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Examining the Thermal Comfort Characteristics of Naturally Ventilated Residential Buildings in New Zealand

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Abstract

In New Zealand's (NZ) mild climatic conditions most residential houses are ventilated naturally, mainly by opening windows. Previous studies have found that an overwhelming proportion of housing stock performs poorly from both a thermal and health perspective and hence there is a need to better understand this.

Now, analytically evaluating the thermal comfort characteristics of residential houses subject to natural ventilation is particularly challenging, as the solution is not explicit. Determining a solution requires the heat and mass transfer assessment to be driven by complex and non-linear phenomena associated with the natural ventilation driving forces of the wind and thermal buoyancy, along with other factors such as climate, building envelope and geometry as well as the occupants.

As such, this work utilises dynamic simulations to examine the variation of thermal comfort, in terms of the Predicted Mean Vote (PMV), of a model house equivalent to a size of a typical room under NZ climatic condition and for various operating conditions. To achieve this, it examines the PMV of the room with open and shut windows positions and different air-tightness values utilizing coupled thermal and airflow simulations. The results show that there is significant scope for regulating the thermal behaviour and PMV of relatively air-tight natural ventilated residential houses in mild climatic conditions.

1. Introduction

Thermal comfort is defined as "*that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation*" (Fanger, 1970) leading to a thermal comfort index known as Predictive Mean Vote (PMV) and Percentage of People Dissatisfied (PPD). The PMV index considers various quantities, physical activity, physiological and psychological factors (Fanger, 1970) for assessing thermal comfort as shown in Equation 1.

$$f(M, Clo, v, t_r, t_a, P_w) = 0 \quad (1)$$

Where M is the metabolic rate, Clo is a clothing index, v the air velocity (m/s), t_r is the mean radiant temperature (°C), t_a the ambient air temperature (°C) and P_w is the vapour pressure of water in ambient air (Pa).

In examining Equation 1, it is apparent that local air velocity plays a role in determining the thermal comfort in a space. In this regard, natural ventilation of a building may influence the thermal comfort level by removing excess heat by direct cooling (Francis et al., 2004). In doing this, the driving force for natural ventilation is either buoyancy created by a temperature difference between the indoor and outdoor, or wind pressure (Linden, 1999). Additionally, ambient environmental factors, building geometry, the terrain around the buildings and the adjacent obstacle dimensions can also impact the natural ventilation of a building. Furthermore, the combined effect of the two driving forces of the natural ventilation could be reinforcing or resisting each other (Hunt and Linden, 1999).

With respect to thermal comfort, the PMV is categorized into three comfort categories (Table 1) (EN ISO 7730, 2005) with those ranging between ± 0.5 being broadly considered as a comfortable environment (ASHRAE-55, 2010). The "C" category, having a higher PMV value on the comfort scale range, may be considered as acceptable to people accustomed to naturally ventilated environments.

Table 1. Thermal comfort categories (EN ISO 7730, 2005)

Categories	PMV range	Percentage of people dissatisfied (PPD)
A	± 0.2	< 6
B	± 0.5	< 10
C	± 0.7	< 15

Currently in NZ, there are approximately 1.6 million residential houses (Buckett and Burgess, 2009) typically constructed with metal roofs mounted on timber frames, a larger floor area and little or no insulation. As such, airtightness for most NZ houses varies from a base infiltration of 0.3 air changes per hour (ach) to 0.9 ach (Bassett, 2001), however, it is traditional to ventilate residential houses passively by opening windows (Ryan et al., 2008). Combining this behaviour with the NZ Building Code (NZBC), which does not enforce achieving any minimum indoor air temperature, indoor air quality (IAQ), air-tightness or moisture level has resulted in many NZ homes exposing occupants to a risk of developing health issues (Fitzgerald et al., 2014).

Given that no standard definition of "thermal comfort" is enforced in NZ, and the status of "thermal comfort" dynamics for NZ houses is not well understood, this study examines the thermal comfort characteristics of a typical NZ residential building.

