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Indoor Air-Quality Control by a Fuzzy-Reasoning Machine in Naturally Ventilated Buildings

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ABSTRACT

This paper investigates the performance of a fuzzy reasoning machine for the control of indoor air quality in naturally ventilated buildings. Simulations have been performed using a new airflow and pollutant transport model, which has been developed and validated for this purpose; CO_2 concentration was used as the indoor-air quality (IAQ) index for these simulations. Results have shown that satisfactory IAQ levels can be maintained, while good stability of the control parameter (i.e. window opening area) was achieved. The impact of such a controller on indoor-air temperature was also studied. The performances were not as good as expected, but were not negligible when compared with the normal conditions of use of the building. Copyright © 1996 Elsevier Science Ltd.

INTRODUCTION

Ventilation is an important parameter for the control of indoor-air quality (IAQ) in buildings.[1] Introducing fresh outdoor-air and removing air pollutants and odours from interior spaces is necessary for maintaining

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acceptable IAQ levels. However, ventilation rates inside buildings have been seriously reduced in order to better control the cooling or thermal load and so reduce the energy load. In many cases though, this contributes to an increase in indoor-air quality problems and to what is generally known as 'sick building syndrome'.[2] For these reasons, IAQ is now a major concern in building design.

Demand-controlled ventilating (DCV) systems offer an efficient solution for the optimisation of energy consumption and indoor-air quality.[3] The main characteristic of DCV systems is that ventilation rates are modified according to the value of a certain parameter, for example the CO_2 concentration, which is representative of the pollutant load in the room. This technique has already been successfully applied in many cases using mechanical ventilation.[3–5]

Natural ventilation is a vital and extensively used alternative to mechanical ventilation in terms of cost and operational simplicity. Occupants can open or close the windows thus allowing the outdoor air to flow through the space and create a positive thermal sensation. For passively cooled buildings, natural ventilation is the main technique for achieving indoor thermal-comfort and the only means for satisfying IAQ requirements. Moreover, provided that the outdoor-air quality is acceptable, natural ventilation, unlike mechanical ventilation, is not a pollution source.[6]

A major problem, however, with controlling natural ventilation is the continuously varying environmental condition. In particular, variations of wind velocity might cause continuous changes of the controlled parameter, for example the window opening area. For that reason, the use of classical control techniques (i.e. PID or ON–OFF controllers) cannot be applied in this case.

A recent technique, known as fuzzy logic, has emerged over the last 20 years and offers many advantages regarding the control of 'ill defined' systems.[7] An important advantage of fuzzy logic lies in its ability to describe not-clearly-defined variables. In practice, fuzzy controllers have also been acknowledged for their robustness and flexibility.[8,9]

The perception of indoor-air quality is a typical example of an imprecisely defined variable and can thus successfully be represented by fuzzy sets. Moreover, fuzzy logic has already been applied successfully to the control of thermal and visual comfort, thereby giving satisfactory results.[10–12]

The performance of a fuzzy-reasoning machine (FRM) for the control of indoor-air quality in a naturally-ventilated building has been simulated using a multizone airflow and pollutant transport model. Variable occupancy was assumed and simulated, the occupants being the only source of pollution; CO_2 concentration could thus be used as the pollution-level index. This provides accurate predictions, as many studies have already shown.[3]

THE AIRFLOW AND POLLUTANT TRANSPORT MODEL

Presentation

Although many tools exist for the simulation of thermal performance and airflows in buildings, it is difficult to have access to the main code and thus even more difficult to add any new functions. Therefore, a new tool was developed for the purpose of our study. The transient system simulation program TRNSYS[13] was used as the basis of such a tool for thermal simulations. A new routine for the simulation of multizone airflows and pollutant transport was developed and coupled to the existing TRNSYS routines. This routine accounts for natural ventilation driven by temperature differences, and wind velocities through cracks or large openings and calculates the concentration of any number of pollutants in each zone.

Mathematical model

This routine calculates airflows in a zone from and to adjacent zones and the outdoor environment. It is a multi-zone airflow network model, in which each node represents one zone. Under natural ventilation, these airflows, whose mathematical models are given in the discussion, occur through cracks and large openings.

For cracks, the power law equation is used:

$$Q_v = k_f (\Delta P)^{n_f} \quad (1)$$

where Q_v is volume flow rate (m^3/s), ΔP is pressure difference (Pa), k_f is flow coefficient ($m^3/s/Pa^n$) and n_f is the flow exponent.

The flow coefficients and exponents are calculated according to Ref. 14 as follows:

$$n_f = 0{\cdot}5 + 0{\cdot}5 \exp(-0{\cdot}05 W) \quad (2)$$

$$k_f = 0{\cdot}0097(0{\cdot}0092)^{n_f} L \quad (3)$$

where L is the crack length (m) and W is the crack width (m).

An air flow through a large opening is bi-directional, depending on the existing pressure differences across the opening. In order to determine these flows, the neutral level, corresponding to a velocity (and thus a pressure difference) equalling zero is first determined.

The pressure difference between two zones (1 and 2) is determined as follows:

$$\Delta P(z) = P_{01} - P_{02} - g\, z\, (\rho_1 - \rho_2) \quad (4)$$

with P_{01}, P_{02} as absolute pressures of zones 1 and 2 (Pa), z as relative height of the considered element (m), and ρ_1, ρ_2 are air densities in zones 1 and 2 (kg/m^3).

