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Evaluation of thermal comfort and cooling loads for a multistory building

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Abstract. The latest UK Climate Projections (UKCP09) show that mean daily temperatures will increase everywhere in the United Kingdom. This will significantly affect the thermal and energy performance of the current building stock. This study examines an institutional fully glazed building and looks into the changes in the cooling loads and thermal comfort of the occupants during the occupied hours of the non-heating period. Furthermore, it investigates the effect of relative humidity (RH) on thermal comfort. The Design Summer Year (DSY) 2003 for London Heathrow has been used as a baseline for this study and the DSY 2050s High Emissions scenario was used to examine the performance of the building under future weather conditions. Results show a 21% increase of the cooling loads between the two examined scenarios. Thermal comfort appears to be slightly improved during the months of May and September and marginally worsen during the summer months. Results of the simulation show that a relative humidity control at 40% can improve the thermal comfort for 53% of the occupied hours. A comparison of the thermal comfort performance during the hottest week of the year, shows that when the relative humidity control is applied thermal comfort performance of the 2050s is similar or better compared to the thermal comfort performance under the baseline.

Keywords: thermal comfort; relative humidity; energy consumption

1. Introduction

UK Climate Projections examine three different greenhouse gas emissions scenarios and show how future climate could change, if we fail to reduce our emissions. The high emissions scenario, could result in an average summer temperature rise of 5°C in the south west of England by the 2080s (Defra 2009). This will significantly affect the thermal and energy performance of our buildings.

Commercial buildings with fully glazed façade are popular in the UK. They allow the daylight to penetrate into the interiors of the building and provide an unrestricted view of the outside to the

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Table 1 Seven point thermal sensation scale (ISO 2005)

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

occupants. Moreover they contribute to the aesthetics of the building. However, the amount of solar gains resulting from the glazed façade could cause overheating in the building and negatively affect the thermal comfort of the occupants, while increase the cooling demand and as a result the energy use.

Achieving thermal comfort conditions is important in order to ensure the well-being and productivity levels of the occupants. Furthermore, when considering educational buildings thermal comfort has also been related to student performance (Zomorodian *et al*. 2016).

This study examines the differences in cooling loads and thermal comfort in a higher education building under current weather conditions and future projected weather conditions of the 2050s. The building selected for this study is the Paragon building which is being used by the University of West London.

2. Literature review

2.1 Predicted mean vote (PMV)

Buildings that are cooled or heated mechanically can also overheat if the ventilation system is, for example, undersized or poorly controlled. Here BS EN 15251 (BSI 2007) defines the acceptable indoor conditions according to the PMV index, and overheating is therefore a function not only of temperature but of the humidity, air speed and the clothing and activity of the occupants. The extent of overheating will also be judged according to the PPD.

Predicted mean vote is arguably the most influential and widely used thermal comfort model (Kim *et al*. 2015). It is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale (Table 1).

PMV may be calculated for different combinations of metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity and air humidity (ISO 2005).

From the PMV value the predicted percentage dissatisfied (PPD) can be determined. PPD is an index that establishes the number of people that feel dissatisfaction from the thermal conditions. It can be calculated by the following equation

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) \tag{1}$$

(ISO 2005)

Fig. 1 View of the paragon building (source uwl.ac.uk)

2.2 Effect of relative humidity on thermal comfort

For the most common thermal comfort human application relative humidity levels can vary between 30%-70%.

The effect of relative humidity on the thermal comfort it is not considered to be significant when indoor temperature is within the recommended range. It is generally accepted that within the ‘comfort’ range (20-26℃) humidity has a second order of importance, as operative temperature rises towards the body temperature evaporation and respiration become important mechanisms for heat loss from the body (CIBSE 2015).

