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## Keywords

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# Numerical analysis of indoor thermal comfort in a cross-ventilated space with top-hung windows

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**Abstract**

Natural ventilation can be used in residential buildings in several Australian climatic zones and well-designed windows have the potential to facilitate indoor thermal comfort by allowing occupants to control volumetric outdoor airflow and indoor air velocities. Top-hung window is one of the most popular window types in Australia. This paper investigates the effect of the attributes of top-hung windows (i.e. window length, aspect ratio, height above the ground, window opening angle and the fly screen porosity) and outdoor air conditions (i.e. outdoor air temperature, wind speed and direction) on indoor thermal comfort during cross ventilation using CFD simulations. The Taguchi method was used to design the simulation scenarios and analysis of variance was used to determine the most significant factors influencing thermal comfort optimisation so as to reduce the number of CFD simulation cases. For the range of parameters considered and a particular case study building, results show that outdoor air temperature, window height and window opening angle are the most important factors influencing indoor thermal comfort in this room. The optimal window configurations for indoor thermal comfort of the case study building are also identified using a signal-to-noise ratio analysis.


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*Keywords:* Cross-ventilated buildings; CFD simulation; Thermal comfort; Taguchi method

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## 1. Introduction

Naturally ventilated buildings have the potential to provide significant energy savings as compared to mechanically ventilated buildings while maintaining good indoor air quality and thermal comfort. Over recent decades, many efforts have been made to examine the performance of different natural ventilation techniques [1]. The effectiveness of natural ventilation in a building is influenced by a combination of internal factors (e.g. floor layout, opening configuration) and external factors (e.g. urban form, building typology) and a number of studies have indicated that the configuration of the windows is one of the most influential factors among the indoor and outdoor factors [2-4]. Window configuration parameters include: window height, window size, presence of a fly screen and window type [5]. Favarolo and Manz [6], for example, simulated a single-sided naturally ventilated building with different window heights and widths, and concluded that the height of the window above the ground had the greatest impact on the effective opening discharge coefficient. Ravikumar and Prakash [7] used a 3-dimensional CFD model of an office room to determine the optimal window opening area and aspect ratio needed to maintain thermal comfort. It was found that the areas close to the walls without windows were more comfortable when compared to the other areas [7]. Maguel [8] compared windows with different types of fly screens to those without fly screen, and the pressure drops through different fly screen types were also determined through field measurements. Heiselberg et al. [9] studied two window types (i.e. side-hung and bottom-hung windows) and opening angles and concluded through laboratory measurements that, for single-sided ventilation, the bottom-hung window had less of a negative influence on indoor thermal comfort in winter. The impact of window parameters in the studies above were analysed individually and to date no thorough investigation appears to have been carried out to examine the overall contribution of all window parameters combined on indoor thermal comfort conditions.

One of the most commonly used methods to analyse indoor air movement and thermal performance is computational fluid dynamics (CFD) simulation [10]. The predicted mean vote (PMV) model is relevant to indoor thermal comfort analysis but it is not suitable for natural ventilation studies as the PMV model is usually used in an ambient environment with steady airflows [11]. As a consequence, an extended PMV model (PMVe) has been proposed for the evaluation of thermal comfort in naturally ventilated buildings [12]. This paper reports on an investigation of the performance of top-hung window configuration factors and how they affect the extended PMV metric (PMVe). The PMVe model was integrated into the CFD simulation tool, ANSYS Fluent [13], to simulate indoor thermal comfort conditions under different window configurations in a case study room.

## 2. Methodology

### *2.1. CFD modelling*

A single top-hung window was placed in the upstream façade of a cross-ventilated room model of dimensions 5× 5 × 3 m (L×W×H) and implemented in ANSYS Fluent [13]. An plane opening was also placed in the downstream wall of the room with the same size and height above the ground as the window opening in the upstream façade, but without a window pane or fly-screen present. For a building model of height H, previous studies [14-16] suggest that the computational domain should be at least 5H in height, the lateral boundaries should be at least 5H from the region of interest and the domain downstream of the region of interest should be extended to at least 10H. These guidelines were followed in the present study. The standard $k$-$\varepsilon$ turbulence model [17] was used for the CFD analysis. Convergence was assumed to be obtained when a minimum of 1‰ was reached for the scaled residuals of mass, momentum, turbulent kinetic energy ($k$) and turbulent dissipation ($\varepsilon$).

