Journal of ELECTRICAL ENGINEERING, VOL. 60, NO. 1, 2009, 12–17

FUZZY LOGIC CONTROLLER DEPLOYED FOR INDOOR AIR QUALITY CONTROL IN NATURALLY VENTILATED ENVIRONMENTS

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This paper provides new indoor air quality control (IAQ) based on fuzzy logic control in natural ventilated indoor environments where no other ventilation approaches are installed or can be installed due to space limitation or economical reasons. For the presented fuzzy logic controller, four distributed sensors inside the indoor environment are used to provide the basic measurable inputs to the fuzzy system. These inputs are the carbon dioxide (CO_2), carbon monoxide (CO), humidity (H_2O) and odors concentrations inside the indoor environment. The fuzzy logic output will provide the required control command to the DC-motor connected to the fan by determining the necessary duty cycle to the PWM module. As a result, fresh air is allowed to replace the polluted air inside the indoor environments such as rooms and small workshops.

The presented results for the conducted simulation scenario have confirmed the ability of the new system to handle the ventilation problem at critical situations compared to natural ventilated indoor environments. Also the presented controller is economically efficient by saving the electrical power and for implementation phase it is also inexpensive.

K e y w o r d s: fuzzy logic control, indoor air quality control

1 INTRODUCTION

Usually fresh air should be composed of many gases components such as oxygen (O_2), nitrogen (N_2), carbon dioxide (CO_2) and carbon monoxide (CO), water vapor (H_2O) and other materials such as dusts, odors and smokes with variable amounts and percents. Unfortunately these amounts or levels may be changed accidentally or intentionally due to human activities or industrial reasons, which results in increasing the concentration of some gases that may be harmful or poisonous for human beings life, for instance there may be an increase in the concentration of carbon dioxide and monoxide and reduction in the oxygen contents of the air especially at closed indoor environments such as rooms, schools or small industrial workshops [1, 2].

The carbon dioxide concentration should be less than 5 % while the humidity level should be below 65 %. The presence of these harmful and poisonous contents in the air may lead to many problems; human beings may loose conscious, and sometimes there may be more severe situations which decrease the possibility to survive and lead to death as time passing [1, 2].

The number of people inside indoor environment at the same place plays an important rule in this issue, where natural ventilation such as windows, doors, and ventilation shafts should be able to refresh the air inside any closed area by removing the poisonous gases and replace them with fresh air which is allowed to enter from outside through the joints and gaps in the windows and doors which contains the necessary amount of oxygen to survive [1, 2], this process should take place more than once during the day to refresh and replace the air for the indoor environment.

Natural ventilation could also keep the room at good climate by removing humidifying air, odors and other harmful substances from the rooms [2]. In fact, natural ventilation does not work fine all the times, especially during winters or cold climates where most of the available resources for natural ventilation are decreased by insulation of these joints and gaps to keep good thermal climate inside the indoor environment.

The necessity for mechanical ventilation systems are raised for these reasons. These systems allow the outside air to flow and refresh the internal air by replacing the removed one through using fans and ducting.

Researcher have addressed this problem for special cases such as buildings furnished with Heating Ventilating and Air Conditioning systems (HVAC) which perform indoor air quality control by various classical control methods or intelligent approaches to keep the inside environment at comfortable temperature and humidity levels [3–12]. In fact, these systems are not always available at all homes, apartments, schools or even small workshops due to many reasons, especially economical ones.

Others addressed this problem especially for highway tunnel ventilations based on intelligent fuzzy controllers [13, 14]. Finally, partial solutions are provided considering the treatment for only one type of gas or odors by controlling its concentration [15–17].

This study aims to provide a new solution for indoor air quality control based on fuzzy logic controller in natural ventilated indoor environment. A brief introduction is presented in this section, in the following section the controller design is covered, in the sequel the simulation results for the conducted experiments are demonstrated, finally the concluding remarks from this work as well as future work are presented.

