CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 5

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

A field study on the thermal comfort performance of a ventilative cooling system in a retrofitted low energy building

Adam O' Donovan[#1], Paul D. O' Sullivan[#2], Michael D. Murphy[#3]

[#]Process, Energy and Transport Department, Cork Institute of Technology, Rossa Avenue, Bishopstown, Cork, Ireland

[1]adam.odonnabhain@mycit.ie [2]paul.osuillvan@cit.ie [3]michaeld.murphy@cit.ie

Abstract

Ensuring optimal thermal comfort performance in low energy building retrofits during the shoulder and summer months is challenging. One of the reasons for this is overheating due to internal and solar heat gains. The prompt removal of this trapped heat, using natural ventilation only, is critical to ensuring adequate levels of thermal comfort in buildings. This study investigated and evaluated the thermal comfort performance of a retrofitted ventilation system in a low energy building. A control space was preheated in order to simulate an overheating scenario in shoulder season conditions. Four ventilation configurations were investigated with one control configuration (no ventilation). The thermal comfort performance of each configuration was evaluated subjectively using two standardised questionnaires based on ISO10551. Thermal comfort was also analysed objectively through the calculation of a variety of thermal comfort indices. The results of each configuration were categorised using ISO7730, where the actual and predicted thermal comfort were compared. Results showed that the Predicted Mean Vote model over-estimated neutral thermal sensation votes by over 100% throughout the study, while failing to register any thermal votes outside of the range -1 to +1. The calculated neutral temperature for participants in the study was seen to be 24.8°C. Overall the results showed there was a difference in thermal comfort performance for two configurations of the same area but with different opening heights. Subjectively the best category of comfort from ISO 7730 was not achieved for any ventilation configuration during the study, with the highest category achieved being category B.

Keywords – thermal comfort, natural ventilation, low energy building

Nomenclature

f_{cl}	clothing surface area factor	PPD	Percentage People Dissatisfied
h_c	convective heat transfer coefficient (W/(m^2.K))	RH	relative humidity (%)
I_{cl}	clothing thermal resistance (clo, m^{2}K/W)	t_a	air temperature (°C)
M	metabolic rate (met, W/m^2)	t_o	operative temperature (°C)
n	sample size	t_r	mean radiant temperature (°C)
$\overline{X}$	sample mean	t_{cl}	clothing surface temperature (°C)

s	sample standard deviation	v_a	relative air velocity (m/s)
p_a	water vapour partial pressure (Pa)	W	effective mechanical power (W/m^2)
PMV	Predicted Mean Vote		

1. Introduction

Buildings are estimated to be responsible for 32% of global final energy demand [1]. In order to reduce energy consumption in buildings as well as the inherent carbon emissions, there is a need for improvements to be made to existing building energy performance. From a European perspective the EPBD Recast requires all new buildings to be nearly zero energy buildings (NZEB) by 2020 [2]. Achieving a similar level of performance in existing buildings requires energy efficient retrofitting. Through improvements to a buildings fabric, increased air-tightness and the ability to utilise passive solar and internal gains significant reductions in thermal energy consumption can be made. The thermal comfort performance of these buildings can also be greatly enhanced during the heating season. However during the shoulder and summer months these low energy buildings can suffer from overheating due in part to solar and internal heat gains but also as a consequence of reduced heat loss through the building envelope.

Guaranteeing both low energy performance and annualised thermal comfort in a retrofitted building is a major challenge, where the design solution can be approached in a variety of ways. In [3] the approach taken showed that considerable reductions in building energy consumption can be made by updating a 1970’s building through passive modifications. In [4] reductions in space heating energy consumption through fabric improvements through retrofitting buildings were seen in the UK. While [5-6] highlighted the potential for large reductions in thermal energy consumption through retrofitting of existing buildings. Retrofitting of buildings has been seen to improve general thermal comfort levels [7]. However the risk of overheating still remains an issue for low energy refurbished buildings and improvements need to be made to mitigate any future overheating risks [8].

Studies on thermal comfort in buildings typically focus on either general thermal comfort [9-13], or investigate the effect of localised phenomena (eg. stratification, draughts) on thermal comfort [14-15]. Evaluating thermal comfort in buildings can be done both subjectively and objectively. Subjective comfort levels are assessed by surveying building occupants regarding a buildings thermal environment through standardised questionnaires. Questionnaires are typically developed in compliance with ISO 10551 [16-17] or ASHRAE guidelines [18].

