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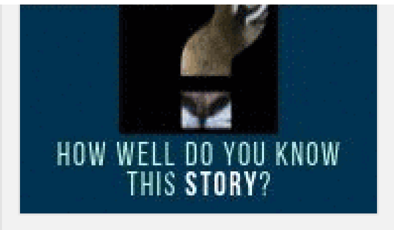

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Noise-reducing vents for windows in warm, humid, tropical countries

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ABSTRACT

Sustainable building design requires the application of natural ventilation, which has three prerequisites – a comfortable outdoor air temperature (20–25°C), unpolluted outdoor air and a low-noise environment (under 55 dBA). There are many locations where the first two prerequisites are met, but the environmental noise makes applying natural ventilation challenging. This research developed an auxiliary noise-reducing vent for windows (NRVW) that allows daylight and outdoor air to enter the room while reducing the penetration of outdoor noise. As an auxiliary, the NRVW is intended to be integrated into any (double) glazed windows with a sound transmission class (STC) above 25 dBA. The research used physical model experiments to measure the NRVW's STC and outdoor–indoor transmission class (OITC). Digital model simulation was used to measure the NRVW's ventilation performance. It was found that NRVW has a rating of STC 18 and OITC 16, and it generates indoor air velocity of 0.015–0.086 m/s in the occupants' zone for an outdoor wind speed of 1–5 m/s. Modification of the room interior increases the indoor air velocity to 0.147 m/s. Computer simulation also demonstrated that, with an occupant inside the room, an outdoor air temperature of 25°C and outdoor wind speed of 1–5 m/s maintained the indoor air temperature at 25.309–25.258°C, indicating that the resulting airflow could keep the indoor air temperature low. Although the NRVW was originally developed for warm–humid climate conditions, it is also applicable for other climates if the required outdoor conditions are met.

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Vent; thermal comfort; natural ventilation; outdoor noise; sound transmission class

Introduction

The 21st Conference of the Parties (COP21), held in Paris on December 2015 and attended by 195 countries, produced five agreements aimed at reducing climate change caused by global warming. Those agreements involved limiting the environment's temperature increase by 1.5°C by reducing the greenhouse gas emission from fossil-based fuels (United Nations Framework Convention on Climate Change, 2015). Despite rigorous studies have been performed to create increasing efficient mechanical ventilation, such as via solar-powered air conditioners (Nkwetta & Sandercock, 2016; Shirazi, Taylor, Morrison, & White, 2017), the human preference to have contact with nature and fresh air makes natural ventilation non-negligible (Lei, Liu, Wang, & Li, 2017). Therefore, in countries where electricity production is still dominated by fossil-based fuel and renewable energy technology is not yet well developed, minimising electricity-consuming air conditioning and optimising passive cooling by natural ventilation should be encouraged.

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Adopting passive cooling in warm–humid tropical countries is challenging. To encourage physiological cooling, air movement is strongly needed (Chang, 2016); however, in this climate, calm days are dominant. Urban heat islands and global warming are gradually increasing urban temperatures above a thermal comfort limit, that is, above 28°C, where air conditioning inevitably provides thermally comfortable indoor environments. This usually happens in low altitude cities. Fortunately, there are many higher altitude cities with cooler outdoor air temperatures, which are beneficial for natural ventilation. In subtropical countries, passive cooling is also needed during the summer season, when the air temperature rises above 25°C, a limit that is infrequent compared with that in the warm, humid tropics.

Although it indirectly relates to thermal comfort, noise becomes an important consideration factor for passive cooling application in naturally ventilated buildings. Traffic noise can reach above 80 dB, creating an unconducive environment for common productive rooms' noise criteria of 45 dBA. Long exposure to traffic noise induces stress, potentially leading to premature death (European Environment Agency, 2017). Passive cooling relies on openings bringing the outdoor noise inside. Thus, it is desirable to construct windows that let in the daylight and comfortable outdoor air in while keeping out the outdoor noise. Noise-reducing vents for windows (NRVWs) are applicable to buildings in cities with outdoor air temperatures ranging from 20°C to 25°C; this range is neither too cool nor too warm.

The development of opening designs in warm, humid countries, such as Indonesia, typically concentrates on thermal and/or visual comfort. For example, Wang examines window size to enhance natural ventilation in Singaporean building (Liping & Hien, 2007). Furthermore, (Feriadi & Wong, 2004) considered windows as a means of applying adaptive thermal comfort in Indonesian buildings. In contrast, in terms of visual comfort, Mangkuto attempted to determine the appropriate criteria for discomfort glare in Indonesia by using windows as glare sources for the occupants (Mangkuto, Kurnia, Azizah, Atmodipoero, & Soelami, 2017). Despite the above examples, little research has focussed on noise transmission from outdoor sources into buildings through openings, that is, windows or vents. Among these limited studies is that of Prianto, who explained the role of various 'krepyak' window modes to respond to outdoor noise penetration (Prianto, Roesmanto, & Suyono, 2014). A 'krepyak' window is a feature of Indonesian architecture created by mixing the Western and Eastern architectural styles used at the beginning of the twentieth century (Sukarno, Antariksa, & Suryani, 2014) and recorded as one of the Dutch colonial heritages suitable to the local Indonesian climate (Setyoaji, Rukayah, & Supriyadi, 2015). A dedicated study assessing thermal, visual, and audial aspects simultaneously in a single opening has not yet been conducted. To address this issue, the present research offers holistic comfort considerations by equipping windows with noise-reducing vents to garner the optimum advantages of each component based on the lesson from Indonesian historical tales, the 'krepyak' window (Figure 1).

Theoretical reviews

Efforts to find a noise-reducing ventilated window

Many studies have been carried out to find openings – that is, windows – which can provide daylight and ventilation while keeping the outdoor noise out. Among the first studies was one by Ford and Kerry (1973), which found that a 100-mm-sized, partially open double-glazing still has a sound reduction index (SRI) that is 10 dBA higher than that of a partially open single glazing. A study conducted by Yu et al. found that, for 2.38-m-high plenum windows with staggered openings, an SRI of 20 dB for frequencies above 250 Hz could be achieved. The higher the plenum, the longer the sound path is, and the larger the SRI becomes (Yu, Lau, Cheng, & Cui, 2017).

Tang conducted a thorough review on the available natural ventilation-enabling noise control devices and grouped them into five categories, as follows: protrusions (such as fins, lintels, and screens), resonant devices, balconies, active noise control (sound cancellation) and plenum

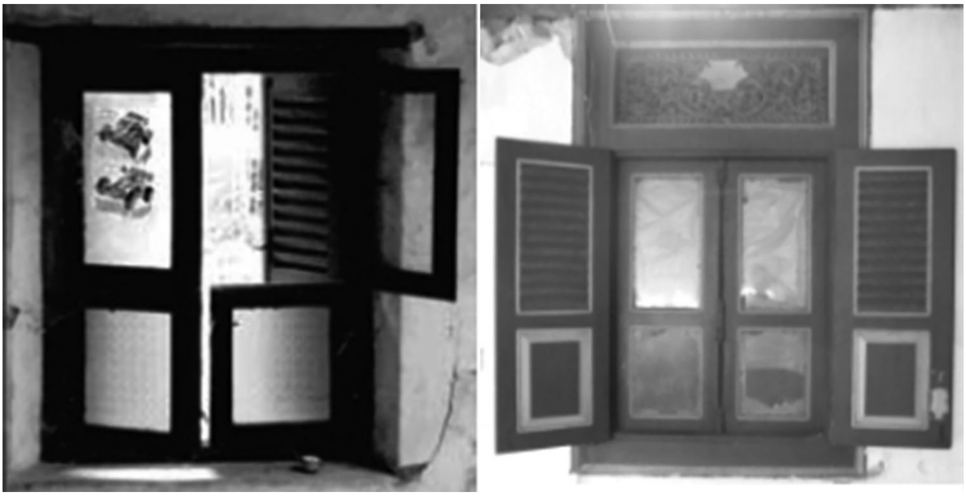

Figure 1. Various type of krepyak windows. Source: Kotagede Heritage District Yogyakarta. Homeowners' Conservation Manual (UNESCO, 2017).

