Design a Multi-Choice Fuzzy Control System of the Greenhouse

Prof. Dr. Kais Said Ismail
Department of Computer Engineering
Collage of Engineering
University of Baghdad
Email:Kais_1946@yahoo.com

Qays Jebur Sabr AL-Jewari
Department of Computer Engineering
Collage of Engineering
University of Baghdad
Email:qais_aljuary@yahoo.com

ABSTRACT

Applications of nonlinear, time variant, and variable parameters represent a big challenge in a conventional control systems, the control strategy of the fuzzy systems may be represents a simple, a robust and an intelligent solution for such applications.

This paper presents a design of fuzzy control system that consists of three sub controllers; a fuzzy temperature controller (FC_T), a fuzzy humidity controller (FC_H) and a ventilation control system; to control the complicate environment of the greenhouse (GH) using a proposed multi-choice control system approach. However, to reduce the cost of the crop production in the GH, the first choice is using the ventilation system to control the temperature and humidity of the GH environment according to the external climate if it is possible, if it is not possible then the second choice uses the FC_T to actuate the cooling-heating system to control the temperature and FC_H to actuate the humidifier-dehumidifier to control the humidity of the GH environment. The resultant is a robust, multi choice and multi-mode capability system. The designed system reflects the fuzzy system capability to deal with complicated environments and its flexibility to use the same design in controlling different applications.

Key words: fuzzy controller, multi-choice, ventilation.

تصميم نظام سيطرة ضبابي متعدد الاختيارات للبيت الزجاجي

أ.د. قيس سعيد اسماعيل
قسم هندسة الحاسبات
كلية الهندسة/جامعة بغداد

قيس جبر صبر الجواري
قسم هندسة الحاسبات
كلية الهندسة/جامعة بغداد

الخلاصة

التطبيقات ذات البارامترات المتغيرة, اللاخطية والمتغيرة مع الوقت تمثل تحدي كبير بالنسبة الى انظمة السيطرة التقليدية. ان هذا التحدي ربما يكون اكثر تعقيدا عند استخدامه للسيطرة على الانظمة عبر شبكات الاتصال السلكية او اللاسلكية. من جهة اخرى فان ستراتيجية السيطرة في الانظمة الضبابية ربما تكون حلول بسيطة, متينة وذكية لمثل هذه التطبيقات.

في هذا البحث سيتم تصميم نظام سيطرة ضبابي يتكون من ثلاث مسيطرات: مسيطر ضبابي حراري, مسيطر ضبابي للرطوبة ونظام سيطرة على التهوية, للسيطرة على البيئة المعقدة للبيت الزجاجي باستخدام نظام سيطرة مقترح متعدد الاختيارات. على اية حال, لتقليل كلفة انتاج المحاصيل في البيوت الزجاجية, فان اول اختيار يتمثل في استخدام نظام التهوية للسيطرة على حرارة ورطوبة البيت الزجاجي بالاعتماد على المناخ الخارجي اذا كان ممكن. واذا لم يكن ممكن, فان الاختيار الثاني يستعمل المسيطر الضبابي الحراري لتشغيل نظام التدفئة-التبريد للسيطرة على درجة الحرارة والمسيطر الضبابي للرطوبة لتشغيل نظام الترطيب-التجفيف للسيطرة على الرطوبة.

ان النتيجة التي تم الحصول عليها هي نظام متين, متعدد الاختيارات والانماط في السيطرة. ان هذا النظام في تصميمه يعكس قابلية النظام الضبابي في التعامل مع البيئات المعقدة ومرونته في استخدام نفس التصميم لعدة تطبيقات.

الكلمات الرئيسية: مسيطر ضبابي, متعدد الاختيارات, التهوية.

1. INTRODUCTION

Traditional control design methods are based on some knowledge, or model, of the dynamic system to be controlled. Most of real life dynamic systems are nonlinear, high complex and too difficult to derive an accurate mathematical model which is crucial for optimal and successful implementation of the control algorithm**, Sabri, et al., 2012.**

A new paradigm for nonlinear systems is the fuzzy control approach. It provides a formal methodology for simulating and implementing a human's heuristic knowledge about how to control a system. Fuzzy control approach is unique in its ability to utilize both qualitative and quantitative information. Qualitative information is gathered from the expert operator strategy and from the common knowledge. It has many benefits over traditional controllers in robustness, cost and flexibility**, Sabri, et al., 2012.**

On the other hand, GH environment is one of the nonlinear complicated systems. Its technology depends on providing favorable environment condition to the plants**, Sabri, et al., 2012.**

