 degrees) and window-to-wall ratio (from 0.25, 0.3 and 0.5) is represented in Table 7. The table shows the measurable scale of different air velocity magnitudes in metre per second (m/s), where the air velocity with high magnitude is represented in reddish colour spectrum. On the other hand, the wind velocity with smaller magnitude is represented in blue colour spectrum.

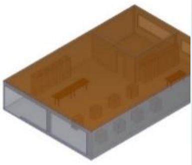
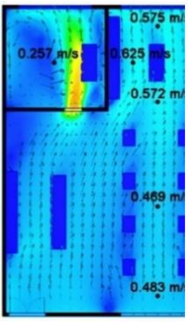
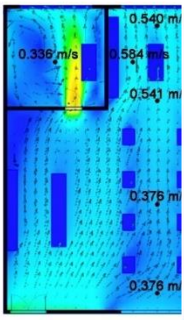
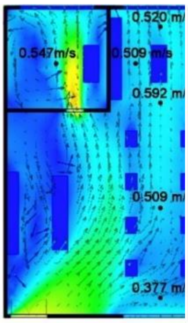
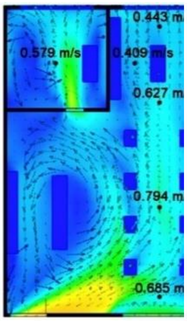
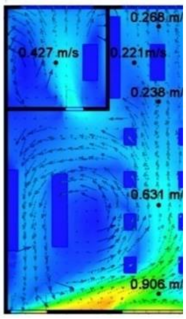
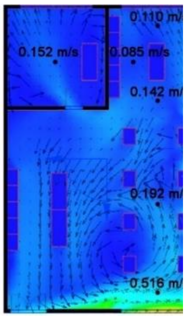
**Table 7**
CFD simulation results of airflow pattern and air velocity distribution of different Wind Angles and WWR

Airflow Pattern & Air Velocity Distribution (m/s)



Colour scale of Air Velocity Magnitudes

| Wind Angles (°) | 0 | 15 | 30 | 45 | 60 | 75 |
|---|---|---|---|---|---|---|
| Study Models | Simulation Results | | | | | |
| *Case Study (WWR=0.30)*<br><br>*Area of Openings: 8.1m²*<br>*Wall Area: 18.9m²* |  |  |  |  |  |  |
| *Study Model 1 (WWR=0.25)*<br><br>*Area of Opening: 6.75m²*<br>*Wall Area: 20.25m²* |  |  |  |  |  |  |
| *Study Model 2 (WWR=0.50)*<br><br>*Area of Opening: 13.5m²*<br>*Wall Area: 13.5m²* |  |  |  |  |  |  |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Study Model 3 (WWR=0.75)*<br><br>*Area of Opening: 20.25m$^2$*<br>*Wall Area: 6.75m$^2$* |  |  |  |  |  |  |

## 4.2 The Airflow Pattern Distribution

The airflow pattern distribution data shown in Table 7 is compared, analysed and summarised in Table 8.

