Ventilation behaviour of occupants driven by outdoor temperature: 12 case studies

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ABSTRACT

This paper presents the results of an Indoor Environment Quality (IEQ) monitoring study (including relative humidity, temperature and IAQ in terms of indoor CO_2) in naturally ventilated dwellings (mainly based on vertical shafts and infiltrations) and the analysis of the data obtained. The aim of the study is to identify patterns that relate occupants' ventilation behaviour to outdoor temperature and to increase knowledge of occupant's perceptions of IEQ. The results could be used to improve ventilation models and building regulations.
The monitoring was conducted in 12 apartments located in Madrid, Spain, with a cold semi-arid climate, over different periods ranging from 15 to 21 days. Occupants completed surveys providing information on their habits, occupancy patterns, ventilation operations and subjective perception of IEQ.
According to the results, occupant behaviour is strongly influenced by outdoor temperature and could reverse the expected performance of the ventilation system. This influence could be significant enough to be used as a driving variable for a method of modelling human ventilation behaviour.

KEYWORDS

Natural ventilation; Occupant behaviour; Dwellings; Indoor air quality; CO_2.

1 INTRODUCTION

The traditional way of ventilating dwellings in Spain was by natural ventilation based on the operation of windows and high levels of infiltration through the building envelope, particularly through windows and window-wall joints. In the middle of the last century, the use of vertical ventilation shafts in wet rooms of dwellings became widespread and is currently the most common ventilation system in existing dwellings. This dedicated ventilation system involves the removal of stale air from wet rooms, the circulation of air from dry rooms to wet rooms and the supply of fresh outdoor air to dry rooms by infiltration. Passive stack ventilation extracts stale air from wet rooms by thermal buoyancy (temperature difference between outdoor and indoor) and Venturi effect. Since 2006, the Spanish IAQ regulation DB HS3, *Código Técnico de la Edificación* (MITMA, 2019) establishes that the reinforcement of natural ventilation with a mechanical fan is mandatory in new dwellings. However, the performance of such ventilation system can be influenced by human behaviour. It is known that occupant behaviour is one of the most important drivers of IAQ, with studies monitoring specific actions such as opening windows or room doors (Calí et al, 2016; Fan et al, 2022; Liao et al, 2022; Navas-Martín, 2023).

It would be very useful to know, on the one hand, the real IEQ of occupied dwellings where occupants modify the operation of ventilation systems. On the other hand, it would be useful to identify parameters that help predict IEQ when it is influenced by the occupants' behaviour. This paper presents the results of the monitoring and analysis of 12 dwellings that are representative of the current Spanish residential building stock. It was found that outdoor temperature is the main factor influencing the ventilation behaviour of occupants, altering the efficiency of the ventilation systems installed in dwellings.

2 METHODOLOGY

In order to focus the scope of the study on a representative sample of the current Spanish residential building stock, dwellings were selected according to the criteria of Garcia-Ortega (Garcia-Ortega, Linares-Alemparte, 2015), based on data from the National Statistics Institute (INE, 2013) on the number of occupants, living area and number of bathrooms.
All of the dwellings were apartments in high-rise residential buildings, located in an integrated urban environment, in the southern plateau of the Iberian Peninsula (city of Madrid) (see Figure 1). Their ventilation systems were mainly based on natural ventilation, including occupant-driven ventilation. The façades were traditional brick masonry cavity walls with thermal insulation.

Figure 1 - Location of the monitored dwellings (black dots) and meteorological stations (red dots: belonging to the Spanish Meteorological Agency; blue dot: belonging to Madrid City Council)

A total of 42 different rooms belonging to 12 dwellings were monitored (see Table 1). Most of the rooms were monitored twice: once in summer and once in winter, with a total of 72 measurements between December 6th, 2017 and March 9th, 2020. All dwellings were occupied during the monitoring and characterisation phase.