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ISSN 1335-3632

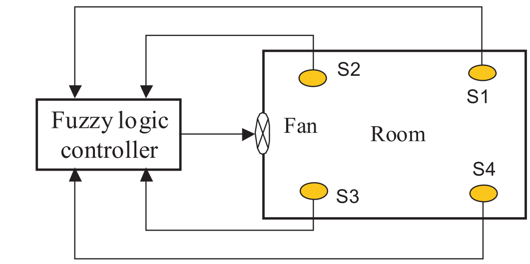

Fig. 1. Proposed controller layout

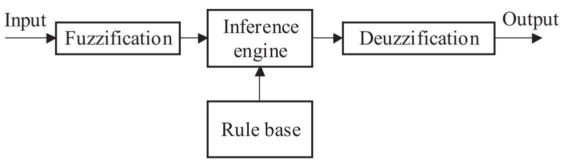

Fig. 2. Fuzzy logic controller main configuration

2 CONTROLLER DESIGN

A set of four distributed sensors (S1, S2, S3 and S4) are used to monitor the available emitted amount of carbon dioxide (CO_2), carbon monoxide (CO), humidity (H_2O) and odors inside indoor environment such as a living room. The best way to represent the behaviour of the different emitted gases and other substances in the air is to use a linguistic description. This can be achieved by using fuzzy logic modelling for the addressed problem or process. The linguistic description or fuzzy logic modelling was introduced for the first time more than forty years ago by Lutfi A. Zadieh [18], where he stated that the fuzzy set theory is generalization for the classical set theory by allowing the variable in the set to partially belong to this set by using a membership value between 0 and 1.

For the presented controller, four distributed sensors inside the indoor environment are used to provide the basic measurable inputs to the fuzzy system. These inputs are the carbon dioxide (CO_2), carbon monoxide (CO), humidity (H_2O) and odors concentrations inside the indoor environment. This arrangement makes the system Multiple Input Single Output control (MISO), accordingly the system cannot be easily modelled or controlled using classical control methods such as PID controllers due to the modelling complexity and the controller implementation taking the four inputs in to account. The benefit from using fuzzy logic is to provide a non-mathematical model for the addressed problem which is more robust compared to classical mathematical modelling. Furthermore, the nature of developing the fuzzy expert rules depends on the human knowledge or action at different situation and condition, which makes the system more reliable to handle critical situations based on its accumulated experience. Another advantage from using fuzzy logic is the ability to modify the system in the future by adding more inputs to the controller where only the If-Then rules need to be modified, while in the classical control this needs a lot of effort.

The objective of the proposed fuzzy logic controller is to maintain the concentration of different emitted gases and other substances inside naturally ventilated rooms within the acceptable levels.

The proposed fuzzy logic control scheme for indoor air quality control is illustrated in Fig. 1. As shown in the figure, a set of four distributed sensors (S1, S2, S3 and S4) will monitor the available emitted amount of gases and other substances inside the naturally ventilated room. These sensors will provide the fuzzy logic controller with the available emitted amount of gases and other substances concentrations inside the room. These data will be used to inference the required output to control the fan movement.

The main configuration of the fuzzy logic controller is shown in Fig. 2. As shown from the figure, this controller mainly consists of four parts; fuzzification part, inference engine, rule base and defuzzification part. Initially a fuzzification process is required for converting the controller input into linguistic fuzzy variables which describe the behaviour of the inputs [20].

The dynamic behaviour of the fuzzy system is described by a set of linguistic description rules (IF-THEN rules). These rules describe the relation between the linguistic inputs and the outputs variables of the fuzzy system based on expert knowledge for the system behaviour. This set of linguistic IF-THEN rules description of the system usually comes in the form: IF (a set of conditions are satisfied) THEN (a set of consequences can be inferred)

IF (x1 is A1 AND x2 is A2 ... AND xd is Ad) THEN (y is B1)

After that an inference mechanism calculates the degree to which the input data match the condition of the fuzzy rules. It also calculates the rule's conclusion based on the matching degree, combining all the inferred rules into a final conclusion. Finally, the defuzzification process maps the fuzzy rules output to a crisp (single) point.

