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INDOOR AIR QUALITY MONITORING AND CONTROL SYSTEM

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F2 – Qualidade ambiental interna

Abstract. *Poor air quality in the built environment is a problem that poses risks to the health of individuals who occupy these spaces. This problem is particularly serious in classrooms, where a large number of people congregate for long periods of time, and where the ability to concentrate is crucial for the successful performance of tasks. This work aimed to develop a solution for monitoring indoor air quality and simultaneously carry out real-time control of ventilation rates in classrooms, at the lowest cost possible. To achieve this, microcontrollers, sensors, and actuators were integrated alongside a web interface and database for monitoring and tracking measurements. The system was made capable of controlling the speed of a fan that provides ventilation to the room, based on the measurement of carbon dioxide* (CO_2) *concentration, thus allowing the use of demand-controlled ventilation techniques. Two demand-controlled ventilation strategies were explored: the on/off and proportional control. The developed system was tested in a classroom at the São José Campus of the Federal Institute of Santa Catarina, where temperature, relative humidity,* CO_2 *concentration, and particulate matter content were measured simultaneously, all the data being recorded and presented in real-time through a web interface. The system was able to maintain* CO_2 *concentration below the levels allowed by indoor air quality standards when operating within the fan's capacity. Results indicated that proportional control strategy was the most effective solution for the problem.*

Keywords: *indoor air quality, demand-controlled ventilation, classroom, remote sensing, internet of things*

1. INTRODUCTION

The quality of the breathed air is fundamental to human health and well-being. Poor air quality can cause serious health problems, such as respiratory and cardiovascular diseases. Studies highlight a correlation between high levels of carbon dioxide (CO_2) indoors and adverse impacts on health and work performance (William *et al.*, 2019). At high-occupancy spaces such as offices and classrooms, implementing efficient ventilation strategies can significantly reduce the risk of disease transmission (Lipinski *et al.*, 2020).

Indoor air quality (IAQ) emerged as a science in the years after 1970, with the energy crisis and the consequent construction of sealed buildings (devoid of natural ventilation), and stood out after the discovery that the decrease in air exchange rates in these environments was largely responsible for the increase in the concentration of pollutants in the indoor air (Schirmer et al., 2011).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) published the Standard 62.1 (ASHRAE, 2022), defining acceptable indoor air quality as “air in which there are no known contaminants in harmful concentrations, as determined by competent authorities, and with which a substantial majority (80% or more) of those exposed do not express dissatisfaction”. ABRAVA (2021) highlights that environments with CO_2 concentration levels higher than the established limits can result in a reduction in people's productivity, resulting from involuntary drowsiness and loss of cognitive abilities. In Brazil, the National Health Surveillance Agency (ANVISA, 2003) established reference parameters for indoor air quality in mechanically air-conditioned indoor spaces (Table 1).

Table 1. IAQ benchmarks

physical quantity	recommended maximum values
CO_2 concentration	1,000 ppm
total aerodispersoids in the air	80 μg/m^3
temperature (summer)	23 to 26°C
temperature (winter)	20 to 22°C
relative humidity (summer)	40 to 65%
relative humidity (winter)	35 to 65%
air renewal (normal space)	27 m^3/h/person
air renewal (high turnover space)	17 m^3/h/person

Controlling air quality indoors involves implementing measures to reduce the concentration of pollutants through a ventilation system (that is, a system that brings fresh outdoor air into the indoor space). In general, these ventilation systems operate all the time throughout the building's operating hours, regardless of room occupancy, which represents unnecessary energy consumption. In some cases, such as schools, the room occupancy rate is quite variable and intermittent, which makes the waste of energy even more remarkable. Therefore, the need to employ a control strategy that is capable of monitoring the occupancy of a room, and then activating the ventilation system only when necessary, is evident. Moreover, the system should be able to adjust to the actual occupancy of the room, that is, introducing only the amount of outdoor air necessary for the number of people occupying the room at a given time. This characterizes the demand-controlled ventilation (DCV) technique (ASHRAE, 2017, 2022), which allows for optimal energy savings.

To define the amount of fresh outdoor air necessary to dilute contaminants inside a space, it is necessary to adequately measure the physical quantities that characterizes the condition of the air within that space. Most of the bioeffluents generation rate is proportional to the number of occupants and their activity levels. The concentration of CO_2, a gas resulting from human metabolism/respiration, can be used as a way to assess the occupancy at any space. Changes in differential CO_2 (i.e., the difference between indoor and outdoor CO_2 concentration) mirror changes in space population. In this way, continuous monitoring of CO_2 concentration in a space allows determining the amount of outdoor dilution air demanded at each instant, enabling the application of DCV.

The strategy demands a control system with CO_2 sensors and an actuator device. Sensors continuously monitor the air in a space and send information to ventilation controllers (actuators), which automatically regulate outdoor airflow when CO_2 concentrations exceed a certain level (Metelskiy, 2011). To further improve this process, IoT applications can be incorporated, allowing integration with other systems, such as remote monitoring and data history storage.

