Indoor air quality investigation in a ventilated demonstrator building via a smart sensor

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ABSTRACT

This study deals with ventilation effects on measured and perceived indoor air quality (IAQ) in a demonstrator building where IAQ problems can occur. Unlike outdoor air, indoor air is usually recycled continuously, which makes it trapping pollutants. Indoor air quality (IAQ) is characterized by a pollutants' concentration, as well as air temperature and humidity. The study's aim is to implement an efficient and smart ventilation system while leaning on continuous measurements of indoor air pollutants in a demonstrator building via a smart sensor based on a Raspberry Pi 3 model B+ card. Such a monitoring system measures atmospheric pollutants (CO_2, CO, VOCs, formaldehyde, $PM_{2.5}$ and benzene) and also comfort parameters (temperature and humidity). It is intended to locate the source influencing the IAQ and, thereby, it will certainly be very helpful to users and to obtain interactive cartography of IAQ. To achieve this, an IAQ monitoring system has been proposed with a newly added feature which enables the system to identify the sources influencing the level of IAQ. It has been developed through a series of measures. Measurements showed that the system is able to measure the air quality level and successfully classify the sources influencing IAQ in various environments like ambient air, chemical presence, human activity, etc. It turned out that the CO_2 level was higher during the occupation periods. Note that classrooms were excessively confined during occupancy periods by calculating the ICONE air containment index. In terms of hygrothermal comfort, the air was dry and very hot, especially in winter. However, the current ventilation system regulates the airflow according to the CO_2-concentration only and does not consider the classrooms' hygrometry. This upsets occupants comfort and influences their productivity.

KEYWORDS

CO_2, Indoor Air Quality (IAQ), Hygrothermal comfort, Smart ventilation, Smart sensor.

1 INTRODUCTION

In the context of the third industrial revolution (TIR), energy renovation has become essential to achieve energy savings in the existing building. As a result, it has become an ecological and social imperative. Increased insulation of buildings and the use of certain materials and products may increase indoor air contaminant concentrations in the absence of effective ventilation. On average, we spend 90% of our time in closed places, and the air we breathe in is not always of good quality. Sources of pollution are potentially numerous (building materials, furniture, paintings, carpets, etc.). The main indoor air pollutants are: CO_2, CO, Formaldehyde, VOCs (Volatile Organic Compounds), Ozone, Benzene, and PM2.5 (Fine Particulate Matter). Several studies carried out by the World Health Organization (WHO, 2000) or (ANSES, 2014) argue today that the quality of indoor air (IAQ) is a public health issue.

Occupants are exposed to the harmful effects of indoor air pollution for many years (Vilčeková and al., 2017). In addition, many diseases are due to poor "IAQ". To date, 12 million French suffer from respiratory allergies according to WHO (World Health Organization). This questions us about IAQ breathed daily (12.10^3 l of air/day). In fact, indoor air is 8 times more polluted than outdoor air according to the Observatory of Indoor Air

Quality (OQAI). For example, the European OFFICAIR project (Mandin and *al*., 2017) focused on IAQ in 37 office buildings. The indoor air quality (IAQ) refers to the health and comfort of building occupants. Consequently, understanding and controlling common pollutants indoors can reduce the risks of indoor health concerns.

The poor quality of indoor air is due to multiple factors. These include excessive moisture, poor temperature, excess VOC, PM2.5 particulate matter (48,000 deaths per year due to PM2.5). In addition, recent studies have shown that there is a direct link between IAQ and individual productivity. In fact, the cost of absenteeism for sick people is 40 billion euros / year in France. In addition, thermal comfort, IAQ, occupant perceptions and impacts of poor IAQ are poorly studied (Sekhar and Goh, 2011).

The main factors associated with poor IAQ are: poor efficiency of some ventilation systems, lack of fresh air and excess CO_2 content (Ai and *al*., 2016). In many studies (Krzaczek and Tejchman, 2012), it has been suggested that measurement of CO_2 content may be useful for understanding IAQ and ventilation efficiency. In fact, effective ventilation eliminates pollutants generated indoors or dilutes their concentration to acceptable levels (Seppänen and Fisk, 2004).