Table 1 – Monitored dwellings

Dwelling code	Year of construction (or main retrofit)	Year/month of measure-ments	Vertical shafts	Permeability of envelope	Number of occupants	Occupant’s behaviour patterns (general surveys)
01	1986 (2014)	17/12 18/06	Yes	low	2	Open windows 5’ in the morning
02	2000	18/07	Yes	high	4	Open windows in function of outdoor temperature and thermal comfort

03	1956 (2000)	18/07	No	medium	2	Open windows 5’ in the morning; all night in summer
04	1960 (2016)	18/07 19/01	Yes	low	4	Open windows for a few minutes in the morning and afternoon. Open the windows a lot in summer
05	1987	18/07 19/12	Yes	high	2	Open windows 10 - 60’ in the morning; all night in summer
06	1991	18/08 18/12	Yes	high	4	No specific habits
07	1970	18/08 20/03	Yes	medium	2	Open windows in the morning. In leaving room: open window all the day except in winter (in winter only open at night)
08	1963	18/08 19/02	Yes	medium	2	No specific habits
09	1956	18/09 18/11 19/02	No	medium	1	Open the bathroom window after showering, open other windows when feel it is necessary, usually once a day
10	1982	18/09 19/01	Yes	high	2	Open windows 10’ in the morning; in summer leave a small opening all day, and total open window at night
11	1960	18/09 19/03	Yes	low	4	Open windows 5-10’ in the morning
12	2011	18/10	Yes	low	1	No specific habits

The Köppen or Köppen-Geiger climate classification is BSk: Dry, Semi-Arid or steppe, Cold climate. In BSk climate, winters are cold or very cold, and summers can be mild or hot. Rainfall is low. It could also be considered as a continental climate. It can be found in temperate latitudes and far from the sea, such as in inland North America or the steppes of Central Asia.
CO_2 concentration, relative humidity (%) and temperature (°C) were monitored and recorded at 5-minute intervals using Rotronic CP-011 and Wöhler CDL 210 sensors and data loggers. These monitors were placed in dry rooms, mainly bedrooms and living rooms. In some dwellings, wet rooms (kitchens and bathrooms) were also monitored. The display screens were hidden so as not to influence the occupant’s behaviour.
Integrated radon measurements (Bq/m^3) were also carried out in potentially problematic premises, but no significant concentrations were detected.
The correct operation of the shafts was checked using an anemometer and a capture hood model PCE-VA.
All the collected data were subjected to an analysis process to eliminate possible measurement or collection errors.
Meteorological data were obtained from stations 3195 and 3194U of the Spanish Meteorological Agency (AEMET) and from station 28079102 of the Integrated Air Quality System of Madrid City Council (Ayuntamiento de Madrid) (see locations in Figure 1):

- Air temperature: hourly and average per day (°C).
- Relative humidity: hourly and average per day (%).
- Wind speed: average per day and gust (m/s).

General surveys were conducted to identify occupant’s behaviour patterns and motives that could lead occupants to deliberately alter the operation of the ventilation system. In some cases,

a short-period survey was conducted, in which recent and detailed information on ventilation operations was collected.
Parameters related to the occupants, ventilation systems, construction factors and dwellings layout were also characterised. Occupant behaviour was analysed in relation to indoor CO_2, outdoor and indoor temperatures, indoor relative humidity and average wind speed and gust. Statistical analysis was performed using R Software Version 4.2.0 (R Core Team, 2022).

3 RESULTS AND DISCUSSION

83% of the analysed dwellings have natural ventilation systems with exhaust shafts located in wet rooms in addition to infiltration through the building envelope. The rest of the dwellings have natural ventilation based just on infiltration through the building envelope.
Meteorological variables such as outdoor temperature, atmospheric pressure and wind would be expected to be the most relevant driving variables and to have the strongest influence on the efficiency of natural ventilation and consequently on the indoor CO_2 concentration. However, this is not reflected in the monitored CO_2 results.
According to the temperatures recorded (see Figure 2), which show an important indoor/outdoor temperature gradient in winter, stack passive ventilation due to thermal buoyancy should properly perform in this season.

