Fuzzy controllers for HVAC-VAV systems to maintain IAQ

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ABSTRACT

The term air conditioning not only prescribes comfort temperature and the relative humidity, but also the quality of air inside the room. Indoor air quality (IAQ) has become a concomitant of air conditioning. The pollutants generated inside the room affect the quality of air inside the room. The major pollutants considered are CO_2, sulfur dioxide, toluene, etc. Monitoring and controlling of all the pollutants is cumbersome. CO_2 is considered as the surrogate index of pollutants. Appendix D of the ASHRAE standards 62-1999 recommends a ventilation rate of 15 cfm per person. To incorporate this in the optimal system design, the instantaneous occupancy level is required. It is imperative that the instantaneous CO_2 level and the generation rates must be known to estimate the instantaneous occupancy level. Thus measurement of the CO_2 level inside the room is performed by the ventilation control, which thereby maintains IAQ and in turn the comfort level. The problem with the CO_2 as an indicator of occupancy is the accuracy level and the time response of the sensor. Furthermore the system is non-linear. These factors call for more accurate design of the controllers. So, fuzzy controllers can be chosen as the best option. It has been found that the system settling time has been very well improved. This indicates that the fast varying occupancy level can be monitored and controlled, thereby maintaining the IAQ inside the conditioned space.

INDEX TERMS

Ventilation; Fuzzy controller; Indoor air quality

INTRODUCTION

Maintaining good indoor air quality (IAQ) inside air conditioned spaces demands fresh air for ventilation. To maintain the IAQ at lower energy cost, variable air volume (VAV) systems are recommended. ASHRAE standards 62-1999 recommend a set value for the ventilation to be 0.4 cmm/person (15 cfm/person) for an office room. This requires knowledge of the occupancy level variation inside the conditioned space and the corresponding demand for ventilation air quantity. Demand-controlled ventilation (DCV) is considered an effective way of controlling the ventilation and maintaining the IAQ at the minimum energy cost. However over-ventilation and under-ventilation of the conditioned space can be avoided if suitable controllers are employed in DCV systems. The measured CO_2 concentration inside the conditioned space is considered an indirect indication of occupancy, from which the ventilation demand can be arrived at. A case with a single zone duct mounted sensor is considered. The following assumptions were made.

- The generation rate per person of the occupants is 0.00027 cmm (0.01 cfm) (as per standards for an office room).
- The outdoor air CO_2 concentration is assumed to be constant (300 ppm) (Murarri).
- A base level of 15–50% of design ventilation rate has to be given as a part of the building component (Schell and Turner 1998)
- The in-/exfiltration is zero.

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This paper particularly deals with the design and performance comparison of a fuzzy controller with conventional controllers for an office room. The software used is MATLAB.

CONTROL STRATEGIES

For controlling the ventilation using on the CO_2-DCV method, the problem is that it is mainly dependent on effective modelling of the conditioned space so that it takes into account all the required dynamics of the system. In this paper, the modelling is done taking the CO_2 as the input variable and the ventilation flow rate as the output variable. The ventilation flow rate includes the building component and the occupancy component. This occupancy component depends on the CO_2 level inside the room. The next problem may be associated with the characteristics of the CO_2 sensor. The best time response of present day sensors (for 300–1000 ppm range) is only 30 s. Hence, to have better control, the time constant of the system should be as low as possible, which suggests the use of a fuzzy controller instead of conventional controllers. Further, the transient effects should also be taken into account for the design of the fuzzy controller. The poor time response of the system with the conventional controller will lead to under- and over-ventilation, which is worse than the case without the controller.

MATHEMATICAL MODELLING

The first step in the design of a controller is modelling of the system under study. The modelling is followed by open loop analysis. Then the controller is designed and closed loop analysis done. The steps are presented below.

Space Modelling

The mechanical system needs to be defined as a mathematical model. This mathematical modelling of the system is done using the well-mixed model (Ke and Mumma 1997).

