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REAL-TIME CONTROL OF OCCUPANTS THERMAL COMFORT IN BUILDINGS

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ABSTRACT

Providing satisfactory indoor environmental conditions, air quality and thermal comfort through adequate ventilation is crucial in maintaining safe, healthy and comfortable buildings. Since, heating, ventilation and air conditioning (HVAC) systems are significant contributors to energy consumed in buildings, natural ventilation solutions are being increasingly utilised.

This study investigated the use of natural ventilation as a solution to maintaining healthy and comfortable environmental conditions in a large mixed-use demonstrator building, the Engineering Building (EB) at the National University of Ireland (NUI) Galway in Ireland.

The results presented in this paper provide valuable information about the operation of the building and will allow for future validation of computational models to test different building operation strategies.

INTRODUCTION

People spend on average 90% of their lives indoors (US EPA 2012). All aspects of human life, from working, sleeping, studying to taking part in leisure activities can occur indoors. It is thus vital to provide safe, healthy and comfortable indoor environmental conditions for building occupants. Ventilation, which is the supply of fresh air and the removal of stale air in an indoor space, is key to providing satisfactory indoor environmental conditions, air quality and thermal comfort.

The building sector is responsible for about 40% of the total final energy consumption and over 30% of total CO_2 emissions worldwide (IEA 2014). Half of the energy consumed by buildings is due to the use of heating, ventilation and air conditioning (HVAC) systems, which help maintain satisfactory indoor environmental conditions. In order to reduce the environmental impact of buildings, energy efficient measures, including natural ventilation solutions, are being increasingly utilised in buildings. However, natural ventilation systems can pose challenges, such as ensuring comfortable thermal conditions in buildings.

Thermal comfort criteria

The satisfaction of building occupants with the indoor thermal environment is estimated by calculation of the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) and local thermal comfort criteria (ISO 2005). PMV and PPD have been used in the evaluation of building performance in terms of thermal comfort since 1970's (Fanger 1970). In the last number of years, there has been an increase in the use of building simulation tools, such as the whole building simulation or computational fluid dynamics (CFD), in order to evaluate and optimise buildings' performance at the design stage. However, it is imperative that those tools can accurately represent buildings at the operation stage, in terms of both energy consumption and thermal comfort performance.

Thermal comfort represents an occupant's sense of satisfaction with a zone or space. It is influenced by the following environmental factors and individual characteristics:

- Air temperature,
- Relative humidity,
- Mean radiant temperature,
- Air velocity,
- Clothing level,
- Activity level / metabolic rate.

The formulation of PMV and PPD was a result of a series of laboratory experiments carried out in a controlled environment (i.e. climate chamber). Those experiments attempted to relate the environmental comfort criteria (such as air temperature, velocity, humidity) and clothing and activity levels with predicted levels of occupant comfort (Fanger 1970). The PMV is an index that predicts the mean value of the votes of building occupants on the 7-point thermal sensation scale (Table 1).

The PMV can be calculated using Equations 1-4, which cover all of the environmental factors and individual characteristics mentioned above.

Table 1. Thermal sensation scale for the predicted mean vote (PMV) (ISO 2005).

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

$$PMV = [0.303 * e^{-0.036M} + 0.028] * \{(M-W) - 3.05 * 10^{-3} * [5733 - 6.99 * (M-W) - p_a] - 0.42 * [(M-W) - 58.15] - 1.7 * 10^{-5} * M * (5867 - p_a) - 0.0014 * M * (34 - t_a) - 3.96 * 10^{-8} * f_{cl} * [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} * h_c * (t_{cl} - t_a)\} \quad (1)$$

$$t_{cl} = 35.7 - 0.028 * (M-W) - I_{cl} * \{3.96 * 10^{-8} * f_{cl} * [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} * h_c * (t_{cl} - t_a)\} \quad (2)$$