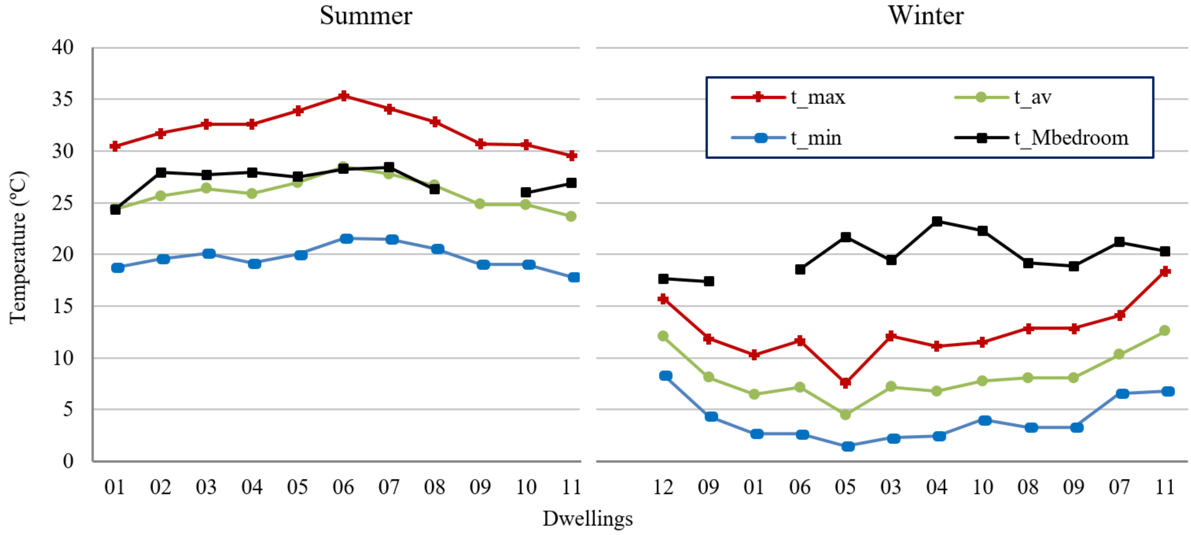

Figure 2 – Average outdoor temperatures recorded during the measurement periods for each dwelling at Station 3194U: t_max: of the daily maximum, t_av: of the daily average, t_min: of the daily minimum; and daily average of indoor temperature in master bedroom. Dwellings are sorted by month of measurement.

This would lead us to expect a higher ventilation rate (and lower concentration of CO_2) in winter. However, the opposite occurred: monitored data showed a significant increase in CO_2 concentration in all rooms in winter compared to the concentration in summer. Average CO_2 concentration for each room within dwellings 01 to 12 is shown in Figure 3. Basic statistics of average concentration of CO_2, number of occupants and living area per occupant are shown in Table 2.

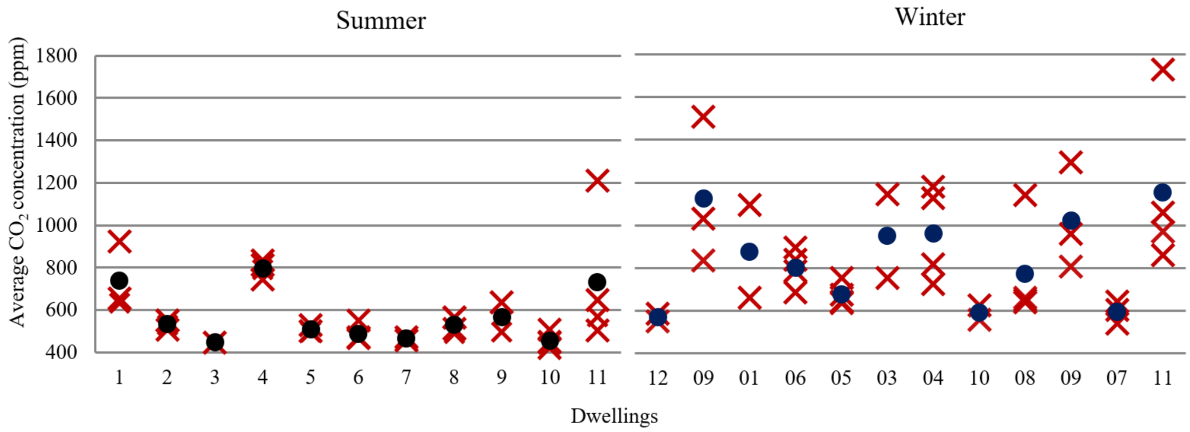

Figure 3 - Average CO_2 concentration. Red cross: for each room within dwellings 01 to 12. Black dot: per dwelling. Dwellings are displayed in the chronological ordered by month of the measurements.