2. Methodology

Analytically evaluating natural ventilation is particularly challenging, as the solution is not explicit. Determining a solution requires the heat and mass transfer assessment to be driven by complex and non-linear phenomena associated with the natural ventilation driving forces of the wind and thermal buoyancy, along with other factors. However, the software package TRNSYS integrated with a COMIS simulation can be used to develop a multi-zone coupled thermal and airflow model to predict airflow through openings and temperature and PMV for a zone based on heat and mass conservation laws with its well-mixed assumption (Hiller et al., 2002).

The spatial requirement of identifying at least one average value of thermal comfort performance indicator factor (PMV) for a typical room or zone of a residential building is considered sufficient to reveal an overall scope for regulating thermal comfort of the natural ventilated room or zone of the residential houses. As such, the multi-zone coupled thermal-airflow modeling approach with a TRNSYS-COMIS simulation can provide an average value of PMV to assess thermal comfort behaviour.

2.1. Building Model

To determine the behaviour of the thermal environment in a typical NZ building, the TRNSYS Type 56 model was used. This model utilizes a standard heat balance method and was used to model a zone with an air node. For this study, a single room of 3 m length, 3 m width, 3.6 m reference height (including 0.6 m of the sub floor space) and an internal volume of 19.75 m^3 was modelled. It was assumed that the building was located in Auckland NZ at 36.85˚ S, 174.76˚ E, with each wall oriented with respect to the cardinal directions and a single window on the north face. The building façade details are shown in Table 2, where it was assumed the room was constructed with an R-value just meeting the minimum NZBC.

Table 2. Building façade description

Building Facade	Description	R-value
External Wall	Timber frame direct fixed cladding	1.9
Floor	Suspended floor with lining under the joists and gap between insulation and lining	1.5
Roof	Timber frame skillion roof	2.9
Window	Double glazed sliding window (1.8 m. width x 1.5 m. height) fixed vertically on the Northern wall	0.34

Given the wide variability in air-tightness of NZ buildings, several conditions were examined; airtight, average, leaky and draughty buildings corresponding to uncontrolled ventilation rates of 0.3, 0.5, 0.7 and 0.9 ach respectively (Bassett, 2001). Additionally, an ultra-airtight building with 0.03 ach, meeting the passive house airtightness standard (Passive House Institute, 2016), was also considered. Furthermore, it was assumed that the room was occupied by a person at rest producing a heat of 100 Watt (sensible-60 and latent-100).

In addition to the uncontrolled ventilation, a COMIS airflow analysis based on a network model of the building was performed to explore the influence of controlled natural ventilation of the building space. In doing this, the temperature and humidity were calculated in the thermal model at each time-step and passed to the airflow model so that updated information was used to estimate node pressure and mass flow. The wall average pressure coefficient C_p values for low rise buildings with a length to width ratio of 1:1 and a shielded condition given by Orme (1998) were used to model the building. In doing so, COMIS solves a system of nonlinear equations to determine the node pressures and the mass flow in each link using air mass conservation in each node.

To achieve the ventilation, a Large Vertical Opening (LVO type 1) (COMIS 3.2, 2005) with a maximum opening size of 0.9 m (width) by 1.5 m (height) was used to model a sliding window. In doing this, a Window Opening Factor (WOF) defined as 1 for open and 0 for shut condition was applied. Further, intermediate WOF values of 0.25, 0.5, 0.75 were considered to explore the effect of the size of the opening on the thermal conditions. Finally, the thermal comfort level of the zone was assessed by computing the PMV index according to Fanger's thermal comfort relationship (Equation 1) for the free running condition, with no additional heating, cooling or plug loads and time-dependent forcing function that nullifies night time window natural ventilation (meaning the windows can only open between 8 am and 5 pm).

3. Results and Discussion

Having developed the thermal model of a naturally ventilated building, it was decided to explore how the space behaved for a range of conditions. To illustrate this point, Figure 1 shows the effect of the window, at various fixed WOF(s), on the PMV in an ultra-airtight building for a typical NZ summer day in January. It can be seen that the PMV follows the air temperature in the zone closely, thus illustrating that the zone air temperature (T_a) is one of the important factors for assessing thermal comfort in the space.