Objectively, the built environment can be evaluated through the measurement of a variety of environmental and personal factors in order to calculate thermal comfort indices. The predicted mean vote (PMV) and percentage of persons dissatisfied (PPD) indices [19] are some of the most widely used indices for evaluating the internal environment of a building. Typically used to evaluate air-conditioned spaces, the universality of the PMV model has been questioned in its capabilities in evaluating naturally ventilated buildings [20], at times over predicting of thermal sensation in warm climate field studies [21]. Several adaptations to this model have been proposed to make it more applicable to in naturally ventilated buildings [22-23]. However typically thermal comfort in naturally ventilated buildings is evaluated using the adaptive method proposed in EN 15251 [24]. Developed by [25] the adaptive approach assesses comfort based on the operative temperature index, where a varying operative temperature limit applies to buildings in free running mode during the cooling season. The adaptive model can be adopted in assessing thermal comfort, assuming that occupants are allowed to adapt to their thermal environment freely through, clothing adjustments, the use of operable windows or blinds, or the consumption of hot or cold drinks [26]. The tolerance of building occupants to internal temperatures can be also be broadened through the use of mixed mode ventilation [27] or allowing occupants to adapt freely [28].

This paper presents the findings from a thermal comfort study in a recently retrofitted low energy building. The ventilative cooling system in this naturally ventilated building was assessed by examining the thermal comfort performance of four ventilation configurations. Typical mean ventilation rates and dominant driving forces for each of these configurations were previously investigated experimentally by [29-30]. The overall aim was to determine which configuration provided the best level of thermal comfort in a simulated overheating scenario during the shoulder season.

Materials and Methods

2.1 Experimental Setup

The study was conducted in a north facing seminar room of the "Zero2020 retrofit testbed" building [31] which is part of the wider campus of Cork Institute of Technology (CIT) in Cork, Ireland. Figure 1 indicates the location of all sensors during the study. All parameters were measured at heights in accordance with ISO 7726 [32]. Air temperature was measured at heights of 0.1m, 0.6m and 1.1m, while all other parameters including globe temperature, relative humidity and air velocity were measured at a height of 1.1m. Air velocity was measured in both locations indicated using two bi-directional anemometers where one anemometer measured velocity in the x-axis of the room and another measured velocity in the y-axis of the room. Table 1 below details the accuracy of all instruments used in the study.

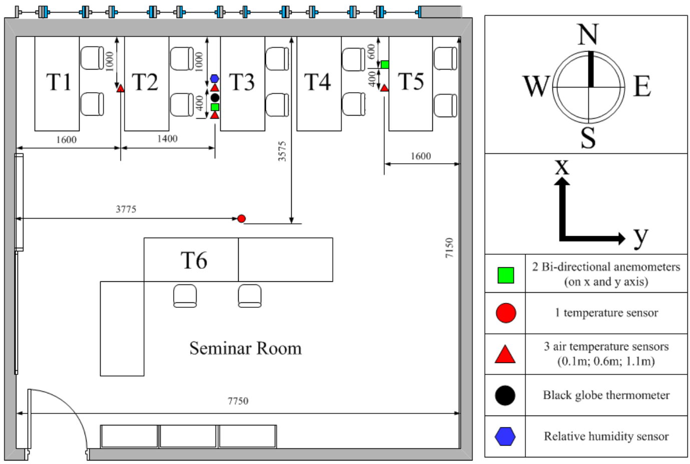

Fig. 1 Seminar room layout with parameter measurement points indicated

Table 1. Accuracy and recording intervals for all instrumentation used

Parameter	Model	Operating range	Accuracy	Interval
Temperature	Hanwell 4002T	-40°C to 60°C	±0.1°C (-10 to 40°C)	1 min.
Temperature	QUESTemp 36	-5°C to 60°C	±0.5°C (0°C to 120°C)	1 min.
RH	Hanwell 4115RHT	0% to 100%	±2% (0% to 90%) ±3% (90% to 100%)	1 min.
Velocity	E+E Elektronik, EE576-V3B2	0m/s to 2m/s	±0.08m/s (0.2m/s to 2m/s)	1 sec.