windows/double-wall structures with staggered air inlets and outlets; the final category is the most promising one (Tang, 2017). Sakamoto et al. found that protrusions are not effective because their noise reduction is relatively small (1–10 dB) and they require large sound incidence angles (more than 80°) to achieve an insertion loss above 4 dB (Sakamoto, Ito, & Asakura, 2008). Resonant devices, although offering transmission loss around 22 dB, are bulky and tend to block air passage (Field, 2000). Despite their popularity in reducing street noise, balconies provide no more than 10 dB of noise reduction. Sophisticated active noise controls are claimed to have 10 dB of noise reduction (Kwon & Park, 2013), but they are bulky and tend to block the air passage; moreover, they are not reliable for building façade applications. They are still in the conceptual stages. Plenum windows have relatively higher sound insulation than other categories do. A study conducted by Lee found that plenum windows with 75-mm air cavities could have sound transmission class (STC) 30–40, which is considered very good (Lee, 2016). Tang concluded his review by stating that plenum types are the most promising noise-reducing ventilated windows for tropics and subtropics, and they can be developed further by combining them with other sound attenuation devices working based on resonant and noise-cancelling principles (Tang, 2017).

Tadeu and Mateus found that double-glazing only gives better sound insulation than single glazing does if the air chamber is close to or greater than 50 mm thick (Tadeu & Mateus, 2001); different thicknesses of the two glasses also gives better insulation than the same thickness does. A longer air cavity, and thus, longer airflow path, give higher sound reduction (Ford & Kerry, 1973).

Outdoor air temperature

Lower air temperature requires slower air speeds to avoid cold drafts. Thus, in locations where the air temperature is in or close to the thermal comfort zone, only low air speed is needed. The Center for Built Environment (CBE) thermal comfort tool calculates that, with an air temperature of 25°C and relative humidity of 70%, only an air velocity of 0.01 m/s is needed to create comfort; this is reflected by the predicted mean vote (PMV) of 0.06 and predicted percentage of dissatisfied (PPD) of 5% (Figure 2). Zero air speed or no air movement is not recommended to avoid stuffiness and pollutant accumulation. *Standar Nasional Indonesia* (Indonesian National Standard; SNI 03-6572) recommends an air speed range between 0.15 m/s and 0.25 m/s for warm comfort at an effective temperature of 25.8–27.1°C with a relative humidity range of 40–50%. This relative humidity range

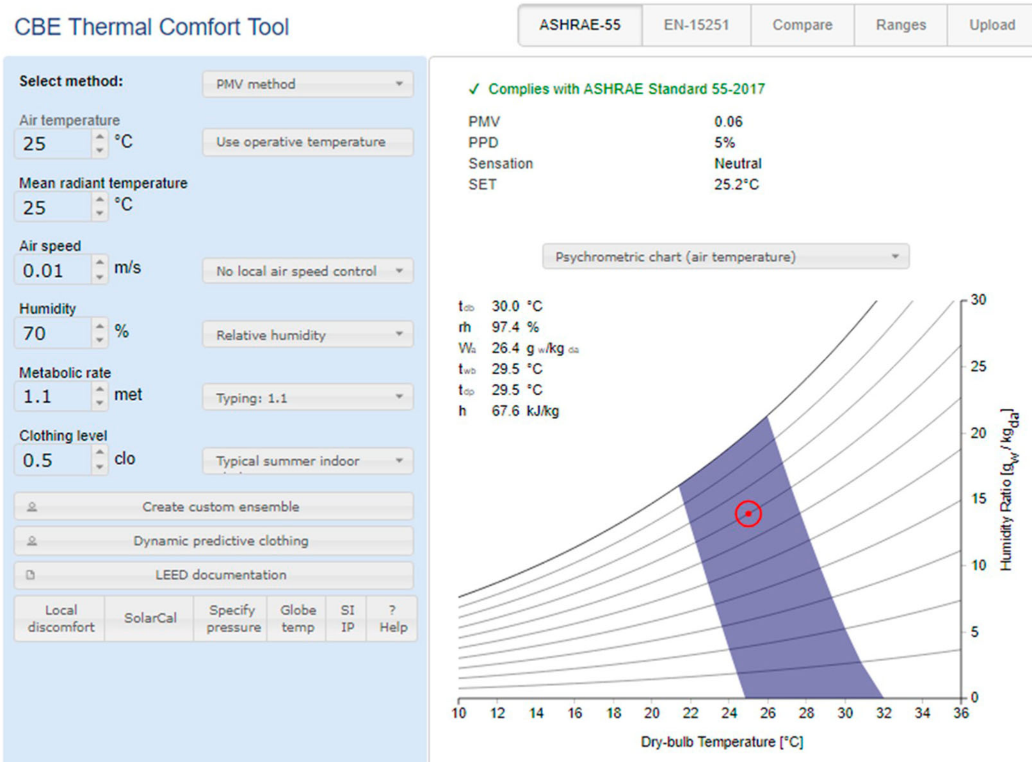

Figure 2. Center for Built Environment thermal comfort tool shows people wearing typical indoor clothes and doing typing can be thermally comfortable at air temperature of 25°C with 70% relative humidity and only 0.01 m/s air speed. Air speed of more than 0.3 m/s is uncomfortable.

is only feasible for air-conditioned rooms, as outdoor air's relative humidity is commonly higher than 60%. Karyono et al.'s study in Jakarta found that a comfortable temperature is near 27.7°C (Karyono, Sri, Sulistiawan, & Triswanti, 2015).

In a warm, humid, tropical climate, locations with lower air temperature can be found at higher altitudes. The relationship between air temperature and altitude is expressed as Equation (1):

$$T = Tsl - 0.6h\,^{\circ}C, \tag{1}$$

where T is the air temperature of a location (in °C), Tsl is the average air temperature at sea level (in °C) of the same or similar latitude to the corresponding location, 0.6 is a constant and h is the location's altitude (in 100 m). For Indonesia, for example, the Tsl is 26.8°C. Thus, if we delimit a maximum outdoor air temperature of 25°C as a comfortable temperature, theoretically, places located at 300 m above sea level should have a comfortable air temperature. These places are the targets of NRVW application.

Outdoor noise and indoor noise criteria

Outdoor noise has become a more intense problem in the presence of unnatural sounds, such as traffic and industries (Wang, Si, Abdul-Rahman, & Wood, 2015). In dense urban areas, traffic noise is worsened since the hard surfaces of the urban canyon exaggerate the traffic sounds. Meanwhile, in rural areas, traffic sound energy is easily dispersed in the open air and absorbed by softer surfaces, such as greeneries and soil (Bucur, 2006).

The two most widespread problems related to noise occur in residential and office buildings. In residential buildings, to obtain good sleep quality, a quiet bedroom with a noise criterion (NC) of 25–30 (equivalent to 35–40 dBA) is required. A healthy sleep requires a quiet bedroom (Fietze et al., 2016). In office buildings, clerical activities such as reading, writing, typing, and holding meeting require NC 30–35 (equivalent to 40–45 dBA) (Long, 2014; Schlittmeier, Feil, Liebl, & Hellbrück, 2015). Although this is not as low as required in the residential building environment, office rooms still need low noise to support good-quality, productive workspaces. Unlike residential buildings that can be located in residential zones, office buildings are usually located in business areas for easier public access.