Health and economic issues related to IAQ are important. As a result, it seems important to plan actions to improve both IAQ and energy savings. Ventilation is an important part of building energy consumption (Cao and *al*., 2016). Since 2005, the effects of air change rate on occupant health have been examined by a multidisciplinary group (Sundell and *al*., 2011) and (Seppänen and *al*., 1999). In the literature, several studies have shown that the ventilation rate in classrooms is often below the minimum value (Fisk, 2017). In addition, the effect of IAQ in school environments negatively influences academic performance (Mendell and Heath, 2005). Therefore, finding a compromise between the energy aspect and the health aspect is very delicate. For this purpose, we have proposed a solution based on the study of intelligent ventilation that helps to maintain the health of occupants in terms of IAQ while optimizing the rate of air renewal. The influence of ventilation flow on IAQ has been studied in several studies. When the ventilation rate is high, the IAQ is better (Seppänen and *al*., 1999). The Ministry of Environment and Health launched the IAQ Action Plan in 2013. Our study is based on the automation of the existing ventilation system in the demonstrator building using a smart sensor that we developed in-situ. This sensor measures several air pollutants (CO_2, VOCs, formaldehyde, benzene, CO, PM2.5) as well as comfort parameters (temperature, humidity, etc.). The sensor is developed via a Raspberry Pi 3 card that allows the connectivity of the case. The measurements are made in real time and allow the building manager to know the comfort situation (thermal and sanitary) in each space of the building and act instantly in case of malfunction of the ventilation system.

2 DESCRIPTION OF THE EXPERIMENTAL APPROACH

We conducted three sets of IAQ measures and comfort parameters in the demonstrator building located in Lille. We measured CO_2, VOCs, formaldehyde, CO, benzene, ozone and PM2.5. The comfort parameters were evaluated (temperature and humidity). At first, one of the rooms of the building (T201) was instrumented. Note that this room can accommodate up to 56 students (see Figure 1 and Figure 2).

2.1 Geometry of the instrumentation room and positioning of the sensor

The instrumentation of the room (T201) was carried out by placing the sensor in the middle of the wall behind the occupants and at a height of 1.50 m above ground level (the height of sitting occupants). In general, the sensor must be close to the source of pollution.

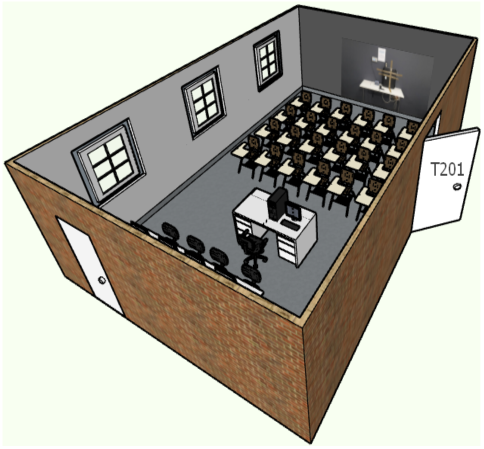

Figure 1: T201-room 3D view

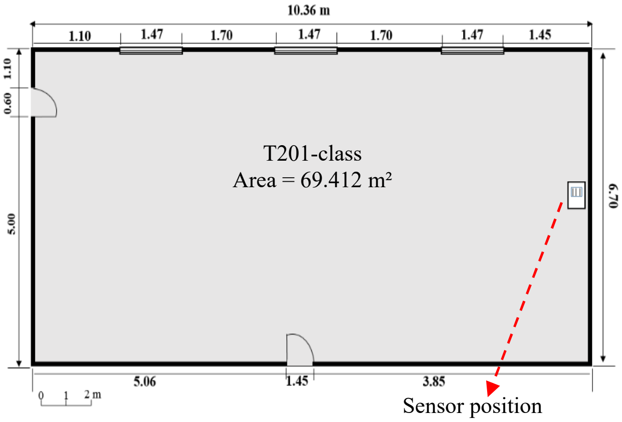

Figure 2: T201-room dimensions and smart sensor position

2.2 Strategy of the experimental study

The strategy adopted here is based on 4 steps. The first is to determine the experimental room for measuring air pollutants. The second is based on the development of the box connected with a Raspberry Pi card that includes all sensors measuring air pollutants and comfort parameters (T °C and HR %). The third step is storing measurements in the database and viewing in real time on the webpage / display screen. The last step focuses on the action of the ventilation system, according to the data sent by the housing, on the modulation of the air flow according to the comfort situation.

We propose a solution that ensures a compromise between the needs of sanitary comfort (in terms of IAQ) and hygrothermal comfort while ensuring an energy saving of about 20%. A good IAQ improves occupant productivity by reducing absenteeism.

Figure 3 and Figure 4 summarize our measurement strategy.