2.2 Study description and procedure

The field study took place during two study days in May 2015. In total the thermal evaluations from 35 participants (n=35, females = 10, males = 25) were gathered. Each study day consisted of two thermal comfort assessment sessions, with one in the morning and one in the afternoon. The maximum number of participants allowable for each study session was 10, due to space limitations. Each session consisted of four 30 minute tests which evaluated four ventilation configurations as shown in Figure 2. Subjective evaluations during all tests were gathered using two standardised questionnaires based on ISO 10551. One questionnaire (Survey A) asked questions regarding the participants fixed parameters (eg. location, age, gender, etc). The second questionnaire (Survey B) was a subjective thermal comfort questionnaire, which evaluated each participants personal state during the study.

RS – 01 (Test 1) RS – 02 (Test 2) RS – 03 (Test 3) RS – 04 (Test 4)

Fig. 2 Ventilation configurations from left to right: RS-01 (no ventilation), RS-02 upper louvre only, RS-03 lower louvre only, RS-04 both louvres open.

In order to simulate an overheating scenario for each test, the centre of the room was preheated to 26°C (±1°C) using six electrical space heaters (2000W each). Three desk fans (30W each) were used to ensure that the temperature of the air in the room was sufficiently distributed spatially (using 14 temperature sensors), assuring uniform temperature conditions for each participant. Once the set-point was reached, the space heaters were removed, the participants were seated and the test began.

Fig. 3 Image of study conducted on the 28th-29th of May 2015. A maximum of 10 participants were seated at any one time during each test and all subjective evaluations and objective data were gathered at the end of each 30 minute test.

In order to evaluate the effect of adaptive ventilative actions only on occupants in a low energy space, participants were told to choose their clothing level at the beginning of each session and maintain this clothing level until the end of the study. Participants undertook typical sedentary activities throughout the study (i.e. reading, writing, watching etc.) as shown in Figure 3. Subjective data from questionnaires was collected via an online survey. Survey A was gathered first at the start of each session and Survey B was gathered at the end of each test. Internal environmental data was gathered continuously throughout each test. External weather data was gathered at 5 minute intervals, at a height of 10m on the roof of the building.

2.3 Thermal comfort models utilised

Three thermal comfort indices were used to evaluate the thermal comfort performance of this low energy building in a simulated shoulder season overheating scenario. The PMV index was used to calculate the predicted comfort utilising six parameters, four environmental parameters (air temperature, relative humidity, mean radiant temperature) and two personal parameters (clothing level and activity). The mean radiant temperature was determined using equation 8 in Annex B of ISO 7726 [32]. The PMV model is used to determine the mean vote of participants evaluating a thermal environment using a 7-point thermal sensation scale (cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2), hot (+3)). The PMV was calculated using an algorithim based on the source code for ISO 7730 shown in Equation 1 and was validated against the sample outputs presented in Table D.1 [33]. The PPD index was calculated using Equation 2.

$$\begin{aligned} PMV = &\left[0.303e^{((-0.036\cdot M)+0.028)}\right]\{(M-W) \\ &- 3.0510^{-3}[5733 - 6.99\ (M-W) - p_a] \\ &- 0.42[(M-W) - 58.15] \\ &- 1.710^{-5}M(5867 - p_a) - 0.0014M(34 - t_a) \\ &- 3.9610^{-8}f_{cl}[(t_{cl}+273)^4 - (t_r+273)^4] \\ &- f_{cl}h_c(t_{cl} - t_a)\} \end{aligned} \tag{1}$$

$$PPD = \ 100 - 95e^{(-0.3353(PMV^4)-0.2179(PMV^2))} \tag{2}$$

The operative temperature for each minute during each test was also calculated using Equation 3, in order to show the dynamic response of the internal environment to each natural ventilation configuration. This index was used also to calculate the neutral temperature of occupants during the study. In order to compare configurations regarding predicted and actual performance, the categories of thermal environment [33] stated in ISO 7730 where used.

$$t_o = \frac{t_a\sqrt{10(v_a)} + t_r}{1 + \sqrt{10(v_a)}} \tag{3}$$

3. Results and Discussion

In order to represent the environmental conditions as study participants were completing the online questionnaires the average of the last two minutes of environmental parameters were taken when calculating the PMV and mean operative temperatures for all test results shown in this paper. The clothing level for males ($\overline{X}$ = 0.70, s = 0.18) in the study was slightly higher than that of females ($\overline{X}$ = 0.66, s = 0.22). Table 2 shows the actual thermal votes of participants in the study where the PPD is calculated using the actual mean vote (AMV) shown.