**Table 8**
Observation and analysis of airflow pattern distribution in different study models

| Study Models | Airflow Pattern Observation | Analysis |
|---|---|---|
| *Study Model 1 (WWR = 0.25)*<br>*Case Study Model (WWR= 30%)* | • Indoor whirlpool formed at the supply inlet area and workshop office when the wind angle is at 0°.<br>• As wind angle increases, the indoor whirlpool becomes larger and formed at the machinery area at wind angle 30°.<br>• As wind angle increases more than 45°, indoor whirlpool spreads from machinery area to working areas 1 & 2. | <u>*Working Area 1*</u><br>• Whirlpool is initially formed at this area and shifts towards the inlet opening as the wind angle increases.<br><u>*Machinery Area (location point B)*</u><br>• At wind angles 0° – 30°, cross-ventilation occurs. Thus, polluted indoor air at the machinery area can be exhausted out and being replaced with fresh air.<br>• However, as wind angles increases beyond 45°, indoor whirlpool is formed, and the polluted indoor air will be circulated back within the workshop.<br><u>*Office*</u><br>• Whirlpool is formed at wind angle 0° and shifts away from the outlet as wind angle increases.<br>• Indoor polluted air is not fully exhausted but being re-circulated back to the area.<br>• This happens due to the diversion of wall in the workshop.<br><u>*Working Area 2*</u><br>• Minimal whirlpool is formed at this area when WWR=0.25 and wind angle is 75°. In general, this area has relatively better air circulation and indoor cross-ventilation. |
| *Study Model 2 (WWR = 50%)* | • Indoor cross-ventilation is formed clearly along the main air circulation path before wind angle reaches 45°.<br>• At wind angle 45°, indoor whirlpool starts to form at working area 1.<br>• The whirlpool becomes larger at wind angle 60° and spreads to the machinery area at wind angle 75°.<br>• Indoor whirlpool moves towards the inlet opening as the wind angle increases. | |
| *Study Model 3 (WWR = 75%)* | • Indoor cross-ventilation is formed clearly along the main air circulation path before wind angle reaches 30°.<br>• However, at wind angle 30°, minimal whirlpool is formed at working area 1.<br>• The whirlpool becomes larger at wind angle 45° and spreads to the machinery area at wind angle 60°.<br>• Indoor whirlpool shifts towards the inlet opening as the wind angle increases. | |

### *4.3 Air Velocity Distribution*

The air velocity distribution for the different WWR and wind angles at various location points (A, B, C, D, E, and F) were recorded, tabulated and analysed.

Figure 8 to 11 show that as WWR increases, indoor air velocity increases. At WWR below 0.50, wind angles at 0o – 30o produce optimal indoor air speed within the acceptable range of air speed stipulated under DOSH (2010). Beyond WWR=0.50, wind angles 45o and 60o manage to produce indoor air velocity distribution within the acceptable range of DOSH Standard. Wind angle of 75o has the lowest air velocity distribution among all WWRs and does not meet the standard criteria of DOSH Standard. WWR=0.30 and above shows that most of the air velocity values at specific points are within acceptable range of DOSH Standard.

