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# FUZZY CONTROL OF CARBON DIOXIDE CONCENTRATION IN PREMISES

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*Abstract*: - The carbon dioxide concentration in rooms with varying number of people is an important safety and comfort factor. Its control via ventilation is accompanied by two drawbacks - the increased energy consumption and dependence on the quality of the fresh air used. Fuzzy logic can ensure energy efficient control of the carbon dioxide concentration. The aim of the present research is to develop a design procedure for fuzzy logic controllers (FLC), to apply it to a laboratory HVAC system and to assess its performance in real time experimentation. The main results are a design procedure for two structures of FLCs – with and without reference, real time investigation of the designed systems and comparison of their performances.

*Key-Words*: - Carbon dioxide concentration control, fuzzy logic controller design procedure, Laboratory HVAC system, energy efficiency, MATLAB™ real time experimentation

## 1 Introduction and State of the Art

The fresh air contains a variety of gaseous components such as oxygen, nitrogen, carbon dioxide ($CO_2$), carbon monoxide (CO), water vapours, etc. and also dust, solid particles and smoke. Their concentrations change under the influence of human activity and the operation of machines and installations which results in an increase of the toxic components concentrations and a reduction of the oxygen concentration. This may turn dangerous especially in closed spaces – rooms, public buildings, schools, industrial premises [1].

The number of people in a premise affects the $CO_2$ concentration to a greater extent than the air humidity [2]. This sets demands on the contemporary systems for heating, ventilation and air-conditioning (HVAC) to consider the concentration of carbon dioxide as one of the basic factors which characterize the microclimate in a premise together with the air temperature, humidity and speed [3]. Thus the HVAC systems ensure both thermal comfort and reduction of the harmful emissions due to machines or people impact.

The HVAC systems, however, are estimated as one of the heaviest energy consumers in a building. They also possess the greatest potential for energy savings. Therefore, building energy management systems are developed with the aim to reduce energy consumption in the HVAC systems [4]. To increase the working environment comfort at lower expenses, new control approaches have been suggested that replace the less effective classical ones. The application of fuzzy logic for a model free robust control of a variety of nonlinear and MIMO plants has become nowadays one of the most successful in many areas [5-8]. It has been established that in the modern buildings the intelligent control improves the control system performance and reduces in addition the energy consumption [9]. Most investigations in literature are related to temperature and humidity fuzzy control [1, 10]. In [11] the fuzzy control is divided between two fuzzy logic controllers (FLCs) – one for temperature, humidity and air drift, and a second – for concentrations of $CO_2$, CO and dust. Fewer systems have been reported to deal with the reduction of the concentration of carbon dioxide Energy saving control algorithm for temperature, humidity and $CO_2$ concentration with priority to safety is developed in [12] where the control of a variable in the range is switched off. In [13, 14] genetic algorithms are applied for minimization of the number of rules and optimization of the membership functions in the fuzzy control temperature, humidity and $CO_2$. The energy saving aspects are treated as whole separately [15, 16].

The aim of the present paper is to develop a procedure for design of energy efficient fuzzy logic controllers (FLC) for the concentration of carbon dioxide in a room, to apply it to a laboratory HVAC system and to assess its performance in real time experimentation using MATLAB™.

## 2 Design Procedure for Fuzzy Logic Control of Carbon Dioxide Concentration

The design procedure is based on the method suggested in [8]. It requires expert estimates for the plant parameters $P^o(s)=[k^o, T^o, \tau^o]$, and their worst variation –

here accepted as 20% increase of $k$ and $\tau$ and 20% decrease of $T$, which affects system stability. Thus the worst varied plant becomes $P^{w}(s)=[1.2k^{o}, 0.8T^{o}, 1.2\tau^{o}]$. The expected smoothly nonlinear character of the plant is described by the couple nominal plant - multiplicative plant model uncertainty $[P^{o}(s), l(s)]$, $l(s)=[(P^{w}(s)-P^{o}(s)]/P^{o}(s)$.

This design procedure considers two structures of FLC for the concentration of carbon dioxide.

The first structure with block-diagram in Fig. 1 is a stabilization system for a preset low reference $y_r$. The system comprises a standard incremental PI-like FLC. It is based on Fuzzy Unit (FU) – the static nonlinear fuzzy part, pre-processing and post-processing. The FU has with two inputs– the normalized system error $e$ and its derivative $\dot{e}$ in the range [-1, 1] and an output - the normalized control rate $\Delta u$, which is post-processed by an integrator and then via a Pulse-Width-Modulator (PWM) is passed onto a solid state relay (SSR) to control the power supply to the fan for inletting fresh air. The derivative of error $\dot{e}$ is obtained at the output of a first order differentiator with transfer function $W_d(s)=K_d T_d s.(T_d s+1)^{-1}$, which serves also as a noise filter.