Different applications have been implemented using the fuzzy logic controller (FC): **Chao, et al., 2000.** A fuzzy logic controller was designed for staged heating and ventilating systems. The controller was implemented in two environments, the greenhouse, and the broiler house. The input variable is represented by six linguistic terms. The output variable represents the heating and cooling stages and it is represented by six linguistic terms, two terms for heating, three terms for cooling, and one term for no change state. The defuzzification method is integer center of gravity (ICOG), where the value of center of gravity is rounded to the nearest integer, to get proper stage value. **Isizoh, et al., 2012.** A fuzzy logic based-microcontroller was designed to control the temperature of an environment by regulating a heater and the speed of a fan. The microcontroller receives the environment temperature from a sensor through analogue to digital converter (ADC), makes the fuzzy control actions, sends control signals to the fan and heater using an output interface device, and displays the controller result temperature using a display unit. It was a combination of software and hardware. **Saudagar, et al., 2012,** a fuzzy PID temperature controller for GH was designed by using Atmel's 89C52 microcontroller and actuating a cooling-heating system. The inputs to the fuzzy controller are the error which is fuzzified to nine triangular membership functions and change in error which is fuzzified to three triangular membership functions. The output is fuzzified to six triangular membership functions. The input to the PID controller is the error signal added with the output of the fuzzy controller, **Hasim, and Aras, 2012,**a room temperature controller was designed using Matlab fuzzy logic toolbox. It was used to control two room parameters, the temperature and the humidity. The input signals are setting value of temperature and temperature difference (have five membership functions), the measured humidity (three membership functions), feeling mode and mode selection. The output signals are the compressor speed (six membership functions), fan speed (five membership functions) and operation mode (humidifier or air conditioner), **Shome, and Ashok, 2012.** Two fuzzy controllers was designed to control the steam temperature and water level in an electric boiler. The input to the fuzzy temperature controller is fuzzified to six parts, while the fuzzy water level controller is fuzzified to four parts. The outputs of the two controllers are fuzzified to three parts. The system with the temperature monitoring was implemented by using a microcontroller programmed with the fuzzy knowledge base rules, **Das, et al., 2013.** A hardware room temperature and humidity controller was designed using fuzzy logic. The controller is a combination of two fuzzy controllers: The first one is the temperature controller to control the speed of a heat-fan and cool-fan, taking the room temperature and its difference with a user set temperature as input variables; and the other is the humidity controller to control the humidifier and exhaust-fan speed, taking the room temperature and humidity as input variables. The temperature controller input variables each of seven linguistic terms. The defuzzification method is center of average, **Bai, 2013.** An adaptive incremental fuzzy PI controller (AIFPI) was presented for a heating, ventilation, and air conditioning (HVAC) system. A fuzzy controller was used to adapt the gains of a PI controller to overcome different disturbances. It consists of two parts, each one contains a fuzzy and PI controller, the first part is used to control the temperature, and the second part is used to control the humidity. The fuzzy controller receives and delivers two inputs and outputs linguistic variables respectively, each of seven linguistic terms, to determine the change in the PI input gains. The change of calculated PI input gains is added to the previous values to overcome the disturbance effects.

However, most of the systems use the ventilation as a single choice cooling-only control system where the outer climate permits for such applications for most of the seasons. Other applications using a cooling-heating systems without ventilation to control temperature. In Iraq climate, ventilation control systems cannot be applicable only for a few months, also; it may be useful at the night but it is not at the daytime. Therefore, the multi choice control strategy may give a more flexibility with the applications that is designed to operate for all seasons, using the low coast ventilation system if it is possible, otherwise use the other systems which are more expensive without performing any changes in the GH design structure.

2. SYSTEM DESCRIPTION

Three systems will be used to control the temperature and humidity of the GH. They operate in a proposed approach that will be called a multi-choice control system approach. These systems are: cooling-heating system which is controlled by fuzzy temperature controller, humidifier-dehumidifier which is controlled by fuzzy humidity controller and ventilation system which is controlled by fuzzy ventilation system.

However, three modes of operation are suggested to determine the decision making criteria in the ventilation system and organize the cooperation of the ventilation with the other two systems to provide a desired GH climate.

3. GH MODEL AND PARAMETERS

The GH model for the temperature and humidity are derived in Eq. (1) and Eq. (2)**, Nachidi, et al., 2006.** with the internal and external GH environment parameters have been given in **Table 1, Nachidi, et al., 2006.** Some parameters were given in **Rodríguez, et al., 2010** and**, Nachidi, et al., 2008.**

$$T_a(k+1) = \frac{t_s}{C_{cap,q}}\left(\mathrm{E}_q + \tau S_o - C_{cap,q,v}\, V\,(T_a - T_o) - \ h_T\,(T_a - T_o)\right) + \ T_a \tag{1}$$

$$w_a(k+1) = \frac{t_s}{C_{cap,h}}\left(\mathrm{W}_h - V\,(w_a - w_o) - h_w\,(w_a - w_o)\right) + \ w_a \tag{2}$$

4. DESIGN OF FUZZY TEMPERATURE CONTROLLER

4.1. Signals Definition and Parameters Assignment

1. Select the internal GH temperature $T_a(k)$, reference temperature $T_r(k)$.
2. The minimum and maximum reference temperature values are T_{min} = 0 and T_{max} = 100. However, although GH temperature do not reach 100 ◦C but the system will be examined for a higher ranges.
3. The normalized error signal is

$$e(k) = \frac{T_r(k) - T_a(k)}{T_{max} - T_{min}} \tag{3}$$

therefor e(k) ∈ (-1,1).