Besides measuring CO_2 concentration, it is worthwhile to have a more complete measurement station that could assess other air quality parameters, such as air temperature and relative humidity, and particulate matter content. Temperature and relative humidity are important for monitoring thermal comfort in air-conditioned spaces. Particulate matter (PM) refers to fine particles that may be present in air, such as dust, smoke, soot, aerosols and other chemical compounds, which can be emitted naturally or by human activities (ASHRAE, 2017). The amount of PM present in the air of a space is also a major factor for evaluating air quality, as it includes not only solid particles which can be harmful to health when inhaled, but also aerosols, the main vehicle for transmitting bacteria and viruses. Concern about this class of contaminants became even more notable after the global Covid-19 pandemic (Stephens *et al.*, 2022).

In addition to measurement, we sought to design a system that could also make all measured values available remotely, so that it could be accessed by any interested party, not only building managers and technicians responsible for HVAC systems maintenance, but also for the building users. People can hardly acquire awareness about something they cannot see, feel directly and immediately, or measure. Making real-time data on air conditions in indoor environments available to any interested party has the potential to considerably increase this awareness (Silva *et al.*, 2019). Beyond the obvious advantages in terms of preventive and predictive maintenance, by allowing the maintenance manager to easily and quickly view current and historical indoor air conditions, which can indicate possible failures and inadequacies in the design or installation of systems, such an initiative can contribute enormously to raising awareness on IAQ issues on the general public. This is very significant in a school environment, where we are educating for a more sustainable society, and even more significant in the particular case of the São José campus, where future air conditioning and refrigeration technicians are being trained.

In buildings for commercial use, access to information on indoor air quality conditions has great marketing potential, not only in terms of making it clear to the client/user that the building in question meets technical health and safety standards, but also as a competitive differential advantage in relation to the competition. So, a measurement system like the one being proposed has a clear commercial appeal.

Moreover, it is desirable that all the hardware should be made as cheap as possible. This is a major factor to facilitate the implementation of effective air quality control in developing countries, where economic issues are always strongly restrictive, even more in educational facilities, which are mostly managed and supported by the public administration.

In this way, the present work aimed at developing a real-time monitoring and control solution for indoor air quality at low cost. A system was designed to measure indoor air data (CO_2 concentration, air temperature and humidity, and PM content), share the measured data through internet, and controlling a ventilation system.

2. MATERIALS AND METHODS

2.1 System design

The system proposed may be categorized as an embedded system, that is defined as a type of electronic system dedicated to performing a specific task, continuously interacting with the environment through sensors and actuators (Ball, 2022). The design and development of such systems demands knowledge of several areas such as programming, process control, data acquisition technologies (analog/digital conversion and sensors) and actuators (digital/analogic conversion and PWM). Such systems may also involve the use of communication networks. Embedded systems are categorized as reactive systems, as the application executed directly depends on the environment in which they are inserted (Ball, 2022). For this reason, they are designed to operate in real time, that is, actions must be carried out quickly and reliably to ensure the correct functioning of the system.

The main functional characteristics outlined for the control system were: /i/ data acquisition: the system should be capable of measuring CO_2 concentration, air temperature and humidity, and PM content; /ii/ data processing and storage: the system should have capacity to adequately process all the data collected by the sensors, and storing the data for later analysis; /iii/ control: the system should have a controller capable of analyzing the collected data and making autonomous decisions based on pre-defined parameters; /iv/ communications: in order to allow remote operation, the controller should have a wi-fi capability; /v/ integration with ventilation system: allowing the controller to activate the ventilation system appropriately; /vi/ user interface: the prototype should contain an intuitive user interface, which allows visualization of collected data, current indoor air conditions and actions performed by the control system.

Microcontroller. The core of embedded systems is the microcontroller, highly integrated electronic devices that have a central processing unit (CPU) and execute a set of operational instructions. Furthermore, they also include all the peripherals necessary to run applications, such as counters, memories, buses, timers, communication interfaces (serial, ethernet, bluetooth and wi-fi) and analog-to-digital converters, among other common resources (Ball, 2022). These integrated circuits are widely used in a variety of embedded systems due to their ability to incorporate complete functions in a single instrument. The use of microcontrollers makes it possible to create more efficient and economical systems, while offering greater control and precision over the functioning of the system.

It was determined that the controller should have wi-fi capability. The wi-fi technology is a convenient and efficient way to connect devices to the internet without the need for cables, as it uses radio waves to transmit data securely and reliably (Baños-Gonzalez *et al.*, 2016). Several options of microcontrollers with wi-fi capability available in the market were analyzed. The ESP8266 microcontroller (Espressif, 2022) was selected. It presents a 32-bits architecture, clock of 80 MHz, RAM and flash memory of 160 kb and 16 Mb respectively, has a built-in wi-fi module, 17 GPIO (general-purpose input-output ports), and can support several I/O interfaces, such as SPI, I2C, UART and I2S. It meets the specifications required by the system in terms of memory, processing and number of available pins. Furthermore, it has a lower cost compared to other models.