Relative humidity affects thermal comfort more significantly at higher temperatures. It is recognised that at higher temperatures-particularly in high relative humidity, which limits the body’s ability to keep cool through perspiration-heat stress can occur while the body cannot maintain its core temperature of 37℃ (CIBSE 2014). High levels of relative humidity can work against the evaporative cooling effects of sweating and leave the body prone to overheating (Boduch and Fincher 2009). The combination of high temperature and high humidity introduces a feeling of sultriness or oppression, which occurs above 70% relative humidity at 21℃ and above 60% relative humidity at 23℃ (DIN 1994). A maximum room relative humidity of 60% within the recommended range of summer design operative temperatures would provide acceptable comfort conditions for human occupancy and minimise the risk of mould growth (CIBSE 2015).

2.3 Weather data

The weather data that have been used in the simulations are the TM49 Design Summer Years (DSY) provided by CIBSE (CIBSE 2014). The weather data are provided for current and future weather conditions, for three different locations (Gatwick, Heathrow and London Weather Centre). The DSYs of 1976, 1989 and 2003 are provided based on the observed data and represent three different patterns of summer weather conditions. The DSY of 1989 represents a moderately warm summer while the other two represent more extreme weather conditions. The difference between the DSY of 1976 and the DSY of 2003 is that the first represents a summer with a long period of persistent warmth while the second one represents a more intense single warm spell (CIBSE

2014). The future DSYs have been produced based on the UK Climate Projections (UKCP09) and consider the Low, Medium and High scenarios for greenhouse gas emissions; the time periods 2020s, 2050s and 2080s and the percentile changes considered were the 10%, 50% and 90% percentiles (Jenkins *et al*. 2009).

The UK Climate Projections (UKCP09) show that in the future we can expect hotter and drier summers and more severe weather. This study aims to examine the performance of the building under the projected extreme future weather conditions and compare it with the performance of the building under the current weather conditions. The 2050s High greenhouse emissions scenario represents the worst case scenario and has been selected to be used in the simulations. The 2003 DSY represents an extreme summer with a long period of persistent warmth and has been selected as a baseline.

3. Methodology

3.1 Description of the building

The Paragon building is located in the West London, at the Brentford site of the University of West London. The School of Psychology, Social Care and Human Sciences and College of Nursing, Midwifery and Healthcare are based at the Brentford site. The areas of the building are being used as classrooms, lecture theatres, offices, laboratories, IT rooms. The building also houses the university’s library and a canteen. It remains operational during the whole year and during the summer period is also used for the university’s summer school classes. Total area of the building is 11167 m^2, it has 11 floors and a mezzanine level and the total height is 45.57 m. The largest proportion of the building’s façade is covered by a curtain wall façade. The rest of the façade is a solid wall.

Heating is provided to the building by a packaged boiler system that comprises of three gas fired boilers. Two gas valves are fitted to provide control of the fuel to the boilers. Cooling is provided by a chilled water system that comprises of 3 air-cooled chillers. Chilled water is circulated by 3 pumps which are designed to allow a flexible operation in response to demand. Also differential pressure switches are located across the pump section that provides a feedback signal indicating the water flow status in the flow pipework.

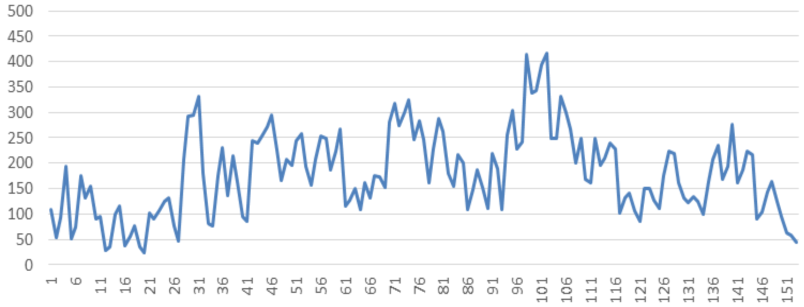
There are three air handling units (AHU) located at the third floor and one located on the roof that supply fresh air to the building via fan coil units. The AHU that is located on the roof is serving all floors while from the three AHU that are located on the third floor one is serving the two lecture theatres, one is serving the floors from ground to third and one is serving the floors from fifth to ninth.

