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Improving Thermal Comfort Regulating Potential in Naturally Ventilated Residential House

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Abstract

Maintaining the indoor thermal comfort characteristics of a house by modulating natural ventilation is particularly challenging, as the solution is not explicit. Determining a solution requires solving the complexity, dynamics, and nonlinearity associated with the natural ventilation driving forces and building thermal behavior. However, prior to finding any solution to this effect, the potential of regulating thermal behavior of the building with respect to different operating conditions needs to be examined in detail.

Previous studies have found that there is some scope for regulating the thermal behavior of relatively air-tight house by opening or shutting the window. 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 various Window Opening Fraction (WOF), different air-tightness values and different level of envelope thermal resistance utilizing coupled thermal and airflow simulations. This work demonstrates that the scope for regulating the thermal comfort behavior of a naturally ventilated residential house improves with a relatively well-insulated envelope.

1. Introduction

In New Zealand (NZ), there are approximately 1.6 million residential houses (Buckett and Burgess, 2007) typically constructed with metal roofs mounted on timber frames, a larger floor area and little or no insulation. Combining this behaviour with the current NZ building code for energy efficiency, (NZS 4218, 2009), 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). That said, it is traditional to ventilate residential houses passively by opening windows (Ryan et al. 2008) to achieve the occupant thermal comfort and reduce the risk of developing health issues.

In saying this, 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 is 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 respect, natural ventilation of a building may influence the thermal comfort level by removing excess heat by direct cooling (Ghiaus et al., 2004). Furthermore, PMV can be divided into three comfort categories as shown in Table 1 (EN ISO 7730, 2005); those ranging between ± 0.5 are broadly considered as a comfortable environment (ASHRAE-55, 2010). The "C" category, having a higher PMV comfort scale range (± 0.7) may be considered as acceptable to people accustomed to naturally ventilated environments.

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

Categories	PMV range	PPD
A	± 0.2	< 6
B	± 0.5	< 10
C	± 0.7	< 15

Finding a solution to control the natural ventilation by regulating the openable window area might help maintain the thermal comfort condition in the occupied space, however it is particularly challenging, as the solution is not explicit. The reason is the prevailing non-linear relationship between buoyancy and wind driving forces of the natural ventilation (Linden, 1999 and Hunt and 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).

In this respect, Pokhrel et al. (2017), in their initial investigation demonstrated that the problem can well be approached by applying Artificial Neural Network (ANN) technique to address the challenges of the non-linear nature of the problem. While doing this, the authors were successfully able to model the ANN and predict the time series of the indoor air temperature of a naturally ventilated house. Additionally, Pokhrel et al. (2016) examined the thermal comfort characteristics of a typically insulated NZ house considering meeting a minimum standard (NZS 4218, 2009). These works considered a range of operating conditions sans variation in envelope thermal resistance and demonstrated a possibility of having a significant scope of regulating the thermal behavior of relatively airtight house by adjusting the window openable area in the summer. However, Ryan et al. (2008) and Bassett (2001), in their research work also revealed the fact that the housing stock of NZ consists of not only a huge variation in airtightness (0.3 to 0.9 Air Changes per Hour (ACH)) but also building fabric characteristics. As such, to fill up the gap in the earlier research works this work particularly aims to include the effect of non-linearity due to different envelope thermal resistance on thermal comfort regulation potential of naturally ventilated residential house particularly focusing summer.

2. Methodology

To determine the performance of the coupled thermal and airflow environment in a typical NZ house, the TRNSYS Type 56 model was used in conjunction with a COMIS (COMIS, 2005) airflow analysis based on a network model of the house. For this study, a single room of 3 m length, 3 m width and 3.6 m reference height, as shown in Figure 1, was modelled. The model was used to simulate values of the airflow through the opening, occupied temperature based on heat and mass conservation laws with its well-mixed assumption (Hiller et al., 2002). While doing this, the temperature was 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. By assuming that one average value of the thermal comfort index of a typical room of the residential houses is sufficient, a secondary analysis of the values of PMV were also performed to reveal an overall scope of the thermal comfort status and its regulating potential.