Sensors. For CO_2 concentration measurement, the SCD30 (Sensirion, 2020) was chosen. It uses the non-dispersive infrared measurement (NDIR) technique (Jha, 2022), and is a high-precision sensor, with a wide measurement range (0 to 40,000 ppm). Additionally, it is also capable of measuring temperature and relative humidity, has low power consumption, and communicates through I2C and UART interfaces (Forouzan, 2008), which allow easy integration with the microcontroller. It also presents a lower cost compared to alternatives.

Regarding PM content, there are different possible measures such as PM1.0, PM2.5, PM4.0 and PM10, which refer to particles with a diameter less than or equal to 1, 2.5, 4 and 10 µm, respectively (ASHRAE, 2017). The HPMA115cO-004 sensor (Honeywell, 2021) was selected to measure PM content in the air. This sensor is designed to measure PM2.5 content, employing the NDIR technique, and uses a UART (Forouzan, 2008) interface for data transmission. The sensor also provides PM1.0, PM4.0 and PM10 values, but these measurements are obtained from the measurement of PM2.5 using empirical relationships. The family of HPM sensors were specially designed to present high precision and a useful life of 10 years.

Actuator. In order to control the speed of the ventilation fan, it was selected the DM02A module (MSS, 2020). This device operates as a dimmer, that is, a power control module capable of adjusting the power supplied to an electrical load (Zhang and Chung, 2014). Adjustment of the electrical energy supply is carried out through the pulse width modulation (PWM) technique, that is commonly used in electronics to control the power of analog devices connected to the output (GPIO) of microcontrolled systems. This technique adjusts the duration of a pulsed signal (the pulse width) applied to an electrical load. When controlling an alternate current (AC) electrical supply, the duty cycle represents the time lapse that electric current is supplied to the load in relation to the total time of the AC cycle. The greater the duty cycle, the greater the energy delivered to the load. The pulse width is usually measured as a percentage related to the time the signal is at a high level compared to the full cycle. For example, a PWM signal with a 50% duty cycle has a pulse width equal to half the full cycle.

The DM02A has 70 dimming levels, allowing control of electrical loads up to 400W. Adjusting the desired level is done by selecting the channel to be controlled, sending a pulse between 500 and 35,000 µs, and each 500 µs step corresponds to a dimming level. The device automatically synchronizes with the electrical network, ensuring that the intensity is maintained constant even in conditions of voltage variation. Thus, the module offers high precision, safety and ease of use, at a low cost.

The ESP8266 microcontroller has GPIO ports that can be used as PWM output. So, the ESP8266 port sends a PWM signal of a square wave type to the DM02A module, which interprets it and modulates the power output to the electric load accordingly.

Ventilation system. A ventilation fan was used to ensure appropriate ventilation in a classroom, with its power regulated by the dimmer. The selected fan was an in-line centrifugal fan type, chosen because its good relationship between capacity and size, which greatly facilitates its installation, especially in buildings that were not prepared/designed to house a ventilation system (the vast majority). The fan has nominal capacity of 925 m³/h, powered by a single-phase AC electric motor of 160 W.

Cost. The total cost associated with the acquisition of materials and equipments (microcontroller, sensors, actuator, and fan) for the system was approximately US$ 407. Other costs related to labor, logistics, installation and maintenance were not included in the analysis. This cost is significantly lower than usual market values.

2.2 Firmware

For a processing unit to perform a task, a sequence of instructions is necessary that indicates which positions in the memory area will be used. Firmware is embedded software that is stored in "program memories". They play a key role in initializing and configuring the functions that the hardware will perform. The ESP8266 microcontroller, with its 160kb of RAM, was used to store variables created and updated dynamically during program execution. The 16 Mb of FLASH memory was used to store the firmware code.

The firmware was developed with Arduino Integrated Development Environment (IDE) (Arduino, 2024), which uses the C++ language and has a specific compiler for the ESP8266 microcontroller. Additionally, third-party libraries were included in the project to complement the functionalities of peripheral modules, providing specific functionalities for each sensor and simplifying the interaction and control of the devices. Details about the construction and configuration of the firmware can be found in Kuhnen (2024).

Acquisition, availability and storage of data. Data acquisition in an IoT system depends on both accurate measurements carried out by sensors and reliable transmission through messaging. Messaging plays a crucial role in ensuring the efficient and secure transmission of data collected by sensors to the systems responsible for making it available and storing it. Furthermore, it enables asynchronous communication between the components of the solution, offering features such as message queues, publish/subscribe topics and guaranteed message delivery and persistence. These features contribute to efficiency and reliability in data acquisition.

The MQTT protocol (MQTT, 2022) was adopted due to its lightness, efficiency and ability to deal with asynchronous communications. It is a machine-to-machine communication protocol based on the TCP/IP protocol. Widely used in IoT, this protocol facilitates the efficient exchange of information between connected devices. Its architecture centered on the publish-subscribe model allows devices to exchange information through an intermediate server called a broker. In MQTT, devices play different roles: producers (publishers) send messages to the broker, while consumers (subscribers) subscribe to specific topics to receive messages. This approach enables efficient asynchronous communication, where devices can send and receive data independently.

