Development of setting methods to control outdoor ventilation airflow rate in office buildings

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ABSTRACT

Ventilation is essential for the health and comfort of building occupants. It is particularly required to dilute and/or remove pollutants emitted by occupants' metabolism and activities. The concentration of metabolic CO_2 is well correlated to metabolic odour intensity. Therefore CO_2 concentration can be efficiently chosen as an indoor air quality index when occupants are the main source of pollution inside the buildings. This paper presents the results of a research work conducted to adjust and compare five advanced techniques based on CO_2 level measurement in order to adapt ventilation extractor fan speed to the intermittent occupation of an office. An experimental one-zone cell called Hybcell was chosen to compare these five control technologies (i.e. on/off, proportional integrative regulator, fuzzy logic control, analytical control function, and radio frequency identification) under the same conditions. A method was developed to define the setting parameters of a proportional integrative and a fuzzy logic control regulator of an extract fan. Criteria based on control precision, command stability and global air exchanged were then established for the final evaluation. The results revealed fine control accuracy. They showed a good stability with a reduced and simplified setting period for the developed methods compared to current controllers.

KEYWORDS

Indoor air quality; carbon dioxide; ventilation; regulation; intermittency

INTRODUCTION AND OBJECTIVES

Carbon dioxide concentration (CO_2) may be considered in a no smoking area as an indicator of the pollutants emitted directly by occupants according to their number. It can be used especially in variable occupancy zones (meeting rooms, conference halls, restaurants, classrooms...). Currently, high carbon dioxide concentrations in offices can be an indirect indication of poor ventilation and contaminant build-up. Since people give off carbon dioxide when they breath, the level of it found in buildings is an indicator of whether or not sufficient ventilation is present to dilute it and flush it out of the building (ASHRAE 1999). At CO_2 levels above 1000 parts per million by volume (ppmv), occupants generally experience decreased satisfaction, poor air quality perception, and increased physical symptoms. In general, the ASHRAE standard indicates that if the CO_2 levels are lower than 800 ppmv, this will indicate that sufficient ventilation is being supplied to the building for the populations (ASHRAE, 1999). The reduction of the level to at least 800 ppmv can further improve occupant satisfaction and reduce physical symptoms (Seppanen et al. 1999). Yet it may be almost difficult for the designer to anticipate ventilation needs varying from one day to another throughout the occupation density. Defining CO_2 internal level (called C_{int}) as an occupancy indicator can represent a first method to control Indoor Air Quality (IAQ). Control device like On/Off controller on internal CO_2 level measurement around a set-point concentration C_{sp} is a simple way. Nevertheless problems related to actuators stability for fans and/or openings could appear. Techniques based on PID or fuzzy controllers could be better adapted to ventilation demand. Both of these regulators have been tested by El Mankibi (El Mankibi 2003), but their setting and adjustment period in situ were relatively long to be attractive. In order to get a good compromise between performance, equipments stability and easy setting, we decided to test and compare five different IAQ regulators under the same experimental conditions:

1 On/Off controller on C_{int}
2 PI (Proportional Integrative) on C_{int}
3 FLC (Fuzzy logic controller) on C_{int}
4 ACF (Analytical control function) based on a CO_2 species assessment
5 RFID (occupancy detected with Radio frequency detection)

The purpose of the controller is to regulate the fan extractor speed by maintaining the CO_2 concentration C_{int} around a set-point concentration C_{sp} as illustrated in Figure 1.