Rationale of noise-reducing vent for windows (NRVW) development

NRVWs are developed specifically for naturally ventilated buildings in noisy environment. Combining noise-reducing vents with a window gives occupants the access to daylight (as well as outdoor views) and natural ventilation, while at the same time, preventing outdoor noise from entering the room easily.

Providing access to outdoor views means NRVW should be combined with windows using transparent materials (i.e. clear glass) allowing daylight to enter the room and its occupants to see outside views conveniently, which is essential for creating a healthier indoor environment (Mirza & Byrd, 2018). Windows with upper and lower sills of 2100-mm and 1200-mm heights, respectively, provide sufficient openings for daylight and view. The windows' width is more flexible. However, for side-swing windows' inward opening, the swinging space becomes a consideration, as it reduces the useful room space. A too-small width, in contrast, reduces the viewing field. Window openings of 600–700 mm in width is commonly used as a compromise.

Providing ventilation means NRVW should allow indoor and outdoor air exchanges. As natural ventilation is intended to create healthy and comfortable indoor air, it should be able to change the air room at certain rates and speeds. ASHRAE gives a standard of 5–6 air changes per hour (ACH) for bedrooms and 6–8 ACH for offices. The ACH is higher for rooms with indoor pollutant sources, such as kitchens (7–8 ACH) and smoking areas (13–15 ACH). To induce comfort by physiological cooling, a certain air velocity is required. For 70% RH, ASHRAE-55 (American Society of Heating Refrigerating and Airconditioning Engineer (ASHRAE), 2013) recommends indoor air speeds of 0.1–0.5 m/s at air temperatures of 25–28°C.

To work as a natural ventilation and noise-reduction device, the NRVW design includes air passage and sound absorber. The air passage facilitates free and smooth airflow while reducing sound energy. Unlike forced (mechanical) airflow, natural wind speed fluctuates, and in the case of warm, humid tropics, it is low. A daily averaged wind speed of 3 m/s (11 km/hour) is considered common. With this initially low wind speed, every effort should be made to minimise any passage design that can reduce the speed even more. A streamlined passage is preferable. Meanwhile, to reduce its energy gradually, sound should undergo multiple reflections using absorbers. A smoothly curved form of air passage with a sound-absorbing inner surface potentially does both these jobs.

At an NRVW, outdoor noise penetrates the room via two mechanisms. First, the soundwave hits and vibrates the NRVW so that the sound enters the room; this is structure-borne noise. Second, the sound wave, with the compression and rarefaction of the air molecules, flows into the room through the air passage; this is air-borne noise. To minimise the sound penetration via the former mechanism, an NRVW uses dense materials (timber), as the higher the density of a material, the higher the sound transmission loss becomes. Meanwhile, to minimise the noise penetration through the second mechanism, NRVW applies sound-absorbing materials (glass wool and carpet).

As designers are usually not interested in a bulky form, the thickness of NRVW is limited to 5 cm more than the walls. Consequently, the space for air passage is limited. A thin sound absorber is applied to avoid reducing the air passage's width further. Multiple sound reflections are needed to obtain sufficient sound reduction (see Figures 3 and 4).

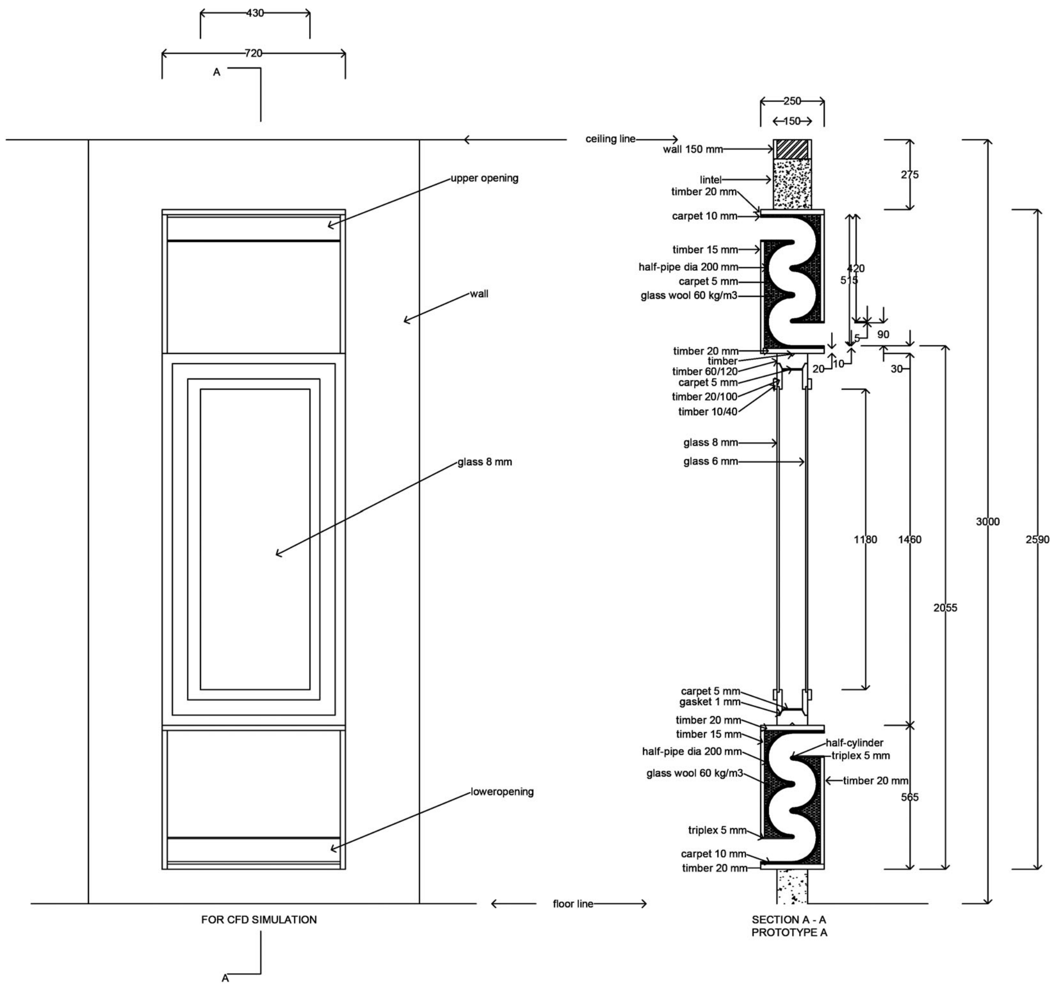

Figure 3. NRVW prototype consists of an upper and a lower auxiliary noise-reducing vent, combined with a double-glazed window in between.

Methodology

Methods

This research used three methods, namely literature review, laboratory measurement, and computer simulation. The literature review method was adopted from the conceptual through the design development stages of the NRVW prototype. Physical measurement with the American Society for Testing and Materials (ASTM) E90 method was used to measure the sound transmission loss of the prototype, that is, the vent part. The computer simulation method with a Computational Fluid Dynamic (CFD) program, namely (CFD-ACE+), was used to simulate and analyse the ventilation performance of prototype.

