Towards Energy-Efficient Ventilation in Buildings: Development of the Smart Window Ventilation System

Behrang Chenari, João Dias Carrilho, Gustavo Botte, and Manuel Gameiro da Silva

***Abstract*—As the building sector is responsible for a large portion of total primary energy consumption in developed countries, it is crucial to improve energy efficiency of buildings' systems. Heating, ventilation, and air conditioning systems play a noticeable role in energy consumption of buildings, therefore, developing efficient strategies for ventilation not only can provide comfortable indoor climate but can also mitigate energy consumption in buildings, which, consequently, will lessen the associated environmental impacts. This paper presents development steps of an intelligent window-based hybrid ventilation system in an ongoing research and development project at the University of Coimbra, known as the Smart Window project. Firstly, the motivation and objectives of the project are provided. Secondly, the current state of development of the project as well as the test condition and location in an Indoor Live Lab is presented. Finally, the future steps of development of the project accompanied by the expecting results are presented and discussed.**

***Index Terms*—Control strategies, demand-controlled ventilation, energy efficiency, hybrid ventilation, indoor environmental quality, Smart Window.**

I. Introduction

Nowadays, energy demand is continuously increasing worldwide, therefore, the negative environmental impact resulting from energy production and consumption has become a major public concern. The building sector is one of the biggest contributors to energy consumption in the world, which is responsible for a large portion of total primary energy consumption in developed countries. Heating, ventilation, and air conditioning systems play a noticeable role in energy consumption of buildings, thus, the design and development of new energy-efficient strategies and products for ventilation systems in buildings is crucially essential. Currently, there is ongoing research promoting energy saving potential in buildings in the framework of the EU Energy Performance of Building Directive (EPBD) [1], which has focused on energy efficiency in buildings. Some authors investigated new energy-efficient solutions for improving ventilation systems in buildings. On the other hand, in the last decade, many studies have concentrated on improving indoor air quality (IAQ) in buildings. There is a tight correlation between ventilation and IAQ, and the reduction of energy consumption associated to ventilation cannot be an excuse to neglect the provision of a suitable indoor climate. Therefore, in developing energy-efficient solutions for ventilation systems, maintaining the indoor climate at an acceptable level must be considered.

As aforementioned, ongoing research is focused on developing energy-efficient ventilation models for buildings. Some studies have only focused on natural ventilation as a passive method in order to make the process of ventilation more efficient [2]-[5]. Some authors used natural ventilation elements such as atria [6], wind towers [7], double-skin facades [8] as well as ventilation openings and windows [9] to provide required ventilation by natural driving forces, namely wind and buoyancy forces. Additionally, some studies investigated energy savings from utilizing different principles of natural ventilation, such as single-sided [3], cross ventilation [10] and stack effects [11]. But, as natural ventilation is not always available, say, sufficient to provide required ventilation rate, more recent studies [12], [13] focused on hybrid ventilation [14]. Hybrid ventilation will exclude the drawbacks of both systems, whereas including their advantages [15].

Moreover, several authors have developed ventilation control strategies that provide acceptable indoor climate quality levels and lowers energy consumption. They believe that the presence of control systems can increase the influence of hybrid and natural ventilation in improving energy saving in buildings, while maintaining a suitable indoor climate. These authors conducted research activities in developing new control strategies to employ natural cooling and ventilation. For instance, Homod *et al.* [16] developed control strategies, which can predict when mechanical ventilation is required in order to maintain acceptable IAQ. In addition to predictive control strategies, rule-based and demand-controlled ventilation (DCV) strategies, as used in [17]-[21], have significant effects on improving energy efficiency of ventilation systems.

Motivation and Objectives

As people spend most of their time inside buildings, it is very important to maintain an adequate IAQ, in addition to thermal comfort, especially for office buildings and schools in which people are working, learning and studying, and where the level of personal control over their indoor environment can be very limited. IAQ and building ventilation are intimately related because ventilating indoor spaces with outdoor air is perhaps the most often used mechanism to dilute pollutants generated inside the building. Ventilation is

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the key issue for providing suitable IAQ, as it is the process of replacing stale indoor air by fresh outdoor air. It can be performed either by mechanical means (mechanical ventilation) or natural driving forces (natural ventilation) or even a combination of them (hybrid ventilation). Employing natural ventilation in buildings results in the reduction of energy consumption, while maintaining an acceptable level of IAQ. Therefore, developing ventilation control strategies that can predict when natural ventilation is available and sufficient, and select between natural and mechanical ventilation as needed, are desirable.