The second FLC structure with the block diagram, shown in Fig. 2, considers no reference and a minimal possible concentration of carbon dioxide which is dependent on the $CO_2$ concentration in the fresh air, used for ventilation. Thus this structure escapes improper references which may lead to continuous ventilation with increased energy consumption without reaching the desired reference.

As the carbon dioxide in the fresh air is constantly changing during day and night, with the building location, the winds, the neighbouring pollutants (industrial plants, roads, pedestrian jams, etc.), the reference for the carbon dioxide concentration should follow the $CO_2$ concentration in the fresh air or no reference should be used.

For both structures the FLC tuning parameters are $q^{T}=[k_d, T_d, k_a]$. The design and tuning procedure follows the steps below.

1. Design of the FU - fuzzy sets with standard membership functions (FMs) and rule base derived, considering that the output has to reduce $e$ and $\dot{e}$ to zero.

2. Estimation of the slopes ($K$, $r$) of the sector-bounding lines of the $\Delta u$-$e$ projection of the control surface of the designed FU and of the radius $\delta$ of the disc around the origin, where the sector-bounding restriction is violated.

3. Tuning of the parameters $q^{T}=[k_d, T_d, k_{aSI}]$ of the defined single-input (SI) FLC applying the modified Popov stability criterion, illustrated in Fig.3, where $r_i=\mathbf{f}[l(j\omega)]$, $P_{1m}^{o}(j\omega)=\mathrm{Re}\,P_s^{o}(j\omega)+j\omega\,\mathrm{Im}\,P_s^{o}(j\omega)$, $K_1=K-r$, $P_s^{o}(s)=\dfrac{W_1(s)W_2(s)P^{o}(s)}{1+r.W_1(s)W_2(s)P^{o}(s)}$. For a stable fuzzy system the Nyquist plot $P_{1m}^{o}(j\omega)$ of the dynamic part of the system in Fig.1 with the uncertainty discs upon it should be located on the right and below the Popov line for all significant frequencies in the range