The laboratory measurement of the NRVW prototype was performed in the sound insulation test facility of the Laboratory of Acoustics of the Research Centre for Housing and Human Settlement, Bandung, in accordance with the ASTM E90-09 standard. This standard is for measuring the sound insulation performance of partitions, windows, and façades. The sound pressure levels in the sound-receiving room and source room were measured simultaneously after pink noise was generated through the loudspeakers installed in the source room. Based on the measured values, the

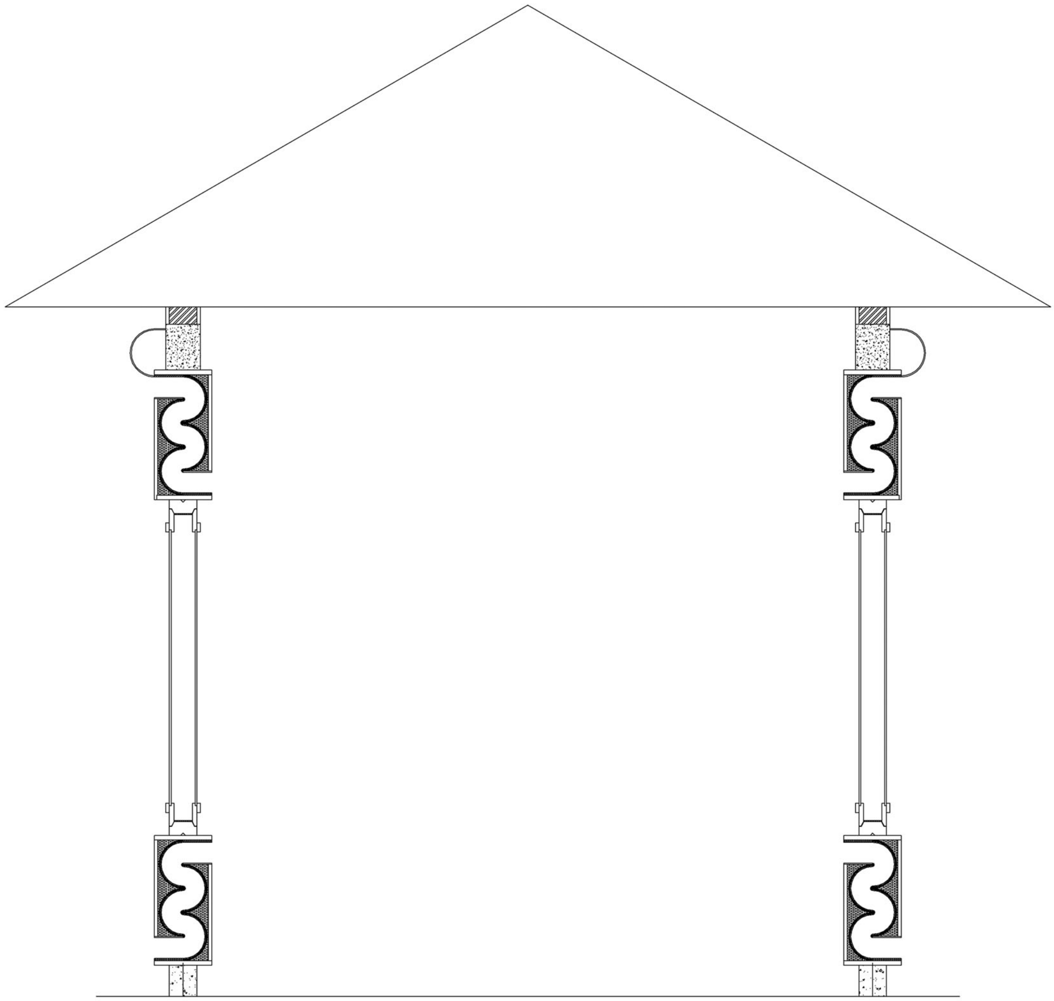

Figure 4. NRVW prototype in the context of a building.

sound transmission loss values were calculated once the reverberation time of the sound-receiving room had been measured. The transmission loss of the test specimen, which is smaller than the sample opening in the test facilities, was calculated according to the Annex A3 ASTM E90-09 procedure. The STC rating was calculated based on the sound transmission loss data according to ASTM E413, and outdoor–indoor transmission class (OITC) classified by ASTM E1332.

An omnidirectional loudspeaker (Brüel & Kjær Type 4292) and two omnidirectional microphones (Brüel & Kjær Type 4189) were used for measurement, and a two-channel building acoustic system (Brüel & Kjær Type 2270) was used for analysing the results. Figure 5 shows the arrangement of the experimental instruments used for the measurement in the reverberation room. Figures 6–8 show the configuration of the NRVW prototype for sound insulation testing.

The sound transmission through the composite wall can be represented as:

$$\tau_c S_c = \tau_f S_f + \tau_s S_s, \tag{2}$$

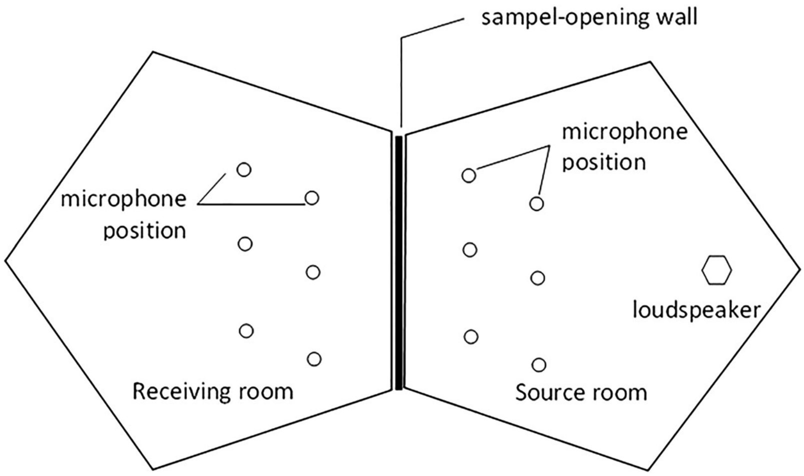

Figure 5. Experimental instrument setup in the reverberation room.

or

$$\tau_s = (\tau_c S_c - \tau_f S_f)/S_s, \tag{3}$$

where τ is the transmission coefficient, S is the area and subscripts c, f, and s represent the composite wall, filler wall, and test specimen indices, respectively. The area of composite construction, S_c, is equal to the test specimen area plus filler wall area ($S_c = S_f + S_s$).

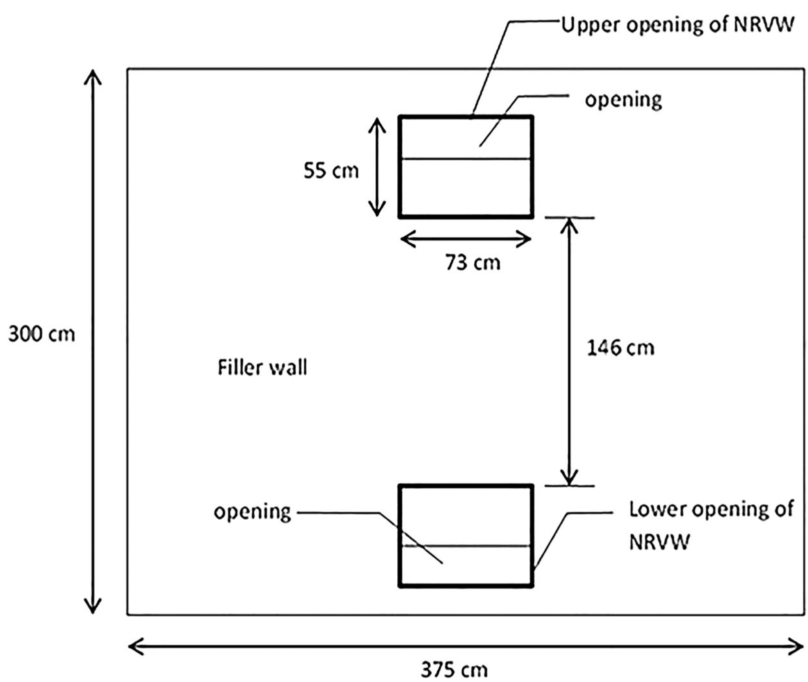

Figure 6. Configuration of the NRVW prototype for sound insulation testing constructed at the sample-opening wall.