3.2 Modelling of the building

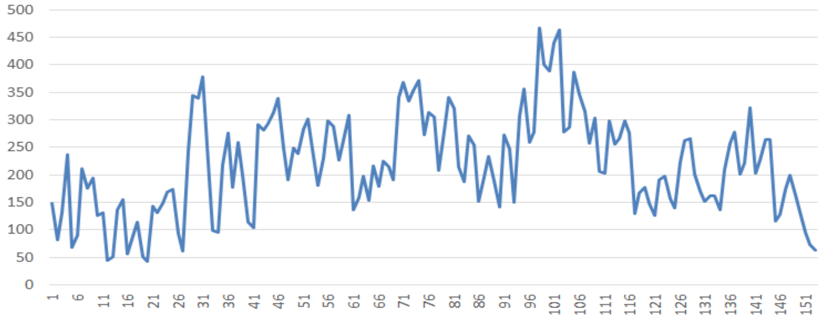
Based on the floor plans the model of the building was created in EDSL TAS software.

Thermal simulations of the building were performed using EDSL TAS version 9.3.2, a building simulation program developed by Engineering Development Solution Software.

The process of modelling a building on EDSL TAS has been described by Amoako-Attah and B-Jahromi (2014). The required steps that need to followed are the preparation of drawings, modelling of the ground floor, modelling of the subsequent floors, thermal simulation process (HVAC: heating, ventilation, and air condoning) and finally the UK Building Regulations studio



Graph 1 Daily cooling loads for baseline calculations (kW)



Graph 2 Daily cooling loads for future weather calculations (kW)

simulation. Flowchart for each step where the required actions for each one are shown in detail can be found in the referenced publication (Amoako-Attah and B-Jahromi 2014).

This study focuses on the non-heating period, Design Summer Year (DSY) weather data have been used to perform the simulations, the results of which were used to examine the changes in cooling loads and thermal comfort. Simulations were performed through the TAS Building Simulator (.tbd) file and the TAS Result Viewer file was used to view the results.

The Design Summer Year was introduced in 2002 (CIBSE 2002) in recognition of the need to have a sequence of warm weather data for use with dynamic thermal simulation programs for the assessment of overheating risk in naturally ventilated and passively cooled (‘free running’) buildings. The DSY represents a ‘near extreme’ warm summer. CIBSE also provides another year of weather data, called the Test Reference Year (TRY), which represents a typical climatological year and is intended to be used for average annual energy prediction. Currently CIBSE provides DSY and TRY weather years for 14 locations in the UK (CIBSE 2006).

The schedule of the building was set to weekdays and weekends. Based on the usage of the building, occupancy profile was set from 08:00 to 20:00 and the cooling set point during the occupied hours was set to 21℃. The relevant NCM internal conditions were applied to the zones of the building. The building materials with their corresponding properties were assigned to the constructions. Windows of the building have been modelled with a blind that covers 50% of their glazing area. The U-Values of the building elements that were used are shown in Table 2.

4. Results

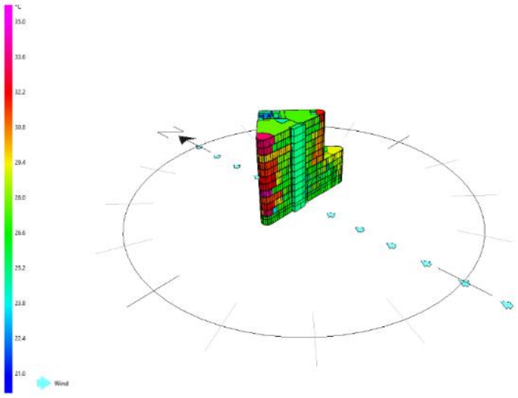


Fig. 2 Mean radiant temperature range at the time of the highest external temperature