Table 2. Descriptive statistics and percentage of persons dissatisfied for thermal sensation votes during the study

	Test No.			
	1	**2**	**3**	**4**
Actual Mean Vote	1.29	-0.40	-0.49	-1.06
Median	1	0	0	-1
Std. Deviation	0.893	0.946	0.981	1.083
Minimum	0	-2	-2	-3
Maximum	3	1	1	1
PPD (%)	40%	8%	10%	29%

The PMV was calculated using the average of four temperature sensors that were at a height of 1.1m. A metabolic rate for sedentary activities (1.2met, 70W/m^2) were taken for all study participants. While the specific clothing levels of each participant as used to determine the PMV, this was without the inclusion of additional clothing for the chairs used. Table 3 indicates the averaged environmental parameters after 28 minutes.

Table 3. Calculated averaged environmental and external parameters for each test. Parameters presented are the average of 4 independent tests.

Time averaged test parameter	**Test No.**			
	1	**2**	**3**	**4**
T_a (°C)	25.6	24.2	23.6	22.4
RH (%)	45	41	38	36
Globe Temperature (°C)	25.9	24.9	24.3	23.4
T_r (°C)	26.1	25.6	25.0	24.3
T_o (°C)	25.9	24.8	24.2	23.3
Velocity (m/s)	0.07	0.16	0.11	0.10
External Air Temperature (°C)	11.5	12.2	12.4	12.9
External Wind Speed (m/s)	3.4	3.4	3.3	4.3

Wind Direction (Degrees)	146.3	139.8	138.3	151.1
PMV	0.53	0.12	0.06	-0.17
PPD (%)	11%	5%	5%	6%

Figure 4 shows a comparison of predicted and actual thermal votes for each test configuration using the average environmental parameters for the last two minutes. It can be seen that a large number of neutral votes were predicted using the PMV model. Overall neutral responses were over-predicted by 100%. The PMV model failed to register thermal votes outside of the range +1 to -1. Table 2 and 3 indicate a difference between the actual PPD and predicted PPD of 29% in test 1, 3% in test 2, 5% in test 3, and 23% in test 4. Table 3 shows the same predicted performance for tests 2 and 3, however this differs in practise. This suggests perhaps a difference in thermal sensation exists due to the height of the louvre opening for low energy buildings. Subjectively, test 1 and test 4 are outside of the categories presented in ISO 7730. Test 2 and test 3 are in categories B and C, respectively.

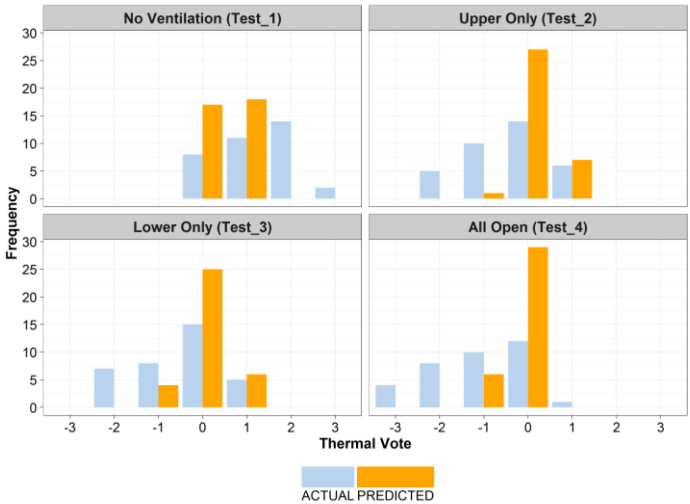

Fig. 4 Bar charts of actual versus predicted thermal votes for each test configuration

Figure 5 shows the dynamic response of each ventilation configuration tested in the study. If the categorisation following ISO 7730 is adopted, the predicted final results categorically for test 1 is category B, test 2 and test 3 are predicted to be in category A, while test 4 is in category B. The no ventilation configuration shows that, if ventilation is not utilised, the control space will remain in category B. If ventilation is applied to resolve the discomfort experienced, RS-02 (Test 2) and RS-03 (Test 3) are seen as better options to restore comfort as RS-04 (Test 4) has with it the risk of overcooling in shoulder season conditions.