Four distributed sensors (S1, S2, S3 and S4) provide the basic four measurable inputs from inside the room to the fuzzy system; the carbon dioxide (CO_2), carbon monoxide (CO), humidity (H_2O) and Odors concentrations. Because the commercially available measurement sensors are not of the same brand and vary with the measurement scale, a pre-normalization step is required for the measured concentration before it can be fed into the inference engine.

Three membership functions are enough to describe each of the normalized input variables measurements as "μ_{Low}", "μ_{Medium}", and "μ_{High}", defined by (1) [19, 20]. Fig. 3 shows the membership functions for the four input variables where triangular membership functions are used to describe the variables.

$$\mu_{\text{Term}}(S_i\colon a,b,c) = \max\Big(\min\Big(\frac{S_i-a}{b-a}, \frac{c-S_i}{c-b}\Big), 0\Big) \qquad (1)$$

Table 1.

IF	CO_2L is L	AND	COL is L	AND	H_2OL is L	AND	OdL is L	THEN	FS is L
IF	CO_2L is M	AND	COL is L	AND	H_2OL is L	AND	OdL is L	THEN	FS is M
IF	CO_2L is H	AND	COL is L	AND	H_2OL is L	AND	OdL is L	THEN	FS is H
IF	CO_2L is H	AND	COL is H	AND	H_2OL is H	AND	OdL is H	THEN	FS is H

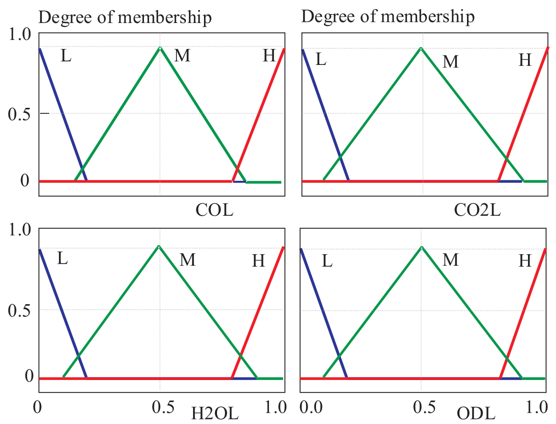

Fig. 3. The membership functions for the four input variables to the fuzzy system.

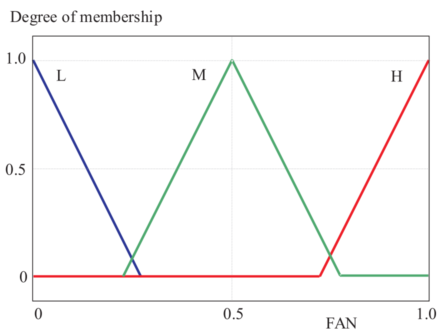

Fig. 4. Membership functions for the fuzzy controller output

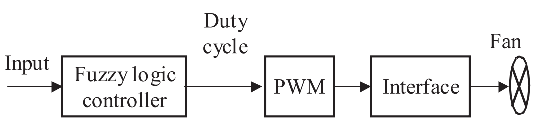

Fig. 5. The interface of the fuzzy logic controller with the fan

where: Term can be "Low", "Medium", or "High", S_i is the normalized input by the ith sensor, $\{a, b, c\}$ are the triangular membership function parameters, b defines the triangular peak location, while a and c define the triangular end points.

The inference engine will determine the required rotational speed for the fan through out the simulation time based on the expert linguistic IF-THEN rules description for the system behavior. The fan rotational speed is fully described by three membership functions as "μ_{Low}", "μ_{Medium}", and "μ_{High}", where the fan rotational speed should vary between zero and the maximum limit speed for the used fan. Fig. 4 shows the membership functions for the fuzzy controller output. As it can be noticed the output range is between zero and one. This value characterizes the duty cycle required by the pulse width modulation (PWM) which controls the DC motor connected to the fan as shown in Fig. 5. For instance, if the fuzzy logic controller output is one the fan will rotate at a full speed, because 100 % duty cycle is provided by the PWM to the DC motor.