Fig. 3 Zoning of the 10th floor and location of room 1004

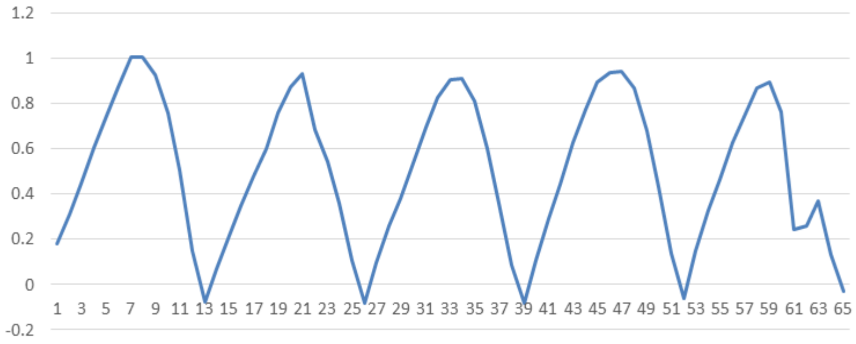
The results show a comparison of the cooling loads of the building for the period from May to September (153 days) under the baseline and future weather data. An analysis of the thermal comfort for a room of the building using the PMV/PPD method is presented. For the analysis of the thermal comfort only the occupied hours are considered (1378 hours).

4.1 Cooling loads

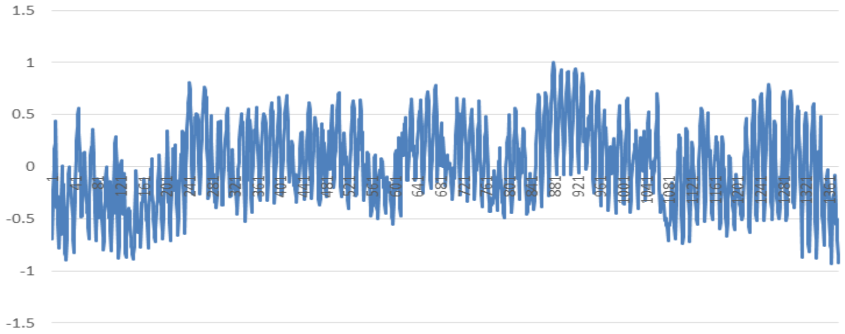
Simulation of the building was performed with the baseline and the future DSY in order to estimate the difference in the cooling loads. All the other parameters of building were identical. The examined period is from May to September. The building under the DSY 2003 weather data had a total cooling load of 658,890 kW. Under the DSY 2050s the total cooling load of building increased by 21% to 802,750 kW. The graphs 1-2 below show the hourly cooling profile of the occupied hours for the two examined scenarios.

4.2 Thermal comfort

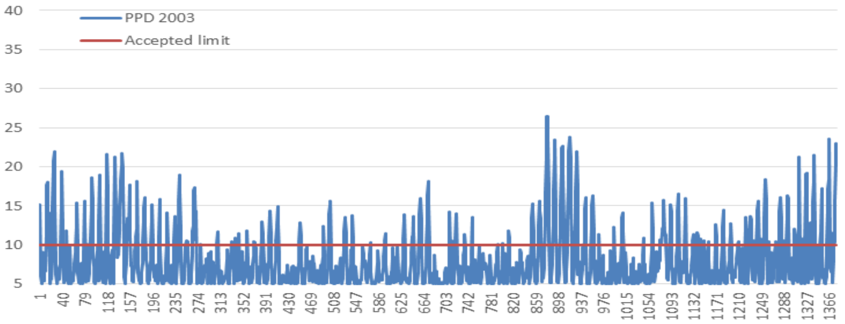
In order to examine the thermal comfort, a rooms located in the east side of the building was