Table 2 – Basis statistics of number of occupants, average concentration of CO_2 and living area per occupant.

Variable	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Number of occupants per dwelling	1	2	2	2	4	4
Living area per occupant (m^2/occ) per dwelling	16.75	25.00	28.25	40.24	60.00	75.00
Average CO_2 concentration (ppm) per room	420	508.8	639	711.4	820.8	1729

Wind and atmospheric pressure are usually recognised as other main drivers of natural ventilation. However, the analysis of the measured hourly values of wind and pressure difference between indoors and outdoors showed no correlation with concentration of CO_2 or HR. The average values of wind and atmospheric pressure over the measurement periods can be seen in Figure 4.

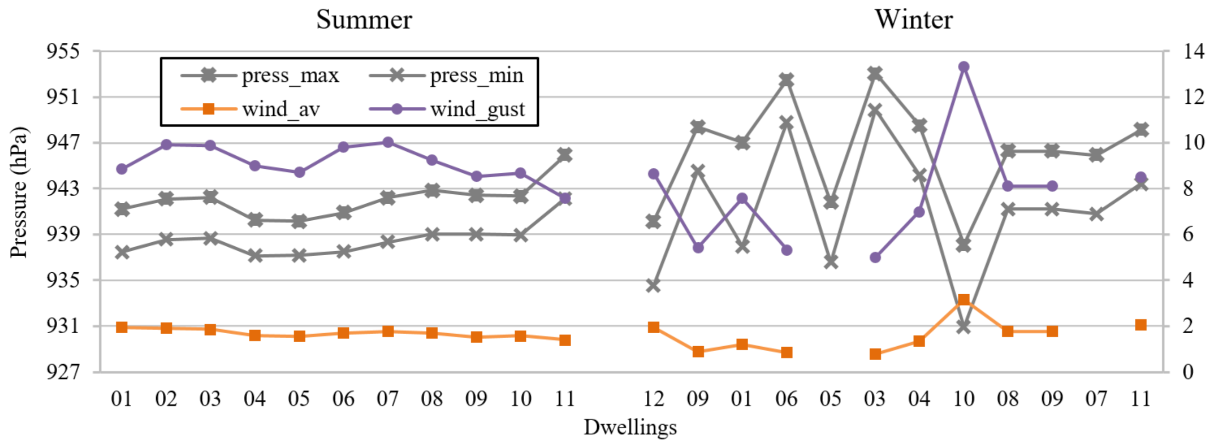

Figure 4 - Averages of the daily maximum and minimum outdoor pressure, wind and wind gust recorded during the measurement periods for each dwelling. Station 3194U. Dwellings are sorted by month of measurement.

An example of the case with the strongest wind and wind gust that occurred during the measurement of dwelling 10 can be seen in Figure 5. The highest wind speed occurred in the afternoon of January 23rd, and remained around average values during the night and the following day. However, no significant influence on the indoor CO_2 or HR concentration is observed.