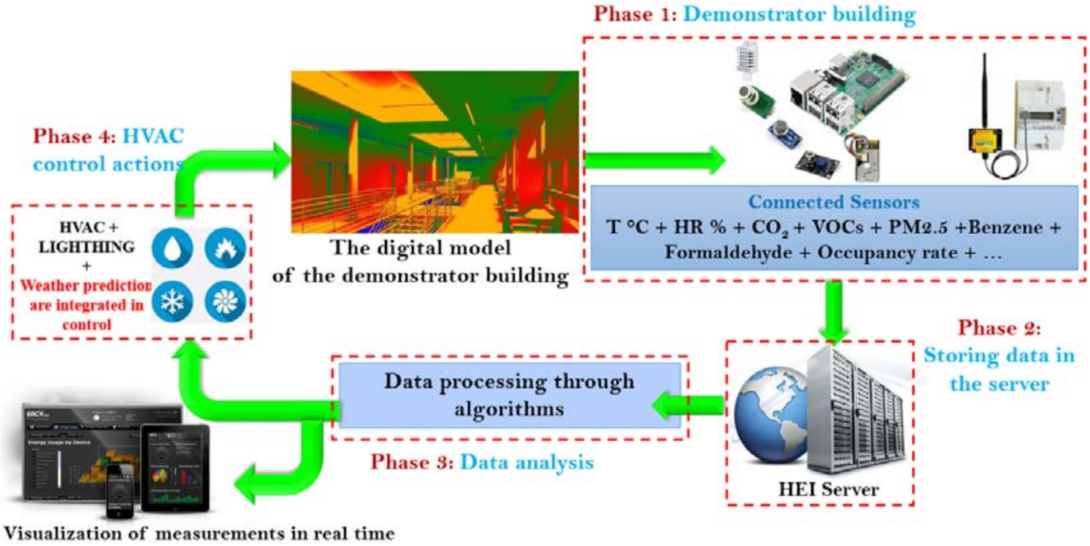

Figure 3: IAQ measurement protocol in the demonstrator building

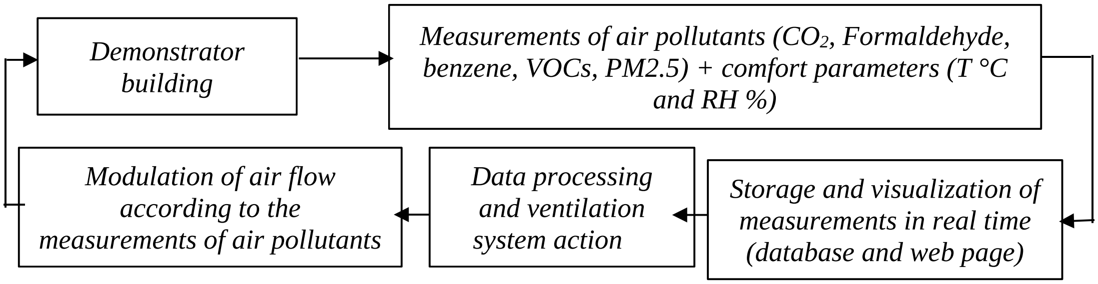

Figure 4: The strategy protocol for measuring IAQ and comfort parameters

3 RESULTS AND DISCUSSION

In this section, we analyse the results of the three measures. A questionnaire was put in place to know the perception of occupants (students) relative to the IAQ and thermal comfort.

3.1 CO_2 concentrations during the three measurement campaigns in room T201

During the three measurement campaigns, CO_2 levels exceed 10^3 ppm (parts per million), which is the maximum value recommended by ASHRAE 62 (ASHRAE, 1988). Remember that CO_2 is produced by the human body during breathing. It is related to human occupation and air change rates. Indeed, when room T201 is occupied, the CO_2 content becomes important. In periods of vacancy, its concentration does not exceed 400 ppm. Moreover, after the course periods, its concentration drops to a minimum value. Indeed, the variation of the CO_2 content is proportional to the occupation. Figure 5 shows the temporal evolution of the CO_2 concentration and the change in the number of occupants, respectively.

The three curves shows (Figure 5) that some spades correspond to a large number of occupancy except that CO_2 concentrations remain low. As the calculation of the occupation number was based on the planning of the T201-room. This explains that the classroom was occupied without being indicated in the schedule. Hence the interest to follow the variation of the occupation with a sensor which allows to count the exact number of the occupants as there is a strong relation between the occupants and the production of CO_2. This is the next step in this work.

