Thermal comfort monitoring in office buildings: a case study

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Abstract. In the framework of EPBD Directive revision, the EU is pushing Member States to pay more attention to IEQ conditions in buildings, by introducing specific requirements to be verified in the calculation methodology implemented in the national building codes. In this paper, the extensive field monitoring of an office building, carried out in the heating, cooling and intermediate seasons of 2022-2023, is described. Main thermo-hygrometric quantities have been measured in different rooms, considering the occupancy profile, users' behaviour and appliances use. Results showed overheating conditions in offices exposed to the south façade, mainly due to solar radiation and internal heat gains. Surprisingly, north-facing offices with heating terminals running are colder than south-facing ones with HVAC systems turned off. Further differences were found in the temperature analysis of free-floating conditions, showing deviations up to 4 °C on average, between south and north facing rooms. For each room, thermal comfort issues were assessed in accordance with EN 16798-1, by calculating Fanger Indexes (PMV and PPD), and by adaptive method in the HVAC systems off-work periods. These findings represent the first results of an in-depth analysis of thermal comfort and IEQ conditions, aimed at assessing how the IEQ conditions can address the building energy audit, increasing, at the same time, energy performance and IEQ levels.

1 Introduction

People spend about of 90% of their daily time in indoor environments and in Europe about 25% of citizens lives in buildings with unhealthy conditions in terms of ventilation or thermal comfort, with significant effects from the health and social points of view [1]. In the framework of ongoing revision of EPBD Directive, the EU has invited Member States to introduce "…requirements for the implementation of adequate indoor environmental quality standards in buildings" to ensure and monitor healthy conditions and air quality for occupants. For this reason, the indoor environ-mental quality (IEQ) control can play a relevant role in the European long-term energy renovation strategy that aims to achieve the reduction of 55% of CO2 emissions by 2030 and the "carbon neutrality" in the building sector by 2050 [2]. The verify of indoor environmental quality levels is a crucial aspect in the evaluation of energy performance of buildings: several studies in the last years have

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highlighted that even in renovated buildings toward high standards of energy efficiency, significant deficiencies can be found in terms of indoor well-being conditions [3, 4].

Furthermore, the improvement of indoor environment quality level can significantly affect the productivity and wellbeing of occupants, especially in non-residential building, like schools or offices, in which the indoor conditions have strong influence on the work performance [5, 6]. In this context, the renovation wave of building stock, required to meet EU climate targets, can represent a great opportunity for the implementation of measures and regulatory instruments to increase the IEQ levels in buildings. The integration of IEQ analysis in the building performance calculation schemes, defined in EPBD framework, can support the energy saving strategies, avoiding significant critical issues at the design stage, and also improving well-being environment for building users.

In Italy, the application of minimum energy requirements (MEPS), provided by law DM 26/06/2015 [7] as well as the compliance with the NZEB (Nearly Zero Energy Building) standards for new buildings, has led the adoption of increasingly higher levels of insulation for building envelope. On the one hand, this leads to relevant reduction of heat losses and consequently to lower energy consumption; on the other, it leads to a greater airtightness of buildings envelope, which in some cases can worsen indoor climate conditions, causing issues such as:

- overheating risk, especially in summer or in the HVAC systems off-work periods;
- poor ventilation and increasing indoor contaminants;
- surface condensation risk.

Similarly, even in many existing buildings, many cases of discomfort were found because of non-homogeneous temperature distribution, generally due to the HVAC regulation systems not adequate to consider the impact of solar and internal heat gains on different zones of the building.

In general, the quality of indoor conditions includes the verifying of several different aspects: thermal comfort, air quality and ventilation, visual comfort and lighting and acoustic assessment.

This study has been focused on the analysis of the main quantities that affect the indoor thermal conditions and air quality for occupants.

Field measurements were carried out, and an extensive monitoring was developed in an office building, by considering more than 15 rooms differently exposed and occupied.

From November 2022 to October 2023, hourly data of air temperature, relative humidity, mean radiant temperature, air speed, were processed to evaluate the thermal comfort in terms of Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). In addition, the CO2 concentration, strictly linked to the occupancy of the room considered, was measured as indicator of air quality and of ventilation rate, during the operating time of the building.