Graph 3 PMV values during the hottest week of the year



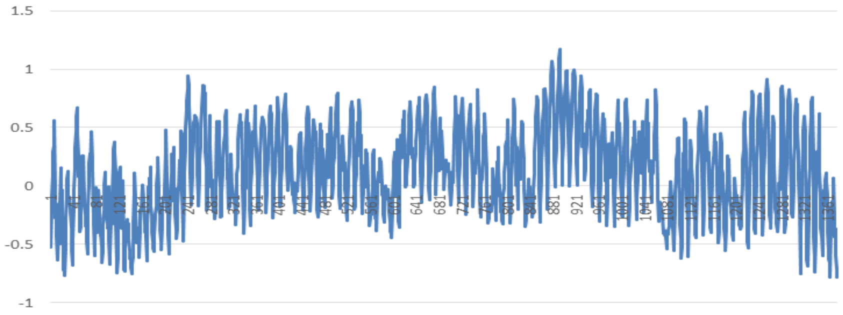
Graph 4 Hourly PMV during occupied hours-baseline



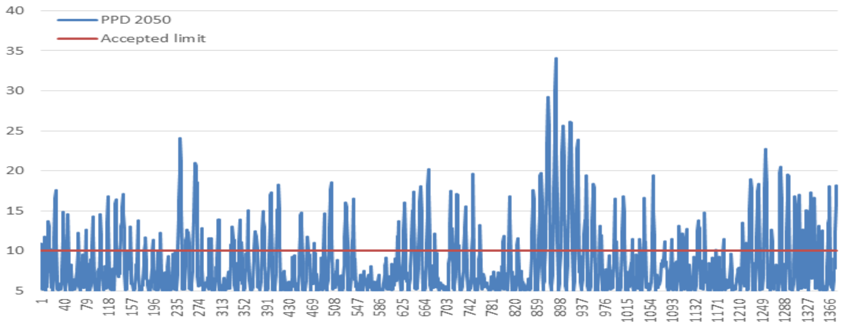
Graph 5 Hourly PPD values-baseline

selected. Room 1004 is used as an office. According to the simulated results that room was found to have the highest mean radiant temperatures in the day and at the time of the highest external temperature. For the calculation of the PMV/PPD values the simulated values of the air temperature, mean radiant temperature and relative humidity have been used. The air speed was set to 0.1 m/s. When considering the calculations for the thermal comfort of the office room the occupants' metabolic rate was set to 1.2 met and the clothing to 0.7. The building is considered to be in Class II, so the acceptable limit for the PMV is ±0.5 (PPD≤10%) (BS EN 15251 2007).

All PMV/PPD calculations presented below are only for the occupied hours of the building for the period from May to September. In total the occupied hours of the examined period are 1378.



Graph 6 Hourly PMV values-future weather



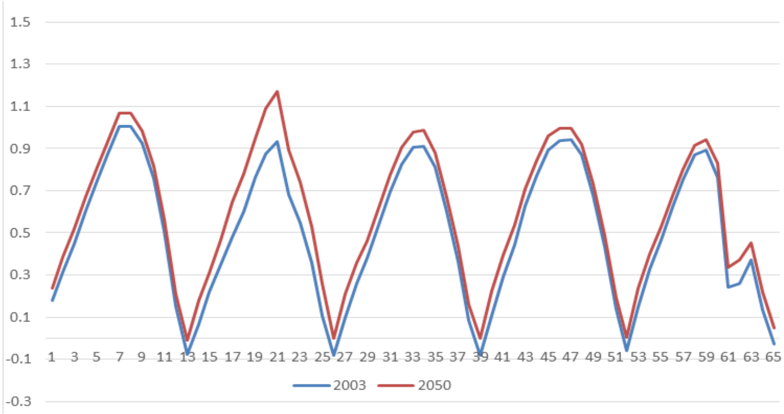
Graph 7 Hourly PPD values-future weather

4.2.1 Room 1004 (office)

Baseline calculations

Graph 3 shows the PMV values of the examined room during the week with the highest external temperature. The examined week is formed by 5 working days, where each one of those has 13 working hours. Consequently the points (13,0), (26,0), (39,0), (52,0) and (65,0) of the graph represent the end of the working day. It can be observed that PMV receives values close to zero at the beginning and the end of the working day. As the temperature rises, thermal comfort decreases and at the middle of the working day when the temparature is at its highest PMV point receives the highest value, which result to the highest percentage of dissatisfied people. The peak point for the examined week occurs either at 14:00 or at 15:00. As the day progresses and external temperature decreases, PMV values decrease until they reach their lowest point at the end of the working day at 20:00.