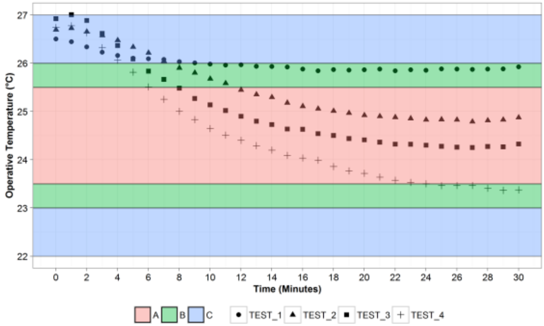

Fig. 5 Average operative temperatures for each minute for each ventilation configuration

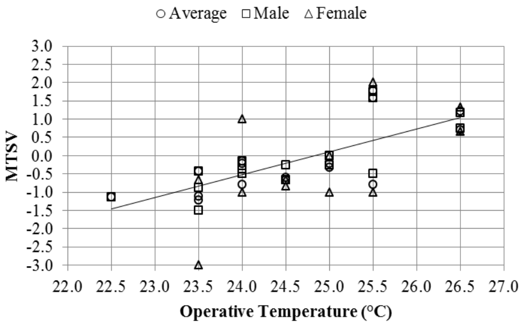

Fig. 6 Observed relationships between mean thermal sensation votes and binned operative temperatures for each test during each thermal comfort session. The linear trend-line shown is for the mean thermal sensation votes for all participants during each test

Figure 6 depicts mean thermal sensation votes (MTSV) for all tests in the study against the operative temperature (binned in 0.5°C intervals). All correlations drawn between MTSV and operative temperatures for average, male and female scenarios were seen to have a statistically large effect size ($r^2 \geq 0.25$). The average neutral temperature calculated was 24.8°C while the male neutral temperature was 24.7°C and the female neutral temperature was 25.2°C. These temperatures are comparable with the optimal scenario presented in ISO 7730 for cooling season performance of 24.5°C.

4. Conclusions

This study presented results from a general thermal comfort evaluation of a natural ventilation system in a low energy space. It evaluated the comfort both subjectively and objectively of four ventilation configurations. Subjectively the highest level of thermal comfort performance detailed in the standards used was not achieved with PPD being greater than 6% for all test configurations. From an objective perspective the study showed that the PMV model did not predict the actual category of comfort that was subjectively indicated. The PMV model failed to register any votes outside of the range +1 to -1 and overestimated the tendency of votes towards neutrality by 100%. The subjective results show that for two louvres of the same opening area that thermal comfort performance can be different where test 2 achieved Category B and test 3 achieved Category C. Overall it can be seen that maintaining high levels of comfort using a natural ventilation system in shoulder seasons is challenging as when cooling is required there is a potential to overcool buildings due to the high climatic cooling potential of the outside air.

References

[1] D. Ürge-Vorsatz, L. F. Cabeza, S. Serrano, C. Barreneche, and K. Petrichenko. Heating and cooling energy trends and drivers in buildings. Renew. Sustain. Energy Rev. 41 (2015) 85–98.

[2] E. Parliament. Energy Performance of Buildings Directive Recast. (2010) 13–35.

[3] P. D. O' Sullivan, F. Delaney, M. O’ Riain, T. Clancy, J. O’ Connell, and D. Fallon. Design and Performance of and External Building Envelope Retrofit Solution for a Grid Optimised Contcrete Structure: A Case Study. In: 30th International Manufacturing Conference, Ireland, pp. 1–12, 2010.

[4] S. H. Hong, T. Oreszczyn, and I. Ridley. The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings. Energy Build. 38 (2006) 1171–1181.

[5] L. Liu, P. Rohdin, and B. Moshfegh. Evaluating indoor environment of a retrofitted multi-family building with improved energy performance in Sweden. Energy Build. 102 (2015) 32–44.

[6] Z. Zhou, S. Zhang, C. Wang, J. Zuo, Q. He, and R. Rameezdeen. Achieving energy efficient buildings via retrofitting of existing buildings: a case study. J. Clean. Prod. 112 (2016) 3605-3615.