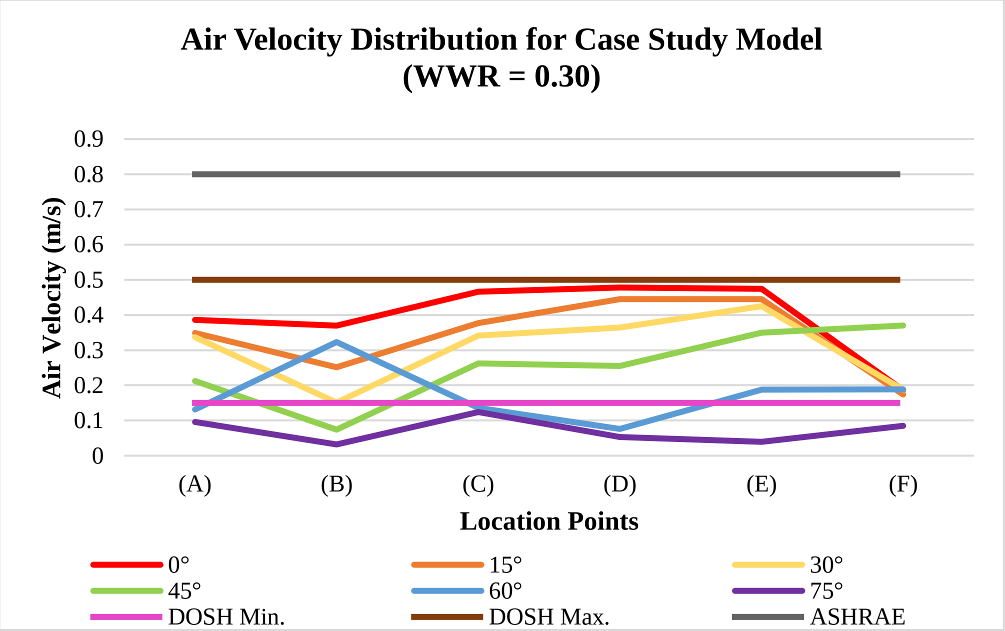


**Fig. 8.** Graph chart for air velocity distribution of case study model (WWR=0.30)

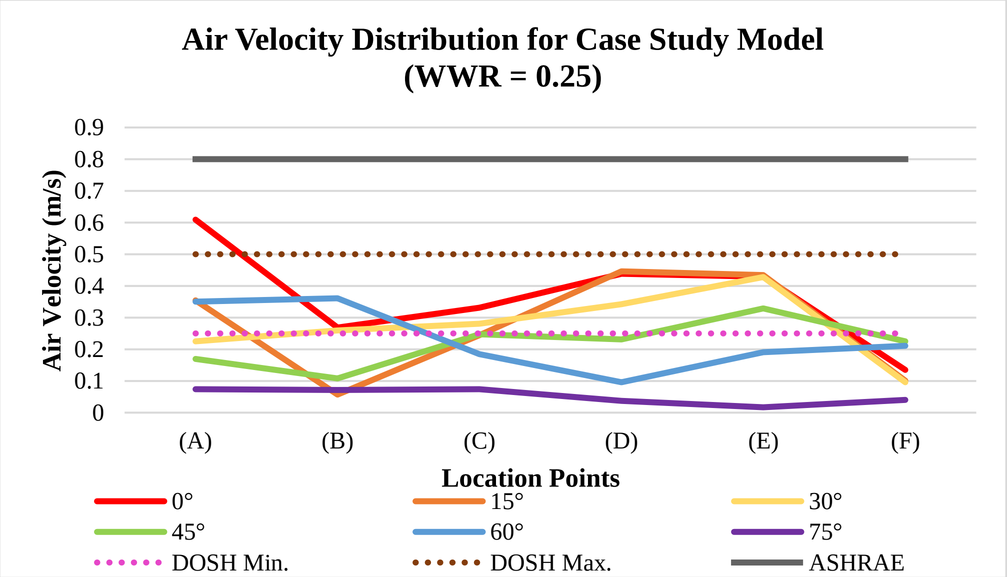


**Fig. 9.** Graph chart for air velocity distribution of case study model (WWR=0.25)

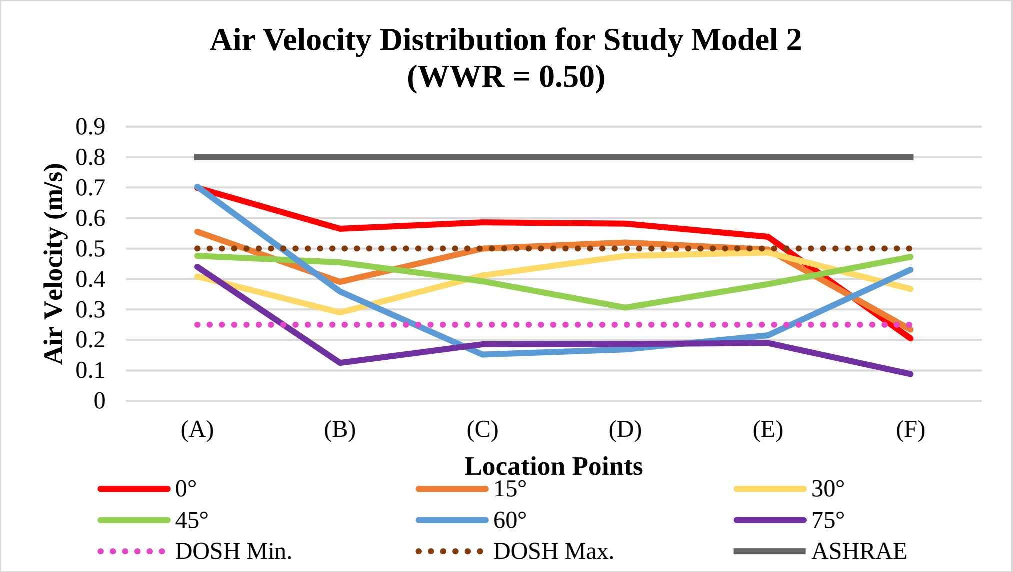


**Fig. 10.** Graph chart for air velocity distribution of case study model (WWR=0.50)

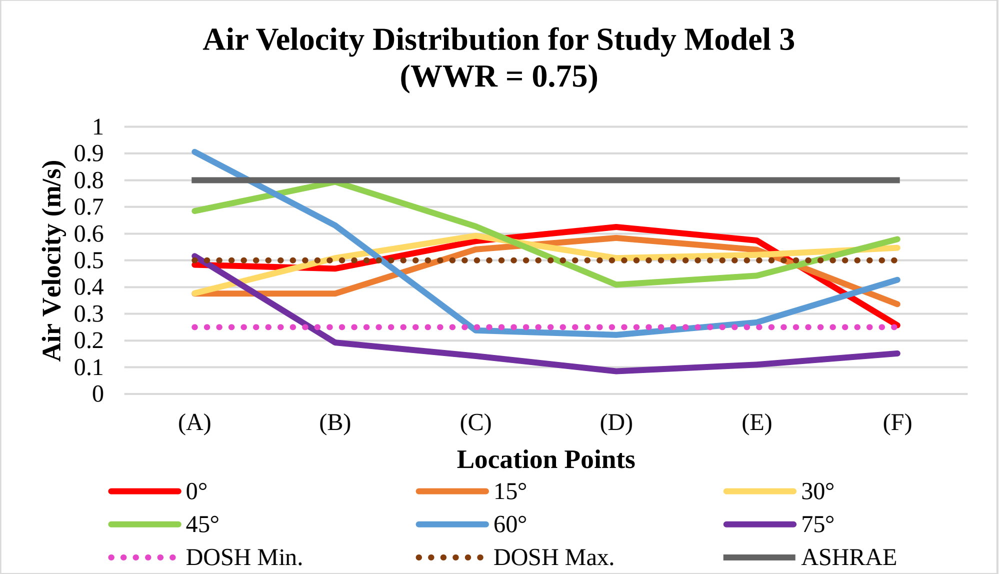


**Fig. 11.** Graph chart for air velocity distribution of case study model (WWR=0.75)

### *4.3 Discussion*

### *4.3.1 Relationship between natural ventilation and WWR*

This section discusses the influence of different WWR on natural ventilation through analysing airflow pattern distribution, air velocity field distribution

### *4.3.2 Airflow pattern and WWR*

According to the study conducted, the coverage area of indoor cross-ventilation increases as WWR increases. Figure 8 shows that the airflow distribution shows indoor cross-ventilation path and pattern occurs clearer and more obvious at WWR=0.5 and 0.75 as compared to WWR=0.25 and 0.3. The study also shows that the diversion of wall will greatly affect the airflow path and thereby reduces the rate of indoor cross-ventilation. This can be derived from the airflow pattern in the workshop office of all different WWR study models. Air is re-circulated back within the office area in all study models of different WWRs. The increase in the magnitudes of WWR has no significant impact on the airflow pattern of the workshop office.

In general, an increase in WWR significantly increases the indoor air velocity field of a naturally ventilated workshop. However, the LMA values are insignificant when the WWR is beyond 0.50. This shows a further increase in WWR will not have a great impact on the air circulation rate. Thus, mechanical HVAC system should be applied to improve the renewal and freshness of air within the workshop. This also implies that an increase in WWR beyond 0.50 reduces the effectiveness of natural ventilation in a workshop as mechanical ventilation system will be required.

### *4.3.3 Air velocity and WWR*

The indoor velocity field distribution indicates that as WWR increases, air velocity within the workshop increases. A significant increase in maximum, minimum, and average air velocity when WWR increases can be observed in Figure 12. However, study model 1 with inlet WWR=0.25 has higher average indoor air velocity than WWR=0.30. This is because study model 1 has smaller inlet size (WWR=0.25) than outlet size (WWR=0.30). According to study done by Moey *et al.,* a better ventilation rate occurs when a smaller inlet is paired with a larger outlet [44].