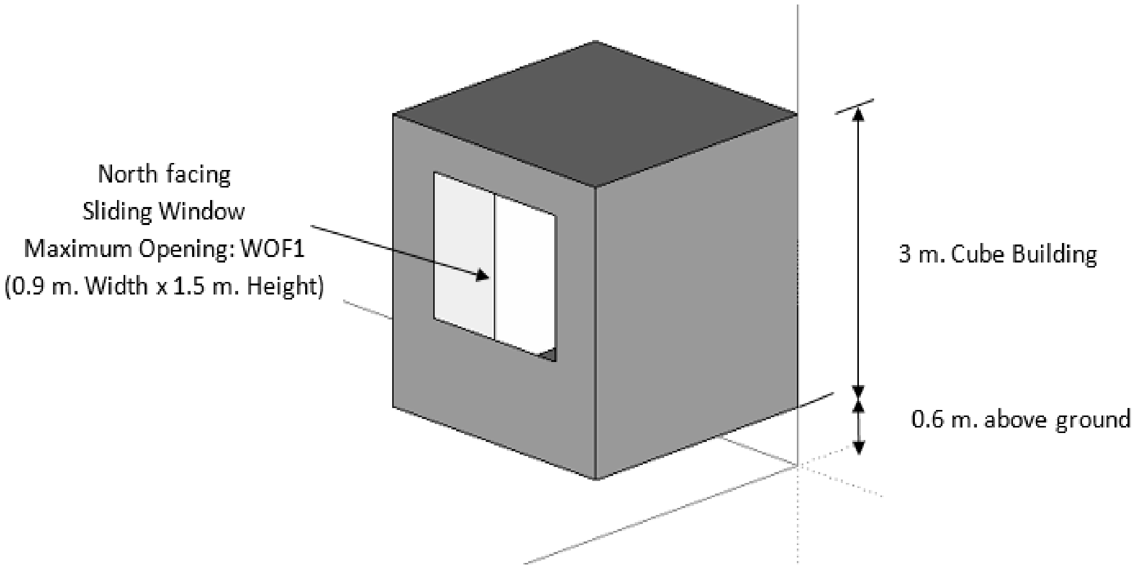

Figure 1. Building 3D model

It is obvious that a building thermal model requires considering the main modes of the building heat transfer (conduction, convection, radiation) along with the external and internal thermal driving forces (Demetriou, 2006); further details of this can be found in TRNSYS 17 documentation (TRNSYS 17, 2009) for standard type 56 building modelling. In saying this, the default values of the constants and exponents were used for the vertical and horizontal surfaces for an internal calculation of surface heat transfer coefficients. Also, the correlation cited on TRNSYS-Users Archives (2007) for the wind loss modelling was used to model the external heat transfer coefficient that are dependent on exterior surface material and wind velocity.

In the modelling, it was assumed that 0 to 5 occupants, producing heating of 100 Watts per person (sensible-60 and latent-40), occupied the room randomly. This rate of heat gain was equivalent to the activity level of the occupant seated at rest inside the house (TRNSYS 17, 2009) making a threshold of internal heat gain from 0 to 500 watts. In addition to this, this simple random model of occupancy producing a relatively wider range of internal heat gain was considered sufficient to absorb the possible effect of internal loads including some additional virtual plug loads. Further, it was assumed that the building was located in Auckland NZ at 36.85˚ S, 174.76˚ E with each wall aligned to the cardinal directions and a single window on the north face. In addition to this, Table 2 presents the building facade details for a baseline envelope thermal Resistance (R-value) (Case 1) just meeting the current standard schedule method for non-solid construction (NZS 4218, 2009), resulting a weighted average envelope thermal Resistance (R_{avg}) value of the house equivalent to 2.01. Further, intermediate insulation layer R-values of 2.6 (case 2), 3.2 (case 3) and 3.6 (case-4) were considered on the envelope components (wall, roof, and floor) to explore the overall improved average envelope R_{avg} of 2.6, 3.22 and 3.44 respectively.