The study aimed at evaluating heating and cooling periods, and at assessing the differences of north and south exposed rooms due to solar radiation. In this building overheating risks for south facing rooms were founded, underscoring the need for specific shading solutions or thermal plant management.

As further proof of the relevant difference of the two exposures, rooms were monitored also in free-floating conditions occurred in the heating seasons (during Christmas holidays). Indeed, in this period the thermal plant was turned off, and temperature in-side the rooms was not conditioned by the HVAC systems nor by the internal gains.

HVAC systems off-work periods were also monitored and analysed by adaptive method, in accordance with EN 16798-1 [8].

Finally, the intermediate season was monitored too. This is one of the innovative contributions of this work, since this period, often underrated in building energy simulations, can entail the most uncomfortable conditions for occupants.

The study is focused on the following indications of the European Directive 2018/844, and explicitly referred in the new EPBD directive, currently under approval, which invites Member States to pay more attention to the analysis of thermo-hygrometric and environmental conditions in the buildings' energy audits, to increase energy performance ensuring well-being for occupants [9].

The peculiarity of the proposed work consists in a large-scale monitoring, which considers several environments with different orientation and occupancy profile; thus, the study provides a comprehensive overview of the critical issues of the building in terms of thermo-hygrometric conditions and ventilation rate, generally not detectable through simulation with quasi steady-state methods (UNI TS 11300 in Italy), commonly used in the EPBD calculation framework. The downtime HVAC systems periods were also monitored and analysed with the adaptive method, in accordance with EN 16798-1. The analysis of the results, at different time scales, will allow for an in-depth comparison with those obtained through numerical simulation (UNI 52016 dynamic hourly method). This represents a crucial step to define, in the coming years, in the national building code, a set of indoor thermo-hygrometric requirements to be verified in the energy audits, according to the targets of the EPBD Directive currently being approved.

This paper presents the first results of field measurements which will allow, in the future research activities, to carry out a comparison with those obtained by application of calculation method of UNI EN ISO 52016 [11], to evaluate the main critical issue of building monitored and highlight the discrepancies between experimental results and numerical simulations. The work aims at assessing how the IEQ conditions can address the building energy audit to specific energy saving actions, to improve the energy performance and, at the same time, IEQ levels.

2 Case study

The case study (Fig. 1) is a building located in the ENEA Casaccia Research Centre in Rome. The building is oriented on the main east-west axis; offices have north and south exposure and are served by a central corridor. In each office, there are one or two occupants.

The building, which is spread over three floors with a flat roof, is equipped with a lift, a server room and laboratories on the ground floor and a meeting room on the second floor, as well as toilets on all floors. Floors are characterized by the same planimetric distribution; therefore, it is possible to define the "typical floor" (Fig. 2) with an area equal to 900 m^2 and a volume of 2700 m^3. Even the offices are similar, so the "typical office" can be schematised with a surface area of 20 m^2 and a volume of 60 m^3 (Fig. 1). The monitoring of thermo-hygrometric and indoor air quality-IAQ parameters was conducted in different offices, selected by identifying the most significant ones, using multi-sensor control units and data loggers.

Fig. 1. Case study: building F83, ENEA Casaccia Research Centre in Rome (left) and "typical office room" (right).

Fig. 2. Typical floor plan – building F83.

3 Methodology

To obtain a systematic monitoring, the equipment has been positioned in different rooms throughout the year, to collect data during the heating, intermediate and cooling seasons, defined in Table 1.

Table 1. Monitoring periods.

Season	Starting Date	Ending Date
Heating	2022 November 8th	2023 April 7th
Cooling	2023 June 15th	2023 September 15th
Intermediate	2023 September 20th	2023 October 20th
	2023 April 15th	2023 May 15th

The middle floor was chosen as the reference floor for monitoring: indeed, it is more representative in terms of occupancy profile, and it allows to avoid considering room with greater heat exchange to the outside. It has been decided, moreover, to monitor at the same period rooms laying in the same wing of the building, but with opposite facing. Hence, when the west wing was considered, both rooms facing north and south were simultaneously monitored. The same occurred when the east wing was considered.

To evaluate thermal comfort monitoring, an adequate experimental apparatus has been identified. Three measuring instruments with CO2 probe (Table 2), turbulence probe (Table 3) and globe thermometer (Table 4) have been deployed throughout the offices.