$$h_c = \begin{cases} 2.38 * |t_{cl} - t_a|^{0.25} & for \quad 2.38 * |t_{cl} - t_a|^{0.25} > 12.1 * \sqrt{v_{ar}} \\ 12.1 * \sqrt{v_{ar}} & for \quad 2.38 * |t_{cl} - t_a|^{0.25} < 12.1 * \sqrt{v_{ar}} \end{cases} \quad (3)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 * I_{cl} & for \quad I_{cl} \leq 0.078\, m^2K/W \\ 1.05 + 0.645 * I_{cl} & for \quad I_{cl} > 0.078\, m^2K/W \end{cases} \quad (4)$$

where:
M – metabolic rate [W/m^2],
W – effective mechanical power [W/m^2],
I_{cl} – clothing insulation [m^{2}K/W],
f_{cl} – clothing surface area factor [-]
t_a – air temperature [^{o}C],
t_r – mean radiant temperature [^{o}C],
v_{ar} – relative air velocity [m/s],
p_a – water vapour partial pressure [Pa],
h_c – convective heat transfer coefficient at the body surface [W/(m^{2}K)]
t_{cl} – clothing surface temperature [^{o}C]

Another useful measure is the PPD, i.e. the percentage of those occupants who would be dissatisfied with the thermal environment (i.e. those who would vote >2 or <-2 on the thermal sensation scale). The PPD is calculated based on the PMV value (Equation 5, Figure 1).

$$PPD = 100 - 95 \cdot exp\,(-0.03353 \cdot PMV^4 - 0.2179 . PMV^2) \quad (5)$$

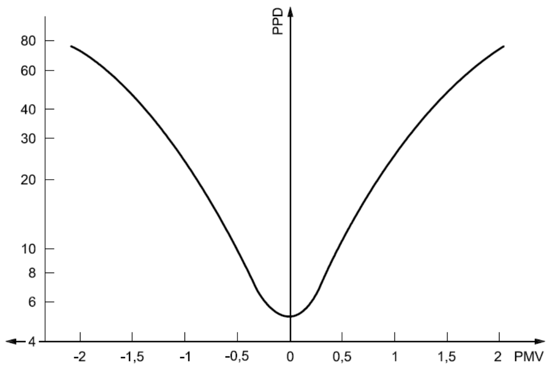

Figure 1. The relationship between PPD and PMV (ISO 2005).

EXPERIMENTAL SETUP

Building overview

This study investigated the use of natural ventilation as a solution to maintaining healthy and comfortable environmental conditions in a large mixed-use demonstrator building, the Engineering Building (EB) at the National University of Ireland (NUI) Galway (Figure 2) (NUI Galway 2012). With a gross floor area of 14,100 m^2, the EB integrates all engineering disciplines on campus accommodating over 1,100 students and 110 staff. The building is a 'living laboratory' for engineering, where structural and environmental building performance is continuously monitored through its entire life cycle in order to illustrate the concepts in undergraduate teaching and in the development of full-scale research. Those real time performance measurements in the EB include:

- environmental behaviour (thermal comfort, air quality and water consumption);
- energy demands (electrical loads such as lighting, computing and HVAC equipment);
- structural behaviour (strain, temperature and movement in the building structure).

The EB operates with a mixed mode ventilation comprising naturally ventilated offices and air-conditioned laboratories, lecture halls and computer suites. A building management system (BMS) controls the environmental conditions (e.g. air temperature, CO_2 concentration and relative humidity) and energy use in the building. The design strategy of the EB incorporated natural ventilation to maintain comfort conditions for 90% of the occupied time in most of the indoor spaces.

Figure 2. Engineering Building (EB) at NUI Galway.

The study utilised real-time monitoring of indoor environmental conditions in a number of occupied rooms within the building to examine the effectiveness of natural ventilation (controlled by the BMS) in providing comfortable indoor conditions. The rooms investigated included a single-side ventilated classroom and a cross-ventilated meeting room, both on the top floor in the north side of the EB. The real-time monitoring involved the measurement of outdoor weather conditions, indoor air temperatures and air velocities. Thermal comfort surveys were also performed to monitor occupants' feedback.