To achieve the ventilation a Large Vertical Opening (LVO type 1) (COMIS, 2005) with a maximum opening size of 0.9 m (width) by 1.5 m (height) as shown in Figure 1 was used to model a sliding window. In doing this, a WOF defined as 1 for fully open and 0 for fully shut was applied. In addition, intermediate discrete WOF values of 0.1, 0.25, 0.5, and 0.75 were also considered to explore the effect of the various window openable area on the thermal conditions. Besides, finding the relative effect of a range of openable area on space thermal conditions and its relative thermal comfort regulation potential, this method of discretizing WOF values was anticipated to help investigate on applying ANN technique to actuate the window to maintain indoor thermal comfort condition.

Table 2. Building facade description

Building Facade	Description	R-Values			
		Case 1 R~NZBC	**Case 2 R 2.6**	**Case 3 R 3.2**	**Case 4 R 3.6**
External Wall	Timber frame direct fixed cladding	1.9	2.4	3.1	3.2
Floor	Suspended floor with lining under the joists and gap between insulation and lining	1.3	3.1	3.5	3.8
Roof	Timber frame skillion roof	2.9	3	3.4	3.8
Window	Vertical double glazed sliding window (1.8 m. width x 1.5 m. height) Northern wall	0.34	0.34	0.34	0.34
Area weighted average envelope resistance (R_{avg})		2.01	2.6	3.22	3.44

Finally, the housing stock was also discretized by its airtightness level from a least airtight-Draughty (DTY) house with 0.9 ACH to the most airtight-Ultra Airtight (UAT) house with 0.03 ACH. While doing this, the un-controlled infiltration equivalent to intermediate airtightness levels defined as Airtight (AT) (0.3 ACH), Average (AVG) (0.5 ACH) and Leaky (LKY) (0.7 ACH) houses were also considered. In a summary, a total of 120 simulations were carried out to observe the effect of 6 discrete WOF values (0 to 1), 5 discrete values of airtightness level (0.03 to 0.9) and 4 different envelope thermal resistance cases (R_{avg} 2.01 to R_{avg} 3.44). Finally, the thermal behaviour of the zone was assessed by computing the indoor room temperature and the values of PMV thermal comfort index for the free running condition, with no additional heating, cooling or plug loads. The analysis was presented particularly focusing the cooling potential of natural ventilation for a representative peak summer month of January.

3. Result and Discussion

To examine the level of thermal comfort regulation potential of the model house, a baseline scenario equivalent to different discrete values of window openable area equivalent to WOF (0, 0.1, 0.25, 0.5, 0.75 and 1) was simulated for 8760 hours with a time step of 1 hour. It generated an hourly time-series of occupied zone air temperature and the PMV profile for different values of R_{avg} (2.01, 2.6, 3.22 and 3.4) and airtightness level (0.03, 0.3, 0.5, 0.7 and 0.9) ACH as defined.

Comparing the simulation results for the model virtual houses with a range of airtightness levels and the values of WOF, Figure 2 and Figure 3 demonstrate that there exists an improved potential for thermal comfort regulation by opening windows in better-insulated houses (R_{avg} 3.4) compared to a baseline insulated (R_{avg} 2.01) house for the summer month of January. Nevertheless, a close comparison of the Figure 2 and Figure 3 shows that there is only a marginal improvement on the maximum achievable percentage of overall thermal comfort instances (~45% for R_{avg} 2.01 to ~48% for R_{avg} 3.44) up to an intermediate value of WOF 0.75 and again lowers further for WOF 1.