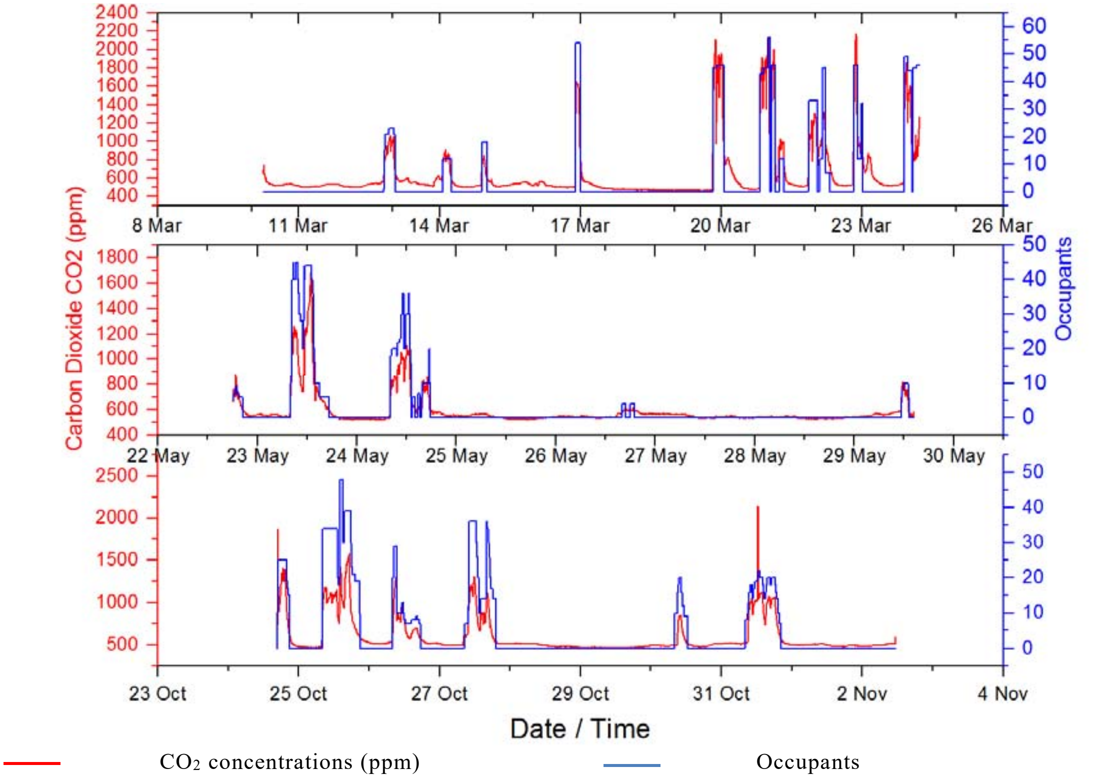

Figure 5: CO_2-concentrations and occupancy rate during the three measurement campaigns

The measurement group during the off-season (March 2017) has very high CO_2 concentrations compared to those in winter and summer. The maximum value of CO_2 during this period exceeded 2.25×10^3 ppm for 5 hours. CO_2 concentrations are low during weekends and at night. Outside these periods, these concentrations were very high. This influences the health of students and generates headaches and lack of concentration. High concentration is due to inefficient ventilation. In order to better visualize the link between CO_2 and occupancy, we calculated the "ICONE" air containment coefficient (see Eq. (1)) for the three measurements and when T201-room was occupied.

3.2 Calculation of the ICON air containment index

The CO_2 concentration measurements in room T201, obtained during the three measurement campaigns, make it possible to define the ICONE index of the premises. This index characterizes the quality of the air change for a given room and occupancy. The decree of January 5, 2012 (Ribéron and *al*., 2016) provides for the calculation of the ICONE based on a continuous measurement of the concentration of CO_2 in the air. The ICONE index varied between 0 and 5 (Table 1).

Table 1: Values of the ICONE index and nature of confinement

Value of the ICONE index	**Selected value of the ICONE index**	**Nature of confinement**
ICONE < 0.5	0	Null
0.5 ≤ ICONE < 1.5	1	Low
1.5 ≤ ICONE < 2.5	2	Way
2.5 ≤ ICONE < 3.5	3	High
3.5 ≤ ICONE < 4.5	4	Very high
ICONE ≥ 4.5	5	Extreme

The ICONE index is calculated according to the following formula ((Eq. (1)) and Table 2.

$$ICONE = \left(\frac{2.5}{\log_{10}(2)} \right) \log_{10}(1 + f_1 + f_2) \tag{1}$$

f_1 is the proportion of values between 10^3 and $1.7*10^3$ ppm $\left(f_1 = n_1 / (\sum_{i=0}^{2} n_i) \right)$ and f_2 is the proportion of values greater than $1.7*10^3$ ppm $\left(f_2 = n_2 / (\sum_{i=0}^{2} n_i) \right)$ avec

Table 2: Coefficient n_i of the ICONE index (with i = 0; 1; 2)

n_0	Between 0 and 10^3 ppm
n_1	Between 10^3 and $1.7*10^3$ ppm
n_2	Greater than $1.7*10^3$ ppm

The ICONE shows that the CO_2 content is between 4 and 5 (very high and extreme) during the month of March 2017 (Figure 6). This indicates that the occupancy density is high and the air change is insufficient, showing that the ventilation system is not efficient. The analysis shows that the measurement of CO_2 cannot be considered alone as an indicator of chemical pollution of indoor air. It is important to measure other pollutants to assess IAQ.