Figure 7. Noise-reducing vents are installed on the soundproof wall of the test chamber (as seen from the sound receiver room). The vents are positioned to simulate their position at upper and lower part of a double-glazed window (which is expected to have an STC of at least 25 dBA, and thus, can reduce outdoor noise from 70 dBA to 45 dBA, as required for indoor noise).

Prototype

To make the design of the NRVW prototype practically meaningful, some assumptions and limitations were set as follows:

(1) Outdoor air is thermally comfortable, even in the absence of wind. For warm, humid, tropical climates, it is at 25°C or lower and RH 70%;
(2) Averaged outdoor noise is around 70 dBA, which is a moderate traffic noise;
(3) Expected indoor noise is 45 dBA or lower;
(4) NRVWs are installed at the opposite walls to encourage cross-ventilation;
(5) The glass pane(s) is openable for cleaning, as well as obtaining larger openings when outdoor noise is low;
(6) NRVWs are mainly used to attenuate air-borne noise;
(7) NRVWs provide smooth passage for airflow in which the plenum has a streamlined form to minimise turbulence;
(8) Together, the roof and ceiling have transmission losses of 40 dB or above;
(9) The reverberation time of the room is 1 s or lower;
(10) Insect and dust problems are tolerated. Installing an insect screen at the opening reduces the air speed up to 80%;

Figure 8. Noise-reducing vents as seen from the sound source room.

(11) NRVWs are especially intended for application to domestic buildings. The application of natural ventilation in non-domestic buildings, especially high-rise buildings, needs more consideration (Carrilho da Graça & Linden, 2016); and
(12) NRVW materials are easily available.

Results and discussion

Acoustical simulation

The sound insulation performance of the NRVW opening is depicted in Figure 9. The experimental result shows that the NRVW opening has a rating of STC 18 and OITC 16. The opening has a lower sound insulation performance for frequencies below 1250 Hz, and the sound insulation increases for frequencies above 1250 Hz. This can be explained by the physical dimensions of the opening. The opening can handle soundwaves with frequencies higher than c/λ, where c is the soundwave velocity in the air (m/s) and λ is the wavelength (m). The maximum wavelength that can be contained and then absorbed by the inner surface of the opening is about 0.25 m; this is physically limited by the opening depth.

The sound insulation performance of the NRVW opening is better than that of an opened wood-framed glass window. Mediastika, Kristanto, Anggono, Suhedi, & Purwaningsih, 2017 showed that even a small opening at a glass (5 mm thick) window created for ventilation could drop the sound insulation performance of the window from OITC 24 to OITC 7 (Figure 10). Hence, based on these experimental results, the NRVW opening can be combined with a fixed glass window to fulfil the fresh air need and reduce noise entering the room instead of opening the window and letting the fresh air and noise in.

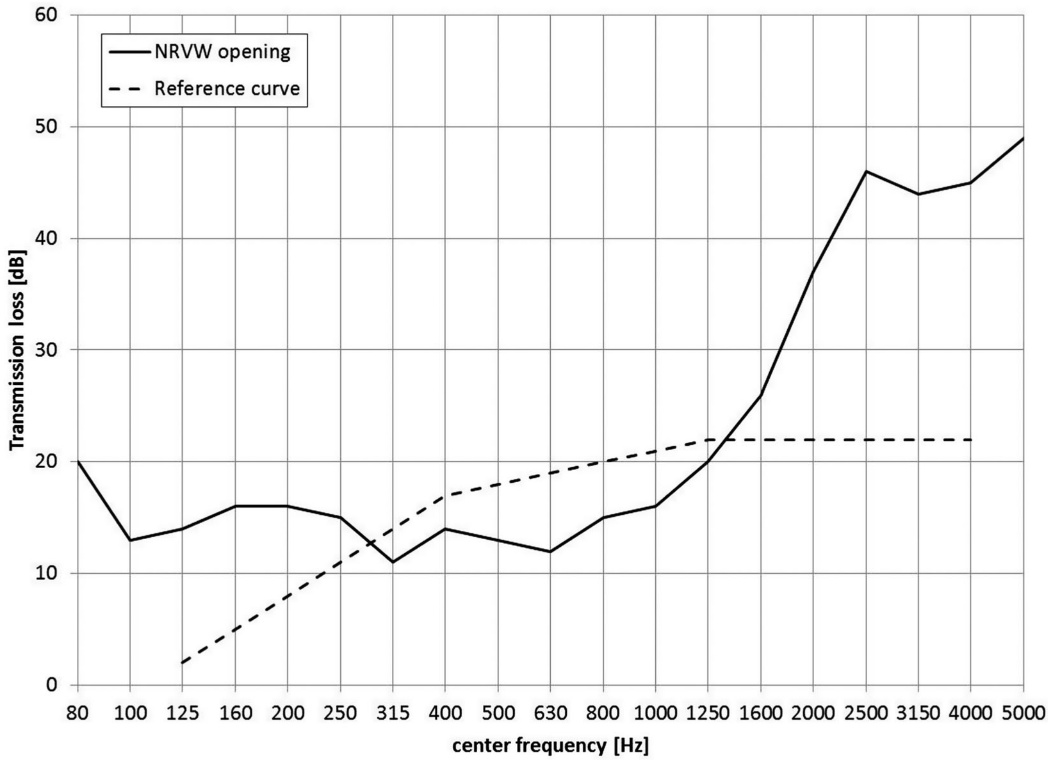

Figure 9. Sound insulation performance of the NRVW opening.

Ventilation simulation

The ventilation experiments start with constructing the following scenarios:

(1) Proposed or initial design of the NRVW prototype;
(2) Modifications on the external side of the building; window frame, external overhang, and louvre;
(3) Modifications on the ventilation path or air tunnel; and
(4) Modifications inside the building, including the internal overhang and ceiling.

All the scenarios are simulated two-dimensionally and measured statistically by probes. Models are developed and tested by blowing wind perpendicular to the inlet domain with speeds of 1, 3, and 5 m/s (Figures 11 and 12).

The criteria of comfortable ventilation are the air velocity (m/s) flows inside the habitable area, that is, the work plane at 0.9 m above the floor; maximum possible air speed in the middle of room; and resultant air speed occurring throughout the defined probes. For measuring maximum and resultant air velocity inside the model, a vertical line probe is placed in the centre of the room at a height of 0.2–2.8 m above the floor. Furthermore, to assess the distribution of air velocity, a horizontal line probe is also placed 0.9 m above the floor, starting and ending with each distance of 0.5 m from the opposing walls.