Data sharing is important in the implementation of systems in the context of IoT. It is essential to create dashboards to present this data to end users. Node-RED (OpenJS, 2022) was the graphical interface chosen to process and visualize data. It is an open-source visual programming tool that has a set of tools for processing and manipulation. After processing the data, Node-RED create a dashboard for real-time viewing (Fig. 1), that can be accessed remotely through a browser compatible HTML interface, and can send notifications via email or messages. Furthermore, it makes possible to send this data to a database, allowing the storage and subsequent retrieval of the information.

Data storage is essential to have a reliable, scalable database capable of handling large volumes of data coming from IoT devices in real time. Furthermore, it is essential that this database offers efficient storage and retrieval mechanisms, ensuring quick access to the necessary information, security and data integrity over time. To meet specific time series demands, it is crucial to utilize a Time Series Database (TSDB) with high write performance, agile data location, efficient compression, and easy scalability. InfluxDB (Naqvi and Yfantidou, 2018) was the database chosen for the system. It is an open source TSDB, and a good solution for handling large volumes of queries and writes per second while minimizing impact on the operating system. It stores time series of measurements with timestamp and stands out for its data compression capacity, facilitating database scalability. By using InfluxDB in conjunction with Node-RED, it is possible to receive and properly store the sequence of data coming from the sensors and the actuator. The correct configuration of the database allows the continuous flow of data, enabling subsequent analysis.

Figure 1 summarizes the flow of information within the system. The sensors collect the data and send it to the ESP8266 microcontroller, which acts as a bridge between the sensors, the actuator and the MQTT broker server on the internet. The microcontroller sends the data to the MQTT broker through the wi-fi connection. The MQTT broker forwards the data to the Node-RED environment, where it is processed and made available on a dashboard accessible through an HTTP web interface, allowing users to monitor and visualize the collected data. Furthermore, Node-RED stores this information in an InfluxDB database.

2.3 Control system validation

In order to validate the fan's response to the power control module, experimental tests were carried out at a test bench. Fan activation was controlled by the DM02A module through PWM technique, varying the control level from 0 to 70, with intervals of 5 units (each interval corresponding to approximately 7% of the full scale). For each established control level, electrical (voltage, effective current, active power and power factor) and aerodynamic (average air speed supplied by the fan) data were recorded. Air speed measurement was carried out using a hot wire anemometer (Testo, 2024b). The flow rate was calculated based on the measured speed and the cross-sectional area of the conical connector outlet nozzle adapted to the fan outlet.

It was observed that, below control level 10, the motor was not capable of moving the fan rotor. Between control levels 10 and 30, an almost linear direct correlation between fan speed, current and power and the level of control was observed. However, at control level 31 both the current and the power of the fan motor increased sharply and reached maximum values, which remained practically constant up to control level 70, at the same time that the fan’s rotation speed dropped considerably. This effect on the fan rotation speed was only eliminated from level 40 onward, when the fan speed returned to approximately the same direct linear behavior initially observed.

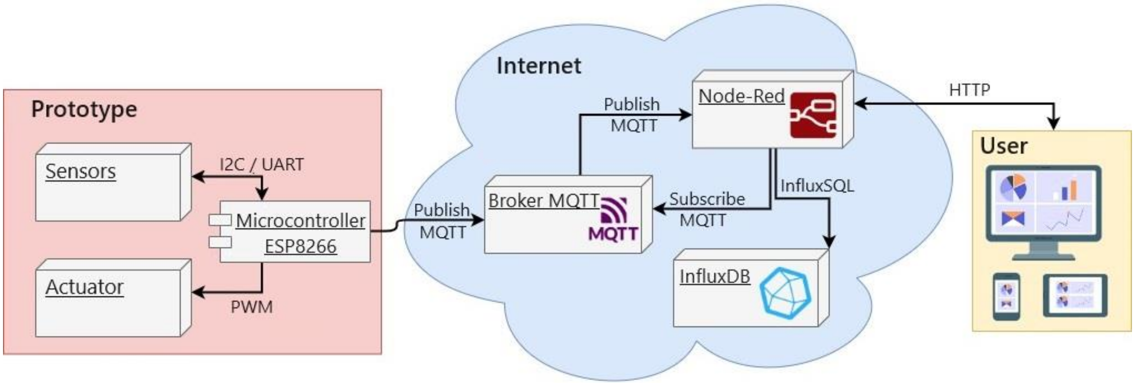

Figure 1. System information flow

This behavior was diagnosed as related to harmonic distortion in the load current, originated from the PWM technique employed by the control module. The very characteristic of the PWM technique, feeding the load through pulses, generates countless harmonics of the network frequency, which severely distorts the waveform of the electrical current being supplied to the motor, producing large changes in reactive power (Bilgic, 2007).