The space to be air conditioned forms a part of the control volume as represented in Figure 1. The mass balance across the control volume gives the following first order differential equation:

$$V\mathrm{d}C\ /\mathrm{d}t = Q_sC_s - Q_SC + Q_fC_a - Q_eC - K_{AD}A_S + N,$$

where C, C_a, C_s, V, Q_s, Q_f, Q_e, K_{AD} and A_s are concentration of the contaminant in the room (ppm), concentration of the contaminant in the outdoor air (ppm), concentration of the contaminant in the supply air (ppm), volume of the room (m^3), supply airflow rate (cmm), infiltration flow rate (cmm), exfiltration flow rate (cmm), adsorption coefficient and room surface area (m^2), respectively. The infiltration flow rate (Q_f), the exfiltration flow rate (Q_e) and the adsorption coefficient (K_{AD}) are assumed to be zero:

$$\mathrm{d}C\ /\mathrm{d}t + Q\mathrm{s}C/V = Q\mathrm{s}C\mathrm{s}/V + N/V. \qquad (1)$$

$$P_d = N/G. \qquad (2)$$

P_d, N and G are occupant density, generation rate of the contaminant in the space (cmm) and CO_2 generation rate per person (cmm / person), respectively.

$$\mathrm{DVR} = R_pP_dD + R_bA_{b,} \qquad (3)$$

where DVR, R_b, R_p, D and A_b are design ventilation rate (cmm), minimum outdoor airflow rate per unit floor area (cfm), minimum outdoor airflow rate per person (cmm), ventilation effectiveness and area of the building (m^2), respectively. The ventilation effectiveness is assumed to be 1. Eqns (1)–(3), when modelled represent a non-linear system. However they can be approximated to a first order system. In the Laplace domain,

$$C(s)/\mathrm{DVR}(s) = \mathrm{C}_2/(s + C_1),$$

where
$\mathrm{C}_1 = Q_s/V$ and $\mathrm{C}_2 = [GV]/[R\mathrm{p}D]$.

Figure 1 Control volume representation of the conditioned space.

Sensor Modelling and Damper Modelling
The CO_2 sensor can be approximated to be a first order system with time constant 30 s. Also, the actuator, namely the damper, is approximated to a first order system with a gain of 1 (per cent max. flow/blade angle opening in degrees) and time constant 1 s.

DESIGN OF FUZZY CONTROLLER

Fuzzy logic is a convenient way to map an input domain to an output domain and it is tolerant of imprecise data (Ross 1995). Fuzzy controllers need to define ranges of inputs which are crisp. A fuzzy knowledge base is defined in terms of rules. With the help of these rules fuzzifications of inputs are done. Then defuzzification brings back the output of the designed controller to a crisp value. MATLAB version 6.1 is taken as the tool for implementing the fuzzy technique (Ross 1995). The rules defined for the design of controller were

IFCO_2 LEVEL IS **LN** THEN VENTILATION IS **LN**
IF CO_2 LEVEL IS **LP** THEN VENTILATION IS **LP**
IF CO_2 LEVEL IS **MN** THEN VENTILATION IS **M**
IF CO_2 LEVEL IS **MP** THEN VENTILATION IS **H**
IF CO_2 LEVEL IS **HN** THEN VENTILATION IS **H**
IF CO_2 LEVEL IS **HP** THEN VENTILATION IS **H**,

where **L** stands for Low, **M** stands for Medium, **H** stands for High, **N** stands for Negative and **P** stands for Positive.

The fuzzy type followed was Mamdani and defuzzification was by the centroid method. Thus the fuzzy controller was designed and the simulation of the system was done in the next stage.

SIMULATION OF CLOSED LOOP SYSTEM

A simple case study of an office room with occupancy of 15 people and an area of 250 m^2 was taken and the closed loop analysis was done in the Simulink toolbox of MATLAB software. The concentration was focused towards the time domain analysis to incorporate mainly the time lag of the sensor. The step and the random variation of the input are given. The control action is taken based on the error signal. The steady state and the transient state analysis results are shown in Figure 2.