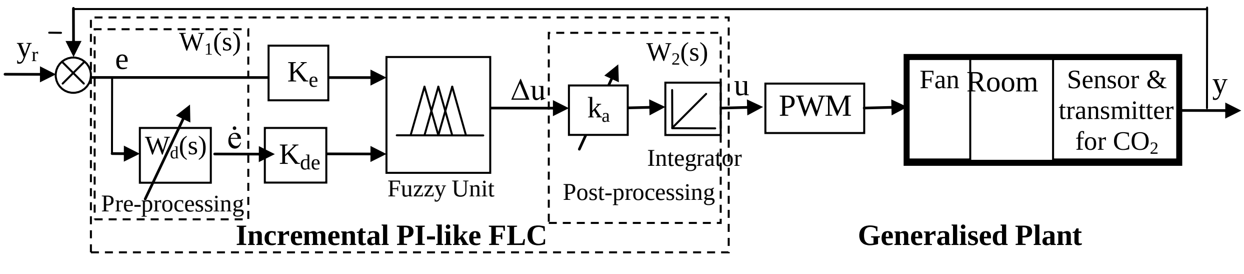


**Fig.1** Block diagram of stabilization closed-loop system with incremental PI-like FLC for $CO_2$ concentration

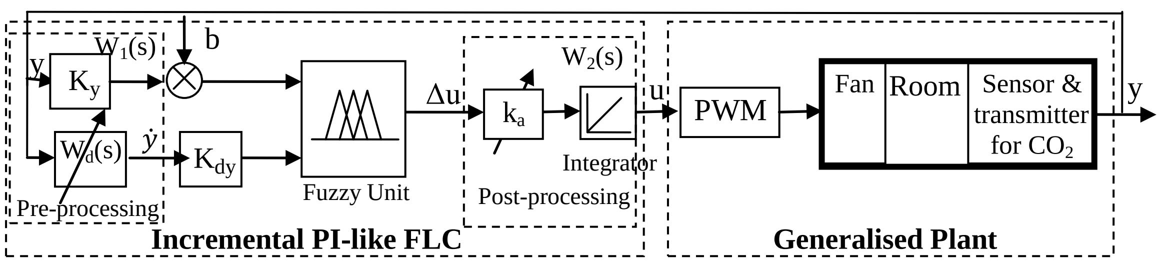


**Fig. 2** Block diagram of PI-like fuzzy control system for $CO_2$ concentration

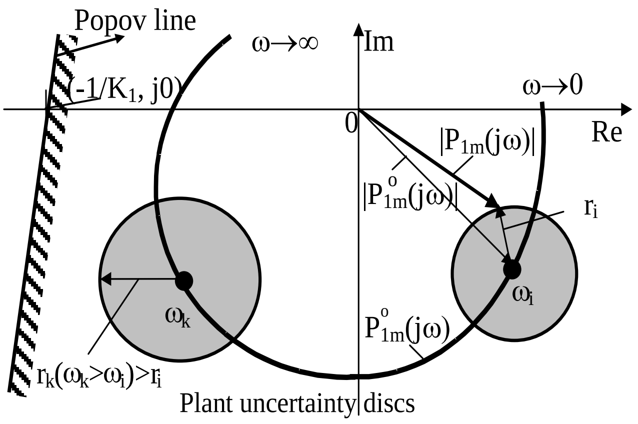


**Fig. 3** Graphical representation of the modified Popov criterion

$D_\omega=[\omega_o.10^{-2},\ \omega_o.10^2]$ rad/s, $\omega_o=2\pi/T^o$ rad/s. This is achieved by selection of proper tuning parameters of the pre- and post-processing parts.

3.1. The tuning parameters take values from defined ranges that ensure effectiveness of differentiation and restrictions, set by $B$, on the closed-loop system settling time $t_s$ and overshoot σ:

$$\left|\begin{array}{l} T_d=(1\div 10)\Delta t, \Delta t=0.1\min(T^o,\tau^o) \\ \dfrac{B.T^o}{T_d}\ge k_d\ge 5T_d, B=(0.1\div 2) \\ k_a=(0.1\div 0.5)\dfrac{T^o}{K_e.K.T_i.k^o.\tau^o}, T_i=k_dT_d \end{array}\right. .$$

3.2. All combinations of the parameters within the defined ranges are tested and those that fulfill the modified Popov criterion are stored.

3.3. The optimal parameters are selected among the stored by additional criterion for disturbance rejection, which requires maximal gain-integral action time ratio of the linearised PI FLC.

4. Correction of $k_{aSI}$ by $k=[\alpha/(1-\alpha)].(\delta_{max}/\delta-1)$ in order to obtain $k_a=kk_{aSI}$, where $\delta_{max}$ is the range for $\Delta u$ in the $\Delta u$-$e$ projection, $\delta_{min}=\alpha\delta_{max}$, $\alpha=0.01\div 0.2$.

5. Computation of the scaling gains on the basis of the maximal expected system error $|e_{max}|$ - $K_e=1/|e_{max}|, K_{de}=1/(k_d|e_{max}|)$.

## 3 Application of the Design Procedure for the Fuzzy Control of the Carbon Dioxide Concentration in a Laboratory HVAC

The part of the laboratory HVAC system which deals with the control of carbon dioxide concentration is presented in Fig.4. It consists of a cabin (room) where via a balloon the carbon dioxide concentration is changed to imitate human activity or increased presence of people.

A plant step response to input $u$=1V is shown in Fig.7. The nominal plant model parameters are estimated via graphical approximation of the step response and are also given in Fig.5. The maximal expected system error is $|e_{max}|$ =300 ppm.

For FCL-structure 1 fuzzy sets with standard membership functions (FMs) are selected, shown in Fig.6, where Z is zero, N - negative, P – positive, NB – negative big and PB – positive big. The rule base is described in the Fuzzy Associative Matrix (FAM), given in Table 1. It is derived, considering that the output should reduce $e$ and $\dot{e}$ to zero.

From the $\Delta u$-$e$ projection of the control surface of the designed FU (Fig.6, Table 1) is registered $K$=3.6, $r$=0.2 and δ=0.4, corresponding to a correction factor $k$=0.25 ($\delta_{min}=0.1\delta_{max}$, $\delta_{max}=1.3$). The computed tuning parameters according to the design procedure are [$k_d$=50, $T_d$=10, $k_a$=0.095]. The system reference is set to $y_r$=550 ppm. The scaling factors are determined to normalize $e$ and $\dot{e}$ in the range [-1, 1] – $K_e$=1/300 and $K_{de}$=1/2500.