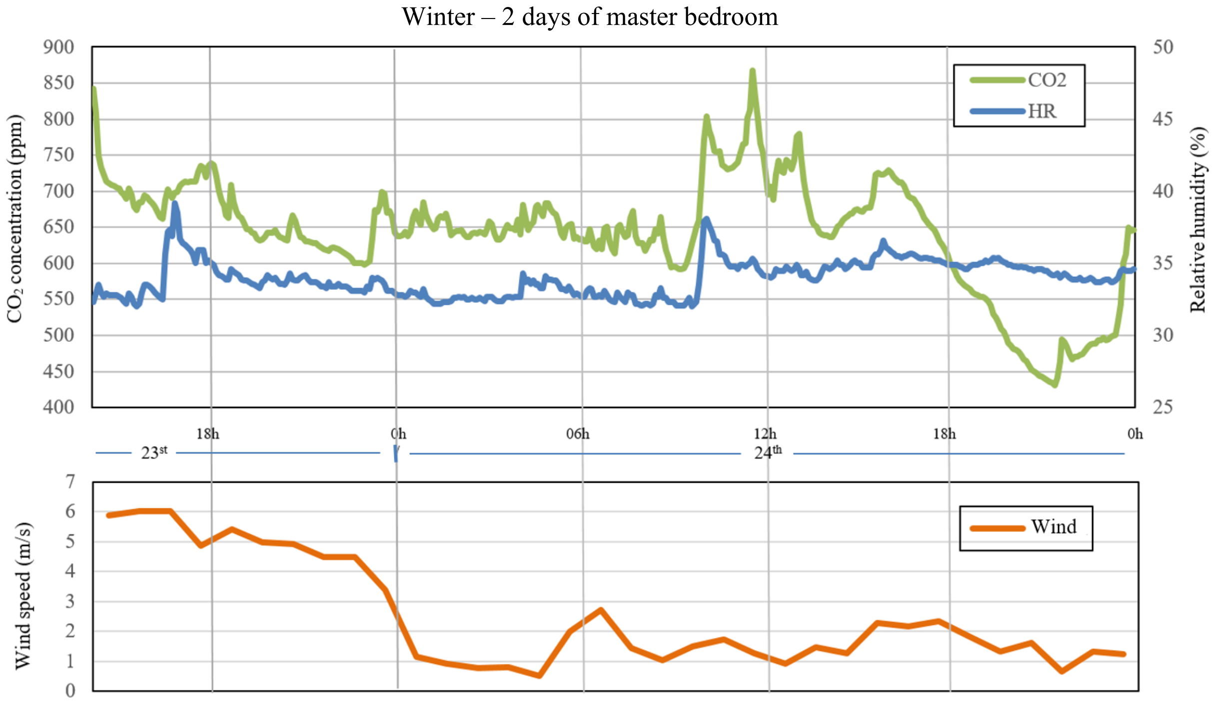

Figure 5 - CO_2 concentration and indoor temperature in the master bedroom of dwelling 10. – Data from January 23rd to 24th 2018

After this, it was assumed that other variables may have been interfering onto CO_2 concentration values, such as the behaviour of the occupants.

Some data of dwelling 01 are displayed in Figure 6 to Figure 9 and discussed below. The results are common to the rest of the case studies.

Figure 6 shows the change in occupant behaviour between June 18th and 23nd in the master bedroom with the arrival of summer and the increase in outdoor temperatures. In particular, the minimum outdoor temperatures (see Figure 7) increased by almost 7°C during this period. Due to the increase in outdoor temperatures, the indoor temperatures also increased. After reaching an indoor temperature of 27.4°C on the night of the 21st, in the short-period survey the occupants reported keeping the interior doors completely open and some windows open for long periods, including at night, thus reducing the CO_2 concentration. No clear influence of other variables such as wind was observed (see Figure 7).

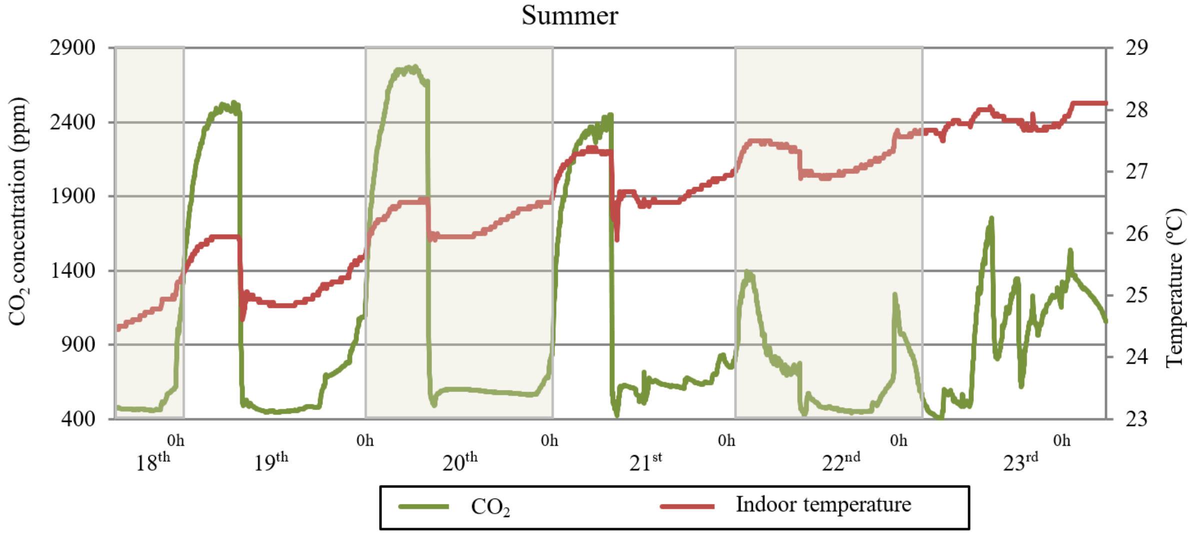

Figure 6 - CO_2 concentration and indoor temperature in the master bedroom of dwelling 01. – Data from June 18th to 23rd 2018