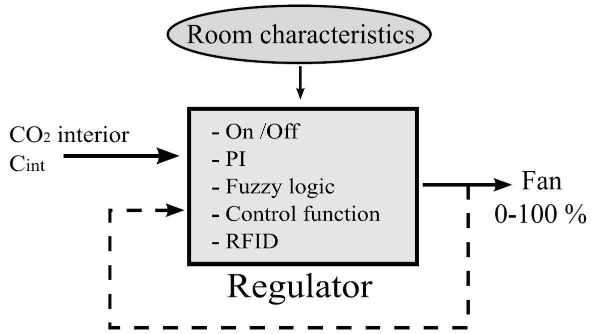

Figure 1: Controllers description

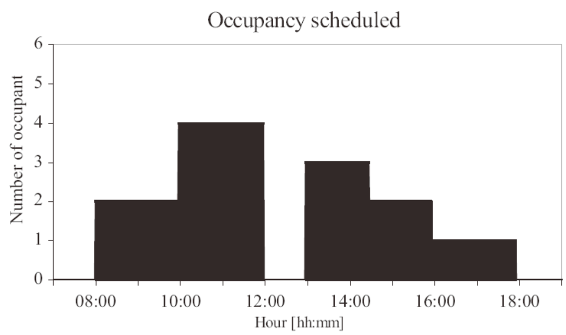

Figure 2: Occupancy scheduled into HybCell

A setting methodology for PI and FLC has been proposed by Richieri depending on the main characteristics of the occupied zone (Richieri, 2007). Finally, five performance criteria (three for the control precision evaluation; one for the stability; one for the total air volume exchanged) let these techniques be compared and evaluated according to their potential use.

EXPERIMENTAL TEST CONDITIONS

Each experiment has been prepared during a one day long period and conducted on the experimental platform called HybCell for the five regulators. In order to analyze the control precision, stability, and performance of each regulator, the experiments required the same test conditions. The airflow rate (Q_{max}= 500 m^3/h) can be controlled and varied between 0-100% by an extractor fan with a linear control law. The virtual occupation (from 1 to 4 occupants) of the meeting room has been scheduled for each controller following the same planning (see Figure 2). In fact, each set-point concentration of CO_2 corresponds to a proper ventilation rate per occupant. For the tests, C_{sp} was fixed at 800 ppmv of CO_2 following the ASHRAE recommendation. A maximum tolerance of 50 ppmv was considered.

EVALUATION CRITERIA FOR THE CONTROLLER PERFORMANCES

A global compromise is expected between performance, equipments stability and easy setting. To compare five IAQ regulators under the same experimental conditions, we decided to identify different indexes defined by Richieri (Richieri, 2007), based on control accuracy (precision, anticipation with C_{max}, C_{error}, C_{ave}), actuator stability (“Stab” number of cycle 0-100%-0) and the total air exchange rate “Vol $_{exch}$” in [m^3] (reduce energy costs).

THEORY AND EQUATIONS

First of all, a one-zone meeting room (volume V_0) is studied with a number N_{occ} of occupants. Each person produces metabolic carbon dioxide with a rate Q^i_{pol}, production directly linked to their level of activity (Liddament 1996). Moreover, the room has been equipped with a controlled fan speed extractor and a CO_2 sensor placed on a wall (1.3 m high, opposite to the inlet airflow openings). If an inert gas like CO_2, is released by occupants and perfectly mixed, the concentration at any time is given by the continuity Equation 1:

$$\sum_{i=1}^{N_{occ}} Q^i_{pol} = V_0 \left(\frac{dC_{int}}{dt} \right) + Q_{cv} \left(C_{int} - C_{ext} \right)$$

Equation 1

Where :

- V_0 : zone volume [m^3]
- Q^i_{pol} : metabolic carbon dioxide production rate for the person i [m^3_{CO2} / s]
- Q_{cv} : Airflow rate [m^3/s]
- C_{int}: Interior CO_2 concentration [ppmv]
- C_{ext}: Exterior CO_2 concentration [ppmv]

SETTING PARAMETERS

On/Off controller

An On/Off controller is the simplest form of IAQ control device. The output from the device is either On or Off, with no middle state. For IAQ control, the output is On (100% or Q) when the internal CO_2 is above the set-point, and Off (0%) below set-point. In that case, we considered:

- 750 ppmv as the lower limit (the fan extractor is Off)
- 850 ppmv as the upper limit (the fan extractor is On)

Analytical control function based on occupancy detection

The applicability of an analytical control function (ACF), given by Equation 2, has been studied on HybCell by Richieri and its numerical model with a test on an intermittently occupied office (Richieri, 2006).