4. The normalized change in error signal is

$$\Delta e(k) = e(k) - e(k-1) \tag{4}$$

Where Δe(k) ∈ (-1,1).

5. The signals e(k) and Δe(k) are the inputs of the fuzzy controller.
6. Select the controller output signal U(k) ∈ (-1,1).
7. The temperature actuator is represented by three states: off (O), Heating (H), and Cooling (C).
8. Select the inputs and output gains ge, gde and gu respectively. **Fig. 1** shows the Simulink implementation of the closed loop fuzzy temperature controller.

The normalization of input and output signals of the fuzzy controller gives the ability to set and modify the desired operating temperature range with more flexibility and less effort, this will generalize the controller application. For example, the change of the operating range of the controller from (0, 100) to (-13, 87) can be implemented by setting T_{min} = -13 and T_{max} = 87 without modifying the membership functions parameters.

4.1 Input Linguistic Variables

Both e(k) and Δe(k) input linguistic variables are fuzzified into seven linguistic terms, triangular membership functions as follows

1. *Zero (x; -1/3, 0, 1/3):* $ZZ = max(min\left(\frac{x+\frac{1}{3}}{\frac{1}{3}}, \frac{\frac{1}{3}-x}{\frac{1}{3}}\right), 0)$
2. *Positive Small (x; 0, 1/3, 2/3):* $PS = max(min\left(\frac{x-0}{\frac{1}{3}}, \frac{\frac{2}{3}-x}{\frac{1}{3}}\right), 0)$
3. *Positive Medium (x; 1/3, 2/3, 1):* $PM = max(min\left(\frac{x-\frac{1}{3}}{\frac{1}{3}}, \frac{1-x}{\frac{1}{3}}\right), 0)$
4. *Positive Big (x; 2/3 ,1, 1):* $PB = min(max\left(\frac{x-\frac{2}{3}}{\frac{1}{3}}, 0\right), 1)$
5. *Negative Small (x; -2/3, -1/3, 0):* $NS = max(min\left(\frac{x+\frac{2}{3}}{\frac{1}{3}}, \frac{0-x}{\frac{1}{3}}\right), 0)$
6. *Negative Med (x; -1, -2/3, -1/3):* $NM = max(min\left(\frac{x+1}{\frac{1}{3}}, \frac{-\frac{1}{3}-x}{\frac{1}{3}}\right), 0)$
7. *Negative Big (x; -1, -1, -2/3):* $NB = min(max\left(0, \frac{-\frac{2}{3}-x}{\frac{1}{3}}\right), 1)$

where x represents e(k) or Δe(k). **Fig. 2** shows the membership functions for both input signals.

It must be mentioned that PB and NB are open right and open left membership functions.

4.2 Output Linguistic Variable

The output linguistic variable U(k) is fuzzified into three linguistic terms triangular membership function

1. *OFF (U; -0.5, 0, 0.5):* $O = max(min\left(\frac{U+\frac{1}{2}}{\frac{1}{2}}, \frac{\frac{1}{2}-U}{\frac{1}{2}}\right), 0)$

2. *Heating (U; 0, 0.5, 1):* $H = max(min\left(\frac{U}{\frac{1}{2}}, \frac{1-U}{\frac{1}{2}}\right), 0)$
3. *Cooling (U; -1, -0.5, 0):* $C = max(min\left(\frac{U+1}{\frac{1}{2}}, \frac{-U}{\frac{1}{2}}\right), 0)$

Fig. 3 shows the triangle membership functions for the output signal U(k).

For simplicity, the signals e(k), Δe(k), U(k), … will be used as e, Δe, U, … respectively if there is not necessity to use the time sequence (k). Also, for simplicity the unit (◦C) will not be mentioned with temperature values.

4.3 Rule Base

The total number of rules (R) equals the number of linguistic terms of first input linguistic variable times the number of linguistic terms of second input linguistic variable (R=7*7=49). **Table 2** shows the rule base of the fuzzy temperature controller, where the general form of the *i*th rule base is

If e is M_{ei} AND Δe is $M_{\Delta ei}$ THEN U is o_i

where M_{ei} is membership function of the *i*th rule in e domain, $M_{\Delta ei}$ is membership function of the *i*th rule in Δe domain and o_i is membership function of the *i*th rule in U domain.

4.4 Fuzzification

The min operator will be used to implement the AND operation in the premise part. The result of this operation represents the rule certainty. Therefor for the *ith* rule

Rule certainty = min ($\mu^i_j(e)$, $\mu^i_k(\Delta e)$)

Where j and k ∈ (1, 2, …, 7) are the membership functions identifier for e and Δe respectively and μ(.) is the membership functions gradient identified by j or k.

4.5 Defuzzification

The center of gravity (COG) method is used, experimentally it gives more stable response, less oscillation and better performance with wired system. The discrete equation of the COG defuzzification is, **Passino, and Yurkovich, 1998.**

$$z_{COG} = \frac{\sum_{i=1}^{R} b_i a_i}{\sum_{i=1}^{R} a_i} \tag{5}$$

Where b_i and a_i are the output membership functions center and area respectively of the *ith* rule in U domain. The Min operator will be used to implement the AND operation in the premise part, so depending on the defuzzification definition of the Min operator, the output membership function area is a trapezoid area calculated in Eq.(6), **Passino, and Yurkovich, 1998.**

$$a = w(h - \frac{h^2}{2}) \tag{6}$$

Where w is the base which is the same for each input membership function, then each rule certainty h is used to compute the area a using the same equation. The difference of area calculation in each rule will be in the value of h.