The experiments presented in this paper are part of the long term building monitoring and analysis of the indoor environment in the EB under various outdoor weather conditions and operational strategies. Thus, the results presented here show only two operational scenarios in winter conditions.

Single-side ventilated classroom

The first experiment aimed at investigating indoor environmental and thermal comfort conditions in a single-side ventilated classroom (windows facing north direction) with the dimensions of 7.60 m (D) × 12.46 m (L) × 3.47 m (H). The experiment was performed during the 2-hour lecture on the afternoon of February 13th, 2014. During the experiment, there were 24 students, 1 lecturer and 2 researchers (performing the experiment) present in the classroom. Figure 3 shows the experimental setup in the classroom. There were (i) 13 air temperature HOBO dataloggers (Onset 2014) placed beside students at their desks (internal wall row: S2, N5, S7, S5; middle row: N1, S1, S4, S9; window row: S8, S13, S3, N2, M); (ii) a thermal comfort meter in the front of the classroom placed beside the lecturer; (iii) surface temperature sensors (Onset 2014) on the floor, ceiling and radiators; and (iv) two wind velocity sensors (Onset 2014) located at window openings controlled by the BMS.

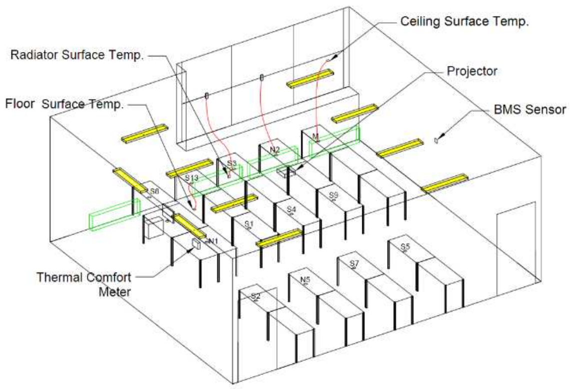

Figure 3. Classroom experimental setup.

Cross-ventilated meeting room

The second experiment investigated indoor environmental conditions in a cross-ventilated meeting room with the dimensions of 4.90 m (D) × 5.89 m (L) × 3.47 m (H). Two external walls had windows facing north and east respectively.

The experiment was performed throughout the day on January 27th, 2014. There were 4 occupants present in the room during measurement period 1 (between 11.15 am and 1.20 pm) and measurement period 2 (between 3.40 pm and 6.00 pm). The occupants were seated at the corners of the table (Figure 4) and the room was unoccupied between 1.20 pm and 3.40 pm.

Figure 4 shows the experimental setup in the meeting room. There were (i) 8 air temperature HOBO dataloggers (Onset 2014) placed at two vertical locations (S3, N1, M, S9 and S4 (*after the experiment it was discovered it wasn't working*), N9, S1, S13); (ii) 3 air velocity sensors (Onset 2014) at manually operated window openings; and (iii) surface temperature sensors (Onset 2014) on the floor, ceiling and internal wall.

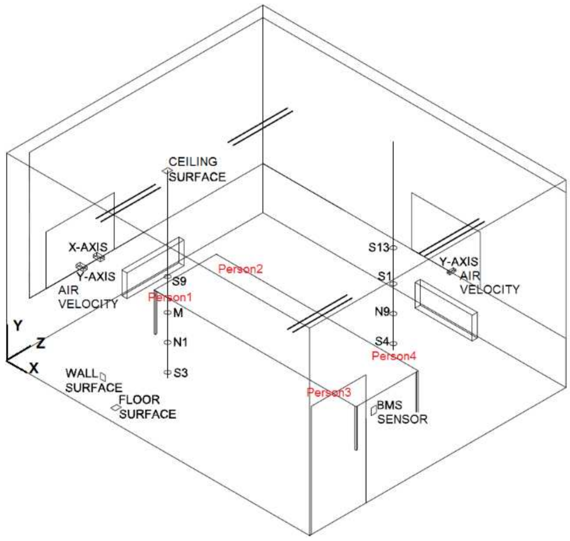

Figure 4. Meeting room experimental setup.

