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Review Article

Review of Window Performance in A Hot and Humid Climate

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ABSTRACT

Incorrect implementation of window parameters, such as configuration, position, and size, cause an unpleasant indoor environment. The authors reviewed window performance in a hot and humid climate in this paper. Articles were screened in detail to determine eligibility, compiled, and organised according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) requirements. The articles included in this review concerned natural ventilation and window performance in a hot and humid climate. Keywords or topics were reviewed and focused on indoor environment comfort. The results demonstrated that sliding windows were unfavourable openings that were nevertheless in demand. This review was performed to guide consumers, designers, and the market of the built environment industry.

Keywords: Hot humid climate, indoor environment, PRISMA, sliding window, window

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INTRODUCTION

A hot and humid climate features high solar radiation and humidity throughout the year. Malaysia has such a climate and records temperatures up to 40°C during the northeast and 32°C during the southwest monsoon (Kamal et al., 2017). This climate has remained unchanged for a decade and is expected to remain until 2099 (Tarmizi et al., 2019).

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In humans, high temperatures cause increased thermal discomfort, decreased consciousness, tiredness, serious headaches, and dizziness (Sung et al., 2014; Bidel et al., 2020). Furthermore, compared to lower temperatures, high indoor temperatures exceeding 37°C cause a substantially higher heart rate and dehydration rate (Y. Chen et al., 2020), which affect physiological and psychological performance (Fan et al., 2019). The recommended range of thermal comfort is between 22.5°C and 25.5°C (Caetano et al., 2017), while 26.3°C and 26.9°C were suggested for coastal regions and rainforest regions, respectively (Guevara et al., 2021). For sedentary activity, the neutral temperature for thermal comfort can increase to 30°C (Wijewardane & Jayasinghe, 2008).

Higher air velocity can escalate the neutral temperature for thermal comfort. Environmental issues drive sustainable design, and health risks are caused by the absence of environmental design criteria or energy storage. They have become the highest priority in the built environment by focusing on green architecture. Cooling the indoor environment consumes high energy due to improper design or user carelessness in the form of energy wastage inside the building (Masood et al., 2017). Hence, renewable energy sources like the sun and wind should be utilised optimally with green design to achieve sustainable development. The sun and wind, which provide heat and airflow, are important parameters affecting indoor air quality and human comfort. Applying natural ventilation can achieve satisfactory comfort and a healthy indoor environment. Enhancing air velocity increases the occupant's sweat evaporation with thorough ventilation (Castillo & Huelsz, 2017). Considering the excellent air circulation (Kim & Kim, 2018), natural ventilation provides fresh air and reduces future health problems.

The indoor environment, human comfort, and natural ventilation are closely related (Cuce et al., 2019). Studies have been performed on temperatures in a hot and humid climate and building occupants' reactions to a hot and humid environment, eventually leading to research on how sustainable design aids building designers and consumers in choosing the right building component design, such as window configuration, for achieving indoor thermal comfort. A suitable window configuration exerted a positive effect on indoor thermal comfort (Zhao & Du, 2020). In this study, the authors examined the most common window types in the market and reviewed their performance. The results reveal the worst window type according to performance so that consumers can choose the best window to fit the function of their building.

METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline (Page et al., 2021) was used for compiling related articles. The PRISMA 2020 guideline is a systematic procedure that guides authors in searching articles from available databases. The PRISMA simplifies the article search by identifying the databases to be used, namely, Scopus, Web of Science, and grey literature. Grey literature is unindexed by primary database sources but is also considered an important information source (Osayande & Christopher, 2012).

In this study, the two main keywords were ‘natural ventilation’ and ‘hot humid climate’, followed by ‘solar,’ ‘opening,’ and the synonyms for ‘window,’ ‘airflow,’ ‘wind flow,’ and ‘air velocity.’ Next, openings (important building components that affect indoor airflow) and windows were divided into design, parameters, arrangement, dimension, position, and size criteria to widen the search.

The early stage of article compilation was crucial to finding and achieving the correct focus topic and yielded 994 articles. The 994 articles were screened by excluding articles based on year (2015–2021), subject area (engineering, energy), document type (article), and language (English). Articles that did not feature the criteria above were excluded and filtered out.

Article eligibility was tested by checking each article that remained after the exclusion process and yielded 135 articles. The full text of the articles underwent eligibility testing to exclude unrelated articles. Subsequently, the exclusion and eligibility testing were repeated, and the articles were finalised and analysed by categorising the information needed. Fewer than 100 articles that were included in this review underwent final screening. The screening continued until articles on sliding windows focused on residential buildings were identified.