Further, it can also be seen that the window infiltration initially increases at a low rate for small WOF (0-0.5), then increases sharply for WOF 0.75 and again rises slowly for WOF 1. At the early stage this is due to the open area restricting the balance of in and out flow from the space, while at the later stage of the drop in the window infiltration rate is due to the small temperature and the pressure difference between outside and inside.

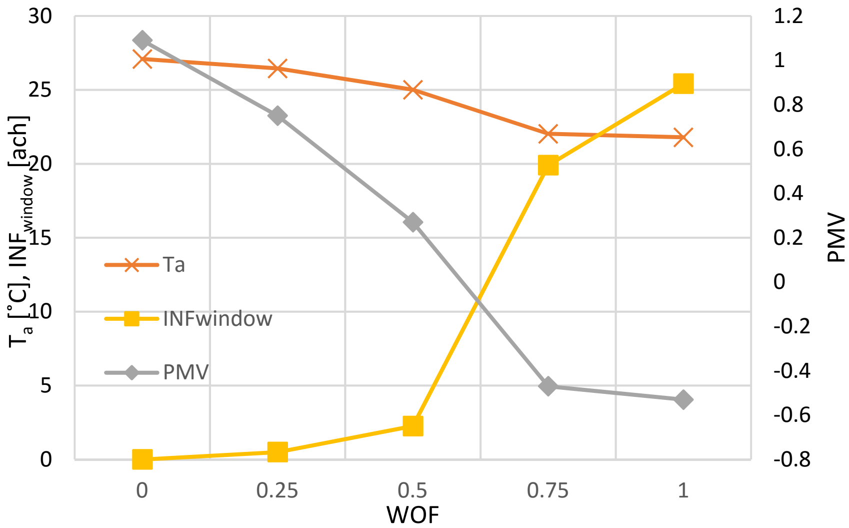

Figure 1. Effect of WOF on PMV and temperature in an ultra-airtight house (January)

Similarly, in Figure 2 it can be seen that the zone relative humidity (RH_a) falls sharply with small WOF(s) as the vapor pressure difference between the outside and inside moves towards zero. An increase in WOF helps bring the zone air relative humidity close to the ambient air relative humidity such that with a WOF of 0.5 this is achieved.

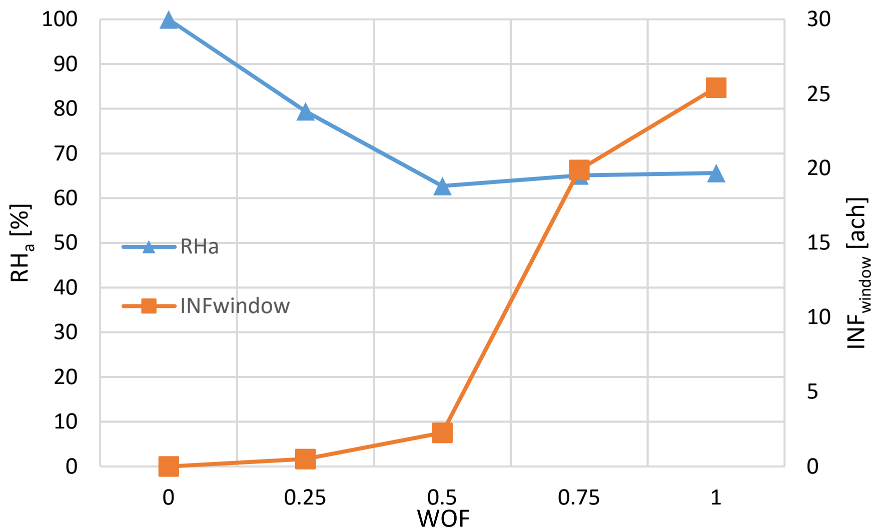

Figure 2. Effect of WOF on relative humidity in an ultra-airtight house (January)

Exploring this further, Table 3 presents mean monthly values of the zone temperature (T_a) and relative humidity (RH_a) observed for the ultra-airtight building when the window is closed, with respect to the ambient conditions (T_{amb}, RH_{amb}). When compared with the standard range ± 0.7 of thermal comfort in a naturally ventilated building (Table 1) the summer months from December to March possess the high potential of improving the PMV by opening the window. Moreover, it is also apparent that by not operating windows, additional steps need to be taken to remove moisture from the building to avoid problems associated with the high relative humidity of the air in the zone.