Weather conditions measurements

The outdoor weather conditions were monitored by an automatic weather station (IRUSE 2014) located at NUI Galway campus approximately 500 m from the EB. The measurements included dry-bulb air temperature (°C) and relative humidity (%), barometric pressure (mBar), wind speed (m/s) and wind direction (°), global and diffuse solar irradiance (W/m^2), and rainfall (mm) (Table 2).

Table 2. Weather station sensor details.

Measurement	Accuracy
Dry-bulb air temperature	± 0.13 °C
Relative humidity	± 1.0% @ 0% - 15% RH; ± 1.5% @ 15% - 78% RH
Wind direction	± 2° (in steady winds over 5 m/s)
Wind speed	± 0.1 m/s (0.3 - 10 m/s); ± 1% (10 - 55 m/s); ± 2% (> 55 m/s)
Rainfall	0.2 mm/tip
Barometric pressure	± 0.5 mb @ + 20 °C; ± 1.0 mb @ 0 to 40 °C; ± 1.5 mb @ -20 to + 50 °C; ± 2.0 mb @ -40 to + 60 °C
Solar global irradiation	± 5 W/m^2 ± 12%
Solar diffuse irradiation	± 20 W/m^2 ± 15%

THERMAL COMFORT SURVEYS

A series of thermal comfort surveys were performed during the two experiments, in the classroom and the meeting room) in order to monitor the occupants' comfort in the particular environment. The surveys were based on the standard thermal sensation scale (Table 1).

During those experiments, the occupants were asked to complete the survey at regular time intervals. The survey included questions concerning their age, height, weight, activity level, consumption of food/drink, clothes insulation and comfort level, i.e. PMV value.

Single-side ventilated classroom

There were 27 occupants present in the classroom during this experiment. Among them, 24 students were asked to complete the thermal comfort survey every 10 min over the duration of 2-hour lecture. Figure 5 shows the students' PMV responses during the experiment in the classroom.

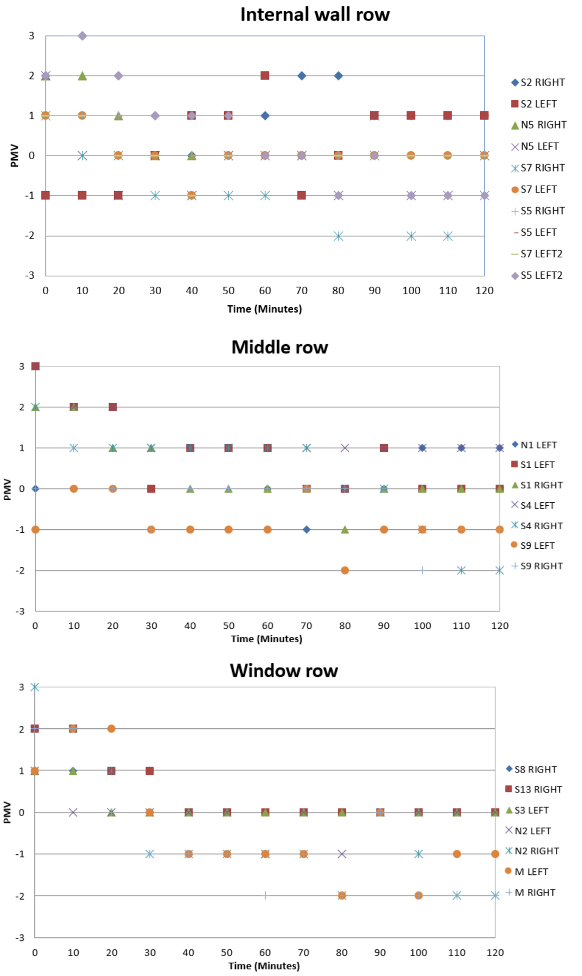

Figure 5. PMV values reported by occupants of the classroom.