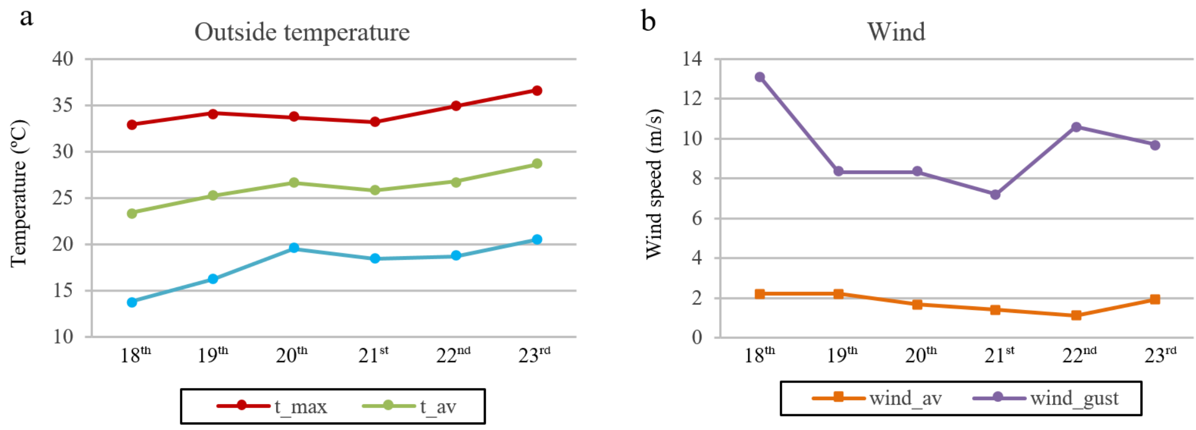

Figure 7 - a – Daily outdoor temperature: maximum, average and minimum. b – Daily wind average and wind gust. – Data from June 18th to 23rd 2018

Figure 8 shows the CO_2 concentrations measured between December 6th and 9th in the same master bedroom as in Figures 6 and 7. The occupants reported leaving the bedroom door open during the nights. However, in the short-period survey, they reported that the door was kept closed on the night from the 6th to the 7th. This resulted in a large increase in CO_2 concentration, greater than the effects derived from the other studied parameters. In addition to this, on the 7th, 8th and 9th, the occupants opened the bedroom window when they got up, which caused a rapid decrease in the concentration of CO_2 and humidity. On the 6th, however, they did not open the bedroom window in the morning, so the room was ventilated more slowly just through infiltration and stack ventilation.