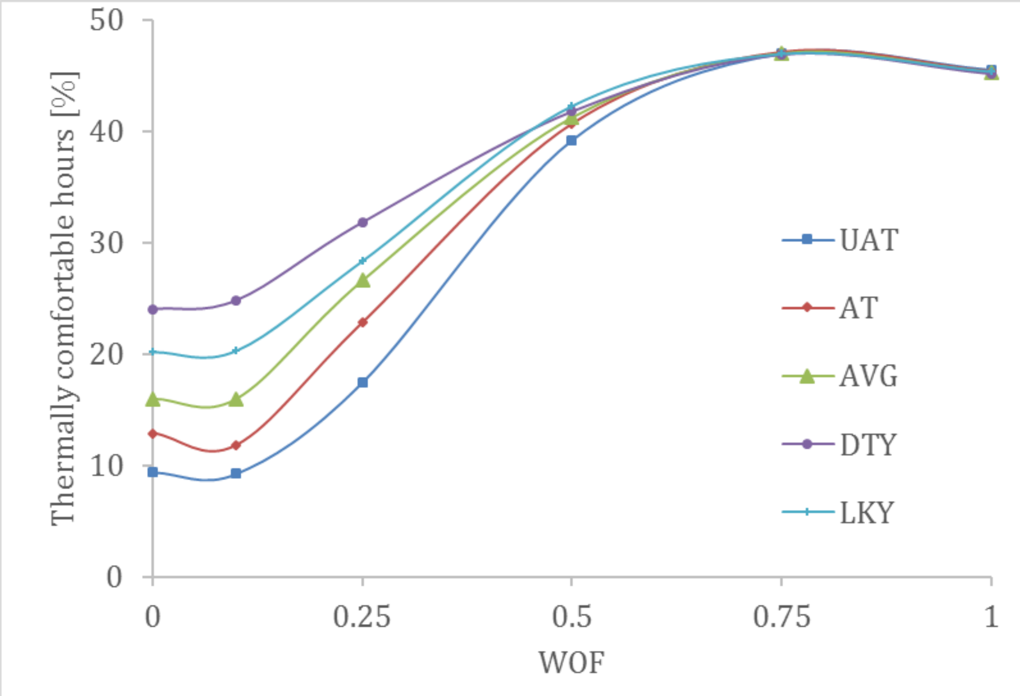

Figure 2. Percentage thermal comfort duration (-0.7<PMV<0.7) with respect to WOF (January, R_{avg} 2.01)