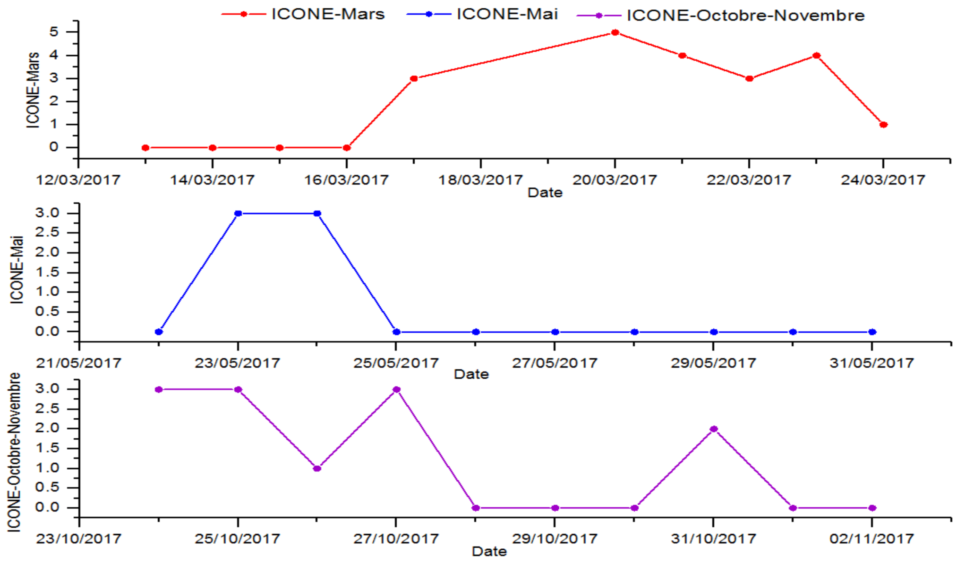

Figure 6 : Calculation of the ICONE during the three measurement campaigns in T201-room

3.3 IAQ assessment

From Figures Figure 7 and Figure 8, the CO_2 concentrations are high and the average value remains below 10^3 ppm. In addition, the concentrations of other air pollutants are low compared to the recommended values. Regarding IAQ occupancy perception, over 60% of occupants surveyed (out of a sample of 100) rated IAQ as good and about 5% as poor (Figure 7). These results can be explained by the lack of perception of the notion of air quality by the occupant. They are unable to determine the parameters to assess IAQ. Occupants perceive IAQ by nasal sensation since most pollutants are odorless and therefore difficult to detect and therefore difficult to detect. It turned out that the answers are contradictory, since more than 50% of the people questioned suffer from several symptoms due to bad IAQ (25% of nasal congestion, 19% of difficulties of concentration, 34% of tiredness, 13% of headaches) (Figure 9). All these symptoms are due to a high concentration of CO_2 in the room. In relation to dust, more than 43% complain of a feeling of dust during class periods.