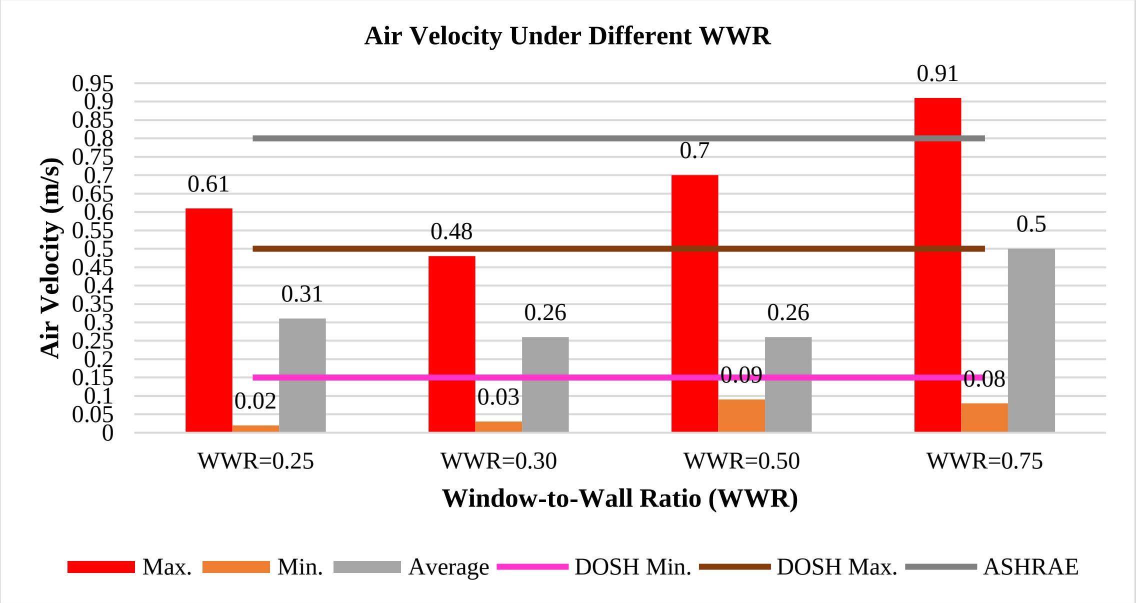


**Fig. 12.** The contrast figures of indoor air velocity under different study scenarios

All the WWR have average indoor air velocity magnitudes within the acceptable range of DOSH Standard which is 0.15-0.50 m/s. With reference to Table 4, this study implies that WWR ranges from 0.25 to 0.75 are optimal in providing a comfortable and windy workshop environment for the occupants.

## 5. Conclusions

In conclusion, IAQ has been a major concern for indoor comfort conditions. The quality of air does not only affect occupants' health but also productivity. The effectiveness of natural ventilation is studied through quantitative CFD simulation on different WWR of the openings. The respective indoor airflow pattern, air velocity, and LMA distribution are collected to analyse their relationship with the effectiveness of natural ventilation.

The outcome of the study underscores the importance of opening size on airflow profile. It is found that larger WWR will increase the indoor airflow rate. The study shows that indoor air velocity fields are within acceptable range of DOSH and MS 1525:2007 Standard is achieved when the WWR is 0.30 and above. However, the increase in air circulation rate becomes insignificant when WWR is beyond 0.50, and the application of active means of ventilation (i.e. mechanical HVAC system) is required. This implies that the effectiveness of natural ventilation reduces as dependence on mechanical systems increases underscoring the ideal WWR for a workshop to achieve ideal IAQ is when WWR=0.30.

Ultimately, while numerous studies on IAQ have been done in building spaces such as residential, offices, and educational institutions. However, IAQ study on workshops is limited. Therefore, it has become the premise of this research to contribute to the knowledge on air movement within a naturally ventilated workshop as indicator of improved air quality. Future research on IAQ of a workshop space can explore the impact of wind angles on air velocity distribution to improve the understanding on air flow inside the space.

## Acknowledgement

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