Table 2. CO_2 probe technical data.

Temperature	
Measuring range	0 to +50 °C
Accuracy	±0.5 °C
Resolution	0.1 °C
Humidity	
Measuring range	5 to 95 %RH
Accuracy	±3 %RH (10 to 35 %RH) ±2 %RH (35 to 65 %RH) ±3 %RH (65 to 90 %RH) ±5 %RH (Remaining Range) ±0.06 %RH/K (0 to +50 °C) long-term stability: ±1 %RH / year Hysteresis: ±1.0 %RH
Resolution	0.1 %RH
Ambient CO_2	
Measuring range	0 to 10000 ppm
Accuracy	±(50 ppm + 3 % of mean value) (0 to 5000 ppm) ±(100 ppm + 5 % of mean value) (5001 to 10000 ppm)
Resolution	1 ppm

Table 3. Turbulence probe technical data.

Velocity - Hot wire	
Measuring range	0 to 5 m/s
Accuracy	±(0.03 m/s + 4 % of mean value)
Resolution	0.01 m/s

Table 4. Globe thermometer technical data.

Temperature	
Measuring range	0 to +120 °C
Accuracy	±1.5 °C or ± (0.004)xT °C (-40 to 1000 °C)
Resolution	0.1 °C

The monitoring methodology was structured as in Fig. 3.

The acquisition rate for each quantity was 15 minutes, and each monitoring phase lasted at least 15 days. During the monitoring period, occupants were asked not to change their habits but only to daily fill in a form reporting their work schedule, the use of fancoil and lighting, and the windows and doors openings. For the data post-processing, the measurements were matched with the daily form. Analyses were carried out considering the days when the rooms were occupied, and a standard working time from 9 a.m. to 3 p.m. Data were hence filtered according to these criteria and were then analysed on different time basis. Thermal comfort was evaluated according to the Fanger's indexes Predicted Mean Vote - PMV and Predicted Percentage Dissatisfied - PPD [11] by the on-line tool provided by the Center for the Built Environment (CBE) from University of California [12]. Moreover, using a psychrometric diagram, the average values of the main thermo-hygrometric parameters of the room were shown, as well as the compliance to EN ISO 13798. Metabolic rate was set to 1.2 met, a typical value for office activity. Clothing insulation was set to 1 clo and 0.5 clo for the heating and cooling seasons, respectively.

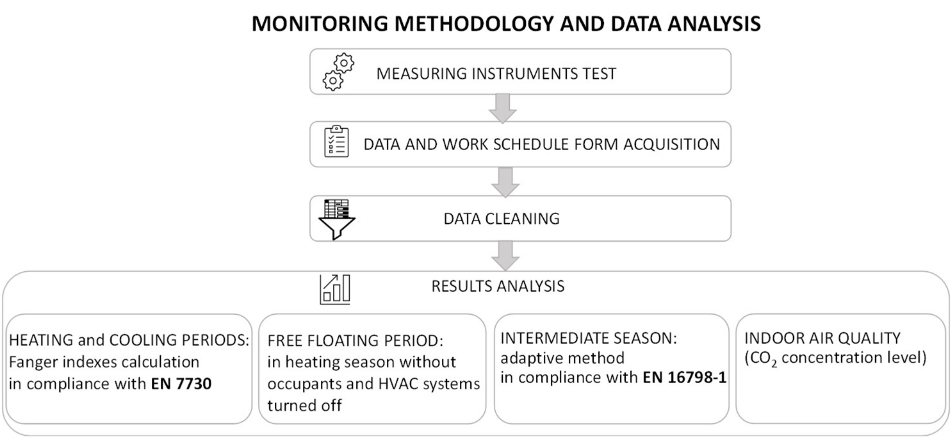

Fig. 3. Monitoring methodology and data analysis scheme.

4 Results

In the following, a selection of the main results obtained during the monitoring campaigns is presented. To highlight the effects of the orientations, rooms with different exposition were selected. Outcomes are showed according to the three seasons (heating, intermediate and cooling), which span from November 2022 to October 2023. Moreover, to assess the effects of the solar gains, results from a free-floating period have been presented, too.