To solve the problem, a filter was implemented using inductors, that provide reactive impedance to electrical current, helping to reduce harmonic distortions. The added inductive load consisted of two inductors mounted in parallel, with equivalent inductance of 220 mH. The connection of this inductive load in series with the load (motor) reduced distortion of the supply voltage to the motor. This resulted in the smoothing of the correlation between air speed (flow), power and control level, as shown in Fig. 2, enabling and adequate control action.

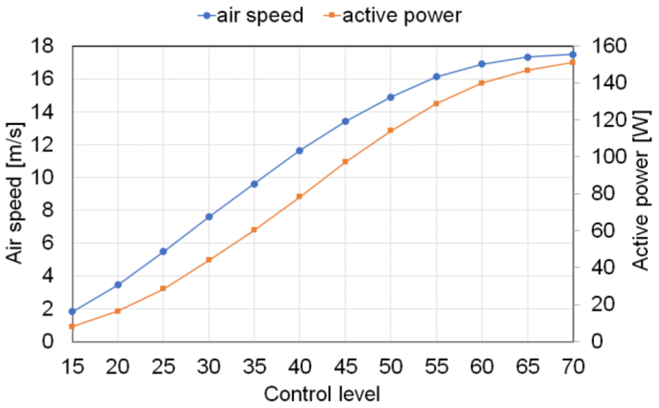

Figure 2. Air speed at fan outlet and active power as a function of control level

2.4 Experimental setup

Test room. Tests took place in Room 05 of the IFSC São José Campus (Fig. 3). The classroom has a length of 9.187 m and width of 5.815 m and is 2,989 m high, resulting in floor area of 53.43 m^2 and internal volume of 159.7 m^3. Room temperature control was carried out through a split-type air conditioner, with a cooling capacity of 30,000 Btu/h.

Outdoor air was supplied to the room by the in-line centrifugal fan. The fan was installed externally to the room, next to the access corridor, and the air was blown into the room through a duct connecting the fan's exhaust nozzle to the room wall. The duct was 1.25m long and had an internal diameter of approximately 145mm, which required the adaptation of a conical connection between the exhaust nozzle and the duct.

CO$_2$ generation. To determine the amount of CO$_2$ to be generated inside the room during the validation tests, the methodology proposed by Persily and de Jonge (2017) was used, where the rate of CO$_2$ generation by an individual is calculated based on biometric data (height and weight), metabolic rate (function of physical activity level) and respiratory quotient.

To estimate the occupancy of the room, the values recommended by the Brazilian standard NBR 16401-3 (ABNT, 2008), namely, an expected occupancy density of 35 people per 100 m^2 of pavement area for classrooms, were followed. Thus, it was estimated that the room would be occupied by 8 male students, 8 female students, and a teacher, totaling 17 people.

Figure 3. Test room

For biometric data, updated typical height and body mass data for Brazilian teenagers were obtained from Bertoldi (2021). As the test room is used by students in the high school age range (14 to 18 years old), typical values for teenagers at the upper end of the range (18 years old) were used. For the teacher, data for a typical Brazilian man (IBGE, 2010), aged 35 to 44 years, was used. The metabolic rate for students was estimated at 1.4 met, as proposed by Persily and de Jonge (2017). For the teacher, the value of 1.6 met suggested by Fanger (1982) for a person carrying out laboratory work applies. For the respiratory quotient RQ, a single RQ value equal to 0.85 was used for all subjects.

The estimated total CO_2 generation rate resulted in 5.87 liters/min. This was the value used in experimental tests. Given the classroom internal volume, and considering the CO_2 concentration in atmospheric air of 414 ppm on a volumetric basis (Global Monitoring Laboratory, 2023), the CO_2 generation rate calculated would require a flow of outdoor air of about 602 m^3/h to maintain a CO_2 concentration limit value of 1,000 ppm in steady state (ASHRAE, 2017). This air flow value was within the capacity range of the selected fan.

During validation tests, the generation of indoor CO_2 was carried out artificially, through the controlled release of the gas from a bottle, equipped with a pressure regulating valve specifically calibrated for use with CO_2. This valve simultaneously reduces gas pressure and controls its flow, using a calibrated orifice. The flow rate is indicated by a manometer, duly calibrated in flow units.

Test procedure. Sensors were positioned at an approximately central point in the room. The room AC system remained off during tests. Before each test, the room was intensely ventilated to eliminate any excess CO_2 remaining from the previous occupancy. The procedure was considered complete when the measurement of the CO_2 concentration in the room reached a value approximately equivalent to the CO_2 concentration of the outdoor air. After this step, doors and windows were closed, leaving only a section of the window partially open, with a small gap, to allow air to be exhausted. This opening was located on the wall opposite to the outdoor air supply duct, ensuring the best possible mixing and homogenization of the indoor air. To promote homogeneous mixing of the CO_2 generated in the environment, the air circulation fans in the test room were kept running. During the tests, the CO_2 concentration of the outdoor air was also monitored, as this data is necessary to calculate the outdoor air flow.