RESULTS

Window Type

The articles included in this study focused on natural ventilation in a hot and humid climate. The included articles were on sliding and pivoted windows (Hossain et al., 2017); sliding, double, and quadruple cut-up sliding windows, fixed and projected windows (Kim et al., 2019); sliding window opening (de Faria et al., 2018); side-hung, top-hung, bottom-hung, and sliding windows (Liu & Lee, 2020; Liu & Lee, 2019); two window bands with a single opening (Tena-Colunga & Liga-Paredes, 2020); fixed, louvre, sliding, and double-hung windows (Z. Chen et al., 2020); sliding windows (Yoon et al., 2020); and sliding, horizontal rectangle windows, and louvre windows (Kitagawa et al., 2021).

Nine articles focused on naturally ventilated conditions: glazing (Kim et al., 2019) and the optimal positioning of the building opening (Yoon et al., 2020). The other articles on natural ventilation featured investigation of the cooling ventilation process (Hossain et al., 2017; de Faria et al., 2018; Kitagawa et al., 2021), hot–cold season (Z. Chen et al., 2020), the performance of indoor ventilation in relation to window design (Liu & Lee, 2019), window-opening degree (Liu & Lee, 2020), and window frames (Tena-Colunga & Liga-Paredes, 2020).

Most of the included studies involved square window openings. Thermal comfort was studied in the articles on square windows with no external shading (Zomorodian &

Tahsildoost, 2017) and typical square windows (Elshafei et al., 2017), while an article on square wind-deflector windows and energy and window rating (Orouji et al., 2019) examined indoor–outdoor temperature and airflow to improve the convection process (Lin et al., 2021). Finally, an article on ordinary square double-glazed windows examined the economic cost of energy efficiency, thermal comfort, and daylight usage (Yılmaz & Yılmaz, 2021).

In the other articles on square window openings, window parameters (Zhai et al., 2019), influence of opening position (Xing et al., 2018), windows of different sizes (Rizal et al., 2020), and triple-glazed air supply windows (Bastien, 2019) were investigated. In this study, the different ratios from square to rectangular shapes (Rizal et al., 2020) were used as a reference in addition to the window parameter (Zhai et al., 2019) and window arrangement topics (Bastien, 2019). Furthermore, airflow patterns (Nalamwar et al., 2017) and volume flux (Derakhshan & Shaker, 2017) were investigated in relation to square windows. Vertical and square windows of various designs were studied, particularly concerning energy savings and cost, effect on the environment, and thermal comfort stimulated by window parameters (Elghamry & Hassan, 2020).

The second most frequently compiled shape-related window opening was rectangular window openings with vertical or horizontal orientation. One study on horizontal window openings focused on the ideal window parameters by investigating sunlight quality and energy intake (Maleki & Dehghan, 2020). Decreased energy intake was observed by determining the ideal window design variables (Foroughi et al., 2018). The topics compiled for horizontal window openings were fluctuation of cross-ventilation and flow field (Hawendi & Gao, 2018), stimulated and distributed wind speed (F. B. Chen et al., 2020), the microscopic change rate of the air (O'Sullivan & Kolokotroni, 2017), window position on the building façade (Hammad et al., 2019), porosities with several wind angles (Gautam et al., 2019) thermochromic glazing (Liang et al., 2018), and sunlight balance with energy performance (Pilechiha et al., 2020).

In the compiled articles, both horizontal and vertical window openings were studied. Moreover, natural ventilation was investigated to identify the effect of window-to-wall ratio position variables (Hamdani et al., 2017), window size, building orientation (Manigandan et al., 2018), and composite shear wall performance by determining the effects of the opening position and number (Badarloo & Jafari, 2018).

In three studies on vertical rectangular window openings, the water flow window configuration effect was examined, focusing on the distribution effects on thermal flow attribution of header design (Chow & Lyu, 2017), high-performance windows (Li & Tang, 2020), and energy performance analyses (Li et al., 2021). One study involved a water flow test with horizontal windows focusing on energy-saving capability (Li et al., 2020). Another two studies used ordinary vertical window openings to investigate indoor thermal conditions by studying passive design (Amir et al., 2018) and various window-to-wall ratios (Sacht & Lukiantchuki, 2017).

Topics on the effect of window ratio–position to air and temperature distribution (Vadugapalayam et al., 2017; Abed et al., 2018) and direction with wind speed (Stamatopoulos et al., 2019) were studied. In one study on energy saving, vertical window openings were favourable for smart windows (Wu et al., 2018) and were also used for an opening experiment on tsunami flow (Moon et al., 2020).