Table 3. Monthly mean values of the conditions for an ultra-airtight building

Monthly Mean	Months					
	November	December	January	February	March	April
T_{amb} [˚C]	17.05	19.1	20.67	20.85	19.8	16.94
Ta [˚C]	23.97	26.47	27.09	26.8	24.8	20.82
PMV	0.08	0.89	1.09	1	0.35	-0.93
Rh_{amb} [%]	71.9	70.85	68.71	70.96	72.35	75.52
Rh_a [%]	100	100	100	100	100	100

Obviously, most NZ buildings are not built to the level of airtightness described previously, therefore Figure 3 illustrates the distribution of PMV for the modelled space with fully open and shut windows during January. From this, it can be seen that when the window opens, the effect of airtightness is less meaningful and all buildings exhibit a similar overall comfort distribution, in terms of hot (>0) and cold hours (<0). However, on closer inspection of the results it was found that the ultra-airtight building delivers the greatest reduction in the number of uncomfortable hot hours with natural ventilation. Following from this, it can be shown that there is significant scope for regulating the thermal environment of relatively air tight houses (in summer) using natural ventilation but this scope decreases with reduced façade airtightness.

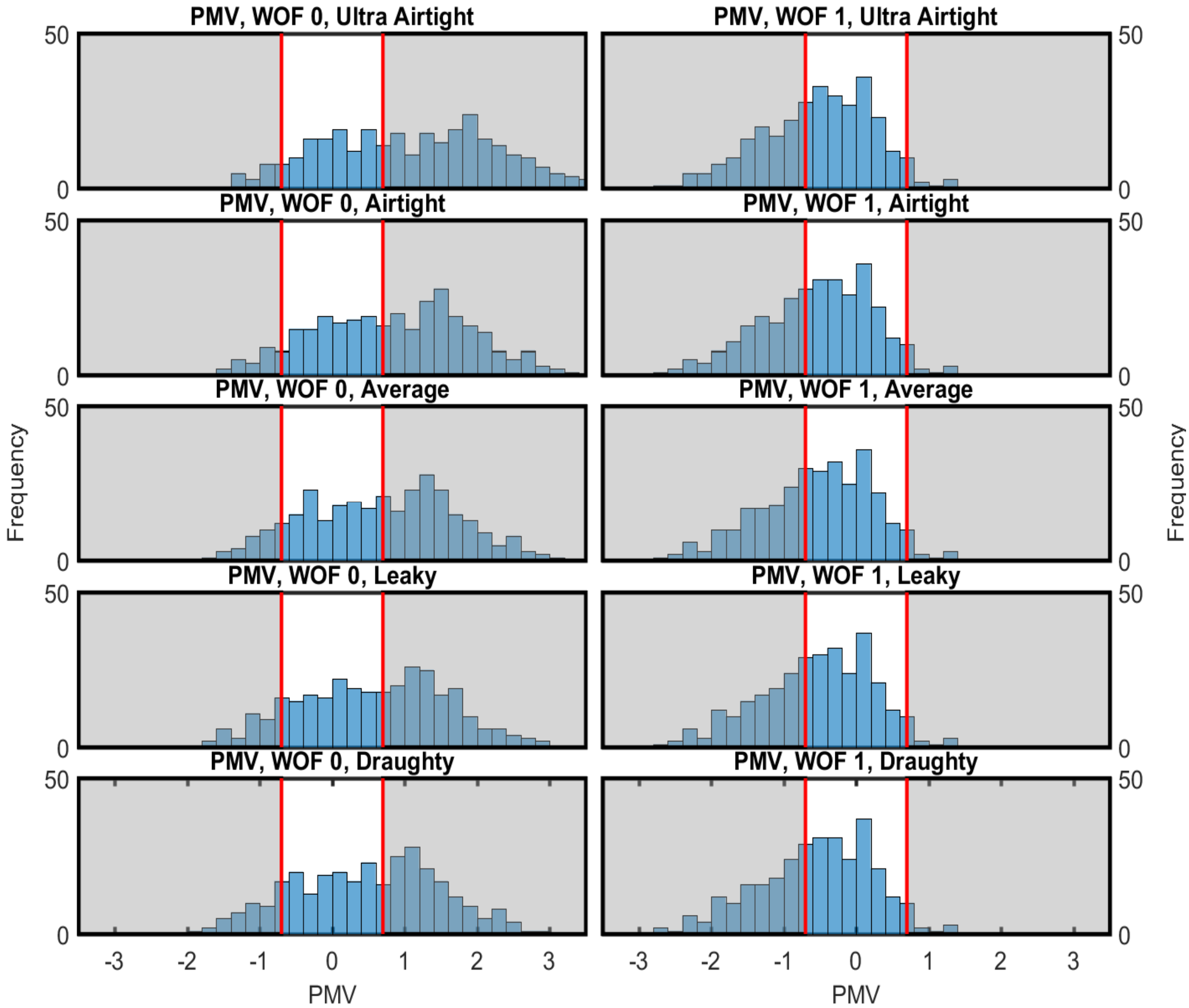

Figure 3. PMV variation with airtightness with shut (left) & open (right) windows

Considering the use of natural ventilation further, Figures 4 show the PMV distribution for the months of January and July. As such it illustrates the comfort levels across the year, considering varying clothing levels (Clo) and WOF 0-1 for the airtight building. The summer clothing level equivalent to 0.5 Clo and winter clothing level of 1 Clo is considered for January and July respectively. From this, it can be seen that for a fixed clothing level in summer the PMV for the zone improves as the window is opened, as one would expect. However, it appears that there may be an optimum opening fraction, as for WOF>0.5 there is an increase in dissatisfaction as shown by the PMV (which suggests a large number of occupants would feel cold). In winter (July) it is clear that any opening of the window will result in already high dissatisfaction levels. Moreover, even with no windows open, there is a high level of dissatisfaction with the zone. This is due to the absence of active heating and also the poor thermal insulation levels used in the walls, the minimum allowable by the NZBC.