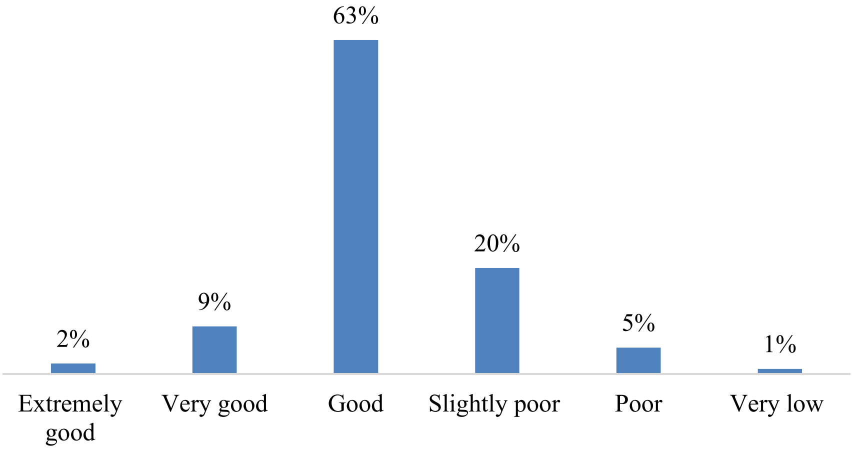

Figure 7: Occupant perception of IAQ in T201-room

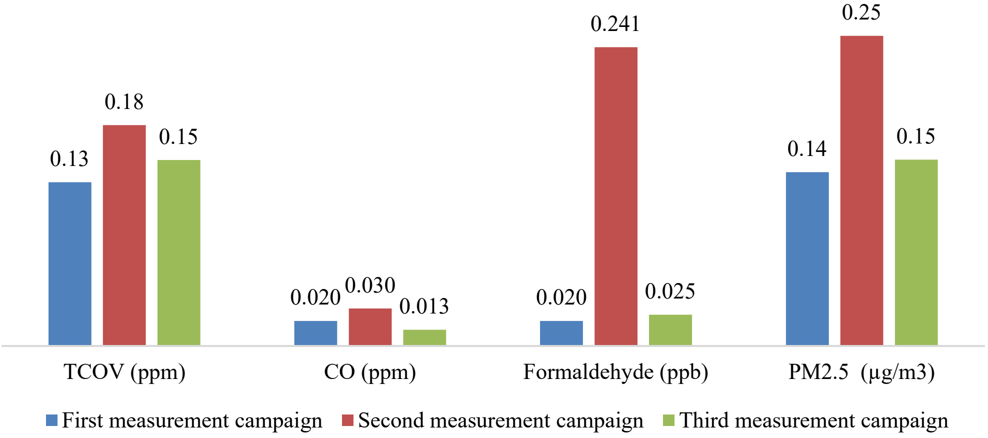

Figure 8 : Average values of IAQ in T201-room

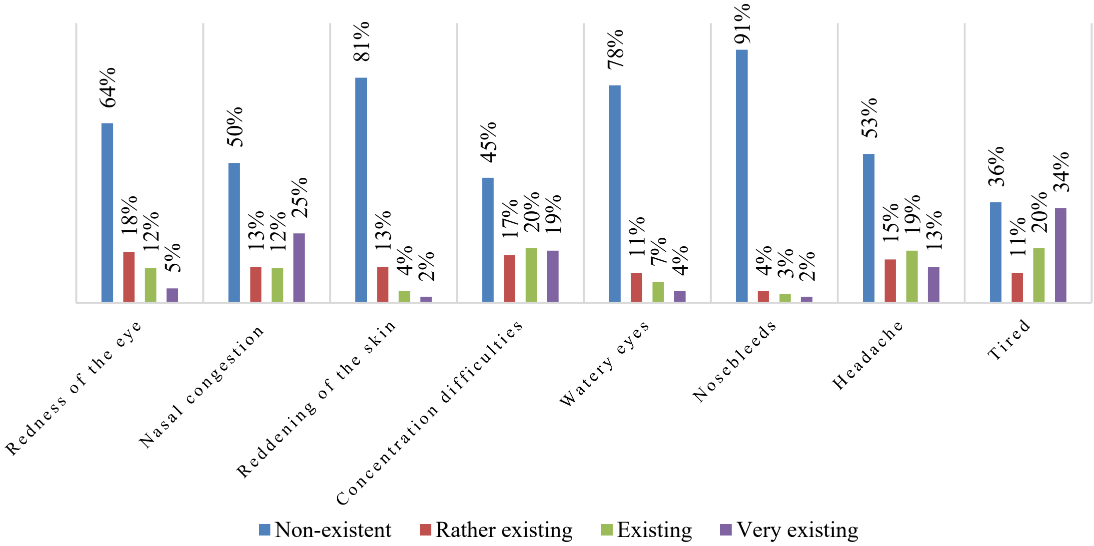

Figure 9: Distribution of responses based on symptoms of poor IAQ

3.4 Hygrothermal comfort evaluation

Occupants health is influenced not only by IAQ, but also by felt comfort. However, we plotted the comfort parameters (T °C and RH %) using the bioclimatic diagram (Figure 12). The ambient humidity varies between 21 and 51% (air being dry). This circumstance can be explained by the regulation of the ventilation system based solely on the temperature measurement. In addition, it is found that the temperature is too high (on average 24 °C) in the room during the entire measurement period (offseason). Knowing that the comfort temperature for a seated person is 21 °C, this one is not established in this case. In fact, the analysis of the comfort questionnaire shows that 80% of occupants (Figure 10) were hot and the air was dry. As a result, more than 42 % occupants (Figure 11) found that hygrothermal comfort conditions were not met (in terms of T °C and RH %). It should be noted that, as soon as it is hot, users tend to open the windows, which leads to a waste of energy.