The simulation was a quasi-steady state simulation with the internal surfaces held of the room held at a nominal temperature of 24.0 °C. The effect on internal thermal comfort conditions of changes to outdoor air temperature, wind velocity and wind direction relative to normal to the upstream face of the room were investigated.

## 2.2. Thermal comfort model

A correction factor, *e*, was multiplied with the PMV index to estimate the thermal sensation vote in naturally ventilated buildings as suggested by Fanger and Toftum [12]. The PMVe model includes the following six variables that are held to influence the thermal sensation of occupants, i.e. occupant activity, clothing, air temperature, mean radiant temperature, air speed and humidity. The values of these six variables were chosen from the literature [12, 18, 19] for buildings in the subtropical area of Australia using natural ventilation for a typical summer day.

Table 1. Parameter values assumed and the resultant PMV correction factor, *e*.

| Metabolic rate ($W/m^2$) | Clothing insulation (Clo) | Air temperature(°C) | Wall/floor/ceiling temperature (°C) | Air speed (m/s) | Relative humidity (%) | $e$ |
|---|---|---|---|---|---|---|
| 70 | 0.5 | Simulated values | 24 | Simulated values | 70 | 0.9 |

The predicted percentage of dissatisfied (PPD) index was used to estimate the fraction of occupants that would be dissatisfied with the indoor thermal comfort conditions. A user-defined function (UDF) [13] was used to integrate the PMVe-PPD model into the ANSYS Fluent code in order to post-process the CFD simulation results to extract the PMVe-PPD values over the desired region within the test room. In this study, PMVe values between -0.2 and +0.2, corresponding to PPD values of less than 7%, were considered to meet indoor thermal comfort requirements in line with the ISO 7730 Class A standard [20]. The PMVe levels at the height of 0.1m (ankle), 0.6m (abdomen) and 1.1m (head) are normally recommended as the representative activity area for seated occupants [18]. In a previous CFD simulation study [21], it was shown that air movement mainly occurred at the window height level in a cross-ventilated room. Generally the bottom of windows in dwellings are relatively close to the head-level height of 1.1m in this research and for this reason the head-level was selected as the area (A) of interest. The key thermal comfort metric for this study was therefore taken as the area fraction, $R$, of a horizontal plane of height 1.1m across the whole room where the local PPD requirement was satisfied as follows:

$$R = A_{1.1m\,PPD\,\leq\,7\%} / A \tag{1}$$

Where $A_{1.1m\,PPD\leq 7\%}$ is the area over which the PPD requirement was satisfied at a height of 1.1m above the floor, and $A$ is the total planform area of the room.

## 2.3. Taguchi method and data analysis

The following configuration variables for top-hung windows were selected to evaluate their impacts on the indoor thermal comfort conditions: window width, window height, height of the window bottom above the ground, window opening angle and fly-screen porosity. In a number of simulations the presence of a fly-screen was modelled as a porous-jump boundary in the CFD model. Two types of fly-screen, and associated pressure drop parameters, were chosen from those described in [8] where screen $R_{w25}$ is representative of woven mesh screens for windows and $R_{w20}$, is a higher porosity screen. Screen flow properties are shown in Table 2.

Table 2. Fly-screen porosity attributes as sourced from [8].

| Screen Type | Face permeability ($m^2$) | Porous medium thickness (m) | Pressure-jump coefficient ($m^{-1}$) | Porosity |
|---|---|---|---|---|
| $R_{w20}$ | $3.11 \times 10^{-9}$ | $10^{-5}$ | $2.334 \times 10^{-3}$ | 0.90 |
| $R_{w25}$ | $2.71 \times 10^{-10}$ | $2.5 \times 10^{-5}$ | $119.3 \times 10^{-3}$ | 0.25 |

The outdoor air temperature, wind direction and speed obviously influence the indoor airflow and temperature fields, thus, the outdoor wind conditions at the window height were also considered in the simulation analysis. The Taguchi method [22] was used to reduce the overall number of simulations required to achieve the objectives of the study, and Table 3 summarises the three levels chosen for each of the eight parameters. Outdoor air temperatures of 18, 22 and 26 °C and external wind speeds range of 2.4, 2.6 and 2.8 m/s were selected in this initial phase of this study as being representative of conditions when occupants are likely to accept a natural ventilation strategy within their building [23]. This range of parameters will be extended in future work. As there were eight factors, each with three levels, the standard orthogonal array, $L_{27}(3^8)$ was selected to design the simulation scenarios (Table 4).