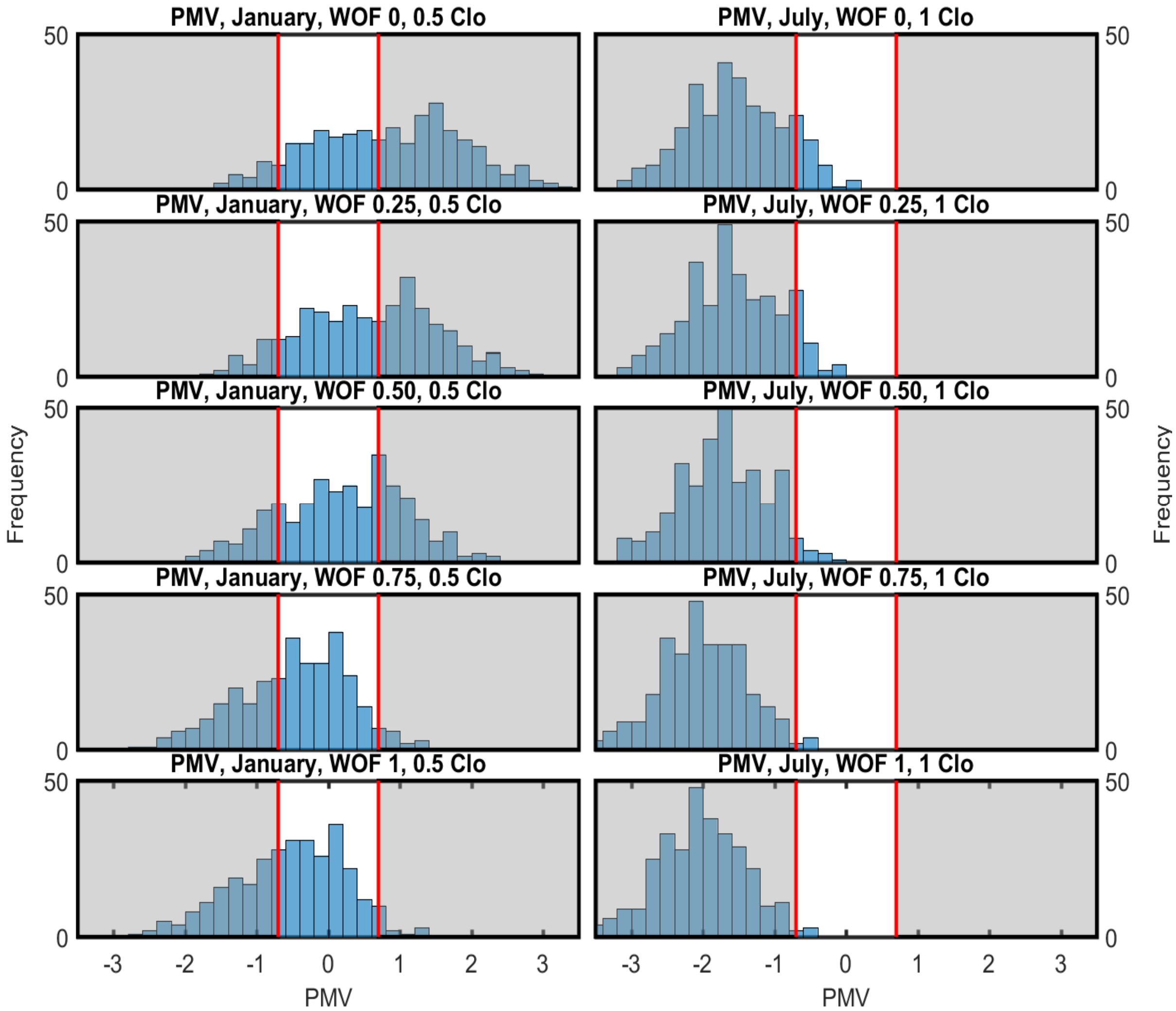

Figure 4. PMV frequency distribution for an airtight house (January & July)

Similarly, Figures 5 and 6 show the PMV distribution for the months of April and October. As such, it illustrates the comparison of comfort level for months on the cusp of summer and winter. In doing so, it shows how an occupants behavior affects comfort in the zone by examining both summer clothing levels (0.5 Clo) and winter clothing levels (1 Clo) and WOF 0-1 for the airtight building.