Although recent studies have shown research activities in development of new control strategies to employ natural cooling and ventilation, there is still an obvious gap in the literature about employing intelligent window-based ventilation control strategies, not only for increasing the share of natural ventilation but also for integrating mechanical ventilation to compensate drawbacks of natural ventilation. This ongoing research and development project aims to fulfill this gap in literature.

This paper presents development steps of an ongoing research and development project, aiming at developing a novel product, the Smart Window, and test a number of ventilation control strategies in order to find the most energy-efficient control strategies that provide acceptable indoor climate.

II. Smart Window: Current State of Development

A. Project Description

In this project, a Smart Window system that allows the use of hybrid ventilation, is being developed to employ the advantages and exclude the drawbacks from both natural and mechanical ventilation. Moreover, several ventilation control strategies are being developed and tested using Smart Window in order to find out the best strategies that can provide an appropriate indoor climate with lower energy consumption. The control strategies, which are based on indoor and outdoor environmental parameters, such as concentration of CO_2, indoor and outdoor temperature difference, wind speed and its orientation, are defined in a way to use natural ventilation as long as possible, otherwise, putting the mechanical system on circuit to provide the required space ventilation. The Smart Window is accompanied by a mechanical ventilator as well as a control system.

B. Prototypes of the Mechanical Boxes

By now, two prototypes of mechanical boxes are built. Fig. 1 shows the first prototype, which is driven by a tangential blower and is currently being installer in the Indoor Live Lab (I2L) [22] facility, located in Department of Mechanical Engineering at University of Coimbra.

Fig. 2 shows the second prototype, which is based upon a centrifugal blower and automatically operable window. The automatically operable windows will have a positive impact in IAQ and energy consumption, while permitting the manual override by the office occupants.

Fig. 1. Prototype of the mechanical ventilation subsystem of the Smart Window hybrid ventilation system (tangential blower).

Fig. 2. Prototype of the mechanical ventilation subsystem of the Smart Window hybrid ventilation system: centrifugal blower (top); automatically operable window actuator (lower left) and control board (lower right).

C. Control Strategies

A number of control strategies were identified as potentially suitable, based on indoor environment parameters and outdoor weather as input data. In particular, the indoor concentration of CO_2 is used to see whether ventilation is required or not. Temperature difference between indoor and outdoor (ΔT), wind speed (WS) and its direction (D) are used to detect the availability of natural ventilation.

In the control strategies, the availability of buoyancy-driven natural ventilation is evaluated according to (1), whereas (2) evaluates the availability of wind-driven natural ventilation.

$$Q = CA\sqrt{2gH\frac{Ti - To}{Ti}} \qquad (1)$$

where Q represents the ventilation airflow rate (m^3/s), C is the discharge coefficient for opening (typically 0.62), A indicates the cross section area of opening (m^2), g is the gravitational acceleration (m/s^2), H represents the height from midpoint of lower opening to midpoint of upper opening (m), Ti is the average indoor temperature (K) and To is the outdoor temperature in (K).

$$Q = KAV \quad (2)$$

where Q represents the ventilation airflow rate (m^3/h), A indicates the cross section area of opening (m^2) and K is coefficient of effectiveness. This coefficient varies with the angle between wind direction and the facade opening. For instance, if the angle at which wind hits the building is 45 º, then the coefficient is estimated to be around 0.4, whereas, if wind hits the building perpendicularly, the coefficient is becomes about 0.8.

According to all the aforementioned parameters, various rule-based (*if CONDITION, then ACTION*) control strategies were reported in the literature (e.g., see Ref. [23]), in which indoor and outdoor environmental parameters are the conditions and different operations of window and fan are the actions.

The control strategies start with simple CO_2-based demand-controlled ventilation (DCV) strategies in the beginning and, going forward, reach more advanced control strategies, considering all the parameters and more advanced operations of window and fan. Table I presents characteristics of some of the developed controls from simple to advanced strategies. As shown, different input parameters and different operations of window and fan, define the control strategy either simple or advanced. Moreover, Fig. 3 demonstrates a simple control strategy in a flowchart.