For the proposed controller several IFTHEN rules are required to describe the system behavior. These rules aim to determine the required fan rotational speed by determining the correct duty cycle for the DC motor connected to the fan. For instance, as in natural ventilation rooms when the humidity or steam level is high inside the room the windows or the doors will be opened to allow the outside air to get inside the room for refreshment.

Twenty four rules are developed for the controller; these rules are based on the different scenarios for the linguistic input variables states. As shown in Table 1, a sample set for the developed rules is shown. "L", "M" and "H" are used as abbreviation for the membership functions "Low", "Medium", and "High" for inputs and output variables.

The Mamdani min-max inference engine is used through out the simulation time [20]:

$$\mu_{\mathrm{R}i}(S) = \alpha_{i1} \wedge \alpha_{i2} \wedge \alpha_{i3} \wedge \alpha_{i4}\,, \tag{2}$$

$$\mu_{\text{output}}(S) = \max\{\mu_{\mathrm{R1}}, \mu_{\mathrm{R2}} \ldots, \mu_{\mathrm{R25}}\} \tag{3}$$

where: S is the set of sensors input (S1, S2, S3 and S4), α_i is the matching degree of a given input which satisfies the condition of the ith rule (Ri), $\mu_{\mathrm{R}i}$ is the fuzzy set output of rule Ri, μoutput is the aggregation of fuzzy set outputs from all rules.

For defuzzification, the mathematical mean value of all the highest values of the aggregate rules output is used to map the fuzzy rules output to a crisp (single) point (4) [20], this output is the required duty cycle for the PWM command to control the fan, this process is illustrated in Fig. 6. The resulted fuzzy surface form the IF-THEN rules showing the relation between the inputs and output are shown in Fig. 7.

$$\mathit{output}(S) = \frac{\sum\limits_{y^* \in H} y^*}{|H|} \tag{4}$$

where: H is the set of output points with highest values.

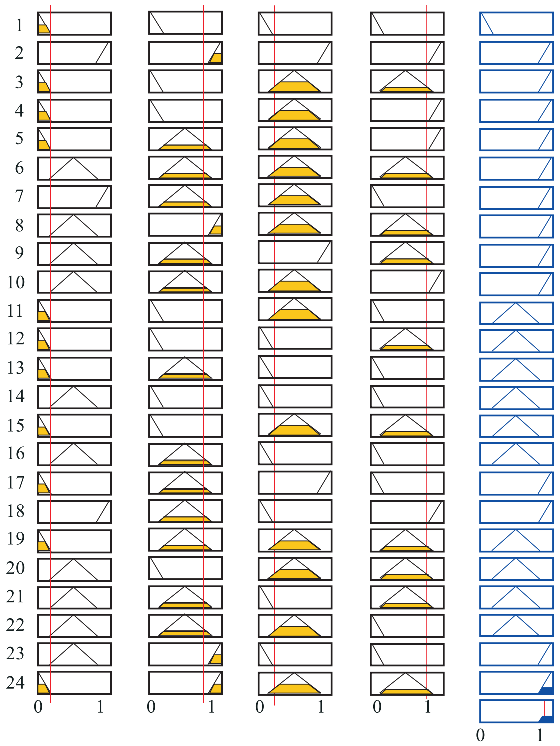

Fig. 6. Rule view for defuzzification of the aggregate all rules output

3 SIMULATION RESULTS

In order to validate the proposed approach for the fuzzy inside air quality control of the room several scenarios had been conducted based on simulated experimental data. Four distributed sensors (S1, S2, S3 and S4) were used to provide the basic measurable inputs to the fuzzy system through the simulation time; namely, the carbon dioxide (CO_2), carbon monoxide (CO), humidity (H_2O) and Odors concentrations inside the room.