Cross-ventilated meeting room

There were 4 occupants present in the meeting room during the experiment, who were asked to complete the thermal comfort survey every 10 min over the two measurement periods (11.15 am – 1.20 pm and 3.40 pm – 6.00 pm). Figure 6 shows the occupants' PMV responses during the experiment in the meeting room.

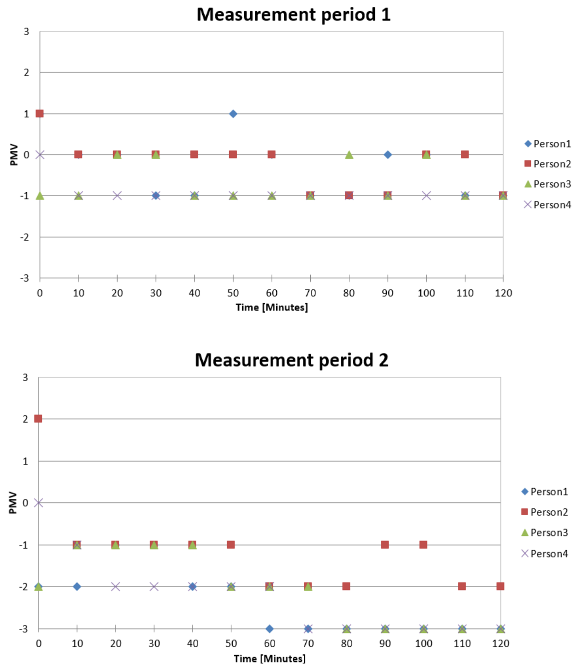

Figure 6. PMV values reported by occupants of the meeting room.

RESULTS AND DISCUSSION

Single-side ventilated classroom

Figure 7 shows the air temperatures measured during the experiment on February 13th, 2014. The shaded areas illustrate the time when the windows were automatically opened by the BMS (based on indoor air temperature and CO_2 concentration set points), with the light shaded area representing 25% opening (10 cm gap) and the dark shaded area representing 50% opening (20 cm gap). A relationship was observed between the air temperatures in the classroom and the windows being open. Furthermore, when the windows were 50% open there was a faster decrease in indoor air temperatures than in the case of 25% opening. The air temperature at location M was the most sensitive to window openings.

The air temperatures in the classroom rose for the first 30 minutes of the experiment, until the windows opened. Then the air temperatures began to gradually decrease until the windows closed for about 10 minutes. For the last 30 minutes of the experiment the windows were 50% open. Figure 7 shows a clear relationship between the distance of the data loggers from the windows and the air temperatures measured. The data loggers located closest to the window (M, N2, S3) recorded the lowest air temperatures in the classroom. Moreover, a similar pattern was observed in all indoor air temperatures, particularly at the locations further from the windows.