Table 3. Case study building and environmental parameters considered and their levels.

| Level | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| | Outdoor air temperature (°C) | Wind speed (m/s) | Wind direction (clockwise from north) (°) | Window opening angle (top-hung) (°) | Window width (m) | Window height (m) | Window height above ground (m) | Fly-screen type |
| 1 | 18 | 2.4 | 0 | 10 | 0.6 | 0.2 | 1.2 | 0 (no screen) |
| 2 | 22 | 2.6 | 30 | 25 | 0.8 | 0.4 | 1.4 | 1 ($R_{w20}$) |
| 3 | 26 | 2.8 | 60 | 40 | 1 | 0.6 | 1.6 | 2 ($R_{w25}$) |

Table 4. Simulation scenario design based on a Taguchi $L_{27}(3^8)$ standard orthogonal array.

| Simulation case | Factor level | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H |
| 1 | 2 | 3 | 2 | 1 | 3 | 2 | 2 | 2 |
| 2 | 3 | 1 | 2 | 2 | 2 | 2 | 1 | 1 |
| 3 | 2 | 1 | 3 | 2 | 1 | 1 | 3 | 2 |
| 4 | 1 | 3 | 3 | 2 | 1 | 3 | 2 | 2 |
| 5 | 3 | 3 | 1 | 3 | 2 | 1 | 2 | 2 |
| 6 | 3 | 1 | 2 | 3 | 1 | 1 | 2 | 3 |
| 7 | 3 | 3 | 1 | 1 | 1 | 3 | 3 | 1 |
| 8 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 1 |
| 9 | 2 | 3 | 2 | 3 | 1 | 3 | 1 | 3 |
| 10 | 1 | 3 | 3 | 3 | 3 | 2 | 3 | 1 |
| 11 | 1 | 2 | 2 | 2 | 2 | 3 | 2 | 1 |
| 12 | 2 | 1 | 3 | 1 | 2 | 2 | 2 | 3 |
| 13 | 3 | 2 | 3 | 1 | 2 | 3 | 3 | 3 |
| 14 | 3 | 3 | 1 | 2 | 3 | 2 | 1 | 3 |
| 15 | 1 | 1 | 1 | 3 | 2 | 2 | 3 | 2 |
| 16 | 1 | 3 | 3 | 1 | 2 | 1 | 1 | 3 |
| 17 | 3 | 2 | 3 | 3 | 3 | 1 | 2 | 1 |
| 18 | 1 | 1 | 1 | 2 | 3 | 3 | 2 | 3 |
| 19 | 2 | 2 | 1 | 3 | 2 | 3 | 1 | 2 |
| 20 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 21 | 3 | 1 | 2 | 1 | 3 | 3 | 3 | 2 |
| 22 | 3 | 2 | 3 | 2 | 1 | 2 | 1 | 2 |
| 23 | 2 | 2 | 1 | 2 | 3 | 1 | 3 | 3 |
| 24 | 2 | 3 | 2 | 2 | 2 | 1 | 3 | 1 |
| 25 | 2 | 1 | 3 | 3 | 3 | 3 | 1 | 1 |
| 26 | 1 | 2 | 2 | 3 | 1 | 2 | 3 | 3 |
| 27 | 1 | 2 | 2 | 1 | 3 | 1 | 1 | 2 |

Analysis of variance (ANOVA) was used to evaluate the influence of the eight parameters on the value of R utilising the sum of squares (SS), the degrees of freedom (DOF), the variance and percentage contribution [24]. Signal-to-noise (S/N) ratio was used to identify the optimal combination of window parameters. The S/N ratio is a logarithmic transformation of mean square deviation to linearise the influences of different parameter levels. The value of R was required to be large, thus, the larger-the-better quality characteristic [25] was applied.

## 3. Mesh sensitivity analysis of the CFD model

In order to minimise any potential inaccuracies related to the CFD mesh density, a mesh-sensitivity analysis was performed using three types of mesh: a coarse mesh, a basic mesh and a fine mesh. For 3-D models, the mesh refinement ratio ($r_{ji}$) is defined as the ratio of the number of mesh elements in two different meshes ($\Delta_i$, $\Delta_j$, $\Delta_i < \Delta_j$), as shown in Eq. (2). This definition was used for the present mesh-sensitivity analysis [25].

$$r_{ji} = (\Delta j / \Delta i)^{1/3} \qquad (2)$$

The recommended mesh refinement ratio for a non-uniform mesh is held to be >1.33 for 3-D models [26]. The number of mesh elements and the refinement ratio for the three types of mesh in this study are shown in Table 5.