The window-to-wall ratio was investigated in a total of 518 simulated window configurations (Marino et al., 2017), while the fenestration system (Mousa et al., 2017), window area luminance (Amirkhani et al., 2018), indoor-outdoor air movement comparison (Wahab et al., 2018), window configuration on energy performance (Altun & Kiliç, 2019), residential energy usage (Mori et al., 2020), and thermal investigation (Koohsari & Heidari, 2020) were studied in relation to various window opening types. These studies involved field measurements (Wahab et al., 2018), surveys (Mori et al., 2020), and computer simulations (Marino et al., 2017; Mousa et al., 2017; Amirkhani et al., 2018; Altun & Kiliç, 2019). One study on energy-saving windows ignored the window type utilised (Bayoumi, 2017), while two studies on natural ventilation in a hot and humid climate focused on defining the perfect window design by various attributions adapted (Hwang & Lee, 2018) and producing a guidance tool for windowmakers focusing on the adaptation procedures related to cost, product quality, and the indoor environment (Arranz et al., 2018).

In one study that did not specify the window shape, air change performance was investigated in an L-shaped room (Rabanillo-Herrero et al., 2020). Other studies investigated the energy efficiency of operable louvres (Scheuring & Weller, 2020) and triple-glazed fluidic windows (Su et al., 2021). In thermal performance studies, experiments were performed on multi-azimuthal windows (Barea et al., 2017). Two studies involved investigations of metacage windows (Fusaro et al., 2020) and acoustic metawindow frames (Fusaro et al., 2021) for simultaneous noise reduction and natural ventilation. Acoustic metamaterial windows were investigated in relation to ventilated tunables (Kumar et al., 2020). An investigation of thermal behaviour in hot and cold seasons did not report a specific smart window shape (El Khattabi et al., 2018). The authors of a study on basic window frames focused on the frame surface temperature (Nota et al., 2017), while a study of wood–aluminium window frames involved an investigation of the thermal properties related to the window-to-wall ratio (Misiopecki et al., 2018). In studies on ordinary window design, improvement in human satisfaction was investigated using artificial intelligence (Karan & Asadi, 2019) and shaded glazed window parameters of different shapes for decreasing energy cooling usage (El Dakdoky, 2019).

In one study on window shapes related to natural ventilation in a hot and humid climate, the authors investigated wind fields after residential building renovating typical house windows (Enteria & Cuartero-Enteria, 2017). In another study on centre pivot windows, bioclimatic design productiveness was identified in relation to temperature and relative humidity (Jamaludin et al., 2017). Finally, typical punch windows were studied to investigate human satisfaction with discomfort, glare and lighting acceptableness (Amirkhani et al., 2017).

Window Performance

This section focused on the variables categorised into single-sided and cross-ventilation conditions. Related variables, such as airflow, focused on the patterns or exchange rates, wind flow, wind speed, or velocity in relation to the types of opening and ventilation. Some articles discussed more than one variable, which included pressure difference, solar gain, temperature, building location, building group layout and orientation, internal space arrangement, and opening design.

The airflow studies involved media that included building models, generic isolated buildings, window simulation models, teaching spaces of a school building, residential buildings, including traditional dwellings, and office buildings. Some airflow studies were conducted in cross-ventilation conditions involving horizontal openings (Shetabivash, 2015; Kosutova et al., 2019), vertical openings (Manolesos et al., 2018), side-hung and bottom-hung casements (Cruz & Viegas, 2016), and vertical openings (doors) along with horizontal windows (Tan & Deng, 2020). Inlet opening affected cross-ventilation and indoor flow patterns (Shetabivash, 2015) while opening the upper part of a façade resulted in the largest velocities in a building (Kosutova et al., 2019). The side-hung and bottom-hung casement studies reported consistent discharge coefficients (Cruz & Viegas, 2016).

Airflow rate measurement was considered an improvement method for future studies. Vertical openings and horizontal windows resulted in greater indoor thermal operative temperature stability by preventing overventilation (Tan & Deng, 2020). The mean absolute deviation of the indoor operative temperature from the neutral operative temperature recorded a reduction exceeding 30%. An airflow study on single-sided ventilation involving the 'Mashrabiya' lattice window reported up to 3.5 m/s velocity for single-sided ventilation due to the oblique windward direction of 3 m/s velocity (Elwan, 2020). An investigation of residential building openings and air change rate concluded that the total number of openings (either window or door) was the important first-order predictor of living area air change rates. Increased attic–outdoor temperature differences caused increased airflow from the living area to the attic (Liu et al., 2018).