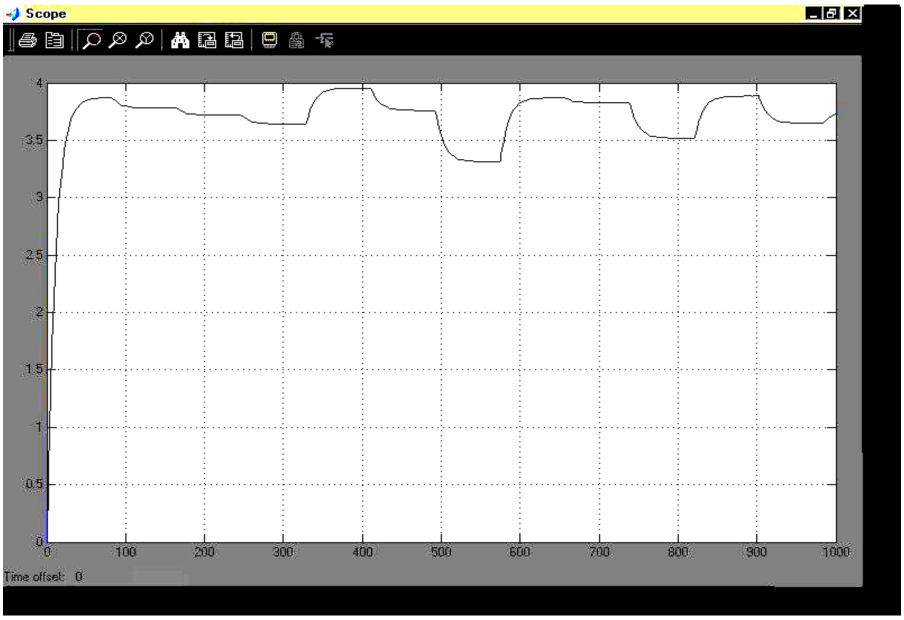

Figure 2 Response of the system with the fuzzycontroller for random variation of CO_2 level. The *Y* axis is ventilation flow rate in cmm. The *X* axis is time in seconds

From the simulation it can be inferred that the settling time of the controller was 81.5 s. It is very low when compared with that of the conventionally adopted controllers. The CO_2 variation in the room was assumed to vary randomly with time and the ventilation for these CO_2 levels are found by simulating the system. The random numbers were generated using the Simulink toolbox of MATLAB. The scope output is presented in Gigure 2. It shows the transient and steady state conditions of the system. From the figure it can be inferred that, the sytem was able to monitor the occupancy variations based on the setlling time of 81.5 s.

RESULTS AND DISCUSSION

From the simulation it was found that the fuzzy controller designed provides good closed loop system performance and proper maintainence of IAQ.

Without the controller the system is very sluggish in nature. But with the controller, the closed loop system performance has been improved in terms of its settling time and the rise time. It is found that settling time is 81.5 s. There is nearly 55% reduction in this time when compared with conventional controllers. This reduced settling time implies that fast varying occupancy conditions can be monitored.

The steady state variation of the ventilation flow rate with occupancy is shown in Figures 3 and 4. Figure 3 gives a standard occupancy variation profile for an office room over a 1 h duration. Figure 4 presents a comparison of the ventialtion flow rate for the cases with the fuzzy controller and constant outdoor air ON/OFF controller. Considering two adjacent time slots at 30 and 31 in Figure 4, the occupancy varies from 1 to 15.Corresponding to this the ventilation flow rate varies from 1.53 to 4.2 cmm. At the next time instant, the occupancy falls to 9 with a drop in ventilation flow rate to 3.57cmm. But with the conventional direct digital control (DDC), irrespective of the variation of occupancy, the ventilation flow rate is maintained at 0.4 cmm/person (constant outdoor air ON/OFF controller). To have a fair comparison with a system with a constant outdoor air ON/OFF controller, the air flow per day is calculated. It is found that with the controller, for the occupancy variation profile as per Figure 3, the ventilation flow rate is 197.590 m^3 per day. For the same situation with a constant outdoor air ON/OFF controller, the ventilation flow rate is 375.65 m^3 per day. There is a reduction of nearly 47.4% of the ventilation flow rate.The proper ventilation flow rate under all conditions of occupancy indicates the good maintenance of IAQ while the energy cost is also kept at a minimum. It is also found that an energy saving of 3.49% can be obtained.