4.1 Heating season

During the heating season, rooms 123 (south exposed) and 127 (north exposed) were monitored contemporaneously. Being located facing each other, they were chosen for a direct comparison. Room 123 shows overheating conditions: differences of about 4 °C and 11% of relative humidity, with respect to room 127, were recorded. These conditions lead to differences the operative temperature. As shown in Fig. 4 and Fig. 5, room 123 is out of acceptability range, whilst room 127 is perfectly in its middle.

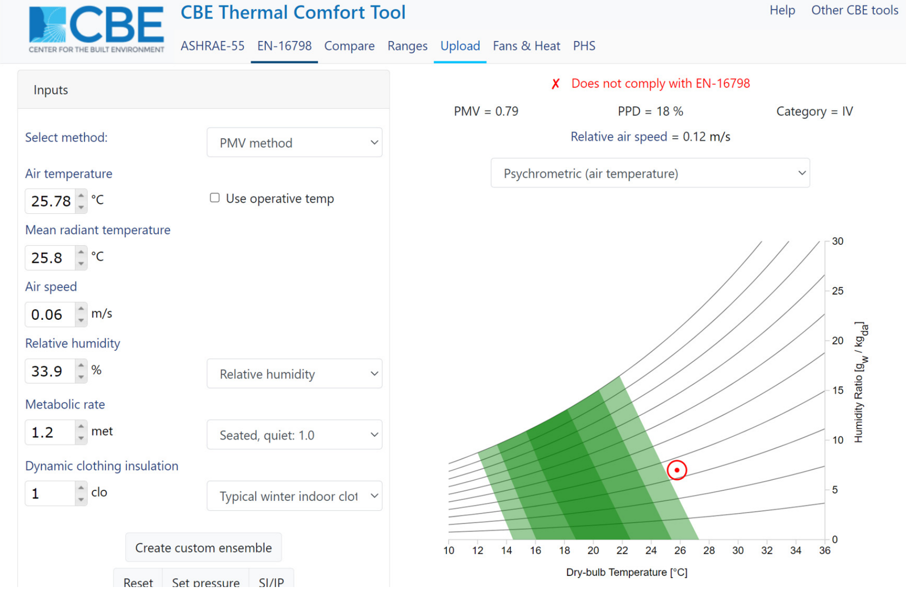

Fig. 4. Room 123 in heating season.

As evident in the figure above, the high values of the air temperature and MRT determine a PMV of 0.79 and a PPD of 18%, which lead to non-compliance with the acceptability ranges of the EN 16798-1.

Moreover, the same rooms were compared in free-floating conditions. Indeed, during the Christmas holidays (that occur in the heating season), the thermal plant was turned off, and temperature inside the rooms was not conditioned by the HVAC systems nor by the internal gains.

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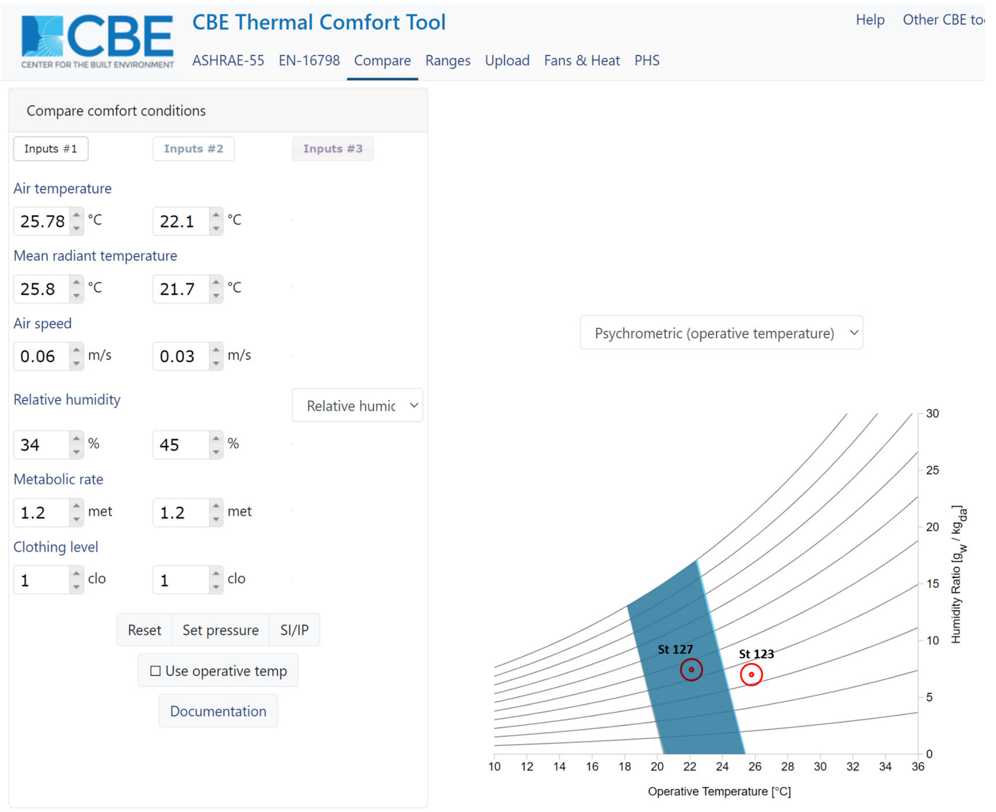