5. CLOSED LOOP FUZZY TEMPERATURE CONTROLLER

Fig. 1 shows the closed loop fuzzy temperature controller with g_e =1, g_{de} =1 and g_u = 1000000, Fig. 4 shows the response for different T_r values.

6. DESIGN OF FUZZY HUMIDITY CONTROLLER

The same temperature controller properties will be used in constructing a fuzzy humidity controllers. With g_e =1, g_{de} =1 and g_u = 1000; **Fig. 5** shows the system response for different H_r values.

7. DESIGN OF FUZZY VENTILATION CONTROL SYSTEM

The designed fuzzy temperature controller uses a cooling-heating system to track the desired temperature independent of the outer environment temperature. Also, the designed humidity controller uses the humidifier-dehumidifier system to track the desired humidity independent of the outer environment humidity.

On the other hand, the ventilation controller uses the outer environment temperature and humidity to change the internal environment of the greenhouse, but with conditions. The use of ventilation system is proper to reduce the cost of using the cooling-heating system or the humidifier-dehumidifier system.

It is necessary to mention that the ventilation system affects the temperature and humidity at the same time, it tries to make the internal temperature and humidity to converge to the external values. So, the ventilation may be appropriate for the temperature but not for the humidity or vice versa. According to this idea three modes of ventilation operation are suggested.

The ventilation system represents a cheap and a first choice of the fuzzy control system. The other two systems represent an expensive and a second choice. They will be actuated for the following cases:-

1. If it is not possible to reach the desired level by the ventilation system.
2. When the ventilation system was actuated but it cannot perform more modifications to reach the desired level.
3. After actuating the ventilation system, to handle the steady state level. However after the temperature or humidity reaches by ventilation to some percent of the desired value such as 1% or 2% and to avoid out of the desired value changes; the heating-cooling or humidifier-dehumidifier system will be actuated.

Design of ventilation control system is implemented in two stages:

1. Construct of ventilation enable algorithm.
2. Design of fuzzy ventilation rate controller.

7.1 Operation Modes

The ventilation system affects both parameters the temperature and the humidity at the same time. This will affect the control action of these two parameters to set them to the desired values at the same time. However, an operation mode is proposed to handle this case. Three mode of operations are proposed as shown in **Fig. 6**.

1. **Mode 0:** disable the ventilation system, so only the heating-cooling and humidifier-dehumidifier systems will be actuated in a single-choice approach.
2. **Mode 1:** ventilation to change internal temperature to the desired value with negligible effect on the humidity. This mode is used when there is not critical effect of ventilation on the humidity.
3. **Mode 2:** ventilation to change internal humidity to the desired value with negligible effect on the temperature. This mode is used when there is not critical effect of ventilation on the temperature.

7.2 Ventilation Enable Algorithm

Using mode 1, there are two cases that determine the use of ventilation (ON or OFF). **Fig.7.a** shows the first case when the outer temperature T_o is greater than internal greenhouse temperature T_a. In this case the reference temperature may be within one of three levels T_{r1}, T_{r2} and T_{r3}. The following steps represent the algorithm of operating the ventilation:

1. If T_r within T_{r1} level then
   a- Set ventilation V to ON.
   b- Set heating-cooling system energy E to OFF.
   c- When $T_a = T_o$ set V to OFF and E to ON.
2. If T_r within T_{r2} level then
   a- Set ventilation V to ON.
   b- Set heating-cooling system energy E to OFF.
   c- When $T_a = T_r$ set V to OFF and E to ON.
3. If T_r within T_{r3} level then
   a- Set ventilation V to OFF.
   b- Set heating-cooling system energy E to ON.

Fig. 7.b shows the second case when the outer temperature T_o is less than internal greenhouse temperature T_a. In this case the reference temperature may be within one of three levels T_{r1}, T_{r2} and T_{r3}. The following steps represent the algorithm of operating the ventilation:

1. If T_r within T_{r3} level then
   a- Set ventilation V to ON.
   b- Set heating-cooling system energy E to OFF.
   c- When $T_a = T_o$ set V to OFF and E to ON.
2. If T_r within T_{r2} level then
   a- Set ventilation V to ON.
   b- Set heating-cooling system energy E to OFF.
   c- When $T_a = T_r$ set V to OFF and E to ON.
3. If T_r within T_{r1} level then
   a- Set ventilation V to OFF.
   b- Set heating-cooling system energy E to ON.

The same algorithms are used in mode 2 (ventilation to change internal humidity).