The neutral level is thus determined by the following equation (its height, Z_n, is given in metres):

$$Z_n = \frac{P_{01} - P_{02}}{g(\rho_1 - \rho_2)} \tag{5}$$

The air velocity through the large opening is given in m/s by:

$$V(z) = C_d \sqrt{2 \frac{\Delta P(z)}{\rho}} \tag{6}$$

with C_d as discharge coefficient, ΔP as pressure difference (Pa), ρ as average density across the opening (kg/m^3), and $g = 9{\cdot}81$ m/s^2.

The two terms corresponding to the flows in both directions can then be determined by integrating the value of the velocity across the opening.

$$Q_{v1} = W_{op} \int_{H_1}^{Z_n} V(z)\mathrm{d}z \tag{7a}$$

$$Q_{v2} = W_{op} \int_{Z_n}^{H_2} V(z)\mathrm{d}z \tag{7b}$$

where Q_{v1}, Q_{v2} are volume flow rates through the bottom and top of the opening respectively (m^3/s), W_{op} is width of opening (m), $V(z)$ is air velocity at height z (m/s), and H_1, H_2 are bottom and top heights (respectively) of the opening (m).

All flows are then calculated using a zone-by-zone system of equations and the Newton–Raphson iterative method. Derived from the previous equations, the mass balance equation is written for each zone as a function of the internal pressure and the residual f of this equation is calculated:

$$f(P_n^i) = \sum_j m_j \tag{8}$$

where P_n^i is the internal pressure in zone i at the n^{th} iteration and m_j are all the incoming (or outgoing) mass flows from (or to) adjacent zones (kg/h).

The new pressures are then determined for the next iteration using the following expression:

$$[J(P_n)]\,(P_{n+1} - P_n) = -(f(P_n)) \tag{9}$$

with $[J(P_n)]$ the jacobian matrix containing all the partial derivatives of all the flow balance equations f regarding all pressures P_i, $(P_{n+1}-P_n)$ is the vector containing all the pressure corrections to apply to the next iteration, and $(f(P_n))$ is the vector containing all the residuals. This is a linear system of equations that can easily be solved.

The iterations stop as soon as all the residuals are lower than a certain value (i.e. very close to zero), defined at the beginning of the simulation.

Once all the internal flows are calculated, the pollutant concentrations are determined by solving the mass equation for each zone:

$$\frac{d(\rho_i V_i C_{ip})}{dt} = \sum_{j=O}^{N_Z} \sum_{k=1}^{NK_{ij}} m_{jik}(1-\eta_{jikp})C_{jp} - \sum_{j=O}^{N_Z} \sum_{k=1}^{NK_{ij}} (m_{jik} + k_{r,ip})C_{ip} + S_{ip} \quad (10)$$

where ρ_i is the density of air (kg/m^3), V_i is the volume of zone i (m^3), C_{ip} is concentration of pollutant p in zone i (kg/kg air), N_Z is the total number of zones, NK_{ij} is the total number of links between zone i and j, m_{jik} is the mass flow rate through link k, from zone j to zone i (kg/s), η_{jikp} is the filter efficiency of link k between zone i and j for pollutant p, and $k_{r,ip}$ is the reactivity of pollutant p in zone i. The subscript O stands for outdoor conditions. In order to simplify and solve these sets of equations, the following assumptions are made:

- The concentration of the pollutant is homogeneous in each zone.
- The density of air is not affected by the pollutant concentration.
- The relative variations of the temperature in the zone are negligible when compared with the relative variations of the concentration of any pollutant in the zone.

Validation

Experiments have been performed during the summer in order to validate the developed model for single-side ventilation configurations. For this particular case, air-flow network models do not perfectly simulate the real conditions. A new technique has however been developed requiring the use of a correction coefficient by which the results have to be multiplied, using a discharge coefficient equal to unity.[15] This correction coefficient is defined as follows:

$$CC = 0{\cdot}1(Gr/Re^2)^{-0{\cdot}34} \quad \text{if } CC \geq 0{\cdot}6 \qquad (11)$$
$$CC = 0{\cdot}6 \quad \text{for all other conditions}$$

with Gr as the Grashof number and Re as the Reynolds number. This technique was thus used for our single-side ventilation experiments.

An office on the second floor of a three-storey building at the National Observatory of Athens (NOA) was selected for the validation of the model. Its floor area is 13·59 m^2 and its height is 4·5 m. It has one window oriented west with a 2·97 m^2 total floor area. The maximum opening area is 1·75 m^2 only. The internal air and surface temperatures were recorded every 30 s and the outdoor temperature, solar radiation, wind direction and velocity were obtained from the meteorological station of the NOA.

Ventilation experiments were then performed using a tracer-gas decay method. N_2O was used as the tracer gas. Injection and sampling points were carefully selected. Once the injection was stopped, the window was opened and the gas concentration measured every 30 s. In all, seven different experiments corresponding to different opening areas were performed.

Using the recorded data and the measured initial N_2O concentration, the decay is simulated using the model described previously.

Typical results showing the difference between simulated and measured concentrations can be seen on Figs 1 and 2. The measured and simulated results are displayed with their error bars corresponding to a 0·1°C error on the temperature measurements and a 5% error on the wind velocity. These results were very satisfactory, having an average 8 ppm overall error for all the simulations. It should however be pointed out that the smaller the opening area, the better the results obtained.