$$Q_{cv}^{new} = \frac{V_0}{C_{sp} - C_{ext}} \left(\frac{dC_{int}}{dt} \right) + \frac{C_{int} - C_{ext}}{C_{sp} - C_{ext}} Q_{cv}^{old}$$

Equation 2

Equation 2 represents the formulation of a three-input ACF of a variable speed extractor fan. In addition, the desired set-point value C_{sp} and the volume V_0 of the room are needed to initialize this ACF. The commanded airflow rate is transformed in a percentage of Q_{max}. We considered a 120 s data capture time-step and gradient evaluation on 5 points for the numerical first derivative of C_{int}. The control required for a waiting time of 10 minutes, the addition of a break loop to stop updating the fan speed as soon as the CO_2 concentration belongs to the tolerance band C_{sp} more or less 50 ppmv.

Proportional Integrative controller

The Ziegler-Nichols method in open loop was adapted to set a PI regulator for the fan speed control (Richieri, 2006). Introducing the difference e^t between C_{int} and the set-point value C_{sp}, the output formulation of a PI command is given at any time step dt (dt = 120 seconds in our case) by Equation 3:

$$PI^t = -Kp \left(e^t + \frac{1}{T_i} \sum_{i=0}^{n} e^{t-i.dt}\, dt \right) \quad [m^3/h]$$

Equation 3

Type	Kp	T_i
P	$\frac{V_0}{\tau (C_{sp} - C_{ext})}$	-
PI	0,9 $\frac{V_0}{\tau (C_{sp} - C_{ext})}$	3,3 τ

Table 1: Ziegler-Nichols value for a P, PI regulator

We proposed to adapt the setting method in open-loop for the Ziegler-Nichols method (Flaus 1994) for a P or PI regulator. The simplified setting device is presented in Table 1. The main difficulty consists in evaluating the volume of the room, as well as the time lag τ (equal 5 min for HybCell).

Fuzzy logic controller

In the same manner, we used a two inputs (error and error rate) one output (fan speed correction) PI-Sugeno type Fuzzy regulator. The FLC membership functions were defined over the range of the input and output values describing linguistically the variable's universe of discourse as shown in Figure 3. The triangular input membership functions for the linguistic labels: Zero, Small and Medium had their membership tuning center values at 0, 0.5 and 1 respectively. The universe of discourse for both e and Δe was normalized from -1 to 1. This FLC used had 25 rules (Table 2) to correct fan speed using seven progressive singletons (Zero, Small, Medium, and Big), whose value was defined by Richieri (Richieri, 2007). The output of each rule is treated as a fuzzy singleton, using the weighted average defuzzification method.

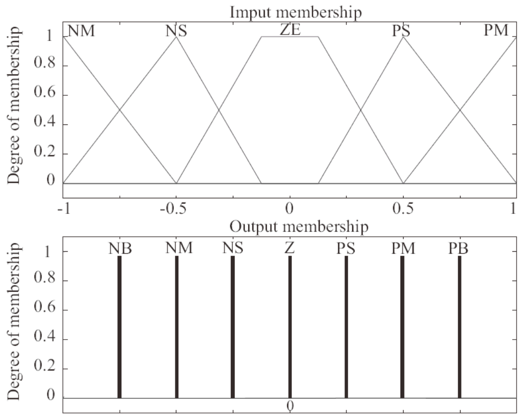

Figure 3: Fuzzy membership function

		Error e				
		NM	NS	ZE	PS	PM
Error rate Δe	NM	NB	NB	NM	NS	Z
	NS	NB	NM	Z	Z	PS
	ZE	NM	NS	Z	PS	PM
	PS	NS	Z	Z	PM	PB
	PM	Z	PS	PM	PB	PB

Table 2: FLC rules

RFID detection

Radio-frequency identification (RFID) is an automatic identification method, relying on storing and remotely retrieving data using devices called RFID tags or transponders. We have virtually simulated RFID as an occupancy detection tool. Considering that each occupant can be immediately detected in the meeting room like in the scheduled occupancy, the correct ventilation rate is directly and proportionally generated for an 800 ppmv set-point value.