7.3 Design of Fuzzy Ventilation-Rate Controller

Starting with mode 1, ventilation may produce large overshot if it is of high rate, or it could not make the internal greenhouse value to converge to the outer value of the temperature if the ventilation rate is below some level. The difference between the outer and the reference (or setting) temperature (OS) will be used as a criteria to determine the proper rate, and it represents the input signal to the single input fuzzy controller as follow

1. The controller input variable OS=| $T_o - T_s$ |. The absolute value of OS is used to include both cases in figures 7.a and 7.b.
2. OS is normalized, so its range between (0, 1).
3. The controller output variable V-rate.
4. V-rate range is between (1, 10).
5. The input variable is fuzzified into four linguistic terms triangular and trapezoidal membership functions
   a- *Small(OS; -0.01, 0, 0.05, 0.1):* $SM = max(min\left(\frac{OS+0.01}{0.01}, 1, \frac{0.1-OS}{0.05}\right), 0)$
   b- *Mid(OS; 0.05, 0.1, 0.2):* $MD = max(min\left(\frac{OS-0.05}{0.05}, \frac{0.2-OS}{0.1}\right), 0)$
   c- *Big(OS; 0.1, 0.2, 0.45, 0.5):* $BG = max(min\left(\frac{OS-0.1}{0.1}, 1, \frac{0.5-OS}{0.05}\right), 0)$
   d- *Very Big(OS; 0.45, 0.5, 1, 1.01):* $VB = max(min\left(\frac{OS-0.45}{0.05}, 1, \frac{1.01-OS}{0.01}\right), 0)$

   Fig. 8 shows the input membership functions of the fuzzy ventilation rate controller.

6. The output linguistic variable V-rate is fuzzified into four linguistic terms single tone membership functions V1, V2, V3 and V10 which are at the values 1, 2, 3, and 10, respectively, as shown in **Fig. 9**.
7. The rule base contains the following four rules
   R1: IF OS is VB THEN V-rate is is V1.
   R2: IF OS is BG THEN V-rate is is V2.
   R3: IF OS is MD THEN V-rate is is V3.
   R4: IF OS is SM THEN V-rate is is V10.
8. The defuzzification method that will be used is the center of average
   Sum=VB+BG+MD+SM
   VR1= V1*VB/Sum
   VR2= V2*BG/Sum
   VR3= V3*MD/Sum
   VR4= V10*SM/Sum
   V-rate = VR1+VR2+VR3+VR4

It is necessary to mention that the fuzzy V-rate controller is used when T_r within T_{r2} range in **Figs. 7.a** and **7.b**, otherwise V-rate will take its maximum value which is 10.

The same result is used with mode 2, but V-rate is divided by 10 as determined by experiment.

8. MODE SELECTION IMPLEMENTATION AND PUTTING ALL TOGATHAR

The fuzzy temperature controller FC_T, the fuzzy humidity controller FC_H and the ventilation control system are combined together to construct the heart of the overall control system. The ventilation system represents point of meting, from which the activity of each controller will be decided by implementing the operation mode.

9. SIMULATION RESULTS

Figs. 4 and **5** represent system response for temperature and humidity when M=0, where there is no ventilation effect on the system. **Figs. 10** and **11** show the ventilation effect on system temperature (humidity) for different Tr (Hr) values when M=1 (M=2). In these figures, it is clear that different ventilation rates are obtained for different reference values. It must be noticed that in **Fig. 11**, the ventilation rate is multiplied by 10 for clear simulation show.

10. CONCLUSIONS

1. The important feature of the fuzzy controller, is that its ability to get the appropriate response by tuning the input/output gains. The change of input/output gains produces the change in the membership functions scale, which can assimilate the large scope of signal variation. So during system design steps, the proper response was produced by changing the input/output gains to an appropriate values.
2. Zero steady state error is produced when the fuzzy controller output (U) is treated as (ΔU) and added to the previous value. (U(k) = U(k-1) + ΔU(k)).
3. A large maximum peak overshot is produced when using a product operation instead of minimum operation to implement the AND operator.
4. A long time of oscillation and more settling time produced when using the Gaussian membership function.
5. The multi-choice control approach may be a good introduction with an environments that have different actuation systems based on some application conditions and coast requirements.
6. The multi-choice control strategy with the fuzzy logic controller produces a bit forward step in control system applications, the resultant system is robustness, very low steady state error and there is no peak overshot that affect system performance.

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Table 1. List of symbols, values and units of GH parameters.