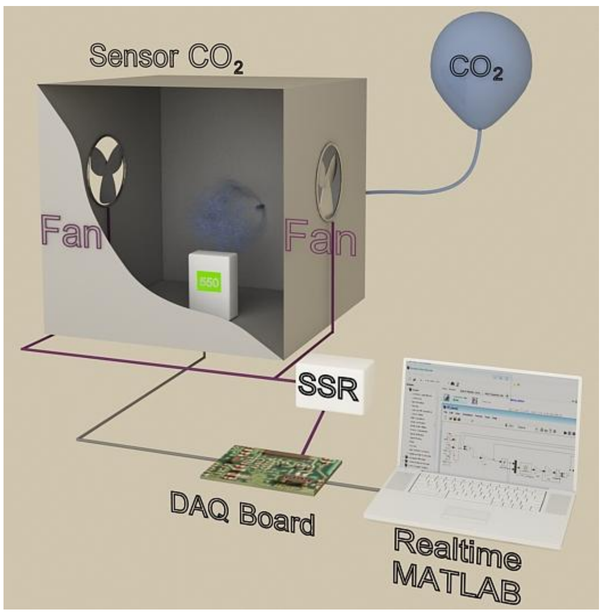


**Fig.4** Experimental setup

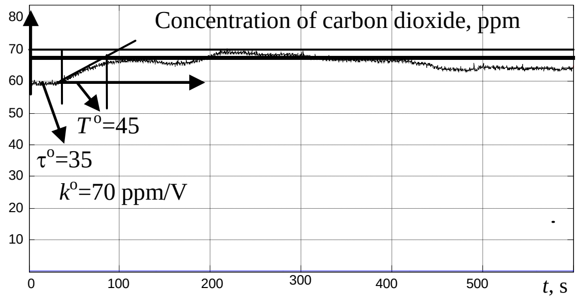


**Fig.5** Plant step response

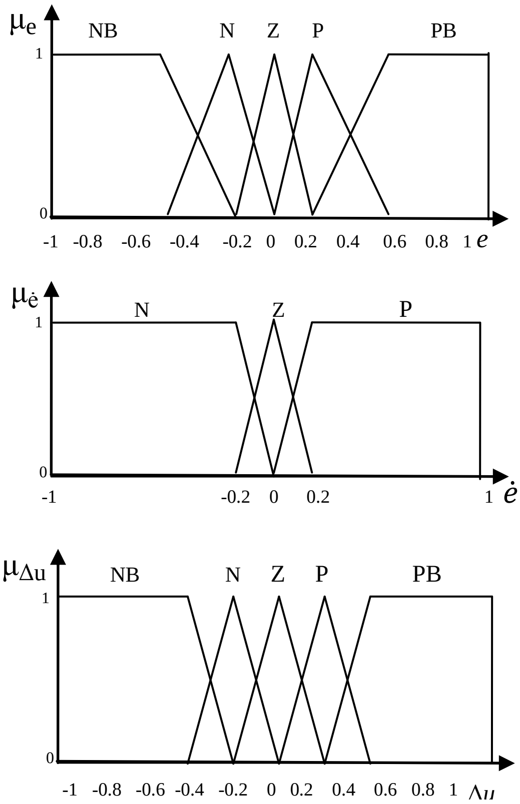


**Fig. 6** Membership functions for FU-structure 1

**Table 1** Incremental PI-like FLC rule base

| $\Delta u$ | | *e* | | | | |
|---|---|---|---|---|---|---|
| | | NB | N | Z | P | PB |
| $\dot{e}$ | N | PB | PB | P | Z | N |
| | Z | PB | P | Z | N | NB |
| | P | P | Z | N | NB | NB |

For FCL-structure 2 the FU is designed using linguistic variables $y$ and $\dot{y}$ for the inputs and $\Delta u$ for the output, all normalized respectively in the range [0, 1], [-1, 1] and [-1, 1]. The MFs are shown in Fig.7. The rule base is depicted in Table 2.

From the $\Delta u$-$e$ projection of the control surface of the designed FU (Fig.7, Table 2) it is obtained $K$=11, $r$=0.01 and $\delta$=0.82, corresponding to a correction factor $k$=0.084 ($\delta_{min}=0.2\delta_{max}$, $\delta_{max}$=1.1). The computed tuning parameters are the same [$k_d$=50, $T_d$=10, $k_a$=0.095]. The scaling factors are determined considering the expected range for the carbon dioxide concentration $y$ Є (300÷900) ppm with desired value 600 ppm, corresponding to the Medium term in the MF from Fig.7, and for its change within a sample period of $|\Delta y|$=50 ppm - $K_y$=1/600, b=-0.5 and $K_{dy}=1/(\Delta y.k_d)$=1/2500.