The included articles also involved studies on single-sided and cross-ventilation conditions due to window opening and closing patterns. One study featured a critical evaluation of passive energy-saving techniques on a hypothetical building refurbishment involving replacing old windows and the need for specific adaptive measures to improve indoor environmental quality (Carlos, 2017). A study on the effect of classroom openings on natural ventilation performance involved an investigation of the ventilation angle and evaluating the performance of natural ventilation using the air–age ratio. The authors reported that outside corridor ventilation was 35.55% better compared to the inside corridor, and large rooms had 30.85% better ventilation than small rooms (Yang et al., 2019).

One study investigated the ventilation behaviour of a double-skin façade building model with a square opening. There were no significant changes for cavity space division into smaller parts, while an additional channel on the northern part of the model was very efficient and directly affected the functionality of the façade (Nasrollahi & Salehi, 2015).

In studies on air velocity, the authors focused on horizontal openings in single-sided and cross-ventilation of residential buildings. Compared to the solid model, porous models demonstrated an average wind velocity at the opening that was 1.54–1.64 times larger with the lowest mean age of air (Saadatjoo et al., 2018). Moreover, various opening patterns were investigated in the natural ventilation of a traditional neighbourhood. The authors reported that night ventilation was the most effective passive cooling in vernacular dwellings in the hot season compared to daytime and full-day ventilation. This strategy reduced the highest indoor temperature while improving thermal conditions for the following day (Michael et al., 2017).

In one article, wind speed for single-sided ventilation was investigated in traditional buildings in Huizhou, China. The analysis demonstrated that the traditional dwellings exhibited good natural ventilation during the summer due to the patio attribution (Huang et al., 2017). In another study, natural ventilation behaviour was investigated with simulation modelling. The model predicted the mass flow rate and heat removed by ventilation with a high level of agreement with the experimental data (Dama et al., 2017). Other than air velocity, the occupants' experiences with air were also investigated, where heritage buildings in Baixa Pombalina, Lisbon, Portugal, were studied using a questionnaire. During the summer, the climate played a major role in controlling the thermal performance of the Baixa buildings (Nunes de Freitas & Guedes, 2015).

One article investigated the building location, building group layout orientation, internal space arrangement, and opening design of traditional dwellings with various openings. Traditional dwellings featured good adaptation to the local climate even during the summer, while thermal simulation revealed unsatisfactory indoor thermal comfort in the cold season (Gou et al., 2015). Building models for the window-to-wall ratio of inlets and outlets resulted in potential good performance of cross-ventilation for the indoor thermal environment and achieved comfort conditions.

An indoor temperature reduction of 4% to 8% was achieved even with less favourable conditions during the hot season. Due to the directly proportional relationship between airflow rate and indoor temperature with inlet and outlet size, larger inlets and outlets provided higher flow rates with proper orientation (Aldawoud, 2016). A single-sided ventilation simulation with a vertical and horizontal opening used pulsating and eddy penetration flow. The model could predict the total flow rate of single-sided natural ventilation in buildings driven by wind pressure. Small openings demonstrated a total flow rate driven by pulsating flow, while larger openings were mainly caused by the mean flow (Zhou et al., 2017).

DISCUSSION

The articles included in this review demonstrated that fewer studies were performed on sliding windows in relation to indoor environments, specifically studies that focused on hot and humid climates, thus resulting in little information on the performance of sliding windows and whether such windows exerted good or detrimental effects on the indoor environments of certain buildings. Substantial industrial and consumer decisions on utilising or choosing window designs that crucially affect the indoor environment are limited to certain sources, such as seller brochures, the internet, and personal experience. Hence, the findings may assist developers and consumers in making the correct decision.

Sliding Windows

In addition to the studies included in this review, previous studies related to sliding windows mainly focused on airborne particles (Sadrizadeh et al., 2018), window orientation with its position related to natural ventilation (Liu & Lee, 2019), and air pollution (Wang et al., 2020). Another study of window types, including sliding windows, focused on single-opening wind-driven natural ventilation (Ruan & Li, 2012), and cross-ventilation was characterised in a study of a classroom with different window and opening types (Nitatwichit et al., 2008).