In addition, a formula to find the resultant (or *Veloc* as used in this research) air velocity flowing in three directions (U, V, and W) is developed as Equation (4):

$$Veloc = sqrt(U^2 + V^2 + W^2). \quad (4)$$

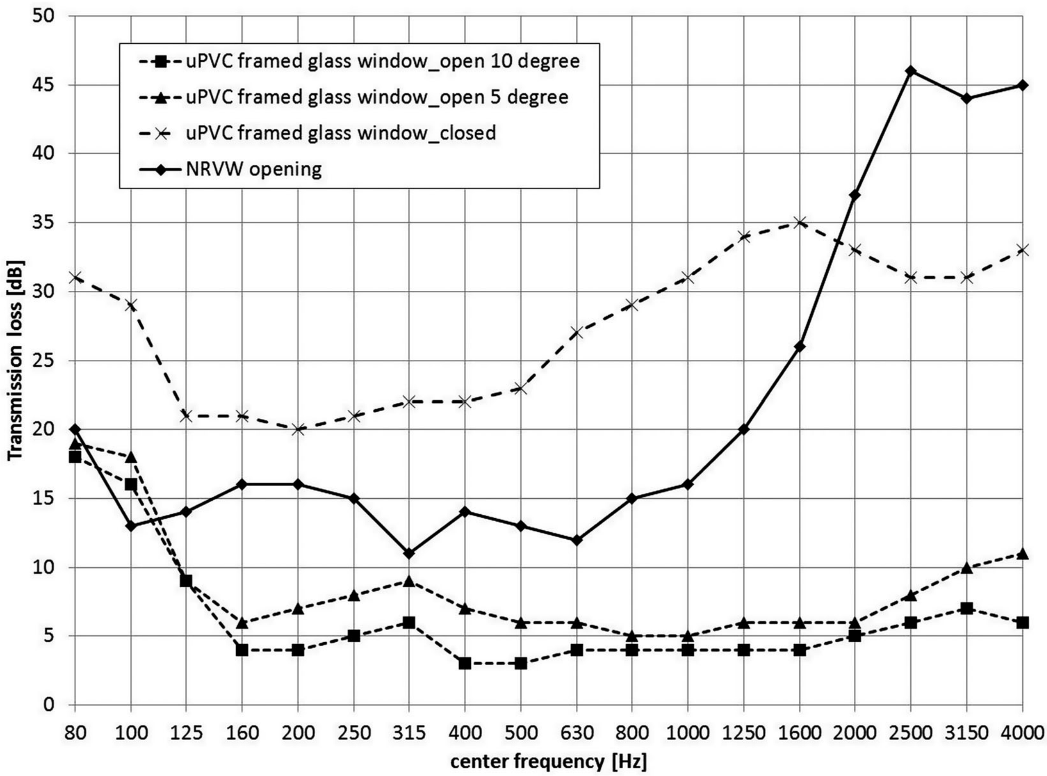

Figure 10. Sound insulation performance of the NRVW opening compared with glass (5 mm thick) windows.

The formula is applied to both line probes and then averaged to represent the resultant air velocity occurring inside the habitable area. A higher value means that more comfort is achieved.

Simulation results for the original model

To measure ventilation performance, CFD simulation is employed by developing the model similarly to the proposed design. This section is intended to be a benchmark for whether further physical

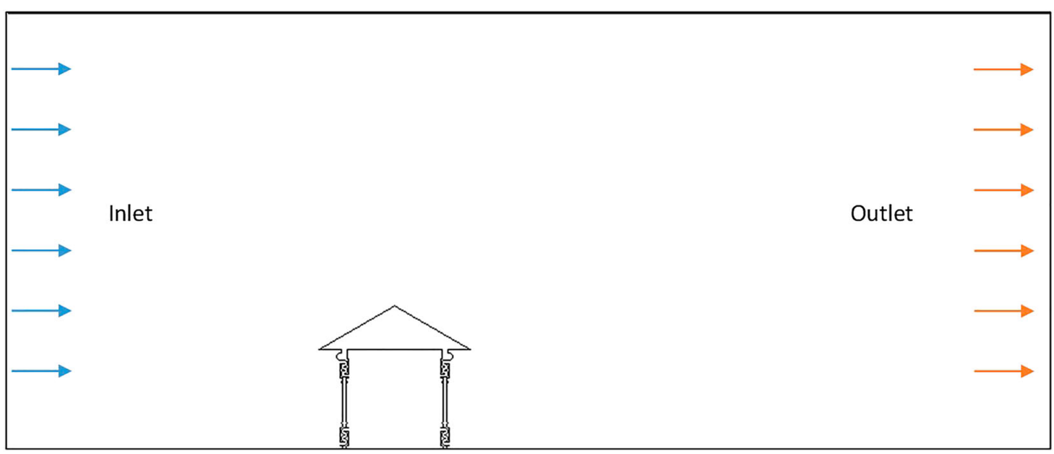

Figure 11. CFD simulation domain with inlet side on the left and outlet side on the right.

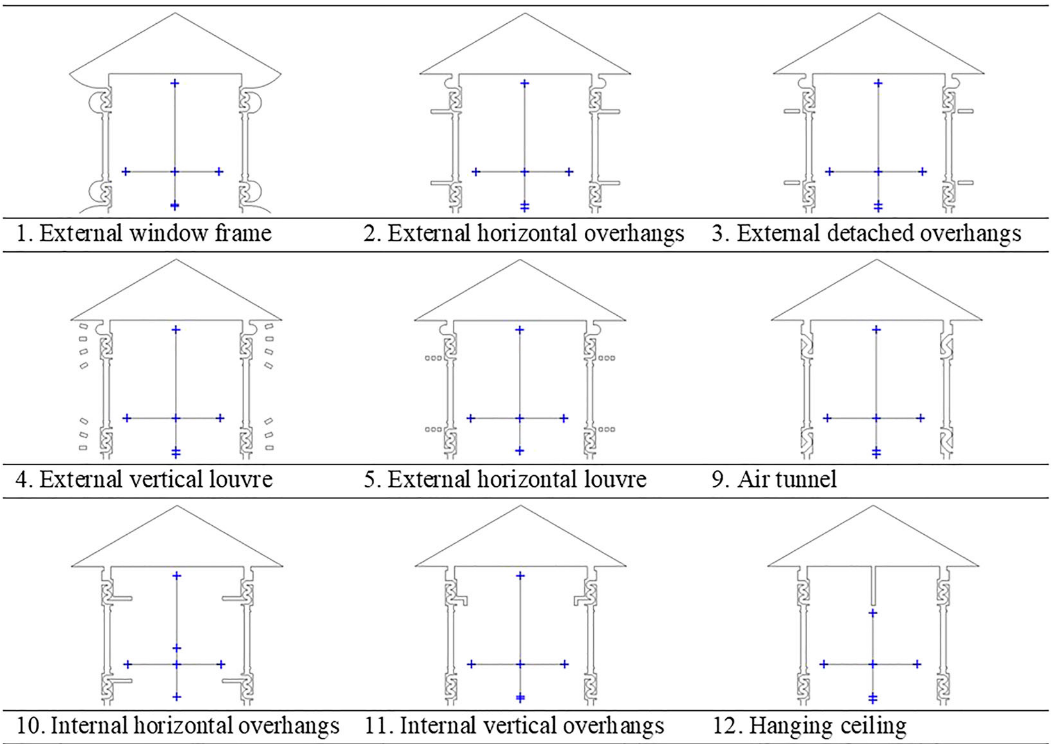

Figure 12. Twelve developed scenarios tested by CFD simulation, based on the original model.

modification is needed to improve the current ventilation performance or not. The standard for achieving comfortable ventilation is an air velocity of 0.01–0.3 m/s (see Figure 2).

Figure 13 shows that the outside air velocity of 1–5 m/s achieve the comfort range (0.01–0.3 m/s) near the surface of the floor, not exactly at 0.9 m above the floor, as desired. The pattern shows that it forms piston ventilation; air from the inlet side is directly expelled across the outlet side. Therefore, the average velocity recorded on the vertical line probe is low, at 0.098 m/s. However, the resultant horizontal air distribution recorded at 0.9 m above the floor reach the desired minimum speed of 0.01 m/s.