Table 5. Mesh refinement ratio between different mesh sizes

| Mesh element | | | Mesh refinement ratio | |
|---|---|---|---|---|
| Coarse ($\Delta_1$) | Basic ($\Delta_2$) | Fine ($\Delta_3$) | $r_{21}$ | $r_{32}$ |
| 2,378,036 | 5,538,229 | 14,541,827 | 1.33 | 1.38 |

A series of the vertically distributed test points that passed through the centroid of the case study room model were selected to compare the air speeds as a function of elevation, $h$, when using the three different types of mesh. The results with the basic mesh matched closely to those of the fine mesh. Since simulations with the fine mesh required more computational time than that of the basic mesh, the latter was used for the CFD simulations.

## 4. Results and discussion

Typical results for the velocity and temperature fields of the case study building are shown in Fig. 1.

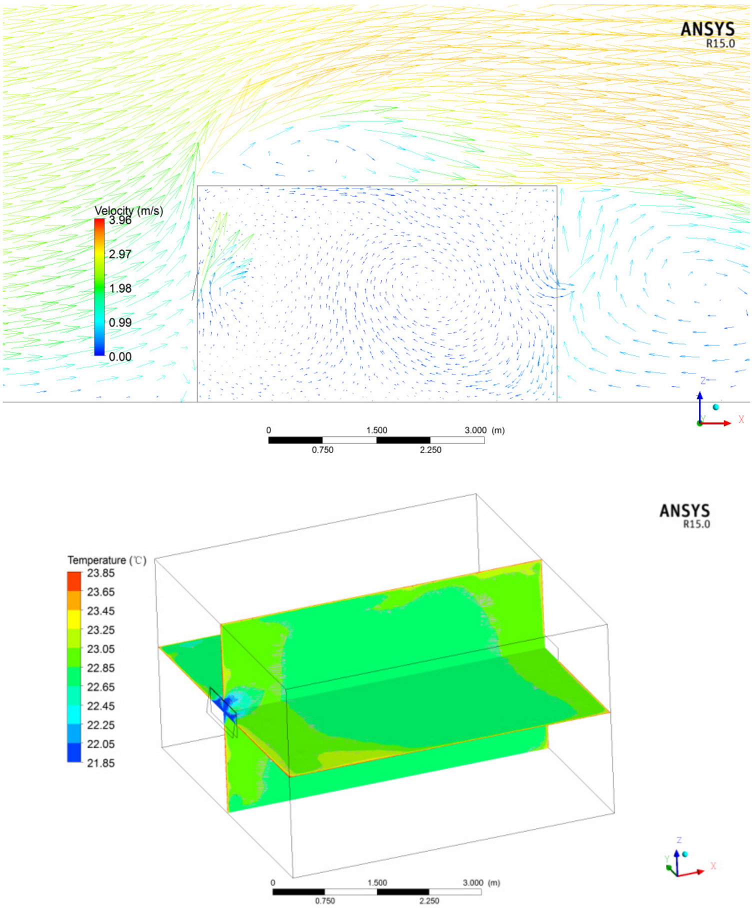


Fig. 1. Example of CFD simulation results for the case study building (Case 20): a) velocity field; b) temperatures.

### *4.1. Influence of window configuration parameters on thermal comfort*

Table 6 shows the results of the ratio of the area that satisfies the PPD requirement mentioned above based on the standard simulation design for the $L_{27}(3^8)$ orthogonal array.