In fact, the analysis of the comfort questionnaire shows that 80% of occupants were warm and the air was dry (Figure 10). From these results, we can state that working conditions are not comfortable. This leads to absenteeism and a drop in the productivity.

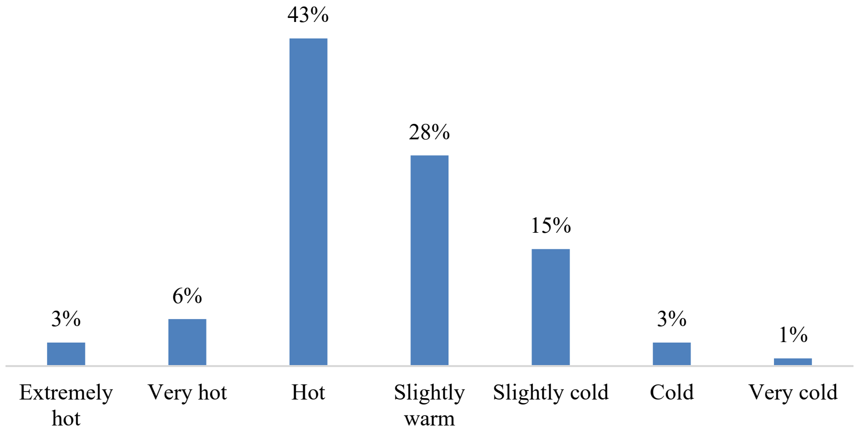

Figure 10: Occupants perception of indoor temperature - March 2017

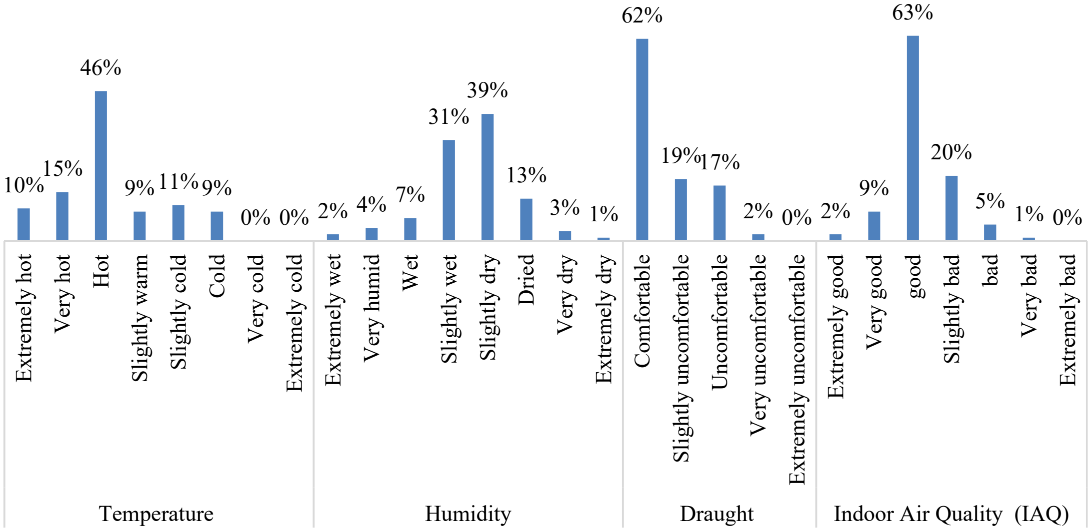

Figure 11: Occupants perception of IAQ and comfort- March 2017

The comfort zone was calculated according to HS (equations (2-3)).

$$HS = \frac{0.622 \times p_{sat}(\theta) \times RH}{101\,325 - p_{sat}(\theta) \times RH} \tag{2}$$

$$p_{sat}(\theta) = \exp\left(23.3265 - \frac{3\,802.7}{\theta + 273.18} - \left(\frac{472.68}{\theta + 273.18}\right)^2\right) \tag{3}$$

where RH is relative humidity [%], HS is specific humidity $[\mathrm{kg_{eau}.kg_{air\ hum}}^{-1}]$, p_{sat} is saturation vapor pressure [Pa] and θ temperature [°C].

Review of Figure 12 shows that more than 60% of the points are located in zone 1 (drought zone) and less than 40% are located in comfort zone 4 (hygrothermal comfort polygon). The ambient humidity varies between 21 and 51% showing that the air is dry. It should be noted that the regulation of the current ventilation system is based only on the measurement of the temperature and not the temperature and the RH %, which explains why the air was dry during the month of March. In addition, our findings seem consistent with the March 2017 survey (the hygrothermal comfort zone being between 1 and 4).