Graphs 4 and 5 below show the hourly results for the predicted mean vote and the percentage of dissatisfied people for the baseline calculations. There are 318 hours with a PPD over 10%. This equals to 23% of the occupied time. It can be observed that the highest concentration of hours above the 10% limit are in the two ends of the graph which represent May and September. Furthermore it can be seen from Graph 3 that during the beginning and the end of the non-heating period the PMV receives negative values up to -0.9, which means that people feel slighltly cool while during the summer months the PMV values are positive with a maximum value of +1.005, which means that people feel slightly warm in the room. The negative values that appear during the summer months represent the beginning and the end of the working day, where under the examined internal conditions people feel slightly cold.



Graph 8 Comparison of PMV values during the hottest week of the year

Future weather calculations

Graphs 6 and 7 below show the PMV and PPD values under the examined future weather conditions. Graph 8 shows the PMV value for the examined room during the hottest week of the year and presents a comparison with the 2003 DSY. As it can be observed the results show a similar pattern with baseline calculations, however the negative PMV values at the beginning and the end of the non-heating period have been reduced (lowest value at -0.78) and the positive PMV values during the summer months have been raised (highest value at 1.17).

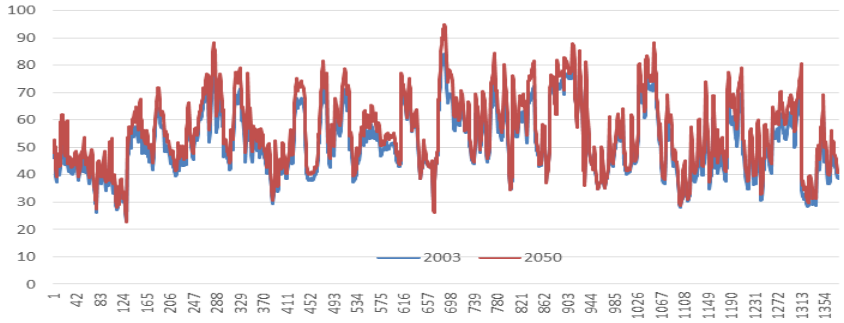
Comparing the PPD results of the two examined weather datasets it can be seen that although the room has the same internal conditions as in the baseline calculations, the thermal comfort of the occupants under the future weather conditions will worsen during the summer months but will be slightly improved during the months of May and September. In the baseline scenario it was estimated that the occupants feel slightly cold during the months of May and September and slightly warm during the summer months. The increased external temperature of the future weather conditions leads to an increase of the mean radiant temperature and as a result of the operative temperature of the room. In terms of thermal comfort this increase in the temperature is beneficial for the months of May and September but has a negative effect during the summer months. Out of the 1378 occupied hours 333 are above the 10% PPD threshold.

Graph 8 below shows the PMV values of the two examined weather scenarios during the hottest week of the year. It can be seen that the thermal comfort of the occupants will be worst during all hours of the working day except from the last one of the working day (20:00).