Symbol	Description	Nominal value and unit
ρ	specific mass of air, $kg_{dry\ air}\ m^{-3}$.	1.2
C_p	specific heat of moist air, $Jkg^{-1}K^{-1}$.	1010
$C_{cap,q}$	heat capacity of GH air, $Jm^{-2}{\circ}C^{-1}$.	
$C_{cap,q,v}$	heat capacity per volume unit of GH air, $Jm^{-3}{\circ}C^{-1}$.	
$C_{cap,h}$	volumetric capacity of GH air for humidity, m.	
h_T	heat transmission coefficient through the GH cover of single layer glass, $Wm^{-2}{\circ}C^{-1}$**, Rodríguez, *et al*., 2010.**	6.2
h_w	leakage air exchange through GH cover, $m\ s^{-1}$.	0.75x10−4
τ	heat load coefficient due to solar radiation, dimensionless**, Nachidi, *et al*., 2008.**	12.0662
t_s	sampling time, second.	0.01
S_o	outside solar radiation, Wm^{-2}.	800
T_a	GH air temperature, ◦C.	
T_o	outside temperature, ◦C.	
w_a	humidity concentration in GH, $kg\ m^{-3}$.	
w_o	outside humidity concentration, $kg\ m^{-3}$.	
V	ventilation rate, $m^3s^{-1}m^{-2}$.	10
V_g	GH volume, m^3.	45
A_g	soil area of the GH, m^2.	15
E_q	energy supply by heating system, Wm^{-2}.	
E_s	heat load by solar radiation, Wm^{-2}.	
E_v	energy exchange by ventilation, Wm^{-2}.	
E_c	energy exchange by transmission through the cover, Wm^{-2}.	
W_h	water vapor exchange using humidifier and dehumidifier system, $kg\ m^{-3}\ s^{-1}$.	
W_c	water vapor exchange through the cover, $kg\ m^{-3}\ s^{-1}$.	
W_v	water vapor exchange with outside air by ventilation, $kg\ m^{-3}\ s^{-1}$.	

Table 2. Rule base of 7x7x3 fuzzy controller.

e(k) \ Δe(k)	PB	PM	PS	ZZ	NS	NM	NB
PB	O	H	H	H	H	H	H
PM	C	O	H	H	H	H	H
PS	C	C	O	H	H	H	H
ZZ	C	C	C	O	H	H	H
NS	C	C	C	C	O	H	H
NM	C	C	C	C	C	O	H
NB	C	C	C	C	C	C	O

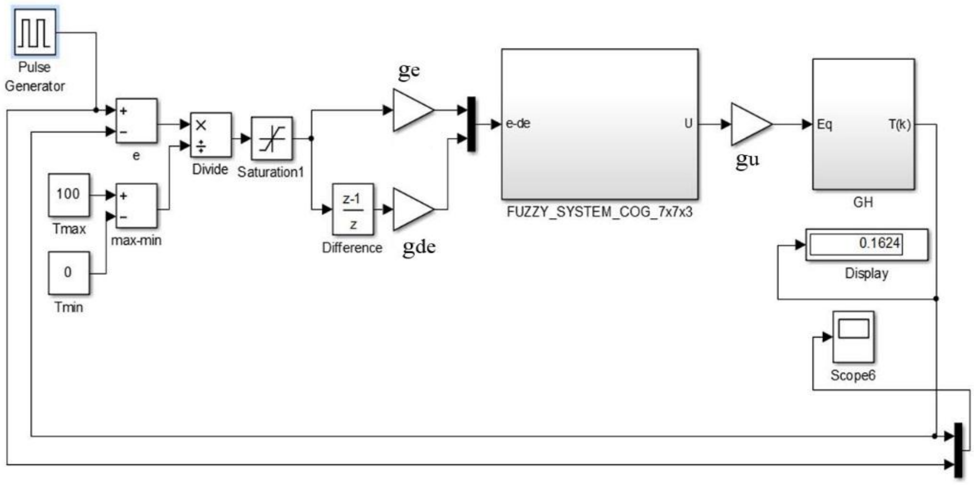


Figure 1. Simulink implementation of connecting the fuzzy controller of the GH system.

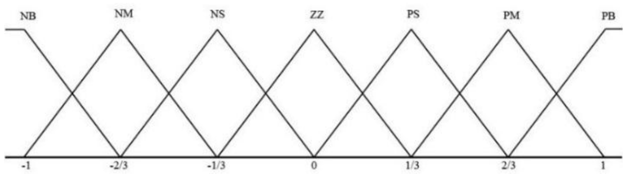


Figure 2. Triangular membership functions for input variables e(k) and Δe(k).

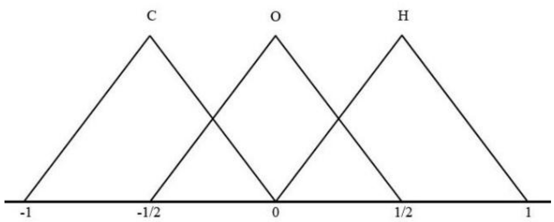


Figure 3. Triangular membership function for the output variable U(k).