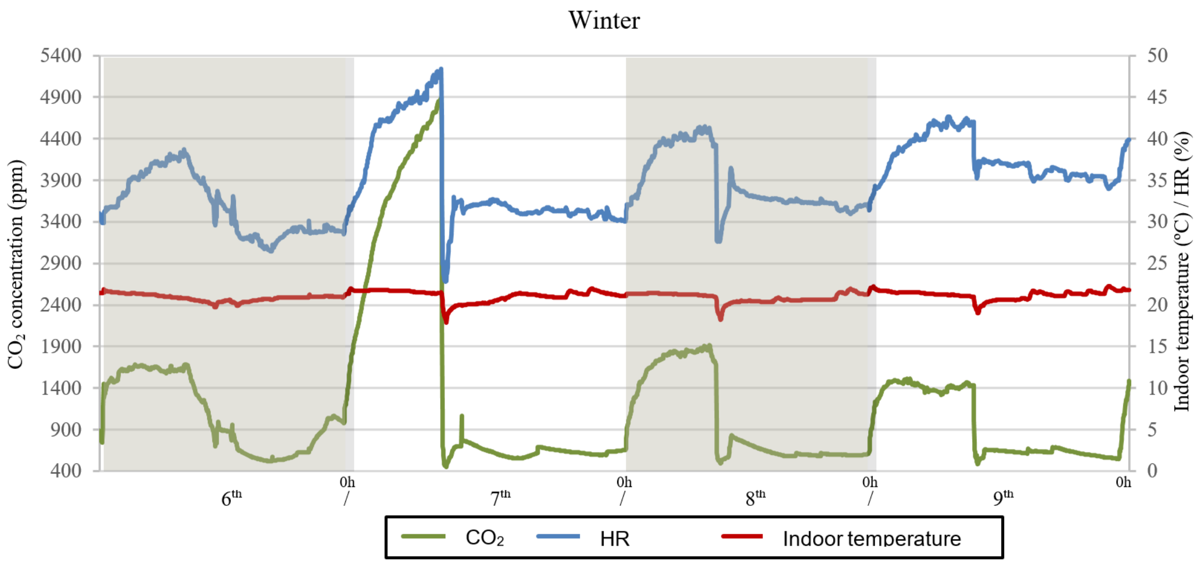

Figure 8 - CO_2 concentration, relative humidity and indoor temperature recorded in the master bedroom of dwelling 01. – Data from December 6th to 9th 2017

In Figure 9 it can be seen that on the 6th and the 7th the lowest temperatures are reached, below zero, changing the ventilation pattern of the occupants during the night of the 6th and producing the highest CO_2 concentration. The wind which occurs on the 9th (see Figure 10), does not seem to have a clear influence on the ventilation pattern neither the IAQ.

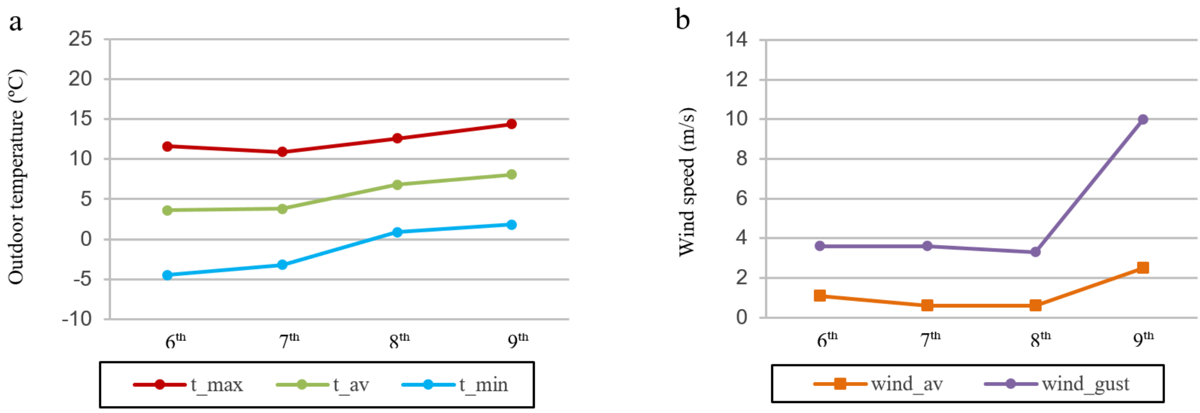

Figure 9 - a – Daily outdoor temperature: maximum, average and minimum. b – Daily wind average and wind gust. – Data from December 6th to 9th 2017

This relationship between the concentration of CO_2 and outdoor temperatures can be observed in all the monitored rooms. In view of the above analysis, it is assumed that this is due to the behaviour of the occupants.

The behaviour of the occupants in relation to the outdoor temperature seems to be behind the reversal of the expected effect of the meteorological variables on the efficiency of the ventilation systems. The occupants hinder the operation of the ventilation system in winter by closing doors, making it difficult for air to flow from the dry rooms to the wet rooms, whereas in summer they favour ventilation by opening windows and doors.

General surveys reveal a ventilation pattern based on opening the windows for 5 to 10 minutes in the morning and keeping them closed the rest of the time. Occupants tend to keep the windows open for longer periods when it is hot, not for ventilating but for providing thermal comfort.

However, when the ventilation patterns of the general surveys are contrasted against the monitored CO_2 concentration data, contradictions are found.