The step responses of the two FLC systems with respect to carbon dioxide concentration and analog control actions are studied in the real time experimentation, using MATLAB™ [17, 18] and depicted in Fig.8 and Fig.9 respectively. FLC - structure 2 ensures good performance at lower control effort.

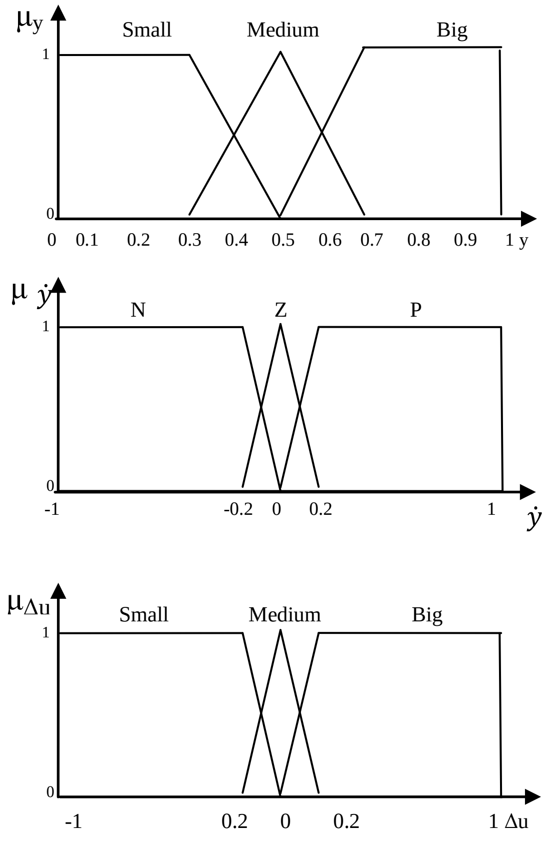


**Fig.7** Membership functions for FU-structure 2

**Table 2** FLC rule base for structure 2

| $\Delta u$ | | *e* | | |
|---|---|---|---|---|
| | | **Small** | **Medium** | **Big** |
| ė | **N** | Small | Small | Medium |
| | **Z** | Small | Medium | Big |
| | **P** | Medium | Big | Big |

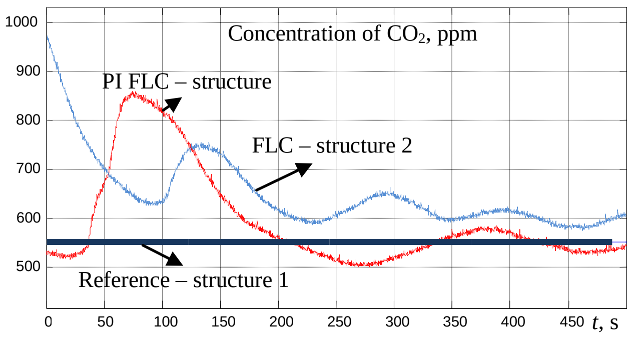


**Fig.8** Closed-loop systems step responses

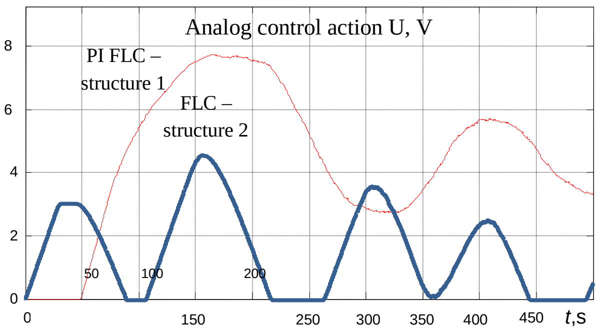


**Fig.9** Closed-loop systems control actions

## 4 Conclusions and Future Work

The main results achieved conclude in the following:

- A developed procedure for the design of two structures of PI FLCs for control of the carbon dioxide concentration from robust stability requirement;

- Application of the procedure to a laboratory HVAC system and experimental investigation of the closed-loop systems in MATLAB™ real time.

FLC - structure 2 showed more economic control for a similar good performance. The future research will be focused on combining of the developed fuzzy control of carbon dioxide concentration with the fuzzy control of temperature and humidity [19].

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