TABLE I: THE CHARACTERISTICS OF CONTROL STRATEGIES

Rule-based control	Mechanical ventilation operation	Natural ventilation operation	Input parameters
Simple	On/Off	Open/Close (O/C)	CO_2
.	Leveling speed	Leveling O/C	CO_2
.	Modulating speed	Modulating O/C	CO_2
.	On/Off	O/C	CO2+ ΔT+D
.	Leveling speed	Leveling O/C	CO2+ ΔT+D
Advanced	Modulating speed	Modulating O/C	CO2+ ΔT+D

D. Installation and Test

As aforementioned, the first prototype is being installed and tested in the I2L. The I2L is equipped with various types of instruments and sensors to measure and monitor energy consumption and IEQ elements, such as thermal comfort, IAQ, lighting, sound level and so on. Fig. 4 shows a set of instruments and sensors installed in the I2L. They are all connected to a computer, which continuously monitors all these elements. Moreover, Fig. 5 depicts a daily monitored IEQ elements in the I2L. The graphs show the changes in each element during a full day, whereas the numbers shows the current value of each element.

For thermal comfort, the Predicted Mean Vote (PMV) thermal comfort index is used. This index was originally introduced by Fanger [24] and has been adopted in current international standards such as, for instance, ISO 7730 [25]. It predicts how a large number of people would vote, on average, about their perception of thermal comfort in a given indoor environment. The scale goes from -3, corresponding to the sensation of cold, with 0 corresponding to a neutral sensation, and up to +3, corresponding to the sensation of hot. Similarly, for IAQ, the concentration of CO_2 is being measured as an indicator of the balance between the ventilation rate and the generation rate of occupant-related pollutants. This shows when outdoor flow rate is required to ventilate the space and provide acceptable IAQ level. For instance, as recommended by many IAQ standards and building regulations, 1000 ppm is normally being considered as a threshold for indoor CO_2 concentration, from which ventilation is required in order to decrease the concentration of pollutants.

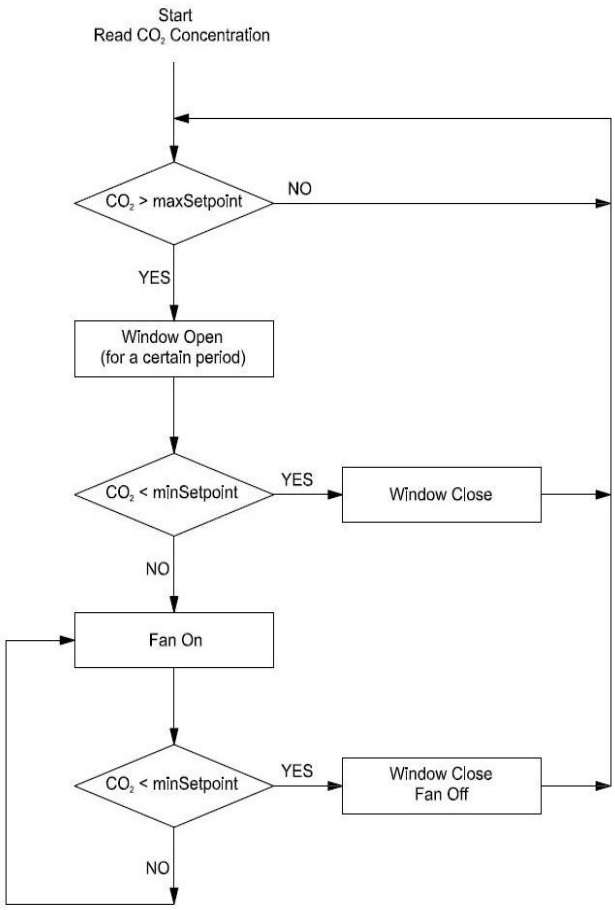

Fig. 3. Simple CO_2-based control strategy.

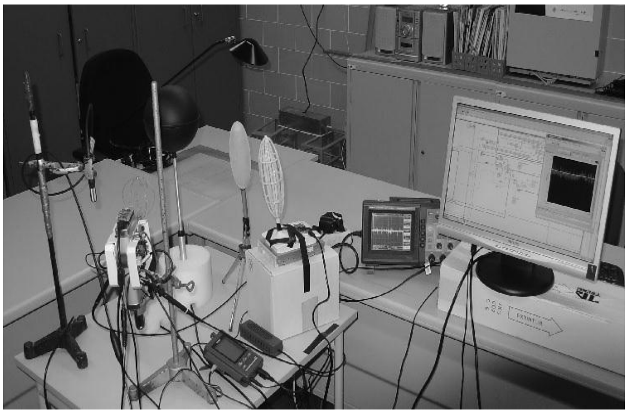

Fig. 4. Set of instruments and sensors at the I2L.

Installing the prototype in the I2L allows us to test all the control strategies, using the available instruments and sensors.

Besides the IAQ and thermal comfort assessment, it is possible to assess the energy consumption associated to each control strategy.