Simulation results for the air tunnel

In scenario 9, multiple curved paths inside the hole were maintained and the extreme turning angles were reduced to prevent the wind from losing its momentum when traveling inside the tunnel yet

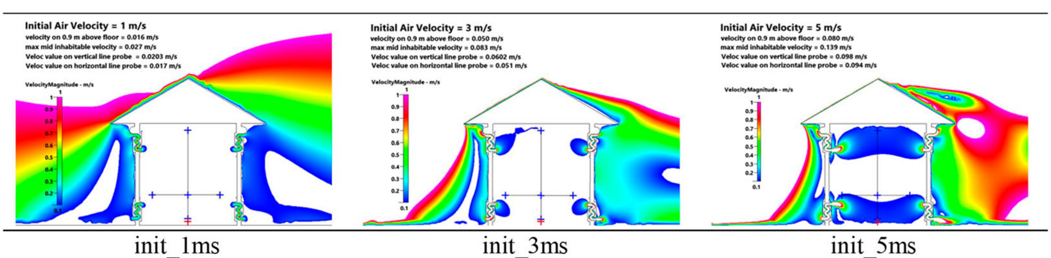

Figure 13. CFD simulation results in the original model.

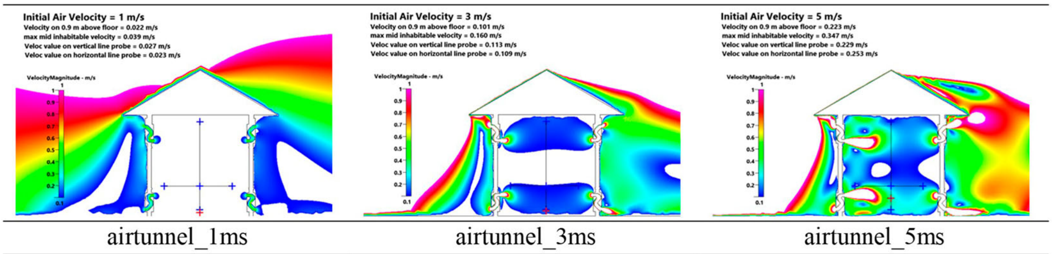

Figure 14. CFD simulation results for the air tunnel.

size and direction of the tunnel inside the room imitate the original model. As a result, a shorter pathway was generated.

Figure 14 shows distinctive differences if outside air speed blows faster than 1 m/s. At 3 and 5 m/s, higher indoor air velocity was produced, as well as the distribution rate. All the measurements recorded air velocity above 0.1 m/s. This experiment also produced the highest recorded maximum velocity of 0.347 m/s, which was slightly above the comfort range. Furthermore, the results of all the line probes were above 0.1 m/s, assuring an even distribution and comfortable ventilation inside the room.

Indoor air velocity and temperature

To build the connection between air velocity and temperature inside a room, a heat source was defined as a person standing in the middle of the room, emitting 100 W/m^2 of heat over their entire bodies; and outside air was blown at 1, 3, and 5 m/s with a temperature of 25°C. To obtain the numerical result, a point probe was placed 0.2 m above the occupant's head. The results were compared to determine the relationship between air velocity and temperature changes (Figure 15).

After the model was simulated, slightly different temperatures occurred when outside air was blown at 1 and 3 m/s, that is, 25.31°C and 25.29°C. However, if the outside air speed was increased to 5 m/s, there was only a 0.005°C temperature change recorded. This phenomenon indicates that, above 3 m/s of outside air, the extra cooling effect is negligible. Therefore, any increase in the outside air speed is futile, as the air velocity inside the room is heavily limited by the vent holes' profile.

Conclusion

With its IOTC of 16 dB, NRVW is useful for reducing the penetration of outdoor noise into the rooms. Further experiments can focus on the application of materials with a higher STC than timber and higher sound absorption coefficient than glass wool.

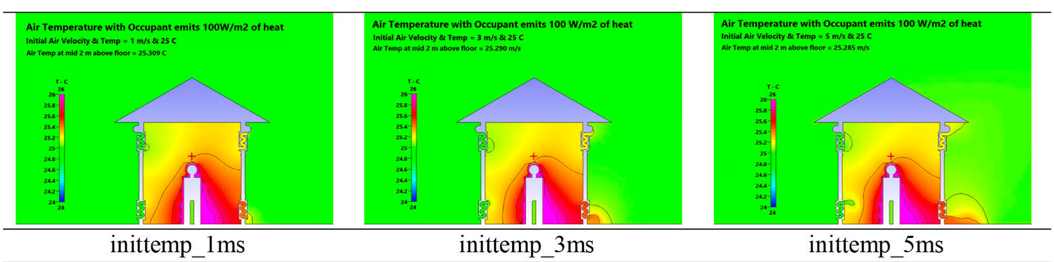

Figure 15. CFD simulation results for indoor air velocity and temperature.

From the results of the CFD experiments on room ventilation performance, the following conclusions can be drawn:

- Room ventilation performance depends highly on the outdoor air direction and velocity;
- Modifications on the external side of the window have little to no effect on room ventilation performance;
- The design of the air tunnel inside the window frame is decisive in determining the overall room ventilation performance, that is, less friction by minimising extreme curves and shortened air path is advantageous for ventilation. This may contradict the acoustic requirements, which need a longer path to absorb more noise; and
- Indoor modifications come second after the air tunnel. Applications or arrangements of room elements may direct the wind to flow inside the habitable area hence improve its ventilation performance.

Moreover, Figure 16 illustrates the fluctuation of room ventilation performance on horizontal work planes gathered from all scenarios. Lines are divided into four main groups; full line is the proposed model, dashed lines represent external modifications, dash-dotted lines symbolise internal modifications, and the dotted line indicates air tunnel modification.

At an outdoor air velocity of 1 m/s, internal modifications are dominant in improving room ventilation performance, as shown by the lines of inthov_1 ms and intvov_1 ms; both are dash-dotted lines. Device to curb the wind from the vents plays an important role to provide relatively higher air speed inside the habitable area; they are in the comfort range of 0.01–0.3 m/s, with a maximum of 0.045 m/s. In contrast, the dotted line – airtunnel_1 ms – had almost the same performance as intcel_1 ms. However, all the external modifications remained on the same position as the original one (init_1 ms), indicating no change appearing on them (Figure 17).

Next, the outdoor air velocity was increased to 3 m/s. In this state, internal modifications with overhangs were still the best solution. However, another dotted line representing the air tunnel increased

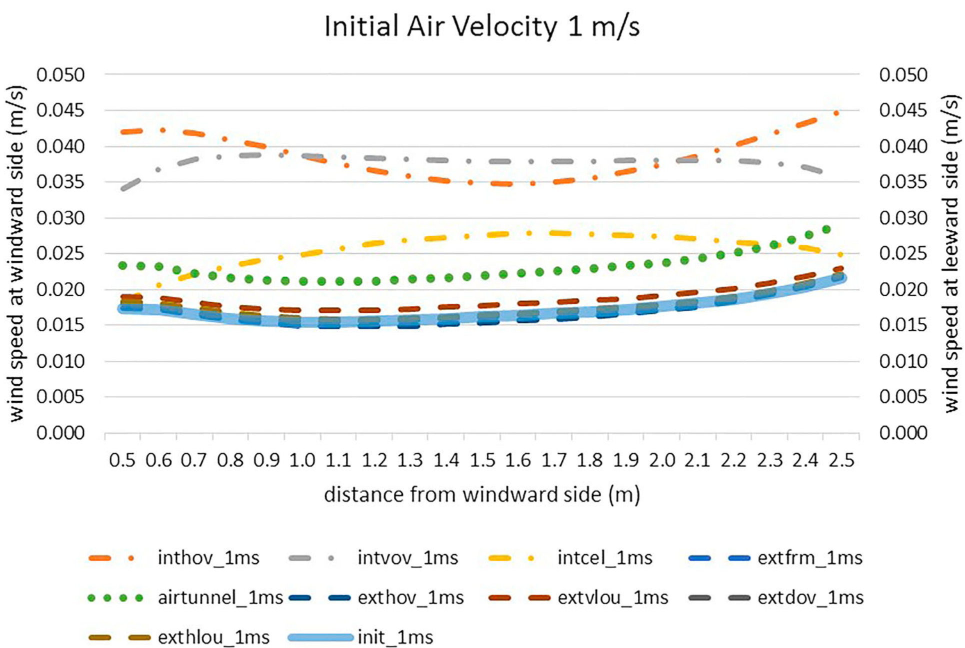

Figure 16. Distribution of air velocity on horizontal work planes from all scenarios with 1 m/s outdoor air.