RESULTS AND DISCUSSION

The five experiments without adjustment have been conducted successively for five days. The controlled fan speed evolution is presented on Figure 4. On/Off command is not presented for readability constraints. The assessment is on the whole positive, because a direct relation between occupation changes and fan speed adaptation was noticed, without serious instabilities. Typical command peaks are observed for PI control, which cannot anticipate the sudden occupant arrival. The experiments show quick reactions to command the suitable airflow rate in FLC and ACF. This observation is confirmed by a global evaluation (Table 3) of these two techniques.

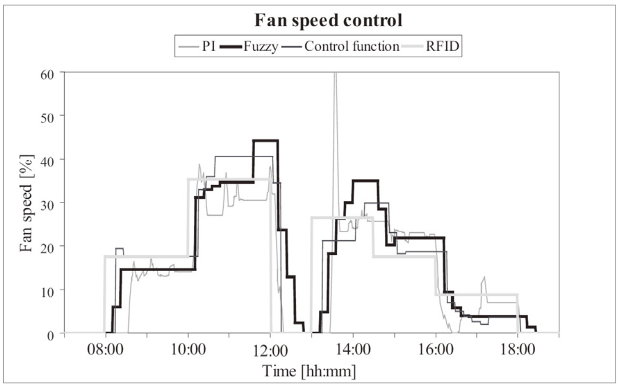

Figure 4: Time series evolution of the fan speed command

	Control accuracy			Stability	Economy
Controller type	C_{max}	C_{ave}	C_{error}	Stab	Vol $_{exch}$ [m^3]
On/Off	916	746	78	19	1332
PI	1145	804	62	1.8	909
Fuzzy	969	792	60	0.8	1055
Control function	965	772	37	0.7	1055
RFID	827	753	28	0.6	1029

Table 3: Evaluation results for the five controllers

A bad anticipation (C_{max} index) for PI controller is noticed with a CO_2 peak of 1145 ppmv (i.e. 200 ppmv more than other techniques). An average overshoot from 100 to 150 ppmv for FLC and ACF remains relatively acceptable since it is a short duration.

The index C_{ave} informs us on the average IAQ breathed by the occupants. FLC and PI are closest to the set-point 800 ppmv. On/Off control generates an over-ventilation rate because through its average concentration is 54 ppmv lower than set-point concentration. RFID is also as lower as ON/Off with 47 ppmv. Control accuracy (C_{error} index) indicates that the On/Off control is the least precise technique. Even with a hysteretic band, the interior concentration C_{int} oscillates around 800 ppmv. FLC and PI controller have the same precision, but the noticeable fact is that ACF is almost as precise as RFID (respectively 37 and 28 ppmv). The control stability (”Stab” index) illustrates that an On/Off control implies a 20 times greater actuators effort than the other control modes. Table 3 shows that PI is twice more unstable than the other techniques. FLC and especially ACF are stable, compared to the ideal RFID case. The volume exchanged Vol_{exch} with On/Off controller is 30% more than a reference RFID. FLC as well as ACF are close to RFID with a volume increase of 2.5 %. PI has a reduced volume exchanged (-11%) to the detriment of stability and control accuracy. The tests have shown that a reduction of 30% in proportional gain will improve the stability index (from 1.8 to 1.2), to the detriment of other performances (from 1145 to 1195 ppmv for C_{max}, and from 909 to 1024 m^3 for Vol_{exch}).

CONCLUSION AND PROSPECTS

Two setting methodologies for PI and Fuzzy Logic Control (FLC) have been tested and compared with a simple On/Off controller and a prospective technique based on occupancy detection (RFID). Their large advantage remains mainly in the stability of fan actuator contrary to On/Off control. In addition, FLC advantage remains in its integration in a hierarchical fuzzy architecture as for a multi-criteria fuzzy control. The setting and tuning methodologies for a PI control avoids long and expensive in-situ adjustments period. Finally, fuzzy control methodology as well as the analytical control function (ACF) has shown a global performance, close to prospective techniques based on occupancy detection with Radio Frequency Identification. Thus IAQ control could be at the same time precise, energy efficient, stable and simple to initialize for intermittently occupied rooms.

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