Fig. 5. Comparison between rooms 123 and 127 in heating season.

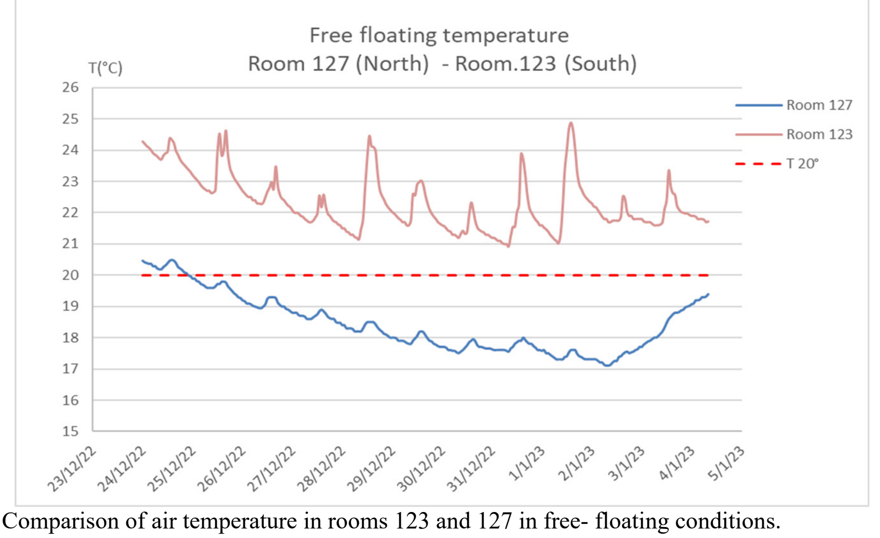

Fig. 6. Comparison of air temperature in rooms 123 and 127 in free- floating conditions.

Temperature trends (Fig. 6) confirms the differences between the rooms. Indeed, starting from December 24th, being without occupants and with thermal plant turned off, the offices show an expected temperature reduction. Room 127 (north exposed) shows a progressive

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reduction from the initial 20.5 °C to the minimum value of 17 °C (recorded on January 3rd). Room 123 (south exposed) starts from 24.3 °C (on December 24th) to a minimum value of 21 °C. However, the overall temperature decrease shows temperature peaks during the midday hours, due to solar gains that maintain the indoor temperature always above 20 °C. As final remark, the temperature difference between the two rooms is, on average, of 4 °C in the 10 days of free-floating conditions.

4.2 Cooling season

For the cooling season, the period from June 15th to September 15th was considered. In Fig. 7, results from a south facing room (119) and a north facing one (131), monitored contemporary from June 16th to July 5th, are reported.