Table 6. CFD simulation results for the set of Taguchi $L_{27}(3^8)$ test cases

| Simulation case | Factor A | Factor B | Factor C | Factor D | Factor E | Factor F | Factor G | Factor H | $R$ | $T_{min}$ | $T_{max}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 22 | 2.8 | 30 | 10 | 1 | 0.4 | 1.4 | 1 | 0.54 | 22.8 | 23.2 |
| 2 | 26 | 2.4 | 30 | 25 | 0.8 | 0.4 | 1.2 | 0 | 0.88 | 24.6 | 25.1 |
| 3 | 22 | 2.4 | 60 | 25 | 0.6 | 0.2 | 1.6 | 1 | 0.94 | 21.8 | 23.1 |
| 4 | 18 | 2.8 | 60 | 25 | 0.6 | 0.6 | 1.4 | 1 | 0 | 20.9 | 22.1 |
| 5 | 26 | 2.8 | 0 | 40 | 0.8 | 0.2 | 1.4 | 1 | 0.93 | 24.4 | 24.8 |
| 6 | 26 | 2.4 | 30 | 40 | 0.6 | 0.2 | 1.4 | 2 | 0.98 | 24.3 | 24.8 |
| 7 | 26 | 2.8 | 0 | 10 | 0.6 | 0.6 | 1.6 | 0 | 0.91 | 24.9 | 25.3 |
| 8 | 22 | 2.6 | 0 | 10 | 0.6 | 0.4 | 1.4 | 0 | 0.71 | 22.7 | 23.3 |
| 9 | 22 | 2.8 | 30 | 40 | 0.6 | 0.6 | 1.2 | 2 | 0.04 | 22.5 | 23.0 |
| 10 | 18 | 2.8 | 60 | 40 | 1 | 0.4 | 1.6 | 0 | 0 | 20.1 | 21.6 |
| 11 | 18 | 2.6 | 30 | 25 | 0.8 | 0.6 | 1.4 | 0 | 0 | 19.8 | 21.0 |
| 12 | 22 | 2.4 | 60 | 10 | 0.8 | 0.4 | 1.4 | 2 | 0.29 | 22.7 | 23.4 |
| 13 | 26 | 2.6 | 60 | 10 | 0.8 | 0.6 | 1.6 | 2 | 0.82 | 24.5 | 25.0 |
| 14 | 26 | 2.8 | 0 | 25 | 1 | 0.4 | 1.2 | 2 | 0.78 | 24.7 | 25.1 |
| 15 | 18 | 2.4 | 0 | 40 | 0.8 | 0.4 | 1.6 | 1 | 0.01 | 20.0 | 21.8 |
| 16 | 18 | 2.8 | 60 | 10 | 0.8 | 0.2 | 1.2 | 2 | 0 | 21.5 | 22.9 |
| 17 | 26 | 2.6 | 60 | 40 | 1 | 0.2 | 1.4 | 0 | 0.89 | 24.4 | 24.9 |
| 18 | 18 | 2.4 | 0 | 25 | 1 | 0.6 | 1.4 | 2 | 0 | 20.0 | 21.3 |
| 19 | 22 | 2.6 | 0 | 40 | 0.8 | 0.6 | 1.2 | 1 | 0.01 | 22.5 | 23.0 |
| 20 | 18 | 2.4 | 0 | 10 | 0.6 | 0.2 | 1.2 | 0 | 0.55 | 20.5 | 21.7 |
| 21 | 26 | 2.4 | 30 | 10 | 1 | 0.6 | 1.6 | 1 | 0.93 | 24.7 | 25.1 |
| 22 | 26 | 2.6 | 60 | 25 | 0.6 | 0.4 | 1.2 | 1 | 0.92 | 24.3 | 24.7 |
| 23 | 22 | 2.6 | 0 | 25 | 1 | 0.2 | 1.6 | 2 | 0.56 | 23.0 | 23.4 |
| 24 | 22 | 2.8 | 30 | 25 | 0.8 | 0.2 | 1.6 | 0 | 0.44 | 23.3 | 23.9 |
| 25 | 22 | 2.4 | 60 | 40 | 1 | 0.6 | 1.2 | 0 | 0.06 | 22.7 | 23.4 |
| 26 | 18 | 2.6 | 30 | 40 | 0.6 | 0.4 | 1.6 | 2 | 0.01 | 20.4 | 21.5 |
| 27 | 18 | 2.6 | 30 | 10 | 1 | 0.2 | 1.2 | 1 | 0.03 | 21.2 | 22.5 |

Using the simulation results shown in Table 6, the percentage contributions of the parameters were determined using the ANOVA method. Table 7 presents the percentage contributions of these factors in influencing the fraction of the 1.1m plane that satisfied the thermal comfort criterion $R$.