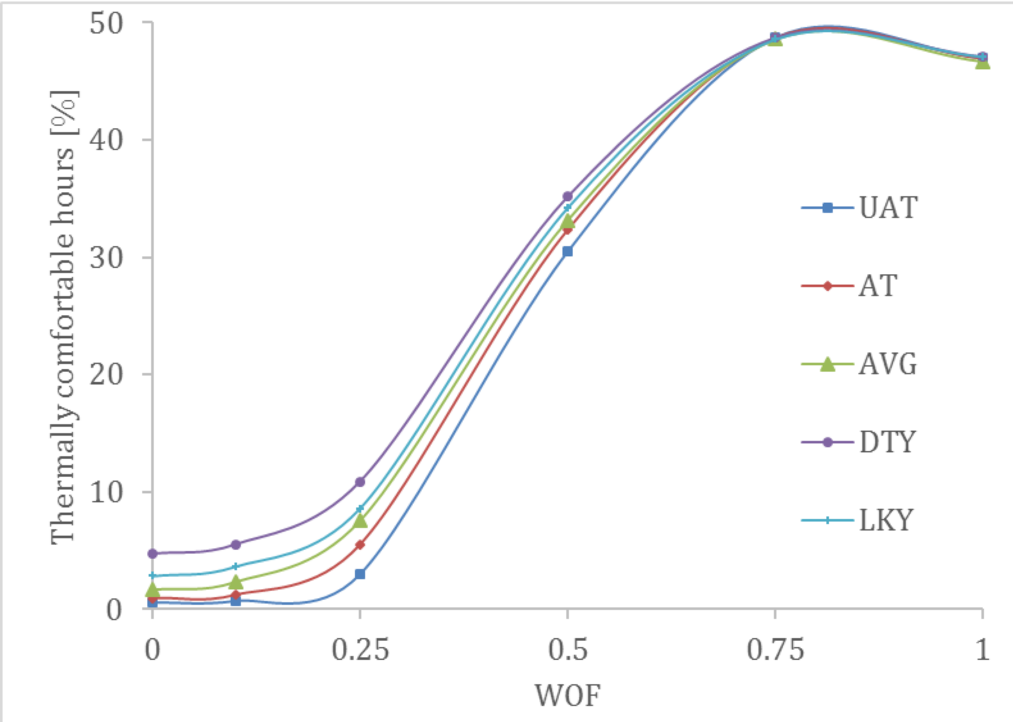

Figure 3. Percentage of thermal comfort duration (-0.7<PMV<0.7) with respect to WOF (January, R_{avg} 3.4)

Apparently, despite having an insulated and airtight house, it reveals that a large proportion of the instances (more than 50%) still fall into either an uncomfortable cold or hot range, making the prospect of any position of fixed openable area is limited for improving thermal comfort of the naturally ventilated house.

Examining the results further for the same set of virtual houses, particularly focusing on percentage of uncomfortable hot period, Figure 4 and Figure 5 demonstrate that envelope airtightness can also play significant role in regulating thermal comfort behavior of the naturally ventilated house. However, the degree of regulating potential reduces with reducing level of the airtightness. It is also obvious from the analysis that there exists a relatively higher likelihood of overheating the indoor environment in better-insulated and airtight houses. Also, the effect of different level of envelope airtightness gradually disappears as the window openable area relatively increases for greater values of WOF.

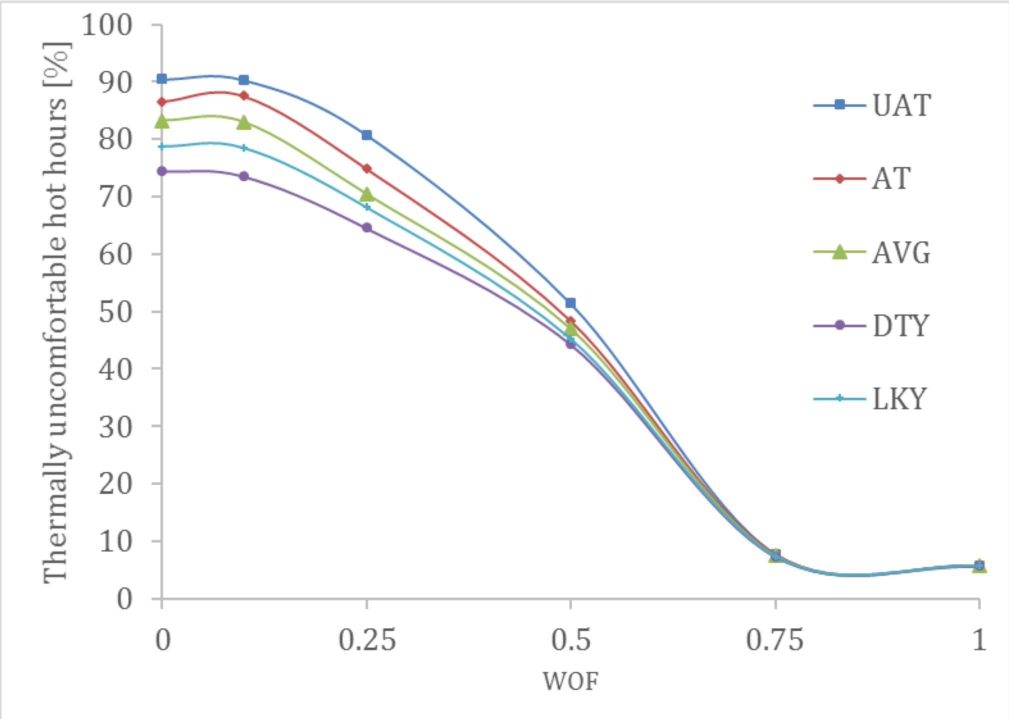

Figure 4. Percentage of thermally uncomfortable hot duration (PMV>0.7) with respect to WOF & airtightness (January, R_{avg} 2.01)