In order to check the performance of the overall simulation tool

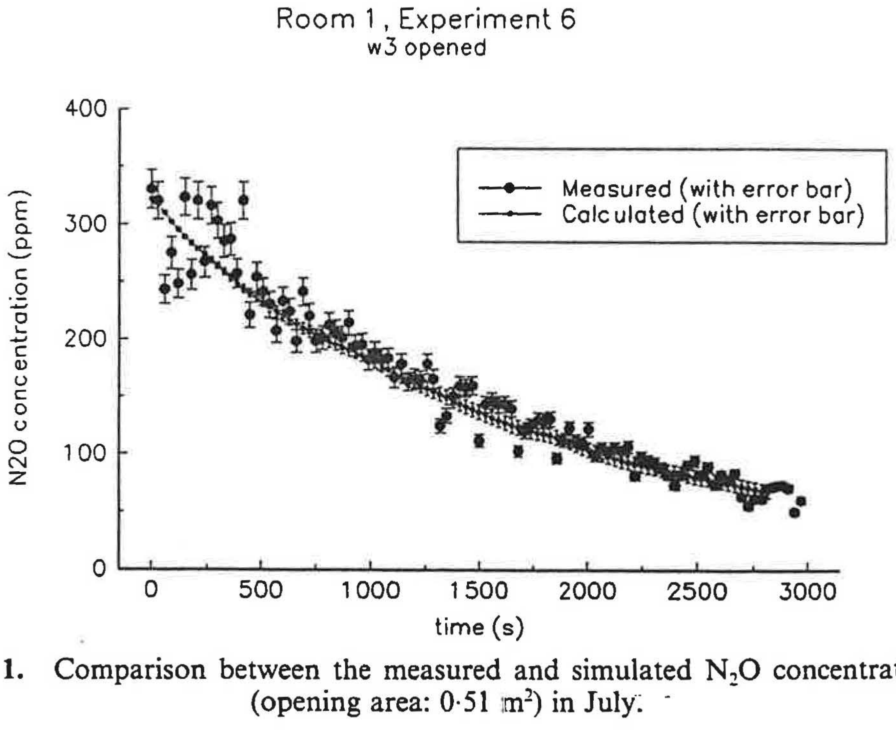

Fig. 1. Comparison between the measured and simulated N_2O concentrations (opening area: 0·51 m^2) in July.

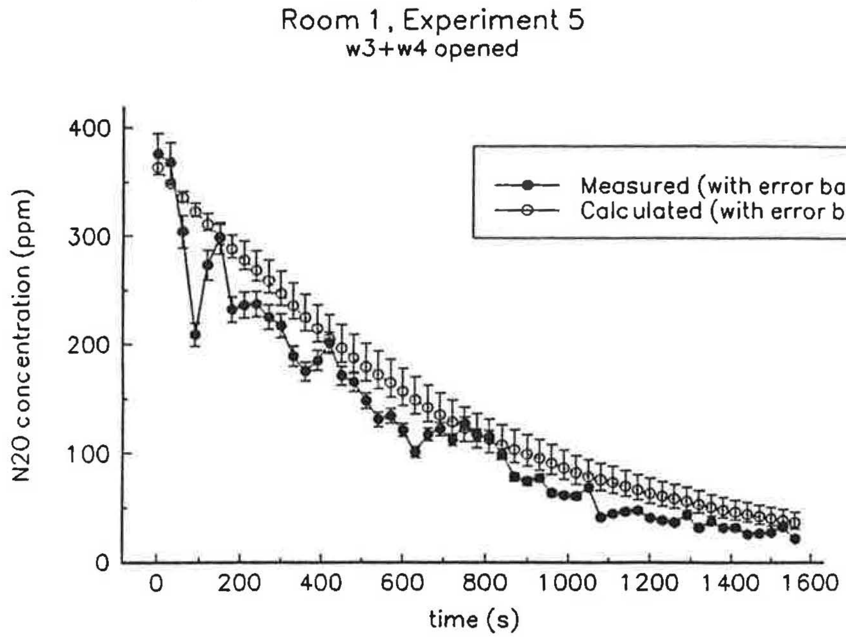

Fig. 2. Comparison between the measured and simulated N_2O concentrations (opening area: 1·18 m^2) in July.

(TRNSYS + multizone airflow and pollutant transport model), a typical day has been simulated. Sensors placed at the windows gave the indication of the opening ratio of the window (i.e. 1, 0·5 or zero). This value and all the environmental conditions were given as inputs to the tool. The simulation timestep was 90 s. The simulated and measured temperatures were then compared. Figure 3 shows the results of this simulation. In order to simplify the readability, hourly values only are displayed. It can, however, be seen that the simulation and measurements match quite well. The average error throughout the day is 0·29°C (std dev: 0·38°C). During the day however, big differences might be found (up to 1·5°C). This can be explained by the coarse accuracy of the measured window opening area. The window might therefore be slightly open while the sensor indicates it is closed (and vice versa). This will affect the thermal gains (or losses) due to ventilation and thus the indoor temperature.

THE FUZZY-REASONING MACHINE

As explained in the introduction, the CO_2 concentration was chosen as the pollution index because it was assumed that the occupants were the only pollution sources and all were non-smokers.