To evaluate the proposed approach in a similar real life situation, the size of the room was assumed to be $36\,m^3$ with one door and one window, while the fan provides $15\,m^3/h$. Initially the sensors were assumed to provide the available initial concentration inside the room. To make the simulation a more critical example and to be able to reflect real life situations, other sources for the emitted gases were assumed to run inside the room at different instants of the simulation time such as the stove for cooking, heater for heating during the winter, and a big number of people interring the room at the same time.

In the following demonstration scenario, the four measured concentrations of CO_2, CO, H_2O and odors by the four sensors (S1, S2, S3 and S4) are shown in Fig. 8, for forty eight hours during the winter season or cold weather conditions, where special attention is given to close most of the possible entrance of air form outside through windows joints or door gaps.

Initially the four concentrations are assumed to be low for the first fifteen hours due to the fact that few activates are performed inside the room which makes the natural ventilation for the room able to keep the four concentrations at acceptable level inside the room.

To evaluate the proposed approach at more critical situations, after the first fifteen hours a number of people is assumed to enter the room and perform some activates like cooking turning the gasoline heater on and so on. Due to these activates the amount of the CO_2, CO, H_2O and odors emitted inside the room will increase in a very

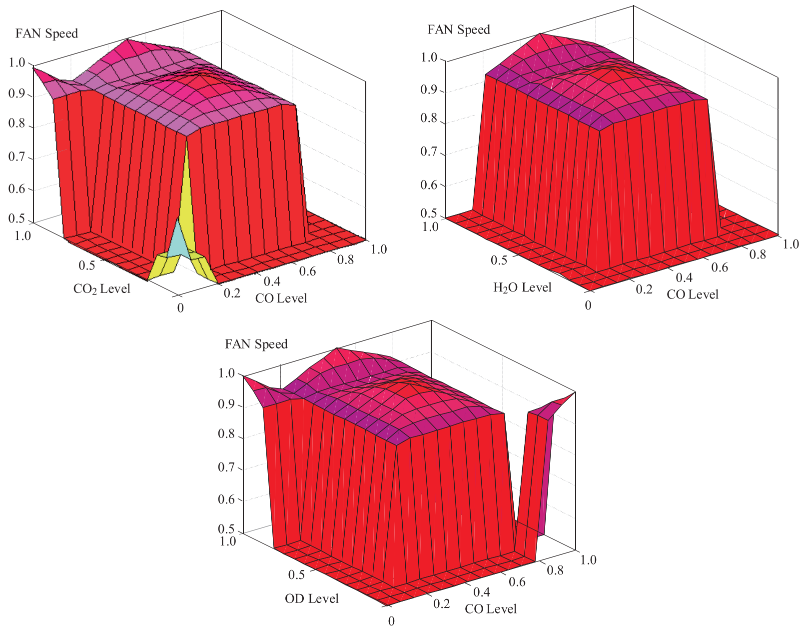

Fig. 7. Fuzzy surface showing the relation between the inputs and output

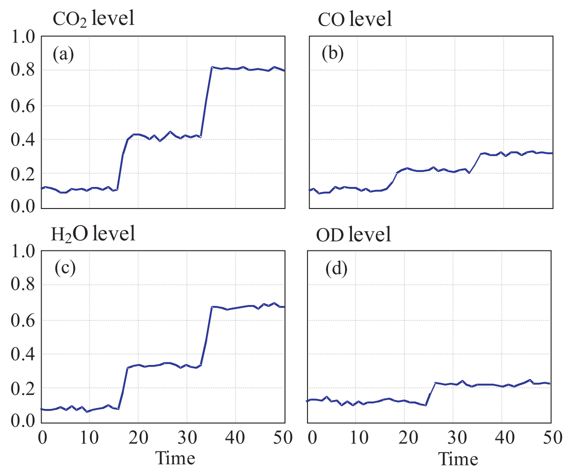

Fig. 8. The four measured concentrations of CO_2, CO, H_2O and odors by the four sensors