For this particular case study building the outdoor air temperature had by far the biggest influence on PPD and thermal comfort with a contribution of 72.5%, followed by window height and window opening angle with 8.0% and 4.7% contributions, respectively. It should be noted that due to the nature of the Taguchi method this initial study used a limited range for some of the variables. It is intended that these ranges be increased in future work.

Table 7. ANOVA analysis and percentage contributions to thermal comfort performance metric, $R$.

| Factor | SS | DOF | Variance | Percentage contribution |
|---|---|---|---|---|
| A Outdoor Air Temperature | 3.099 | 2 | 1.550 | 72.5% |
| B Wind Speed | 0.059 | 2 | 0.029 | 0.8% |
| C Wind Direction | 0.025 | 2 | 0.012 | 0.0% |
| D Window Opening Angle | 0.226 | 2 | 0.113 | 4.7% |
| E Window width | 0.170 | 2 | 0.085 | 3.4% |
| F Window height | 0.363 | 2 | 0.182 | 8.0% |
| G Window height above ground | 0.111 | 2 | 0.055 | 2.0% |
| H Fly-screen type | 0.060 | 2 | 0.030 | 0.8% |
| Error | 0.126 | 10 | 0.013 | 7.8% |
| Total | 4.239 | 26 | | 100% |

### 4.2. Optimal window configuration combinations

The signal-to-noise (S/N) ratios for each level of the parameters are summarised in Fig. 2.

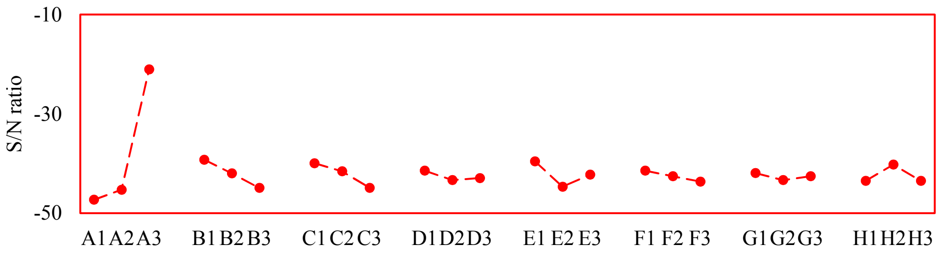


Fig. 2. Signal-to-noise ratio for *R*.

Higher values of the S/N ratio indicate that larger fractions of the room area, *R,* (at an elevation of 1.1m) meet the PPD requirement. In this preliminary study, the optimal parameter level combination for *R* was for the current set of simulations was A3B1C1D1E1F1G1H2. Table 8 shows the simulation results as a function of the optimal parameter level combination identified in Fig. 2.

Table 8. Simulation results based on the optimal combination.

| Optimal combination | Outdoor air temperature (°C) | Wind speed (m/s) | Wind direction (°) | Window opening angle (°) | Window width (m) | Window height (m) | Window height above ground (m) | Fly screen porosity | R |
|---|---|---|---|---|---|---|---|---|---|
| PPD | 26 | 2.4 | 0 | 10 | 0.6 | 0.2 | 1.2 | 1 ($R_{w20}$) | 1 |

It is worth noting that the optimal combination result was a near-optimal solution and not necessarily the absolutely optimal solution as discrete values of the parameters were used in the analysis. However, the solution may be used as a reference point for further optimisation. In addition, the optimal combination identified was only valid for the range of parameters chosen in this study to date. Further simulations are required to build a more comprehensive understanding of the impact of all parameters in a range of practical situations on thermal comfort.

## 5. Conclusions

This paper presents the results of a numerical investigation of indoor thermal comfort in a cross-ventilated building using CFD simulations. The Taguchi method was used to design the simulation cases to identify the near-optimal top-hung window parameters required for the best indoor thermal comfort outcome for a limited range of building and external environmental conditions.

The main conclusions of this study may be summarised as follows:

- CFD simulations of the impact of cross-ventilation on internal thermal comfort conditions in a cross-ventilated space have been successfully carried out.
- Outdoor air temperature, window height and window opening angle were found to be the most important factors influencing the PMVe value in the region of interest (i.e. head level for seated occupants) in the case study building for the range of parameters modelled here.
- The optimal parameter level combination to improve the indoor thermal comfort of the focused area of interest was identified through S/N ratio analysis, which may be used as a reference point for future optimisation and development of a more comprehensive CFD analysis of thermal comfort in naturally ventilated spaces.

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