When using classical (e.g. PID) controllers, the goal is to maintain the

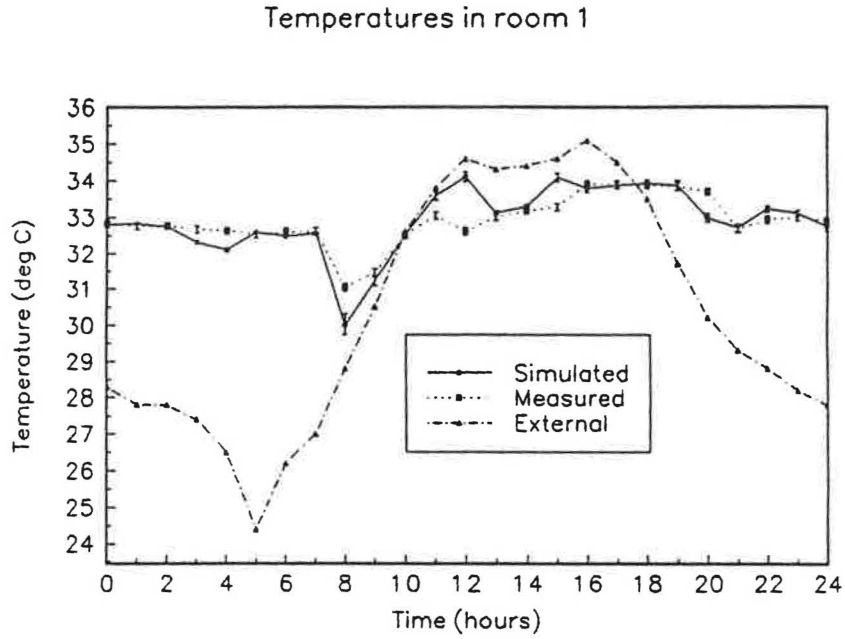

Fig. 3. Comparison between measured and simulated indoor-air temperatures in July.

CO_2 concentration below a certain crisp setpoint defined by the user. This results in the continuous operation of the actuator (i.e. the window opening area). This solution is not satisfactory because such an instability would bother the occupants.

Standard concentration limits have however been defined according to empirical knowledge and are thus imprecise. The controller's CO_2 concentration set-point should preferably be described by a fuzzy set.

The goal in designing the fuzzy-reasoning machine was thus to maintain the CO_2 concentration within certain limits (which correspond better to the imprecision of the 'comfort limit'), while ensuring a good stability of the window's opening-area.

Two parameters were chosen as inputs to the fuzzy reasoning machine (FRM). These parameters are the CO_2 concentration (i.e. the controlled parameter) and the derivative of the CO_2 concentration.

Both inputs are represented by seven different fuzzy sets whose linguistic representations (see Table 1) are the following.

For the CO_2 concentration:

$$CO_2 = \{VVS, VS, S, OK, M, B, VB\}$$

For the derivative of the CO_2 concentration:

$$(dCO_2/dt) = \{BN, MN, SN, ZE, SP, MP, BP\}$$

The membership functions (triangular and trapezoidal only) of both inputs are shown in Figs 4 and 5 respectively.

The process output of the FRM is the change in the window opening area (CWOA) (a real actuator will be a motor moving, but this can easily be modified as the relation between both is linear). The output is represented by 15 fuzzy sets as follows:

CWOA= {VBN, BN, MBN, MN, SMN, SN, VSN, ZE, VSP, SP, SMP, MP, MBP, BP, VBP}

TABLE 1.
Linguistic representation of the fuzzy sets

CO_2 concentration	*Derivative of CO_2 concentration*	*Change in window opening area*
VVS: very very small	BN: big negative	VBN: very big negative
VS: very small	MN: medium negative	MBN: medium-big negative
S: small	SN: small negative	SMN: small-medium negative
OK: satisfactory	ZE: zero	VSN: very small negative
M: medium	SP: small positive	VSP: very small positive
B: big	MP: medium positive	SMP: small-medium positive
VB: very big	BP: big positive	MBP: medium-big positive
		VBP: very big positive

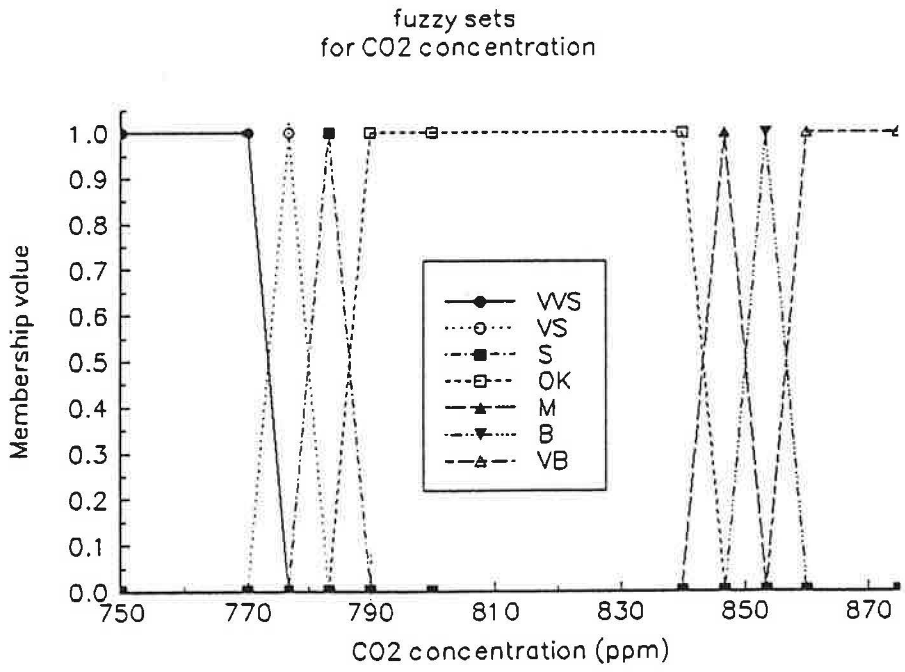

Fig. 4. Fuzzy sets for CO_2 concentration.