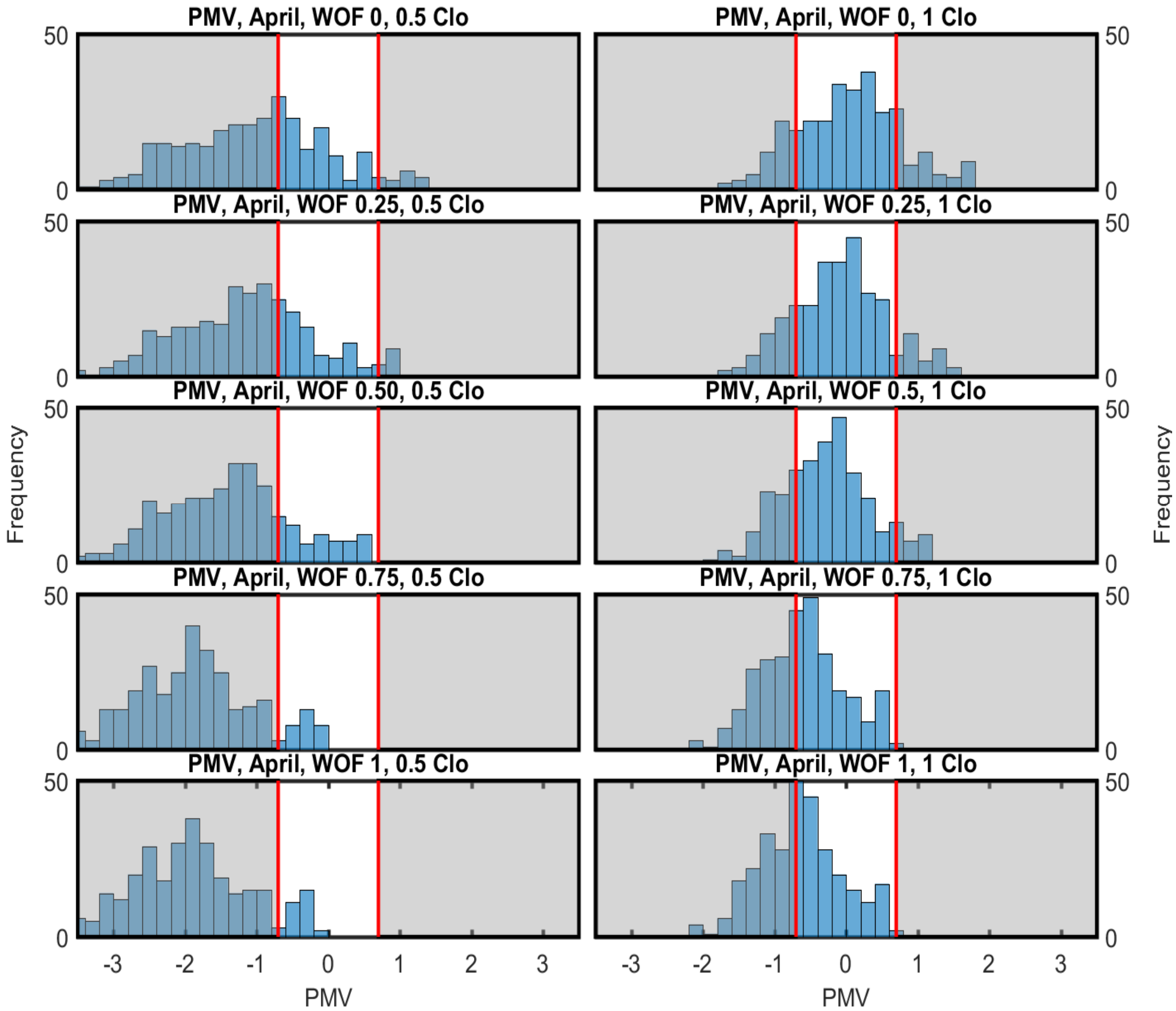

Figure 5. PMV frequency distribution for airtight house (April)

As expected, both figures show that the frequency of uncomfortably cool conditions decrease, and thermal comfortable increases, with an increase in clothing level in these transition months. However, an increase in WOF beyond approximately 0.5 is less effective at maintaining the improvement gained than by increasing the clothing level (1 Clo). Therefore, in transition months the increase in WOF (0 to 0.5) with an adaptation of summer clothing to winter clothing helps improve thermal comfort conditions.