After the initial setup, the measurement systems were started, and the CO_2 generation system was configured and started. The room was then vacated, and the door was kept closed during the test. Data were monitored remotely from outside the room, and stored in the cloud. The total duration of the validation tests was 50 minutes.

Assessment of outdoor air flow. To assist in the analysis of the experimental data and in the evaluation of the effectiveness of the ventilation system, it was necessary to know the actual flow of outdoor air into the room.

It is known (White, 1994) that the nominal air flow information provided for a given fan indicates a flow obtained in standardized experimental tests, and that, when operating this fan in a real installation, the resulting air flow will depend on the flow resistance (pressure drop) values of the installation. However, given the characteristics of the test room, where air exfiltration was performed through cracks and window openings, the theoretical or experimental determination of the effective pressure drop in the installation became unfeasible, since this would be influenced by atmospheric conditions, mainly wind intensity (ASHRAE, 2017). Direct measurement of the supply air flow rate also proved to be complex and impractical.

Therefore, the flow of outdoor air into the test room was determined indirectly, from the measurement of the CO_2 concentration in the room itself. Assuming the following hypotheses: /i/ the exfiltration of indoor air is the only significant process of removing CO_2; /ii/ the air inside the room is completely and perfectly mixed; /iii/ the intensity of CO_2 generation inside the room and the ventilation rate are stable during the period; /iv/ the flow of outdoor air blown into the room by the ventilation fan is exactly the same as the flow of air exhausted from the room (through cracks and openings); applying the principle of mass conservation to CO_2 inside in the test room gives Eq. 1 (ASHRAE, 2017):

$$\frac{dC}{dt} = \frac{G + \dot{Q} \cdot (C_{in} - C_{out})}{V_r} \qquad (1)$$

where dC/dt is the rate of change in CO_2 concentration, G is the rate of CO_2 generation inside the room, $\dot{Q}$ is the flow rate of outdoor air ventilated into the room, C_{in} is the CO_2 concentration at the outdoor air, C_{out} is the CO_2 concentration of air leaving the room and V_r is the total volume of air inside the room. From hypothesis /ii/ it can be assumed that the CO_2 concentration of the air exhausted from the room (C_{out}) is the same as the CO_2 concentration of the indoor air (C_r). The rate of change in CO_2 concentration can be derived from the measurements of the CO_2 concentration of the indoor air. Thus, from the measurements of the CO_2 concentration in the room (C_r) and at the outdoor air (C_{in}), as well as the defined rate of CO_2 generation inside the room (G), it is possible to determine the flow rate of outdoor air ventilated into the room, as shown in Eq. 2:

$$\dot{Q} = \frac{V_r \cdot \frac{dC}{dt} - G}{(C_{in} - C_r)} = \frac{V_{room} \cdot \left[\frac{C_r(t) - C_r(t-1)}{\Delta t}\right] - G}{[C_{in} - C_r(t)]} \qquad (2)$$

3. RESULTS AND DISCUSSION

Validation tests were carried out to evaluate the proposed solution. These tests were designed to verify the system's ability to regulate indoor air quality, and its energy efficiency, considering different control strategies, which were: (I) ***no control:*** in this test, the ventilation system was kept off, allowing the accumulation of CO_2, serving as a reference to evaluate air quality in the absence of a control system; (II) ***on/off control***: the control system activated the ventilation system at maximum level (maximum air flow) when CO_2 concentration exceeded 1,000 ppm, turning off the system when the concentration dropped below that level; (III) ***proportional control***: the control system modulates the fan speed from level 15 to 70, in linear proportion to the measured CO_2 concentration value in the range 800 to 1,000 ppm, that is, when the concentration value reaches 800 ppm, the fan is activated at control level 15, and must be at its maximum speed (control level 70) when the concentration reaches 1,000 ppm. , as depicted in Fig. 4.

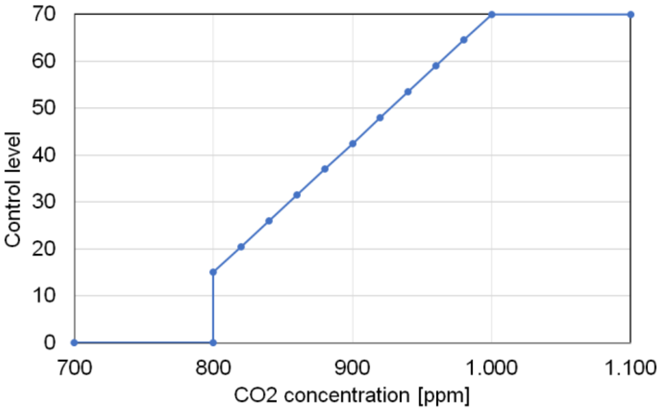

Figure 4. Proportional control logic

3.1 Validation tests results

Figure 5 presents a comparative analysis of the results for the CO_2 concentration. In test (I), a steady increase in CO_2 levels was observed, as expected. Starting at 430 ppm, the concentration exceeded 1,400 ppm in less than 50 minutes, highlighting the lack of control, and exceeding the recommended limits mentioned in Table 1. In test (II), the readings started at 431 ppm and, up to 1,000 ppm, a steady increase was observed, in line with the trend of the test (I). Subsequently, the values stabilized at around 1,000 ppm, with a maximum peak of 1,043 ppm, indicating a relatively good control of the CO_2 concentration, although the recommended limit (Table 1) was exceeded several times. In test (III), readings started at 422 ppm and, up to 863 ppm, a steady increase was observed, and beyond this point measurements stabilized around 950 ppm, reaching a maximum peak of 986 ppm, highlighting that the proportional control strategy demonstrated greater effectiveness in maintaining CO_2 levels within the recommended limits (Table 1).