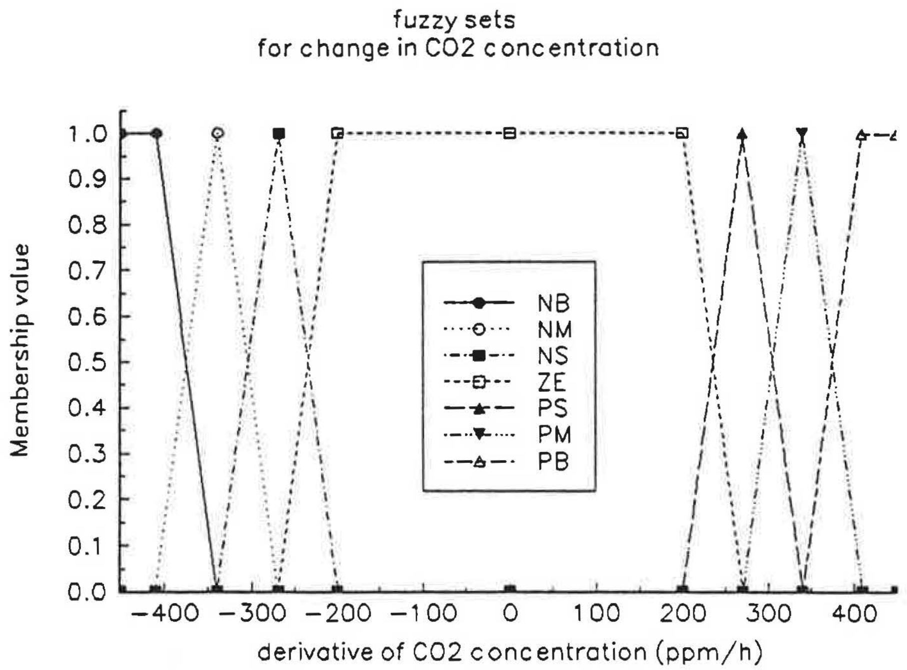

Fig. 5. Fuzzy sets for the derivative of CO_2 concentration.

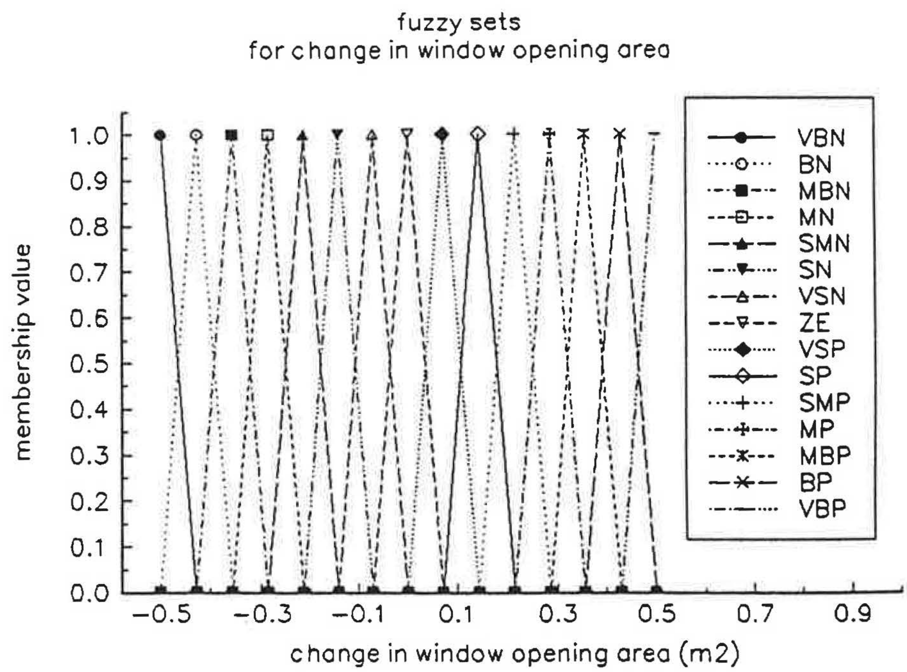

Fig. 6. Fuzzy sets for the change in window opening area.

The corresponding membership functions of this output are presented in Fig. 6. The meaning of these linguistic symbols is presented in Table 1.

Table 2 displays the 49 fuzzy rules, in linguistic form, implemented in

TABLE 2.
Control rules of the FRM (the first column indicates the fuzzy sets for the CO_2 concentration, and the first row the fuzzy sets for the derivative of CO_2 concentration.)

CO_2 \ $\frac{dCO_2}{dt}$	*BN*	*MN*	*SN*	*ZE*	*SP*	*MP*	*BP*
VVS	VBN	BN	MBN	MN	SMN	SN	VSN
VS	MBN	MBN	MN	SMN	SN	VSN	ZE
S	SMN	SMN	SN	VSN	ZE	ZE	VSP
OK	SN	SN	SN	ZE	VSP	VSP	SP
M	SN	VSN	ZE	SP	SP	SMP	MP
B	VSN	ZE	VSP	SP	SMP	MP	MBP
VB	VSP	SP	SMP	MP	MBP	BP	VBP

the FRM. This table can easily be understood as follows. The element read at row 2, column 2 (VBN) means:

If CO_2 is VVS and (dCO_2/dt) is BN then CWOA is VBN.