Figure 3

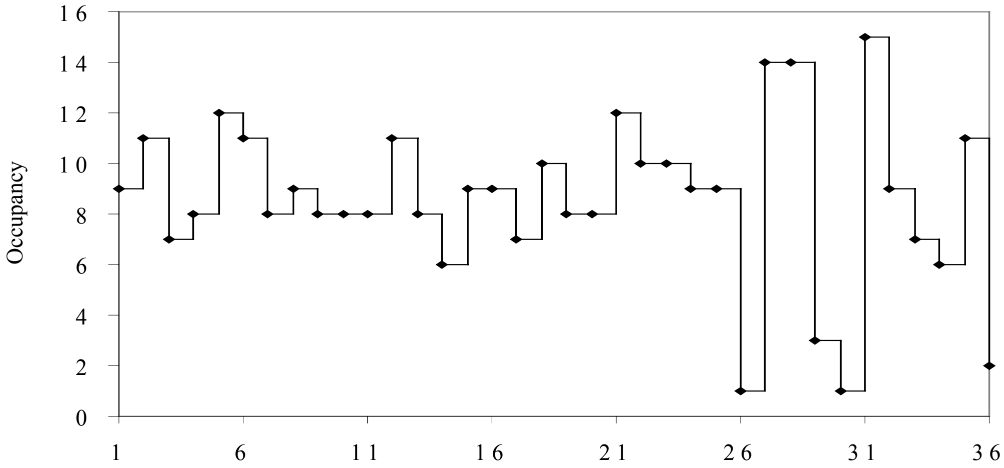

Figure 3 Variation of occupancy over time

Figure 4

Note that in Figure 4, NC refers to the condition without a controller and C refers to the condition with a controller.

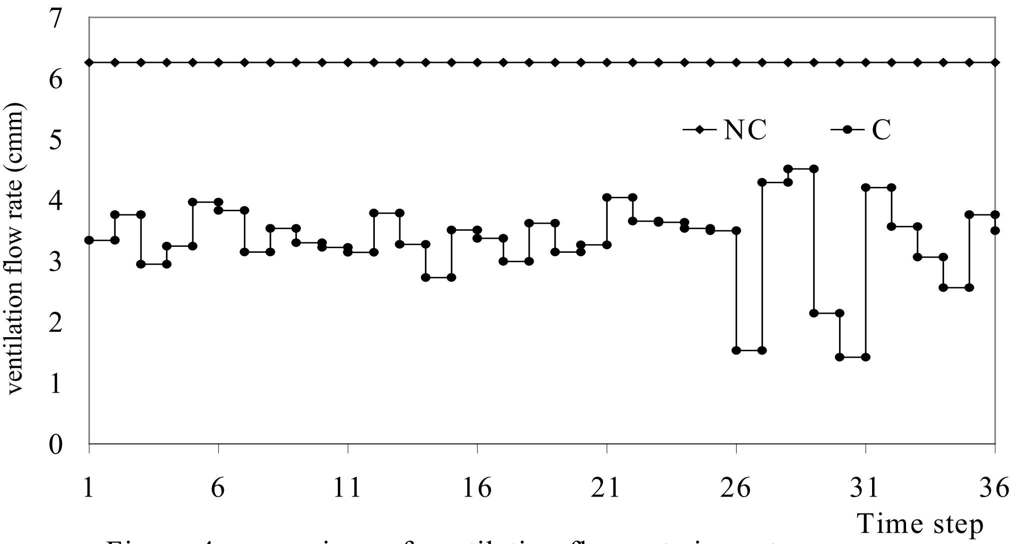

Figure 4 comparison of ventilation flow rate in system with Fuzzy controller and DDC.

CONCLUSIONS

This paper deals with fuzzy controller design considering the dynamically varying CO_2 level due to changes in occupancy. From the reduction in sampling time, it can be shown that the system output is very sensitive to the variation in occupancy. Thereby, in spite of the system non-linearities, the closed loop performance of the system has been found to be good by proper design of an intelligent controller. The ASHRAE standard recommends 0.4 cmm/person as the ventilation flow rate considering a CO_2 set point level of 1000 ppm (TLV) for an office room. In DDC the above 0.4 cmm/person is used as the key factor for controlling the ventilation. When the CO_2 level is lower than 1000 ppm, a lower ventilation flow rate is enough to maintain IAQ. But if the same equation as per standards is employed at lower CO_2 levels also, it results in a greater ventilation flow rate than required. As per the present work an optimum ventilation rate specific to the instantaneous CO_2 level (inside) is achieved through the fuzzy controller designed. This can be proved through experimental evidence. It is to be noted that it does not mean that IAQ is not maintained. Further, by implementing such a control system, the DCV is able to perform in a manner that maintains IAQ but at lower energy consumption by providing the exact ventilation flow rate.

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