Performance of Sliding Windows in Residential Buildings

The most recent field measurement conducted in a residential building demonstrated that sliding windows resulted in low indoor air velocity, high indoor air temperature, and heat accumulation between the window glass (Wellun et al., 2021). This main finding encouraged further investigations of sliding windows, which are still being utilised in residential buildings. However, the low performance of sliding windows may lead to an unpleasant indoor environment and high electricity consumption for indoor cooling.

Table 1 depicts a summary of sliding window performance in residential buildings. Sliding windows were the most unfavourable windows for reducing energy consumption for cooling. In residential buildings in Hong Kong, window design affected ventilation performance by surface regression. The most favourable window type was the side-hung window, followed by the top-hung and sliding windows. A mathematical model was used

Table 1
Summary of sliding window performances

Reference	Aim	Space or window type	Conclusion
Liu and Lee (2019)	Evaluated the influence of window type on ventilation performance.	• Residential building • Sliding window	Sliding windows performed poorly in terms of energy consumption for cooling.
Wang et al. (2020)	Sheltering efficiency of houses equipped with ventilation systems.	• Residential building • Sliding window	Ultrafine particles remained the main challenge in particle penetration into indoor space.
de Faria et al. (2018)	Evaluating natural ventilation systems for cooling potential to deliver comfort while reducing the energy demand of the building.	• Multi-storey residential building • Sliding window	Enlarged window sizes improved ventilation but resulted in an unavoidable increase in heat gain due to glazed area enlargement.
Liu and Lee (2020)	Influence of window opening degree of residential buildings.	• Residential building • Side-hung, top-hung, bottom-hung, and sliding windows	Sliding windows performed the worst compared to other windows.

to determine favourable to unfavourable windows, in which ventilation performance sensitivity depended on wind alteration, followed by ventilation mode, window type, and window orientation. The results demonstrated that ventilation mode was evaluated by air change per hour, where side-hung and top-hung windows achieved 124% and 97% higher ventilation, respectively than sliding windows for maximum air change per hour (Liu & Lee, 2019).

Studying particle penetration into indoor space through windows remains challenging. Particles < 69 mm could penetrate window cracks, while particles between 69 and 100 mm were captured due to the large diffusion effect, which focused on the universal household sliding window. Moreover, an increased ventilation system should be considered to enhance air purification effectively (Wang et al., 2020).

Increasing the total hours over a year for natural ventilation in removing heat gains was achieved by enlarging the free area of the windows by a factor of three in addition to purpose-provided openings for ventilation and fan utilisation. Unfortunately, the window area enlargement resulted in a larger glazed area. The increased heat gain was unavoidable and worsened when the façade faced the direction of solar radiation. Nonetheless, outer louvred shutters could be utilised to avoid overheating on glazed surfaces (de Faria et al., 2018).

The window opening degree also influenced the air change rate per hour. An acceptable opening degree range was 0.6–0.9 for maximum natural ventilation usage. Sliding windows were the worst design preference for single-sided ventilation, with an optimum window opening degree of 0.9. Conversely, with a window opening degree of 0.7, side-hung windows were the best design preference for cross-ventilation (Liu & Lee, 2020).

Sliding windows also yielded low performance in non-residential buildings. Wind-driven natural ventilation performance is an important criterion for optimising the wind direction to achieve window position effectiveness, ideally considering outdoor conditions. Sliding window data provided information on how the window should be positioned correctly to achieve optimised performance. In addition, the information suggested a maximum cooling effect for natural ventilation (Yoon et al., 2020).

Sliding windows were reported as an unfavourable window type for air ventilation. Air entry in the working area of a building was restricted and limited the potential of ventilation to lower the indoor air temperature. In Bangladeshi garment factories, changing sliding windows to pivoted windows potentially decreased overheating by as much as 15% and by as low as 2% of working hours in three different work areas (Hossain et al., 2017). However, sliding windows resulted in the worst air mass flow rate compared to the three other windows tested in a single room opening. At ≥ 45°, the air mass flow rate neared zero. At a wind direction of 0°, the sliding window and conventional side-hung window produced the lowest air mass flow rate compared to the up-down folio window and the multi-sash mid-pivoted folio window with vertical deflectors (Ruan & Li, 2012).

CONCLUSION

The study of sliding window openings is important as they are still used in buildings despite research data demonstrating their unfavourable behaviour and effects on indoor environments. Research information does not educate building designers or consumers on how the sliding window is one of the most unfavourable designs. The reason building designers still utilise the sliding window is unknown but might be due to economical cost and ease of installation. In addition to a detailed investigation of glass behaviour, the questions above should be answered in research soon. Ultimately, the research can be developed into a combined investigation of sliding windows and glass behaviour in the indoor environment.

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