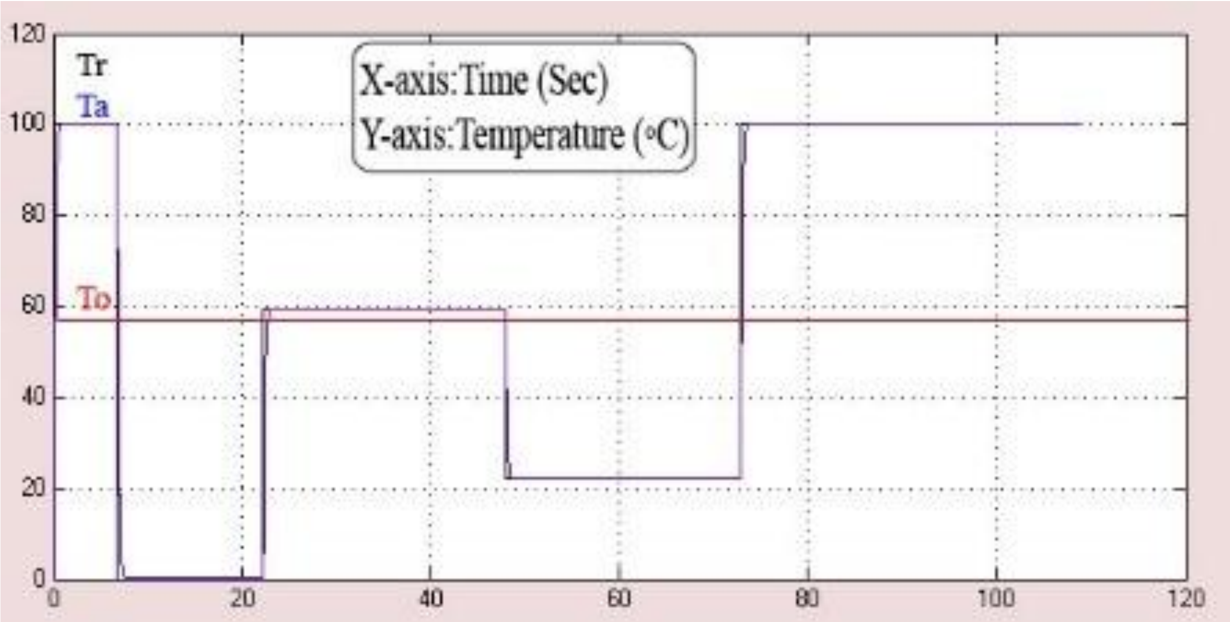


Figure 4. System temperature response where g_e = 1, g_{de} =1 and g_u = 1000000.

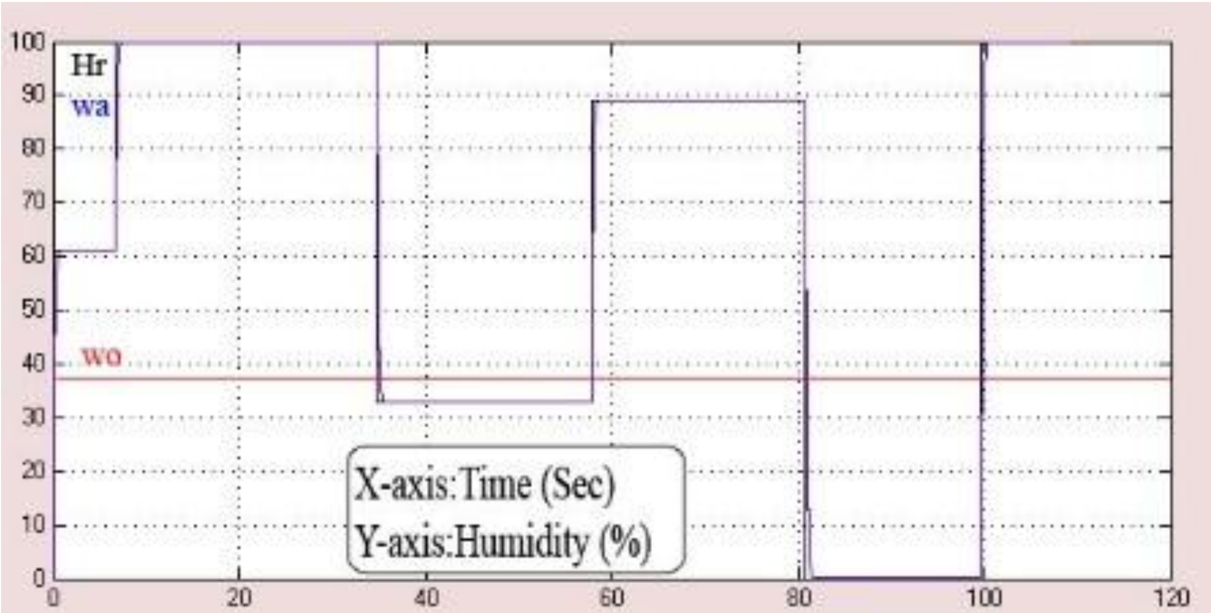


Figure 5. System humidity response where g_e = 1, g_{de} =1 and g_u = 1000.