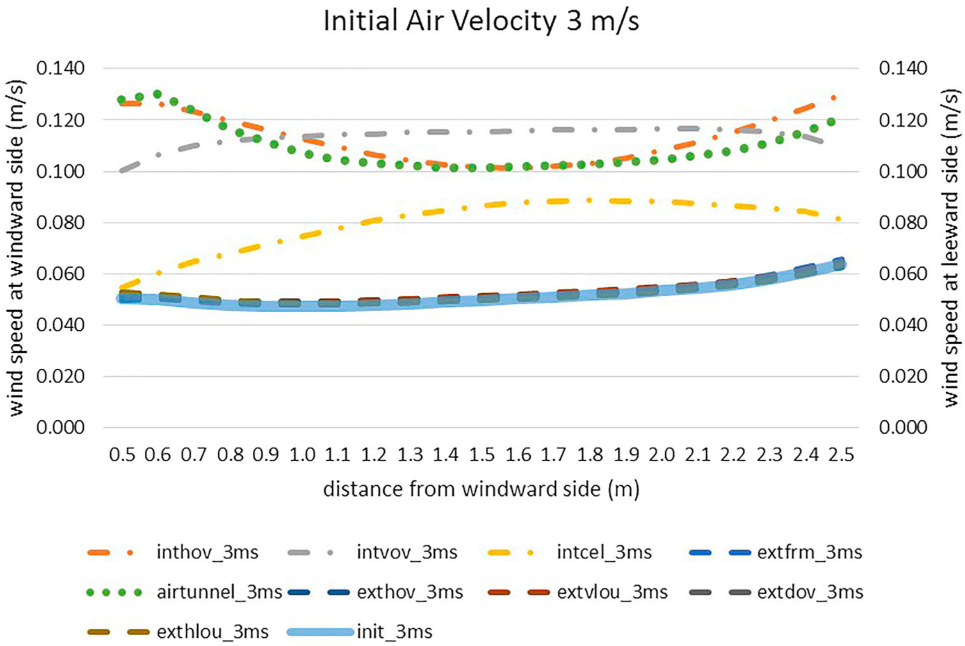

Figure 17. Distribution of air velocity on horizontal work planes from all scenarios with 3 m/s outdoor air.

and stayed on the same level as the dash-dotted lines. As a result, inthov_3 ms, intvov_3 ms, and airtunnel_3 ms were all above the minimum air velocity to provide comfort (all probes recorded more than 0.01 m/s). In contrast, no type of external modification changed from its previous state, even when higher air velocity was introduced in the models (Figure 18).

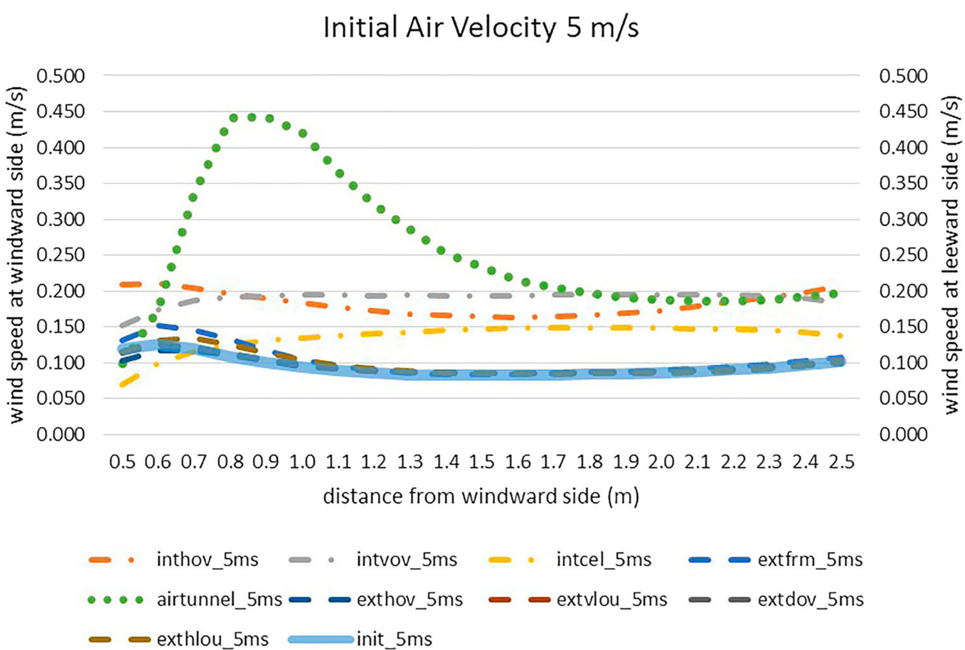

Figure 18. Distribution of air velocity on horizontal work planes from all scenarios with 5 m/s outdoor air.

Finally, a higher outdoor air velocity of 5 m/s is simulated. On this graph, the dotted line soared, reaching its highest record air velocity of 0.45 m/s near the windward side, far above all the other modification types. However, as the dotted line moved to the leeward side, it joined the dash-dotted lines and stabilised. This confirms that air tunnel design is crucial for providing good room ventilation performance at high outdoor air velocity. However, if a uniform air velocity were needed, the internal modification would be suitable for filling the entire room with a constant air velocity. In contrast, any change on the exterior side of the room will be ineffective in terms of improving the room ventilation performance.

Despite its proven noise-reducing and ventilating performance, the NRVW needs to be enhanced in the following manners:

(1) Insects are a problem for natural ventilation in warm, humid, tropical countries, especially at night. Installing an insect screen will significantly reduce the air speed from outside to inside;
(2) Dust accumulates inside vents, especially in the case of sound-absorbing materials; in conjunction with the presence of high humidity, this can be a good spot for fungi to develop;
(3) Wooden windows have gradually lost their popularity and have been replaced by aluminium-framed windows. Aluminium NRVWs can be developed;
(4) The ventilation performance in this study was calculated by computer simulation only. Validation by conducting field experiments in the real environmental context is required;
(5) Airflow and noise propagation inherently correspond to each other, especially with low-frequency noise (under 100 Hz). Therefore, to accurately predict these behaviours, simulations should consider wind-noise interaction phenomena;
(6) To achieve the best application of NRVW, windows should be tightly installed to avoid air infiltration and vibration due to the outdoor wind and noise, respectively; and
(7) Mechanically adaptive noise reducing vents are an interesting topic to be discussed in the future to cope with sporadic environmental changes (fluctuations in external air temperature, humidity, wind speed and noise); this will allow addressing both ventilation and acoustic needs.

Disclosure statement

No potential conflict of interest was reported by the authors.

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