Only when occupants report their recent behaviour in the short-period surveys, on the same day or the day before, ventilation operations and recorded CO_2 match.

According to the surveys and monitored data, the most relevant driving variable influencing ventilation habits of the occupants is the outdoor temperature: Higher outdoor temperatures in summer cause an increase in indoor temperature, and would lead occupants to adopt behaviours such as leaving windows open for long periods, particularly at night, to cool down their homes, indirectly improving IAQ. In contrast, lower winter temperatures would lead them to keep windows and doors closed for longer periods. These results are in line with the global expectations, but they far exceed them: the influence of outdoor temperature in IEQ through occupant behaviour enhances the expected performance of the ventilation system.

In order to improve ventilation models, outdoor temperature could be used as a form of prediction of occupant behaviour.

Figure 10 shows CO_2 concentrations for different types of rooms in winter and summer.

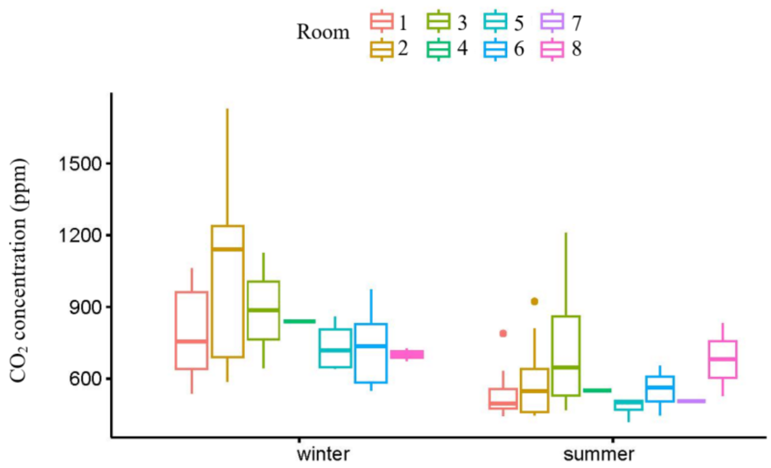

Figure 10 – Boxplot of average concentration of CO_2 per type of room in winter and in summer. Rooms: 1: Living/dining room; 2: Master bedroom, 3: 2nd Bedroom; 4: 3rd Bedroom; 6: Kitchen; 8: Bathroom; 9: 2nd bathroom;10: Other room, e.g. a Home office or Studio

The motives of the occupants for ventilation, based on (Emmerich, 2001), are:

- IAQ control, by diluting pollutants through the introduction of fresh outdoor air;
- Cooling of overheated rooms, by introducing cooler outdoor air;
- Modifying thermal sensation, by creating a draught;
- Cooling overheated rooms at night by introducing cooler night air during hot periods.

According to the results of this study, the motivations of the occupants include thermal comfort, but not the control of IAQ reported by other authors, at least when IAQ is expressed as a function of CO_2 concentration at usual levels.

4 CONCLUSIONS

The main driver of occupant behaviour in terms of actions that can modify ventilation rates and IAQ (such as window and door operation) seems to be thermal comfort rather than IAQ control itself, at least when expressed as a function of CO_2 concentration. For practical purposes and statistical analysis, occupant behaviour in relation to IAQ could be considered as a function of average outdoor temperature.

Unfortunately, occupant behaviour is not easily captured by general surveys. This leads to doubts about the representativeness of general surveys. Only short-period surveys in which recent and detailed operation is gathered can be taken into account, deriving into further representability.

These observations may be useful to model the expected occupant ventilation behaviour in dwellings based on easily obtained variables such as outdoor temperature. This model is necessary to stablish the basis and guidelines for specific retrofit policies, initiatives, regulations, etc. for naturally ventilated dwellings.

However, the results of the analysis could be extrapolated only to cases in the studied climate, with the same cultural background in relation to ventilation behaviour and with similar ventilation systems. Further research should be conducted to test the results in other climate areas and/or with other types of natural ventilation systems.

The data reported by the occupants suggest that they modify the infiltration of the dwelling during the winter in order to avoid heat losses due to the infiltration of cold air. An approach to characterisation is left for a later study.

5 ACKNOWLEDGEMENTS

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