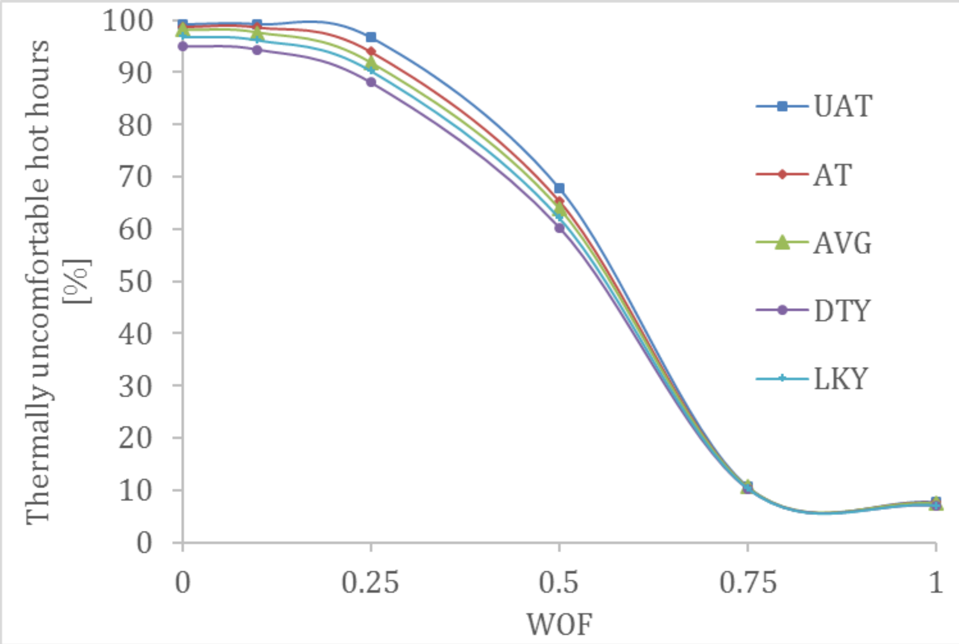

Figure 5. Percentage of thermally uncomfortable hot duration (PMV>0.7) with respect to WOF & airtightness (January, R_{avg} 3.4)

In naturally ventilated houses, the fixed opening of the window during unnecessary periods might also effect the indoor thermal behavior by making it uncomfortably cold. To assess it further, Figure 6 demonstrates an increasing percentage of uncomfortably cold instances for higher values of WOF for the similar set up of virtual houses having different values of envelope airtightness for a baseline-insulated house (R_{avg} 2.01).