The structure of the FRM includes the following elements (displayed in Fig. 7):

- a fuzzifier (converting the crisp inputs into fuzzy sets);
- the inference engine operating the fuzzy rules to obtain the fuzzy output;
- the defuzzifier, converting the fuzzy output into a real value (e.g. change in opening area).

The FRM also includes a database and rule base supplying the inference engine with the fuzzy rules and fuzzy sets described above.

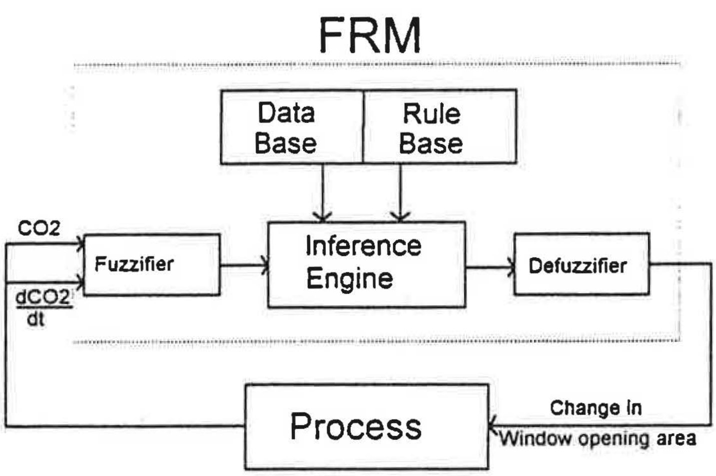

Fig. 7. Basic configuration of the fuzzy reasoning machine.

For our particular case, no quantization was considered (this corresponds to an infinite quantization level). Thus, the fuzzifier was very simple. The real input was converted to a fuzzy singleton with a membership value equalling unity. The inference engine applies the General Modus Ponens[16] using the Mamdani Min–Max fuzzy implication.[17]

In our particular case, the expression of the fuzzy output can thus be simply defined as, (using the 49 rules):

$$CWf(s) = \underset{i=1,49}{\mathrm{Max}}(\mathrm{Min}(fsCO_2^i(x), fsdCO_2^i(y), fsW^i(s))) \tag{12}$$

for any s satisfying: $(-0{\cdot}5 < s < 0{\cdot}5)$, where s is the window opening area, x, y are real inputs for CO_2 and (dCO_2/dt) respectively, $CWf(s)$ is the membership value of the fuzzy output at s, $fsCO_2^i(x)$ is the membership value of the CO_2 fuzzy set called by rule i, $fsdCO_2^i(y)$ is the membership value of the (dCO_2/dt) fuzzy set called by rule i and $fsW^i(s)$ is the membership value of the CWOA fuzzy set called by rule i.

The defuzzifier uses the centre of area (COA) method which can be described as follows:

$$S_0 = \frac{\sum_{i=1}^{N_s} s_i \, CWf(s_i)}{\sum_{i=1}^{N_s} CWf(s_i)} \tag{13}$$

where S_0 is the real output (i.e. change in window opening area), and N_s is the number of defined values on the universe of discourse of s. In our case where all the fuzzy output sets are triangular and of equal width, it is possible to consider the central values only, thus, $N_s = 15$.

SIMULATION RESULTS

The performance of the fuzzy reasoning machine has been simulated using the tool described earlier. An office, with high thermal inertia, corresponding to the one studied for the validation of the tool was used as the basis of these simulations. The building is a free-running building (i.e. no air conditioning) and no external or internal shading is assumed.

Real hourly meteorological data (i.e. outdoor temperature, wind velocity and direction, and solar radiation) corresponding to July 1985 in Athens were used as input and interpolated. The simulation time step was 90 s. Variable occupancy (from zero to 2 persons) was assumed as can be seen in Fig. 8. It was however supposed that the room was unoccupied from 7 pm to 8 am and from 12 noon to 1 pm.

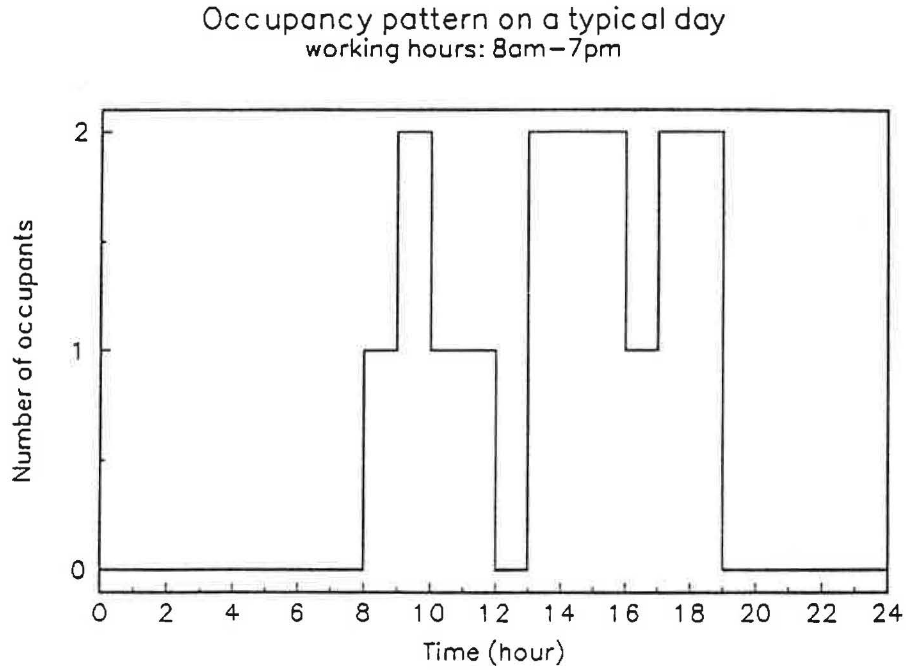

Fig. 8. Typical occupancy pattern in the office.