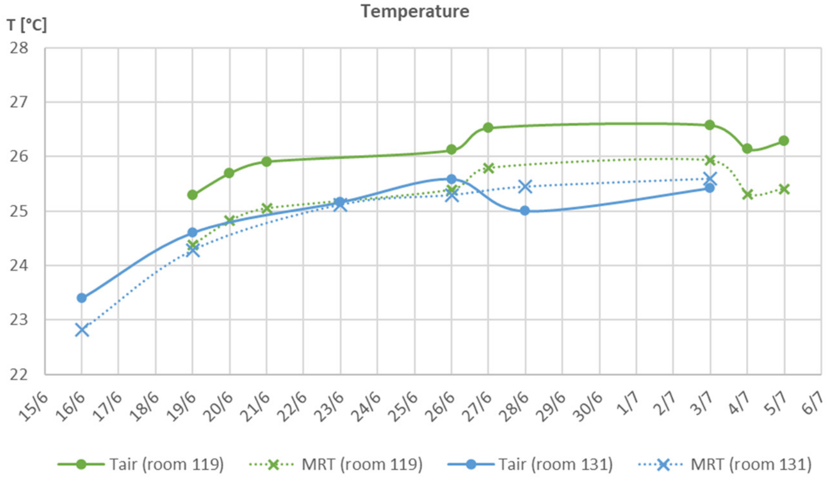

Fig. 7. Comparison of air temperature and mean radiant temperature in rooms 119 and 131 in cooling season.

The air and mean radiant temperatures of room 119 were close, always above 24 °C and with average difference of 0.8 °C. Even room 131 (which is north exposed) doesn't show particular temperature trends. Mean radiant temperature, in this case, is closer to air temperature. The overall trends are lower than those of room 119. Indeed, between the two rooms, the average air temperature difference is of 1.3 °C whilst the average mean radiant temperature difference is of 0.6 °C.

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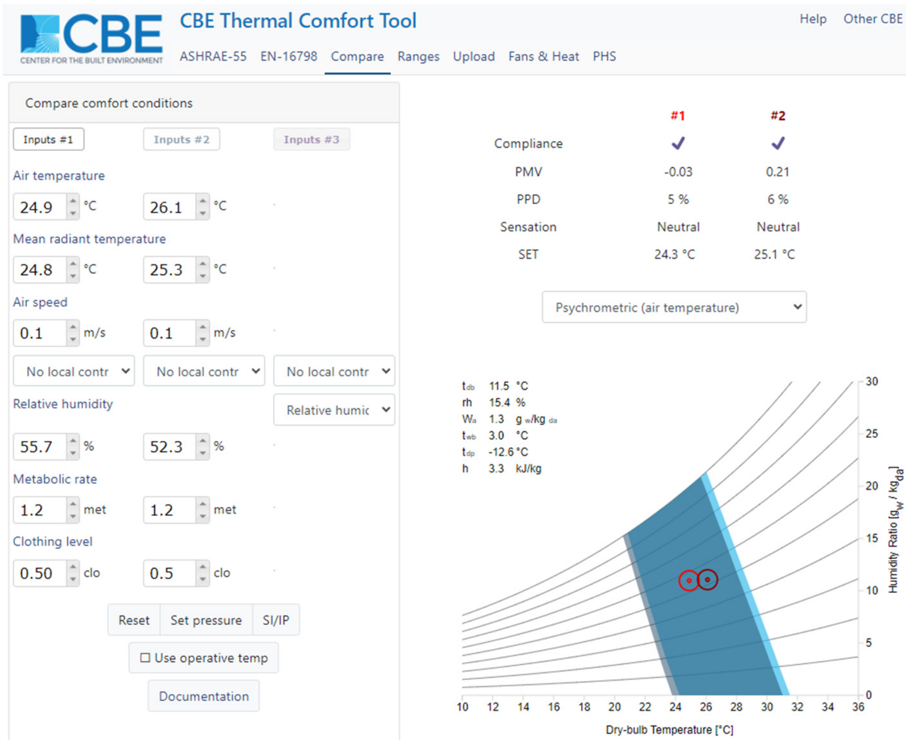

Fig. 8. Comparison between rooms 119 and 131 on the psychrometric chart (from CBE Tool).

Both rooms are in Category I, according to EN 16798. Being the offices monitored in the same period, it is reasonable to compare them in the same psychrometric chart (Fig. 8). The red dot on the left is referred to the north exposed room, the other one refers to room 119. Both fall in the acceptability range, provided by standard.

Other measurements, as mentioned, were carried out in other periods of the cooling season and in other rooms, without showing any relevant issue on the monitored rooms.