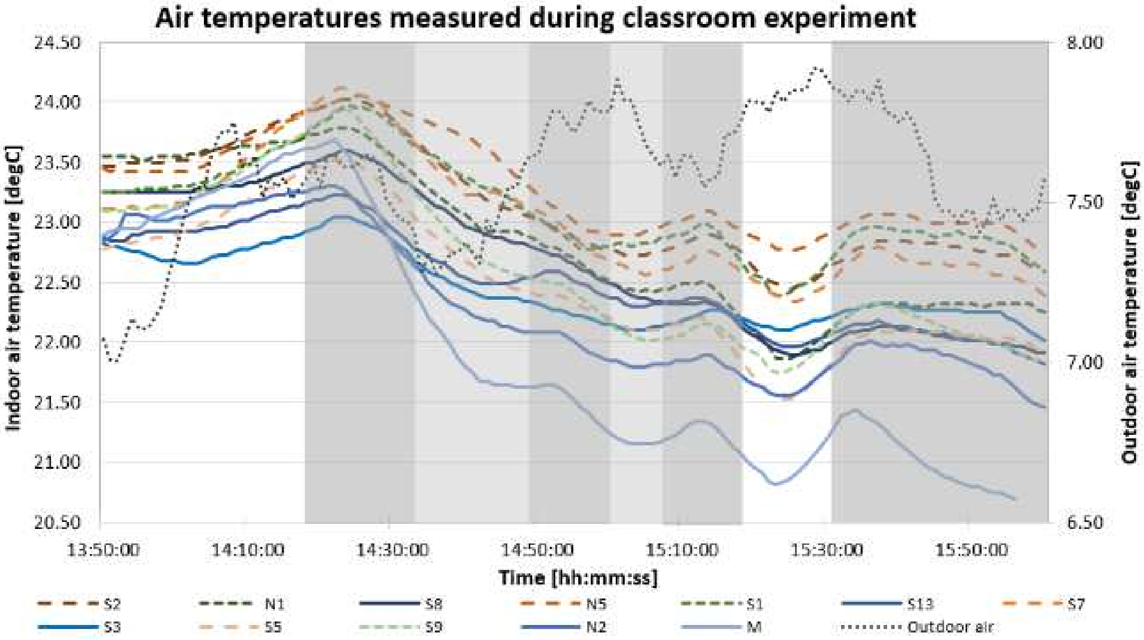

Figure 7. Air temperatures measured during the experiment on February 13th, 2014.

On the day of the experiment, the wind was blowing from the north-west direction (IRUSE 2014). The average, minimum and maximum air velocities measured at the window inlet (perpendicular to the window plane) are shown in Table 3.

Table 3. Air velocities [m/s] measured at the window opening facing north direction in the classroom.

	Horizontal X
Average	0.24
Standard deviation	0.22
Minimum	0.01
Maximum	0.78

The thermal comfort surveys showed generally slightly higher PMV values recorded in the internal wall row and lower in the window row (Figure 5). However, the overall distribution of the PMV values in the classroom was even, with the median PMV of 'neutral' through the experiment. At the internal wall and middle rows, for most of the time the occupants felt 'slightly warm', 'neutral' or 'slightly cool'. At the window row the occupants felt 'neutral' or 'slightly cool' for most of the time.

The experimental PMV values reported by the occupant N2 left (located at the centre of the room) were compared to the theoretical values (Table 4). The comparison showed a quite good agreement between those two sets of data. The differences might have been caused by approximations when assuming the clothing insulation level or metabolic rate (the theoretical calculations do not take ito account the consumption of food and drink, or activity done before the experiment). The PPD values showed quite comfortable conditions at this location in the room, where for the most of the experiment time the PPD did not exceed 10%.

Table 4. Experimental and theoretical thermal comfort values for the occupant N2 left.

Time of the experiment	**PMV_{exp}**	**$PMV_{theoret}$**	**$PPD_{theoret}$**
0	1	0.6	12%
10	0	0.6	13%
20	0	0.7	14%
30	0	0.3	7%
40	0	0.2	6%
50	0	0.4	8%
60	-1	0.0	5%
70	0	0.3	7%
80	-1	0.1	5%
90	0	0.3	7%
100	0	-0.2	6%
110	0	-0.3	7%
120	0	-0.4	9%

The average solar global irradiation on February 13th, 2015 was 212 W/m^2 (maximum value of 366 W/m^2) over the period monitored (Figure 8). The windows of the classroom were facing north and, thus, the solar irradiation entering the room was lower than measured by the weather station. Thus, it wasn't expected that the solar irradiation would have a significant influence on the thermal comfort of the classroom's occupants when compared to the air temperature.

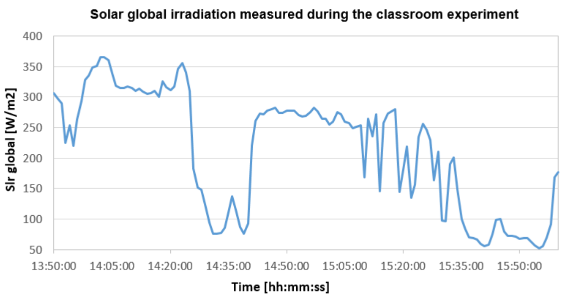

Figure 8. Solar global irradiation measured during the experiment on February 13th, 2014.