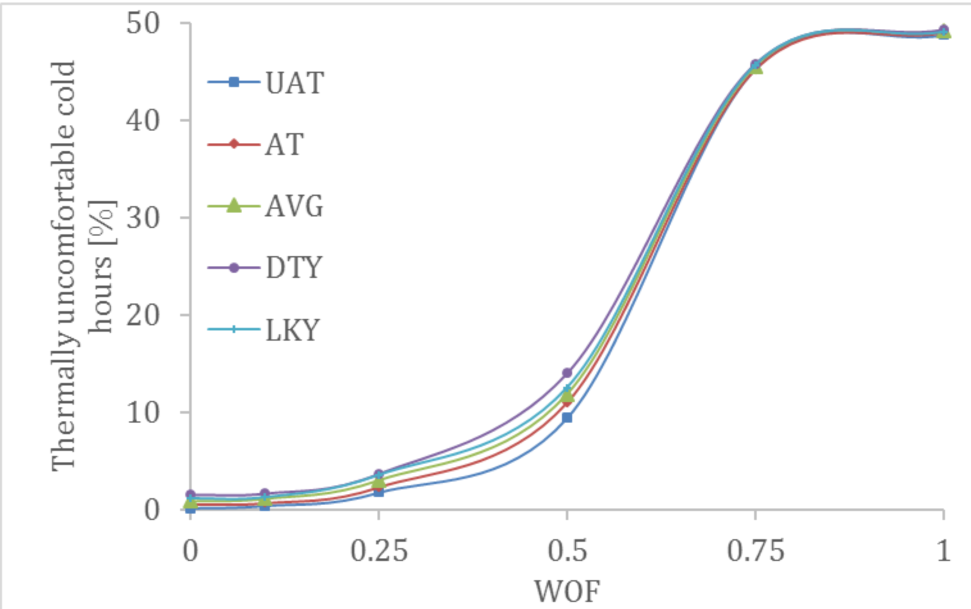

Figure 6. Percentage of thermally uncomfortable cold (PMV<-0.7) duration with respect to WOF & airtightness (January, R_{avg} 2.01)

However, for a relatively better-insulated (R_{avg} 3.4) houses, the resilience towards attaining instances having uncomfortable-cold periods relatively improves (up to WOF value of 0.5) as shown in Table 3. This can be demonstrated by having a maximum value of 4.58 percentage of thermally uncomfortable cold period at WOF value of 0.5 for a drafty (DTY) house. Moreover, the distribution of the values due to various level of airtightness for a specific window opening condition is also not significant despite being better-insulated house (R_{ave} 3.4) making them more favourable for regulating indoor thermal behaviour by adjusting window opening area.

Table 3. Percentage of thermally uncomfortable cold (PMV<-0.7) periods with respect to WOF & airtightness (January, R_{avg} 3.4)

	Uncomfortably cold period [%]				
WOF	**UAT**	**AT**	**AVG**	**DTY**	**LKY**
0	0.28	0.28	0.27	0.28	0.28
0.1	0.14	0.15	0.15	0.14	0.14
0.25	0.41	0.55	0.68	1.08	1.08
0.5	1.76	2.3	2.96	4.58	3.64
0.75	40.55	40.68	40.81	41.08	41.08
1	45.25	45.38	45.78	45.92	45.78

In a summary, the results demonstrates that the improved thermal resistance and air-tightness of the envelope helps to store thermal energy generated internally by occupants, solar load and thermal load due to air temperature. Furthermore, the stored thermal energy can either reduce uncomfortably cool periods or result in an increase in uncomfortably warm periods. However, as the fixed window opening increases, it essentially increases the leakiness of the room by allowing higher air exchanges rates to occur. Ultimately, opening the window can help reduce uncomfortable warm period.

4. Conclusion and Recommendations

This work utilised dynamic simulations to examine the variation of thermal comfort 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 examined the PMV of the room with various WOF, different air-tightness values and different level of envelope thermal resistance utilizing coupled thermal and airflow simulations. In doing this the work demonstrated that the scope for regulating the thermal comfort behavior of a naturally ventilated residential house improves with relatively insulated and airtight envelope.

Additionally, different discrete values of WOF providing different values of window openable areas could result in a varying potential for natural ventilation and indoor thermal comfort. This can be used to regulate and improve the indoor thermal behavior to some extent; and the indoor thermal behaviour might be improved further towards attaining more comfortable period by manually varying the WOF across the day, month-wise and season-wise. Nevertheless, it does not seem practical to continuously adjust the window position manually in a quest to maintain thermal comfort.

In this context, a technique to intelligently actuate the windows and regulate the values of WOF for maximizing the percentage of thermal comfort period by minimizing both thermally uncomfortable hot and cold period needs to be investigated further.

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