Different simulations were performed:

- one with the operation of the fuzzy-reasoning machine;
- one with a closed window all day long;
- three other simulations with the window constantly opened (closed at night and lunch time only), with different opening areas: 0·2, 0·5 and 1·75 m^2 (1·75 m^2 being the biggest possible area).

It should be pointed out that during the normal use of the office, the windows are usually largely open (i.e. more than 1 m^2).

The CO_2 concentration limit was set at 800 ppm, with a ± 50 ppm tolerance. This corresponds to the current standards (between 600 and 1000 ppm depending on the country and building type).

Figure 9 shows the different CO_2 concentrations for the different cases. It can be seen that the fuzzy controller is as efficient as expected because the CO_2 concentration will never exceed 850 ppm. On the other hand, in order to achieve the same result with a constant opening, the opening area must at least be equal to 0·2 m^2. Moreover, with very large openings, the CO_2 concentration will remain at a very low level all day long (i.e. less than 400 ppm for the largest opening case). If the window remains closed all day long, very high concentrations may occur at the end of the day (i.e. up to 1800 ppm) which will lead to serious complaints from the occupants.

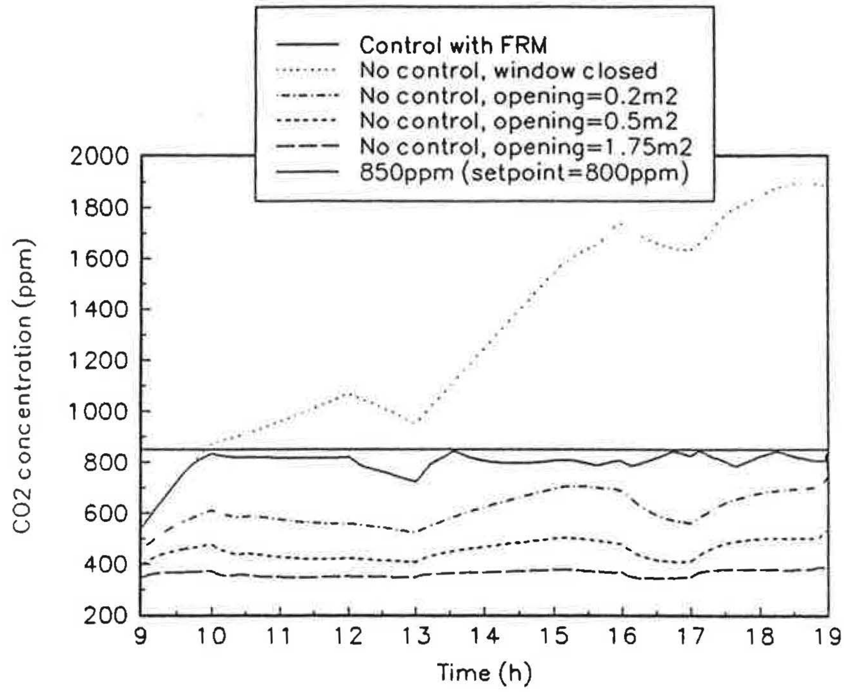

Fig. 9. CO_2 concentration during a typical day in July, with and without control and for different opening areas.

Figure 10 shows that the second objective of the FRM (relative stability of the control parameter) is also satisfied. There is no fluctuation at all in this case and the transition from one step to another is obtained in a continuous and regular move. This is very important in dealing with natural ventilation, as the occupant will not be disturbed by the continuous change.

Finally the impact of the different simulation cases of the indoor temperature has been studied. The results are shown in Fig. 11. Only the afternoon values are displayed, because it is the part of the day when they reach the highest grades having the most negative effect on the thermal comfort. The first lesson from these results is that the biggest difference between the totally open and totally closed cases is not bigger than 0·6°C. This might be explained by the relatively high inertia of the building and the effect of the solar radiation that tends to affect the importance of the heat gains through ventilation.

The difference between the use of the FRM and the constant opening at 0·2 m^2 is very small (i.e. less than 0·1°C), even if the former shows slightly smaller values, but this difference could be up to 0·4°C compared with the full opening case which corresponds to the normal use of the building.