Cross-ventilated meeting room

Figure 9 shows the air temperatures measured during the experiment on January 27th, 2014. It is clear that the air temperatures increased with height (approximately 0.5 ºC between the head and ankle levels). The air temperatures at locations close to the east-facing window (S13, S1, and N9) were about 0.5 ºC lower than those, close to the internal wall (S9, M, N1, and S3), respectively to their height. There was a good correlation between air temperatures at different heights at each of two locations (with correlation coefficients between 0.96 – 0.99). The shaded area on the graph illustrates two measurement periods, during which the occupants were present in the room.

temperatures began to rise steadily due to the heat generated by the occupants and their laptops. When the occupants vacated the room after the measurement period 1, indoor air temperatures decreased by over 1 ºC. When the occupants returned to the room for the measurement period 2, indoor air temperatures increased by approximately 0.5 ºC and remained relatively steady until the end of the experiment. With the decreasing outdoor air temperature, indoor air temperatures dropped slightly in the last 45 minutes of the experiment.

The measured and surveyed results of the classroom experiment showed that the temperature distribution in the room was uneven. In the measurement period 1, the occupants found the conditions generally neutral and slightly cool. However, in the measurement period 2, the occupants found the conditions between slightly cool and cold. This was reflected in the measured data (Table 5), where the average indoor air temperatures were approximately 0.5 ºC higher for the measurement period 1 than 2.

Table 5. Average indoor air temperatures [ºC] during measurement periods MP1 and MP2.

	S9	M	N1	S3	S13	S1	N9
MP1	18.01	17.91	17.62	17.29	17.53	17.29	16.98
MP2	17.45	17.39	17.19	16.88	16.91	16.78	16.41

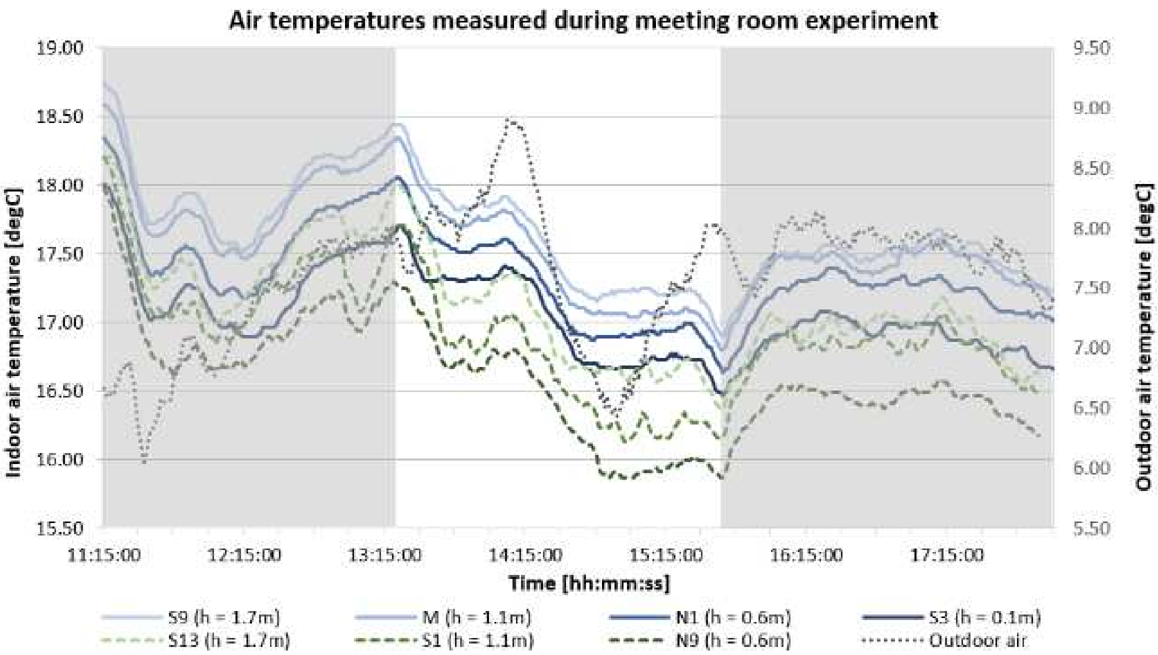

Figure 9. Air temperatures measured during the experiment on January 27th, 2014.