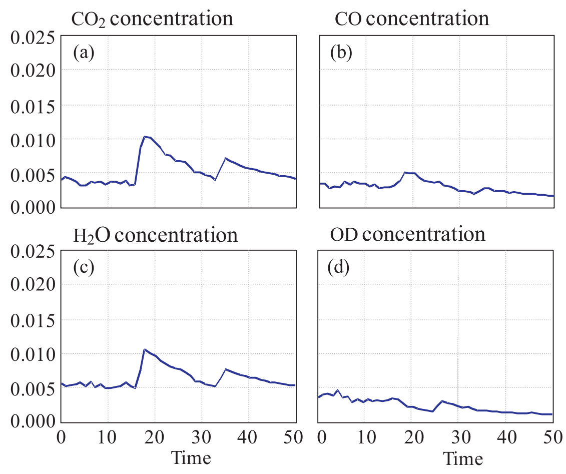

Fig. 9. The concentrations of CO_2, CO, H_2O and odors after using the controller

notable amounts during simulation time, according to the following equations:

$$CH_4 + O_2 \rightarrow CO_2 + H_2O\,. \qquad (5)$$

The same scenario mentioned before is used to evaluate the controller performance. The results after the controller installation are shown in Fig. 9. The simulated measurements by the four sensors are simulated as inputs to the fuzzy logic controller for inside air quality control. By comparing the plots in Fig. 8 and 9, it can be noticed that the controller was able to deal with the increasing amounts of emitted gases and odors inside the room and was able to keep of people occupying the room throughout the simulation time.

The control command of the DC motor through the simulation time is shown in Fig. 10. As shown in the figure, the provided duty cycle to the PWM model will keep the fan working all the time at different speed levels responding to any action that changes the concentration of gases inside the room. As a result the fan will work at a low level speed if there is no high level of the four monitored elements sensed inside the room. This will provide the recommended number of air replacement inside the room by ASHRE [1] and will save the electrical power in an economical way through out the operation time.

When a low level of the four monitored elements sensed inside the room, as shown in the Fig. 8, for the first fifteen hours an average power saving factor of 99.4 % is achieved compared to the on/off control for the fan system. During the next ten hours the level of the four monitored elements sensed inside the room increased, the achieved average power saving factor is about 50 % compared to the on/off control for the fan system during this period. For the last duration of the simulation time, the system deals with a more critical situation, with high level of the four monitored elements sensed inside the room, the system was able to provide 7 % average power saving factor compared to the on/off control of the fan system during this critical period.

4 CONCLUSIONS

In this research a new indoor air quality control was presented based on fuzzy logic control in naturally ventilated environments where no other ventilation approaches can be installed due to space limitation or economical reasons. The presented simulation results have confirmed the ability of the new system to handle the ventilation problem at critical situations. The presented system is also economical for saving the electric power due to the use of PWM module to control the fan. The implementation of this system is simple and inexpensive.

This work can be extended for future work as distributed network sensors through out the buildings, especially old ones, to monitor different gases levels as well as odors to provide the necessary ventilation for all the rooms.

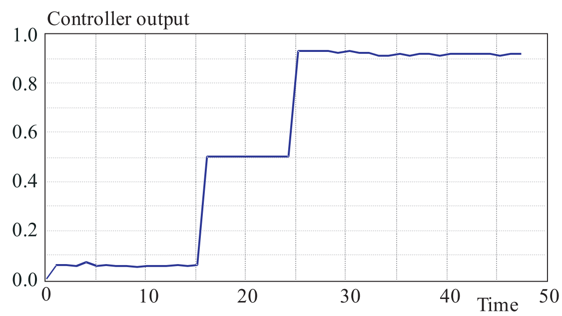

Fig. 10. Controller output providing the required duty cycle for the fan

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Received 30 September 2008

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