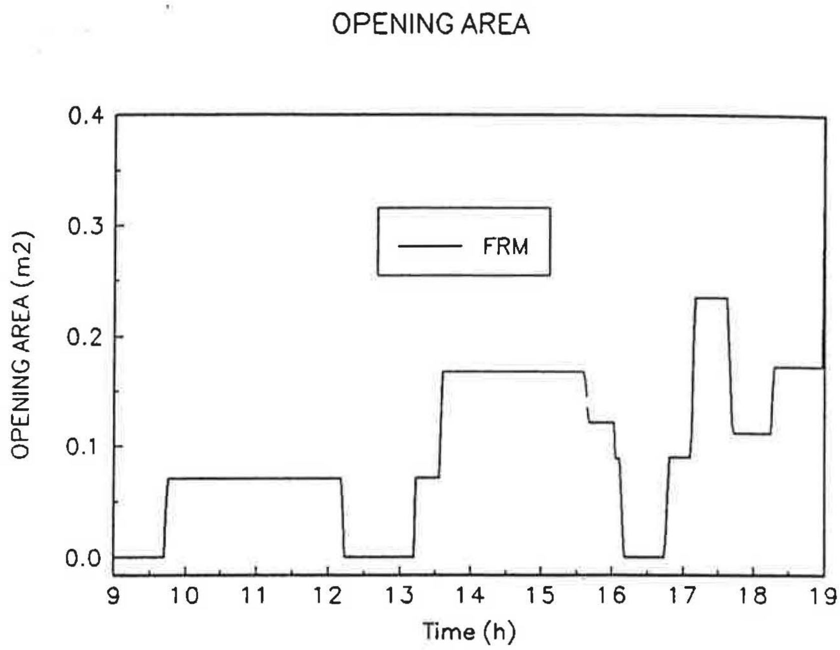

Fig. 10. Opening area of the window controlled by the FRM during a typical day in July.

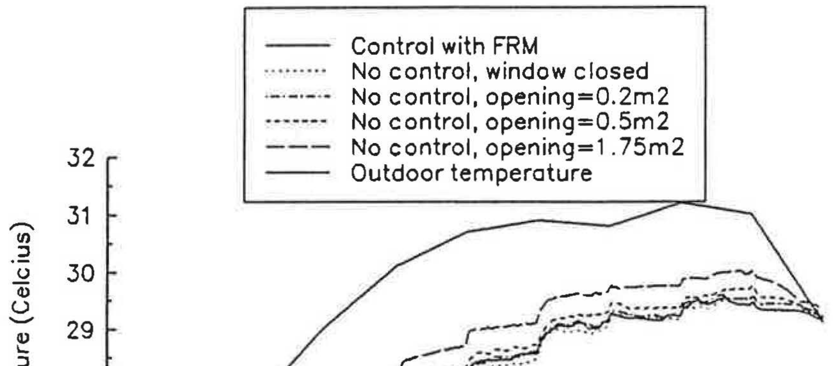

Fig. 11. Indoor-air temperature during a typical day in July, with and without control but for various opening areas.

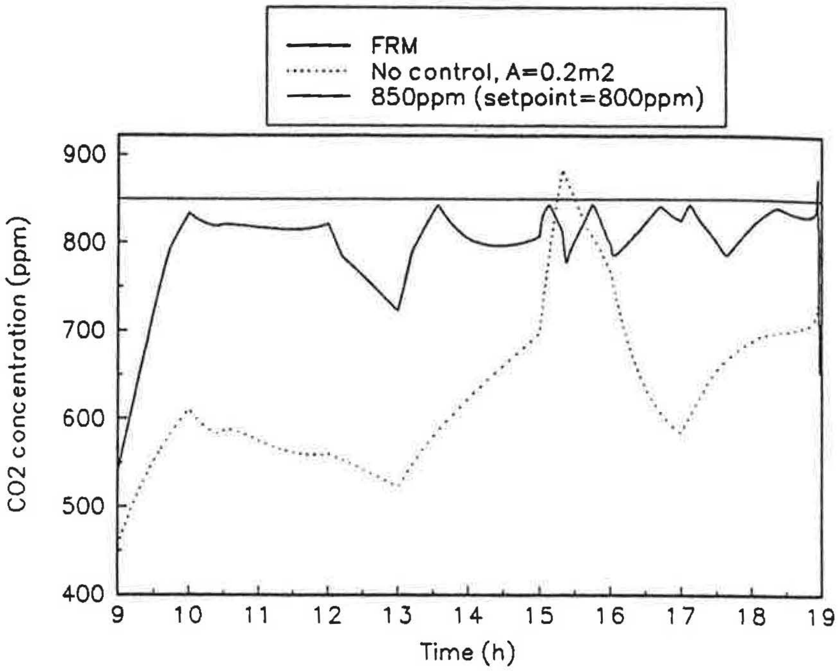

Fig. 12. Impact of a high occupancy (5 persons) on the CO_2 concentration, with and without control.

The use of a constant opening area of 0·2 m^2 seems to be as efficient as the FRM, because the temperature differences are very small and the concentration limit is never reached. However, one should keep in mind that, for different occupancy patterns, this will not be the case anymore. Figure 12 thus shows that, in case of a sudden high occupancy (up to five persons during 20 min), the concentration limit will be exceeded if the opening area remains at a constant value (0·2 m^2), whereas the controller will cope with this sudden change, thereby showing its effectiveness.

The impact of the FRM on the temperature, when compared with the current use (i.e. large opening area), although not as important as expected, is not negligible. Moreover, in the case of high external temperatures (which was not the case here), the difference might become much more important and the FRM will be an efficient solution for reducing indoor temperature while satisfying indoor-air quality requirements.

CONCLUSION

The present paper proposed the use of fuzzy logic for the control of indoor-air quality by natural ventilation. The main result from this study is that such control is possible without resulting in instabilities of the control parameter, in this case namely the window opening area. Moreover, the impact of the use of such a controller on the indoor temperature was not negligible and should be further investigated.

In order however to improve the performance of such a controller on thermal conditions, the temperature difference between inside and outside should be used as another input to the controller.[18] More generally, thermal comfort and indoor-air quality should be controlled simultaneously by such a controller. This requires the use of more parameters as inputs.

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