Figure 6 depicts the control module action. In test (II) the fan came into operation after 25 minutes, when CO_2 concentration reached 1,000 ppm and, when concentration dropped below this value, the fan was turned off. It is important to mention that, although the on-off control mode showed to be capable of maintaining CO_2 in the range around 1,000 ppm, it imposed a greater stress on the electric motor due to the seven starts in an interval of 50 minutes. In test

(III), the action of the fan started at 17 minutes, and the fan was maintained at speeds lower than maximum throughout the rest of the test, predominantly around control level 54 (equivalent to approximately 80% of maximum power), providing better conditions for motor operation and contributing to greater sound comfort (i.e., less noise).

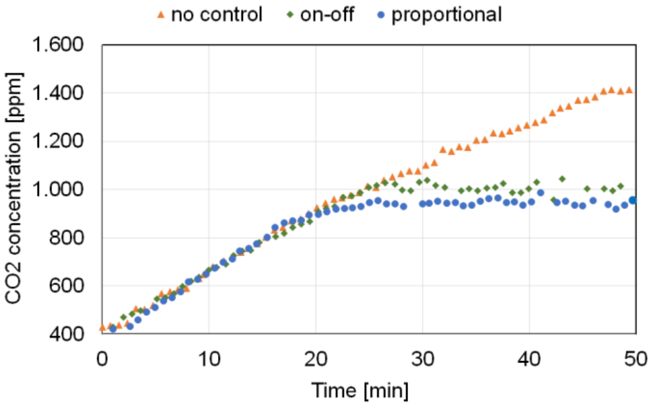

Figure 5. Indoor CO_2 concentration

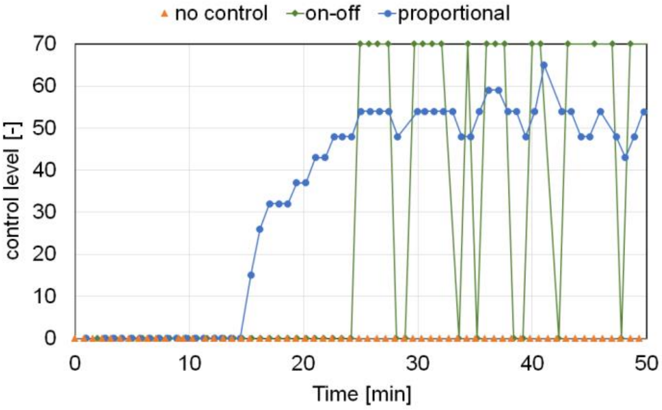

Figure 6. Actuator control level

Regarding PM2.5 concentration measurements, in test (I) it varied between 120 to 150 µg/m^3, reaching a peak of 157 µg/m^3, that occurred around 20 minutes into the test, coinciding with the opening of the door. In test (II) measurements remained in the range of about 140 to 170 µg/m^3. In test (III) measurements started at around 120 to 140 µg/m^3, but from 17 minutes it could be observed a huge increase, coinciding with the moment the fan was activated, and significant oscillations were observed throughout the remainder of the test, with measurements in the range of 140 to 280 µg/m^3. This was due to the dispersion of dust accumulated on the fan into the room, since this was the first test to be executed. This highlights the sensitivity of the system. The results were consistently higher than the limits recommended by Table 1, but it is important to note that the readings obtained may not be reliable due to lack of sensor calibration.

Concerning the results for the outdoor air flow, in test (I), even in the absence of mechanical ventilation, an average outdoor air flow of approximately 256 m^3/h was observed, being this flow rate exclusively attributed to air infiltration through the gaps in doors and windows, and through a small opening that was maintained in one of the window panels. Also, it was observed that there was wind of some intensity outdoors during the test, which may have contributed to the relatively high outdoor air flow. Anyway, it can be noted that natural ventilation was not sufficient to maintain the CO_2 concentration within acceptable limits, clearly demonstrating that the usual configuration of rooms with split-type air conditioning is not capable of meeting air quality requirements.

In test (II), the average outdoor air flow was higher, approximately 457 m^3/h, but lower than that of the test (III), which averaged 590 m^3/h. This difference was due to the behavior of the control modes, since in on-off mode the fan was either on or off, which contributes to a lower average flow rate, while in proportional mode the fan remained operational for longer, resulting in a higher average flow.