4.3 Intermediate season

The measurements of the thermo-hygrometric quantities were also performed during the so-called intermediate season. Two opposite rooms have been monitored, one south-facing (117) and one north-facing (101), and the results are shown in Fig. 9. The chart shows the IEQ condition of the whole period: the south-faced room shows an overall comfort index within the first class of expected quality, while the north-faced room is in the second class. Again, the room exposed to south is significantly warmer than the room exposed to the opposite side.

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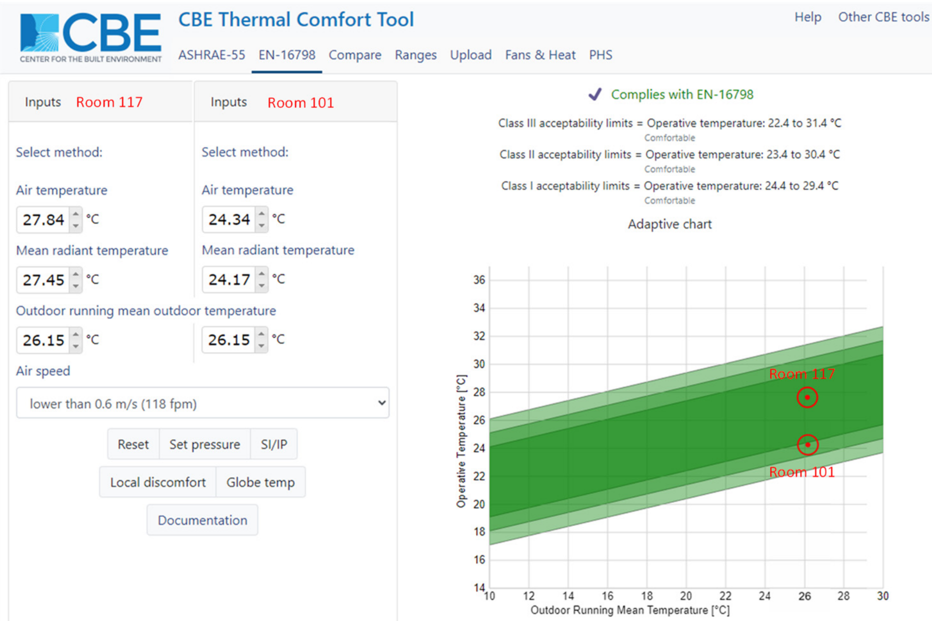

Fig. 9. Representation of rooms 101 and 117 in intermediate season.

During the intermediate season, rooms 122 and 129 (south-facing and north-facing respectively), were also monitored through thermo-hygrometric loggers. Air temperature and relative humidity recorded during working hours are shown in **Fig. 10**. Relative humidity values were always in acceptable ranges. However, air temperature shows quite different trends for the two offices. In room 129, air temperature ranges between 23 °C and 26.5 °C, with an average value of 25 °C. Considering the period and that the HVAC systems was turned off, this value is quite high. Room 122 shows evident overheating. Over the entire monitored period, average temperature is 27.7 °C. Indeed, during the first fortnight, temperature often exceeds 28 °C with a peak of almost 31 °C. During the second fortnight, temperature decreases but it is never below 24 °C.

Fig. 10. Temperature and relative humidity trend of rooms 122 and 129.

4.4 Air quality

The average values of CO_2 concentration were always in the acceptable range, below 1200 ppm. Data in Table 5 are gathered after the data filtering explained before. This proofs that the air change rate was appropriate, as expected, in all monitored rooms.

Table 5. Maximum, minimum and average value of CO_2 of rooms in different seasons.

		MIN	AVG	MAX
		[ppm]		
HEATING SEASON	room 123 (South)	354	459	624
	room 127 (North)	399	472	648
COOLING SEASON	room 119 (South)	513	564	629
	room 131 (North)	394	577	742

5 Conclusions

The challenging goal of increasing the energy efficiency by reducing the consumption in the final uses encouraged a further support for European strategies. On one hand, the refurbishment of building envelope and the upgrade of thermal plants are key factors for reaching this target, on the other hand, great attention must be paid to ensure healthy indoor climate conditions. Recent studies show that building envelope refurbishment does not imply improvement of indoor comfort and environmental quality.