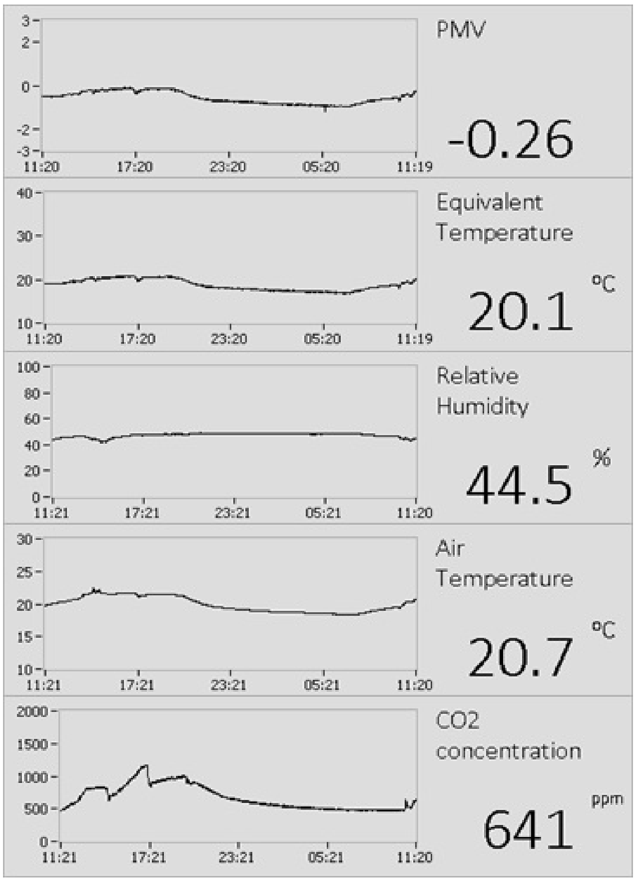

Fig. 5. Monitored IEQ indicators in the I2L.

III. Smart Window: Future Developments

Besides the completed tasks, there are some more tasks in the project work plan. This section presents the future developments of the Smart Window project.

A. Prototypes of Mechanical Boxes

The new prototypes of mechanical boxes are under development, using other types of fan (axial, tangential and centrifugal) with different airflows. This is to assess airflow rate and fresh air penetration inside the space as well as the associated noise and energy consumption by each model. With regard to these data, it is possible to optimize all these parameters.

B. Occupancy Counter

An occupant counter is being developed to be installed at the entrance door of the I2L. This is capable of detecting people entering and leaving the room with two infrared beams, therefore, it can calculate how many people are in the room at any moment in time. Fig. 6 shows the infrared occupancy counter set being developed. This enables the adjustment of the ventilation rate based on real occupancy level, which will help preventing energy wastage. Moreover, a comparative energy performance analysis of different ventilation model (constant volume of airflow, CO_2-based DCV and occupancy-based DCV) is being carried out.

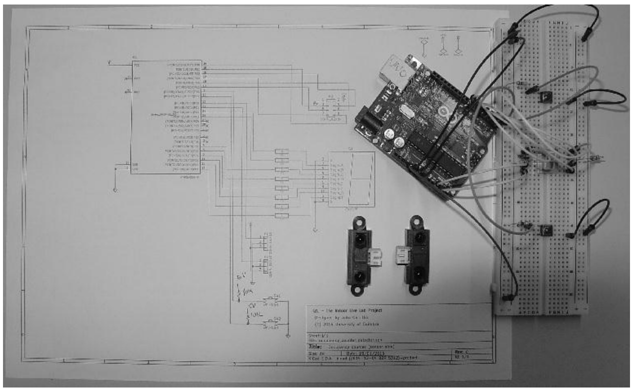
Fig. 6. Development of infrared occupancy counter.

IV. Conclusions

Ventilation is the key issue for providing suitable IAQ, as it is the process of replacing stale indoor air by fresh outdoor air. It is also responsible for a notable percentage of energy consumption in both residential and commercial buildings. Therefore, improving ventilation systems is vital both for improving energy efficiency in buildings and for providing acceptable IAQ. The Smart Window project described in this paper integrates hybrid ventilation to the building facade in order to employ the advantages and exclude the drawbacks from both natural and mechanical ventilation. The paper presented the current development steps of the intelligent window-based hybrid ventilation system in an ongoing research and development project, at University of Coimbra. The motivation and objectives behind this project as well as the current development, ongoing tasks and future work plans were presented and discussed.

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