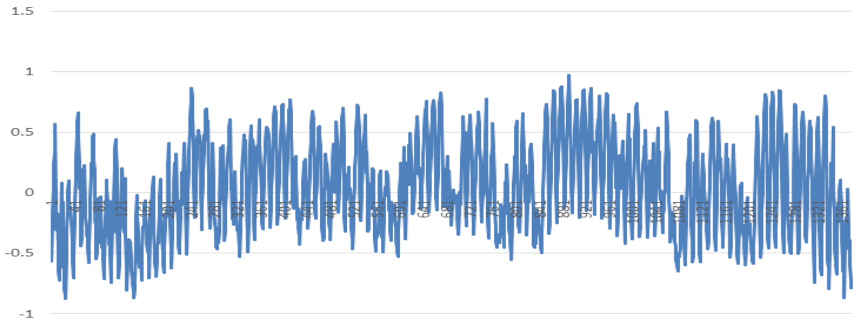
Effect of relative humidity

As discussed above the factors that affect the PMV are the internal temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate and clothing. Air velocity, metabolic rate and clothing are considered to be unchanged during the examined period and are the same for both of the examined scenarios. Internal temperature has been set to 21℃ and the mean radiant temperature used for the calculations of the PMV is calculated by the software package.

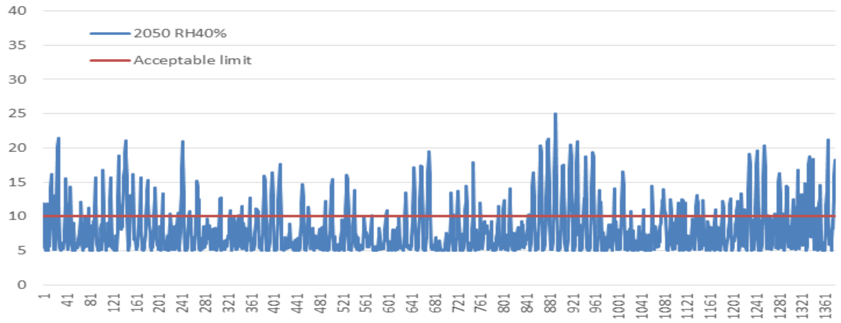
In the simulations, in the results which were presented so far, there was no control set to the values of relative humidity. Graph 9 shows the simulated relative humidity of the room for the two examined scenarios. It can be observed that in both cases the relative humidity receives values outside of the 30%-70% accepted range. In order to examine the effect of relative humidity to



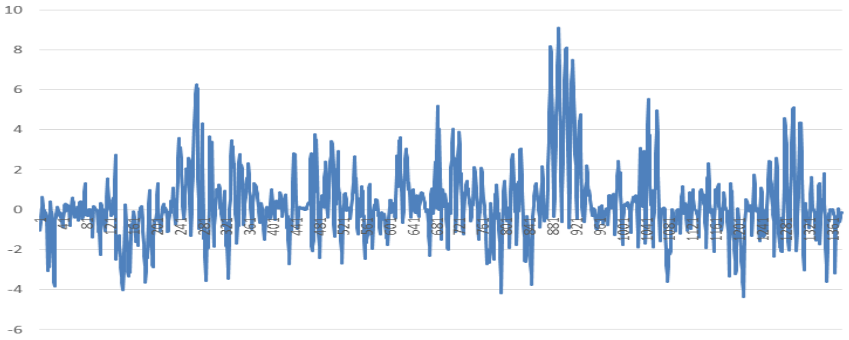
Graph 9 Comparison of the simulated relative humidity between baseline and future weather



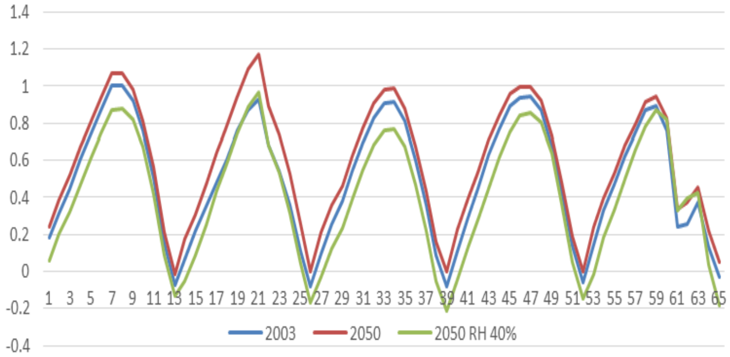
Graph 10 PMV values-future weather-relative humidity 40%