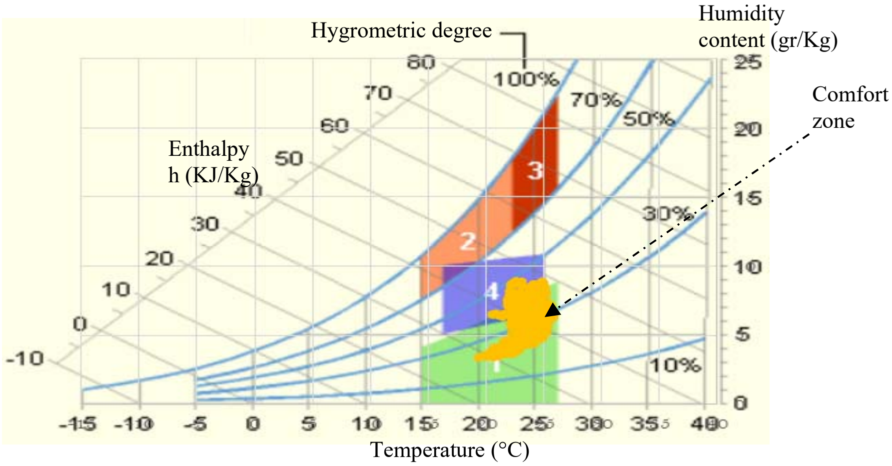

Figure 12: Comfort zone location in the T201-class (March 2017)

3.5 Development of the smart sensor

The results of the three sets of IAQ measures and comfort parameters show that ventilation is not effective. In other word, the high CO_2-concentrations indicate that the ventilated airflow in the demonstrator building is not sufficient. Hence, to improve IAQ and comfort without increasing energy consumption, we proposed a solution that consists in automating the ventilation system to regulate the flow of blown air and extract it if needed via a smart sensor. The developed sensor will equip the demonstrator located in the Lille city (France) to monitor the variation of IAQ and comfort. The "smart sensor" is connected to a Raspberry Pi model 3B card whose the main purpose is to connect the smart sensor (IAQ and comfort parameters) with a ventilation system using the IoT technology (Internet of Things). Measurements are stored in a database via Wi-Fi. Figure 13 shows the development approach of the sensor connected to the Raspberry Pi model 3B card as well as the air pollutant sensors that have been integrated. The smart sensor is in the design and improvement phase.

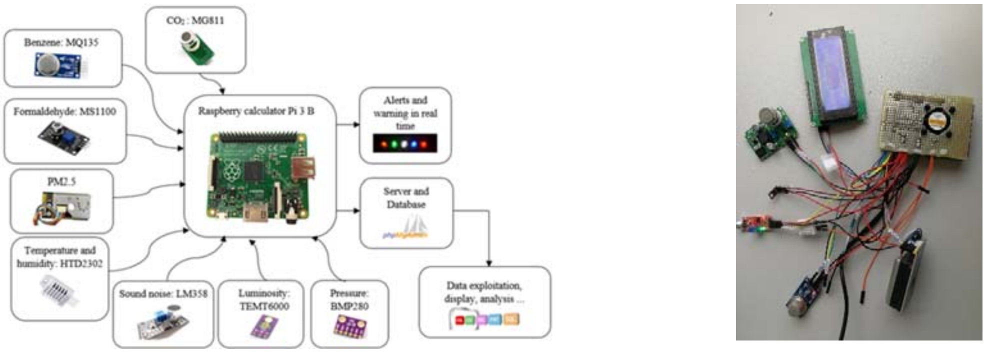

Figure 13: Development of the smart IAQ sensor and comfort parameters (CO_2, VOCs, CO, Formaldehyde, Benzene, PM2.5, humidity, temperature, etc…)

4 Conclusion

This study focuses on indoor air quality (IAQ) measurements and comfort parameters in a demonstrator building. The high CO_2-concentrations measured in the instrumentation room show that the current ventilation system is not adapted to the occupants needs and the rate of air change is not sufficient. To achieve the intended goal, we have proposed a solution based on the development of an intelligent sensor that measures indoor air pollutants and comfort parameters (CO_2, VOCs, CO, formaldehyde, benzene, PM2.5, humidity, noise and brightness) in real time. Based on these measurements, the information is sent to the building managers in case of malfunction of the ventilation, air conditioning and heating systems.

The ultimate goal is the deployment of a hundred smart sensors in the demonstrator building to map the quality of indoor environments (IAQ and comfort parameters) to identify the most polluted parts. Subsequently, the stored measurements are analysed by algorithms and control actions are sent to the ventilation system to adjust the airflow to the actual needs dynamically. In this way, energy consumption is better controlled and comfort conditions are ensured.

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