In this work, the analysis of indoor environmental quality of a real office building has been carried out; the building is part of the ENEA Casaccia Research Centre. An experimental measurement campaign to assess the main thermo-hygrometric quantities has been performed during the heating, intermediate and cooling seasons. The main outcome of the measurements was defining of microclimatic conditions within the building, highlighting critical issues and discrepancies between rooms.

In particular, during the heating season, air overheating occurred in all the offices with south-orientation, mainly due to directly incident solar radiation and internal thermal gains. In north-faced rooms, the measured air temperature is lower than south-faced but still higher than set point established by Italian legislation (19 °C). This discrepancy is also confirmed by measurement carried out in free-floating conditions, i.e. during the heating season but in a period with thermal plant turned off and without occupants.

The cooling season, indeed, does not show such difference. Results from two rooms monitored in the same period were shown. The north exposed room has air temperatures lower than the south one of about 1.3 °C, whilst the difference on the mean radiant temperature is of 0.6 °C. However, the trends are quite similar. Moreover, both rooms are in Category I (according to EN 16798), and perfectly fall in the middle of the acceptability range as provided in the psychrometric chart.

The results obtained in the intermediate season, confirm the thermal asymmetry found in the heating period, with maximum air temperatures 3.5 degrees higher for offices facing south compared to those facing north.

Further study can be based on monitored building, to compare the results obtained by numerical simulation with experimental measurements. The progress in technical standards led to UNI EN ISO 52016-1:2018, which allows the estimation on hourly basis of building energy demand, taking into account as output of calculation, the main thermo-hygrometric parameters such as: air temperature, operative temperature, RH, specific humidity. The comparison of results could allow to predict critical issue in terms of indoor thermal comfort at design stage and address the energy audit of building in order to increase the efficiency of building, ensuring, at the same time, adequate IEQ levels for occupants.

References

1. Buildings Performance Institute Europe (BPIE). How to integrate indoor environmental quality within national long-term renovation strategies. Policy paper. (2019)
2. Council of the EU. 2022. "Fit for 55": Council agrees on stricter rules for energy performance of buildings. Press Release.
3. M. Zinzi, F. Pagliaro, S. Agnoli, F. Bisegna, D. Iatauro. On the Built-Environment Quality in Nearly Zero-Energy Renovated Schools: Assessment and Impact of Passive Strategies. Energies, **14,** 10, (2021) https://doi.org/10.3390/en14102799
4. M. Zinzi, F. Pagliaro, S. Agnoli, F. Bisegna, D. Iatauro. Assessing the overheating risks in Italian existing school buildings renovated with nZEB targets. Enrgy Proced., **142**, 2517-2524 (2017). https://doi.org/10.1016/j.egypro.2017.12.192
5. C. Roelofsen. The impact of office environments on employee performance: The design of the workplace as a strategy for productivity enhancement. J. Facil. Manag, **1**, 247-264 (2002)
6. P. Hellstrom. Assessing the impact of the indoor environment on productivity, Royal Institute of Technology (2018)
7. Ministerial Decree for energy efficiency requirements in buildings, 2015
8. UNI EN 16798-1:2019. Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics
9. https://www.rehva.eu/blog/article/fit-for-55-with-healthy-buildings (published by Federation of European Heating, Ventilation and Air Conditioning Associations – REHVA – on August 30, 2021.
10. UNI EN ISO 52016-1:2018. Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads – Part 1: Calculation procedures
11. P.O. Fanger. Thermal Comfort. Analysis and applications in environmental engineering. (McGraw-Hill, 1970)
12. F. Tartarini, S. Schiavon, T. Cheung, T. Hoyt. CBE Thermal Comfort Tool: online tool for thermal comfort calculations and visualizations. SoftwareX, 12, 1-5 (2020)

Acknoledgements

This study was funded in the Program Agreement between the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) and the Ministry of Environment and Energy Security (MASE), in the framework of "Ricerca di Sistema Elettrico", PTR 2022-2024. The activity is part of the Project 1.5 ''Edifici ad alta efficienza per la transizione energetica -WP.1- "Strumenti e tecnologie per la riqualificazione del parco edilizio nazionale" - LA 1.13- "Misure ed analisi del thermal comfort e IAQ in edifici del terziario ed implicazioni di carattere energetico - parte I"