Regarding energy consumption, test (II) recorded a total consumption of 0.049 kW.h, while test (III) resulted in a total consumption of 0.069 kW.h. This difference in consumption can be understood if compared to the percentage of time in which the room was kept "on target", that is, with CO_2 concentration below 1,000 ppm. In test (II) CO_2 concentration was on target only 64.9% of the time, while in the test (III) the concentration was 100% of the time on target. For comparison, in test (I) the time on target was 48.4%. Then, the on-off control mode, despite stabilizing the CO_2 concentration around the target value, allows this target to be exceeded in a significant part of the total time, while the proportional control mode, being activated from 800 ppm, is able to guarantee that the environment is within the limit established by standards throughout the test time, explaining the greater total energy expenditure, and demonstrating the effectiveness of the system. In any case, the energy consumption of the ventilation system was lower than what would be expected if the ventilation system remained on all the time, clearly demonstrating that the DCV technique is more energy efficient.

CO_2 atmospheric concentration averaged 415 ppm for test (I), 412 ppm for test (II) and 418 ppm for test (III).

3.2 Real-case test

The system was tested in a real-case scenario in the same Room 05 where the validation tests took place. The control system was configured with the proportional control mode. The occupancy consisted of 28 people (27 students plus a teacher), and the CO_2 generation rate was estimated to have been approximately 9.55 l/min. The test lasted 90 minutes, and the average atmospheric CO_2 concentration was 422.5 ppm during this period. The split-type AC system was kept on during the test, set at 23 °C.

During the test, a steady increase in CO_2 measurements was observed, reaching 1,339 ppm after 28 minutes of testing. Stability in CO_2 levels was achieved around 1,340 ppm, higher than the 1,000 ppm limit. It is noteworthy that, despite the ventilation system having been designed for an ambient with less people, it was still capable of maintaining the level of CO_2 concentration restrained.

Temperature measurements initially decreased from 25.3 °C to 23.8 °C and, as the environment reached thermal homogenization and activities in the classroom took place, including students’ movements, the temperature increased, reaching 26.2 °C (at about 34 minutes). Then, as movement in the classroom reduced, temperatures declined, stabilizing around 25.5 °C. The relative humidity started at 64.3%, later stabilizing around 50.7%. This demonstrated that the AC system managed to keep the indoor air within the thermal comfort range, despite the additional thermal load imposed by ventilation.

The PM2.5 measurements remained in the range of 100 to 160 $\mu g/m^3$, higher than the limit established in Table 1. Again, it is important to note that the sensor was not calibrated, lending these results unreliable. A peak was observed when the fan was activated, due to the dispersion of dust accumulated on the fan into the classroom. This highlights a point of concern that is little noticed in ventilation systems, namely, the increase in indoor air contamination caused by contaminants that accumulate in the ventilation system itself when not in use, or from external sources.

The outdoor air flow rate averaged approximately 584 m^3/h. The total energy consumption was 0.1996 kW.h. The results showed that the system operated as expected, although it was unable to maintain the CO_2 concentration level within the desired limit, due to the capacity restrictions of the ventilation system.

4. CONCLUSIONS

A system to assess and control air quality was successfully developed. The system can collect data on temperature, humidity, CO_2 concentration and PM content in a room, and make this information available online. Simultaneously, the system was able to control the speed of a ventilation fan, thus enabling the air renewal of the room through a demand-controlled ventilation technique.

The system was tested in a real classroom, both with simulated occupancy and in a real-case situation. The system was able to maintain CO_2 concentration below the levels allowed by IAQ standards when operating within the fan’s capacity, that is, when the occupancy of the room demanded an outside airflow that was below the maximum flow capacity of the installed fan. The use of the demand-controlled ventilation strategy allowed this performance to be achieved with lower energy consumption.

The total cost of the system (sensor-controller module plus fan) proved to be quite attractive when compared with technical solutions available on the market.

It was realized the need to perform a calibration procedure for the sensors, in order to ensure a reliable performance. This finding can be debited to its low-cost nature. Therefore, the economic advantage of using low-cost sensors is partially compromised by the need to perform this calibration.

A major issue of the proposed solution was the need to test the response of the fan motor to the control module PWM action, and take measures to ensure a linear response of the fan's performance curve. This procedure will be fan-dependent, that is, every family or class of fans from different manufacturers can demand specific measures to ensure the linearization of the equipment's response. This fact imposes extra costs for the implementation of the solution. However, in the case of buildings where multiple rooms are similar in occupancy, it is highly likely that the same fan model, or family of fans, will be the appropriate solution for each room. In this way, the number of necessary fan response characterization tests can be greatly reduced.

Nevertheless, the reduced cost of the system is still worthwhile, when one bears in mind the need to carry out control of indoor air quality in a large number of classrooms at a school, or in similar buildings.

In summary, this work achieved the proposal of a tangible solution for improving ambient conditions indoors. The successful implementation of the monitoring and control system with low cost reinforces its potential as a valuable tool for effectively managing indoor air quality, with positive implications for the health and comfort of occupants.

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The authors are solely responsible for the results and information presented in this work.

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