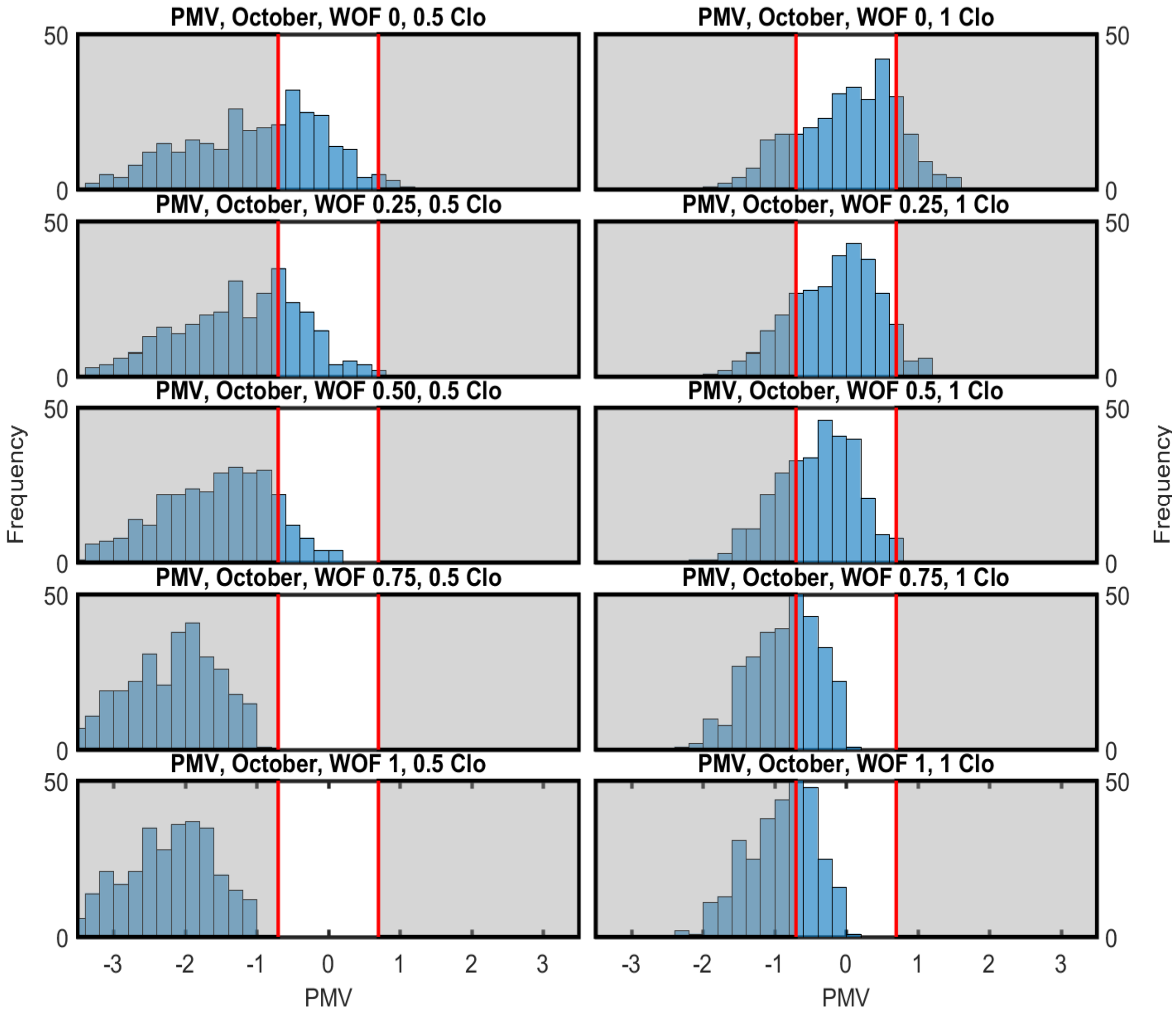

Figure 6. PMV frequency distribution for airtight house (October)

4. Conclusion

This work has shown that thermal and airflow simulations can be used to capture the effect of the natural ventilation through a window in terms of the Predicted Mean Vote (PMV) thermal comfort index of a residential house located in a mild climatic condition of, for example, Auckland. The indoor air temperature and relative humidity can be decreased to the maximum limit equivalent to the ambient air temperature and relative humidity by opening a window in the daytime summer months. This potential can be used to maintain the indoor thermal comfort level of a residential house within an acceptable thermal comfort range. However, this may need to be accompanied by greater levels of insulation than the minimum set by the NZ building code.

As such, there is a significant scope for regulating the thermal behavior and thermal comfort level of relatively air-tight natural ventilated residential houses in mild climatic conditions, and in particular, by opening windows during the summer day time period. The scope can be extended for winter-summer or summer-winter transition months with an adaptation of summer to winter clothing.

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