[7] S. H. Hong, J. Gilbertson, T. Oreszczyn, G. Green, and I. Ridley. A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. Build. Environ. 44 (2009) 1228–1236.

[8] R. S. McLeod, C. J. Hopfe, and A. Kwan. An investigation into future performance and overheating risks in Passivhaus dwellings. Build. Environ. 70 (2013) 189–209.

[9] M. N. Shaharon and J. Jalaludin. Thermal comfort assessment-a study toward workers’ satisfaction in a low energy office building. Am. J. Appl. Sci. 9 (2012) 1037–1045.

[10] M. A. Nico, S. Liuzzi, and P. Stefanizzi. Evaluation of thermal comfort in university classrooms through objective approach and subjective preference analysis. Appl. Ergon. 48 (2015) 111–20.

[11] A. F. Alajmi, F. a Baddar, and R. I. Bourisli. Thermal comfort assessment of an office building served by under-floor air distribution (UFAD) system: A case study. Build. Environ. 85 (2015) 153–159.

[12] M. Indraganti, R. Ooka, and H. B. Rijal. Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender. Energy Build. 103 (2015) 284–295.

[13] A. K. Mishra and M. Ramgopal. A thermal comfort field study of naturally ventilated

classrooms in Kharagpur, India. Build. Environ. 92 (2015) 396–406.
[14] H. Breesch, B. Wauman, and A. Versele. Impact of the use of a front door on Thermal Comfort in a Classroom in a Passive School. In: 35th AIVC Conference, pp. 226–235, 2009.
[15] A. Wagner, E. Gossauer, C. Moosmann, T. Gropp, and R. Leonhart. Thermal comfort and workplace occupant satisfaction—Results of field studies in German low energy office buildings. Energy Build. 39 (2007) 758–769.
[16] ISO 10551 - Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales. 1–25, 1998.
[17] F. R. D'Ambrosio Alfano, B. W. Olesen, B. I. Palella, and G. Riccio. Thermal comfort: Design and assessment for energy saving. Energy Build. 81 (2014) 326–336.
[18] ASHRAE - Thermal environmental conditions for human occupancy, 2004.
[19] P. O. Fanger. Assessment of man's thermal comfort in practice. Br. J. Ind. Med. 30(1973) 313–324.
[20] M. A. Humphreys and M. Hancock. Do people like to feel 'neutral'?. Energy Build. 39 (2007) 867–874.
[21] M. A. Humphreys and J. Fergus Nicol. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy Build. 34 (2002) 667–684.
[22] P. Ole Fanger and J. Toftum. Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy Build. 34 (2002) 533–536.
[23] R. Yao, B. Li, and J. Liu. A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV). Build. Environ. 44 (2009) 2089–2096.
[24] IS EN 15251 - Indoor Environmental Input Parameters for design and Assessment of Energy performance of Buildings addressing Indoor Air, 2007.
[25] F. Nicol and M. Humphreys. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN 15251. Build. Environ. 45 (2010) 11–17.
[26] R. J. de Dear and G. S. Brager. Developing an Adaptive Model of Thermal Comfort and Preference, 1997.
[27] H. Zhang, E. Arens, and W. Pasut. Air temperature thresholds for indoor comfort and perceived air quality. Build. Res. Inf. 39 (2011)134–144.
[28] M. Indraganti, R. Ooka, and H. B. Rijal. Thermal comfort in offices in summer: Findings from a field study under the 'setsuden' conditions in Tokyo, Japan. Build. Environ. 61 (2013) 114–132.
[29] P. D. O' Sullivan and M. Kolokotroni. Time-averaged Single Sided Ventilation Rates and Thermal Environment in Cooling Mode for a Low Energy Retrofit Envelope. International Journal of Ventilation 13 (2014) 153–168.
[30] P. D. O' Sullivan and M. Kolokotroni. Non dimensional analysis and characterisation of driving forces for a single sided slot louver ventilation system. International Journal of Ventilation 14 (2016) (Accepted).
[31] CIT, "Zero2020energy.com," 2014. [Online]. Available: http://www.zero2020energy.com/.
[32] ISO 7726 - Ergonomics of the thermal environment — Instruments for measuring physical quantities, 1–56, 1998.
[33] IS EN ISO 7730 - Ergonomics Of The Thermal Environment - Analytical Determination And Interpretation Of Thermal Comfort Using Calculation, 2006.