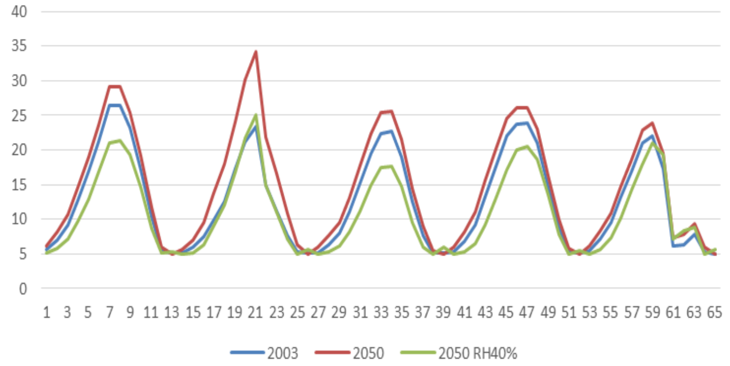
Graph 11 PPD values-future weather-relative humidity 40%



Graph 12 Difference of PPD with and without relative humidity control (future weather)



Graph 13 Comparison of PMV values during the hottest week of the year-3 scenarios



Graph 14 Comparison of the PPD values during the hottest week of the year-3 scenarios

thermal comfort, a set point of 40% was defined and a simulation of the thermal performance of the building, using the future weather conditions was performed. Graphs 10 and 11 show the PMV and PPD values under the examined future weather conditions when the relative humidity control is applied.

Graph 12 above shows the difference of the percentage of dissatisfied people between the scenarios with no humidity control and with humidity control at 40%. Simulations in both scenarios were performed using the future weather data. Positive values mean that the PPD value for this specific hour is higher in the scenario with no humidity control. Out of the examined 1378 hours, 739 have a better thermal comfort conditions when the relative humidity control is applied and 639 hours have better thermal comfort conditions when no relative humidity control is applied. Looking further into the results when the relative humidity control has a positive effect on the thermal comfort it reduces the PPD by 1.35 on average and presents a maximum hourly decrease of 9.1. On the other hand when relative humidity has a negative effect it increases the PPD by 0.97 on average and presents a maximum hourly increase of at the hour where it has the most negative effect it increases the PPD by 4.37. Also it is worth noting that during the period of the warm spell the relative humidity control has its most positive contribution to the thermal comfort. In total under the examined scenario 312 hours are above the 10% PPD threshold.

Graph 13 below shows the comparison of the PMV values for the hottest week of the year. As it can be observed when relative humidity is set to 40% thermal comfort conditions are improved to 2003 levels or better during most of the working hours. However during the hours at the end and the beginning of the day the 2050s scenario with no relative humidity control will have the best thermal comfort conditions between the three examined scenarios.

5. Conclusions

This study aimed to examine the difference in the cooling loads of a fully glazed office building in West London under the 2003 weather conditions and the projected weather conditions of the 2050s and to investigate the effect of relative humidity on thermal comfort. The examined period is from May to September.

Cooling loads are estimated to increase by 21% between the two examined weather scenarios. The building is exposed from all sides and receives no external shading from surrounding buildings. Blinds are installed internally to the windows and cover 50% of their size. Despite the increase of the cooling loads and the fact that simulations of the building in the examined scenarios were performed with the same internal conditions, thermal comfort conditions in the examined room have worsen.

Study of the thermal comfort shows different results for the months of May and September, where the occupants feel slightly cool in the examined space and for the summer months, where the occupants feel slightly warm. Results of the thermal comfort under the projected weather conditions show the same pattern as in the baseline, however thermal comfort is slightly improved during the months of May and September and marginally worsen during the summer months.

Investigation of the effect of relative humidity on the thermal comfort has shown that when the relative humidity is set to 40%, 53% of the total occupied hours had a smaller percentage of dissatisfied people. However if we examine only the summer months thermal comfort is improved on 68% of the total occupied hours. Effect of the relative humidity control on the PPD can also be seen on the Graph 13 where the comparison between the three scenarios is presented.

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