Figure 9 shows the fluctuations in indoor and outdoor air temperatures. Statistically, there was very little correlation between the indoor air and the outdoor air temperature (correlation coefficients between 0.04 - 0.19). Initially the air temperatures in the room began to decrease due to opening the windows at the beginning of the experiment. Approximately 50 minutes into the experiment, the indoor air

On the day of the experiment, the wind was blowing from the north-west direction (IRUSE 2014). The average, minimum and maximum air velocities measured at the window inlet are shown in Table 6. There was no significant difference in the air velocity patterns between the two measurement periods.

Table 6. Air velocities [m/s] measured at the window opening facing north direction in the meeting room.

	Horizontal X	Vertical Y
Average	0.61	0.54
Standard deviation	0.43	0.33
Minimum	0.04	0.08
Maximum	2.18	2.59

The solar irradiation did not influence the thermal comfort of the occupants of the meeting room. It was a cloudy day on January 27th, 2015, with an average solar global irradiation of 88 W/m^2 (maximum value of 434 W/m^2) over the period monitored (Figure 10). The windows of the meeting room were facing north and east and, thus, the solar irradiation entering the room was lower than measured by the weather station. The PMV values reported by the occupants during the measurement period 1 were higher than during the measurement period 2. This was consistent with higher solar global irradiation values during observed measurement period 1. However, the data indicated that indoor air temperatures influenced reported PMV values more than solar irradiation.

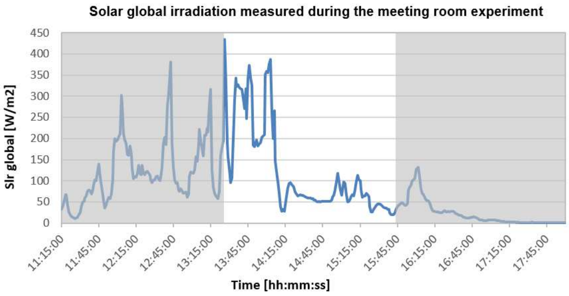

Figure 10. Solar global irradiation measured during the experiment on January 27th, 2014.

CONCLUSIONS

This research has shown that the cross-ventilation provided more even distribution of indoor air temperatures inside the room than in the case of the single-sided ventilation. However, the occupants of the meeting room found the indoor thermal conditions uncomfortable and 'too cool'. Furthermore, prevailing wind conditions could significantly impact on overall expected temperature distribution in those rooms.

The results presented in this paper provided valuable information about the operation of a naturally ventilated building controlled by a BMS. Utilising field measurements and occupancy surveys determined inefficiencies in the BMS controls. Moreover, the findings of this study stressed the importance of feedback from the building occupants in continuous commissioning and fault detection in building operation. Such feedback, in combination with weather data (e.g. prevailing wind direction and speed) can also inform building design to ensure natural ventilation systems enable a uniform thermal comfort experience for building occupants.

In buildings such as the EB, the experiments also suggest that there needs to be consideration of where to locate sensors (particularly air temperature) that are used to control natural ventilation systems. Even within a relatively small room such as the classroom where occupants closer to the window generally described their thermal comfort as being inferior to those farther from the windows.

The measured data gathered in the operating building will play a crucial role in the development, validation and calibration of numerical models (e.g. whole building energy simulation and computational fluid dynamics (CFD) models) to support the control and optimisation in building operation. Measured data in the EB at NUI Galway has already been utilised in building simulation, e.g. (Hajdukiewicz et al. 2013; Hajdukiewicz et al. 2014). This research will support further development of calibrated building simulation models that consider the occupants' comfort aspect as much as the energy or environmental aspect in building operation.

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