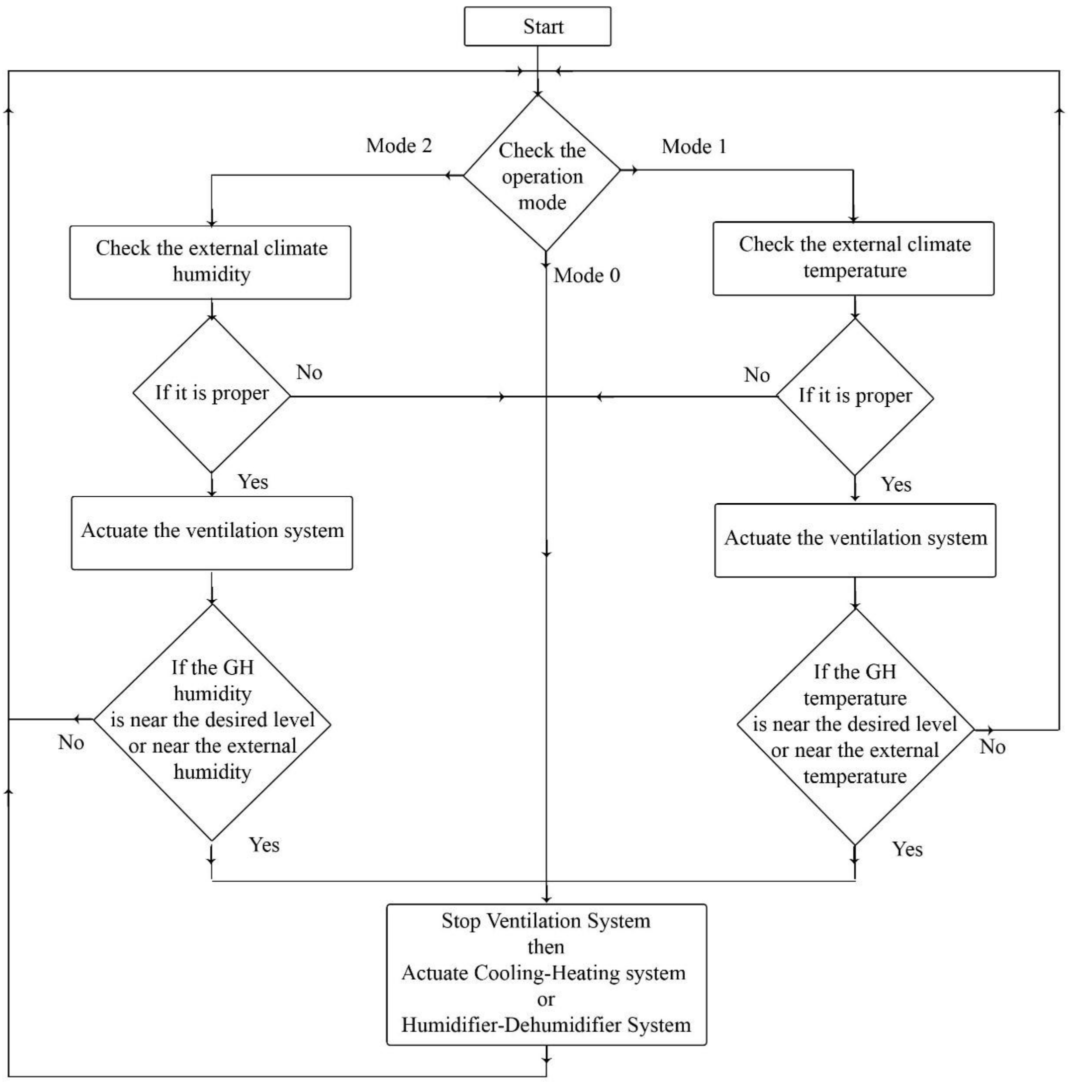
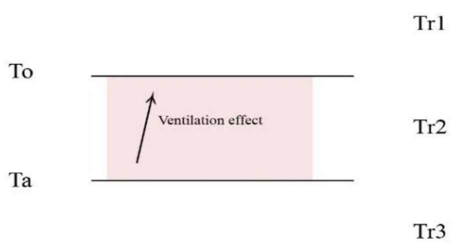
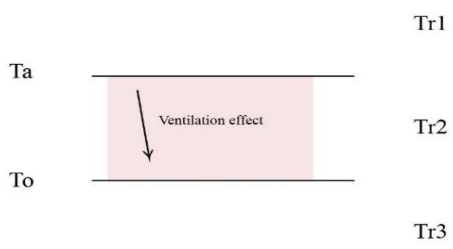


Figure 6. Multi-choice control mechanism.



a. $T_o > T_a$



b. $T_o < T_a$

Figure 7. The Outer temperature with respect to the internal GH temperature.

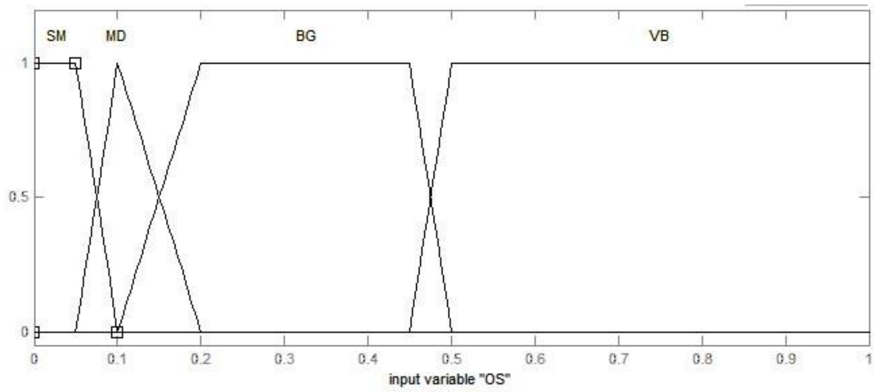


Figure 8. Input membership functions of the fuzzy ventilation rate controller.

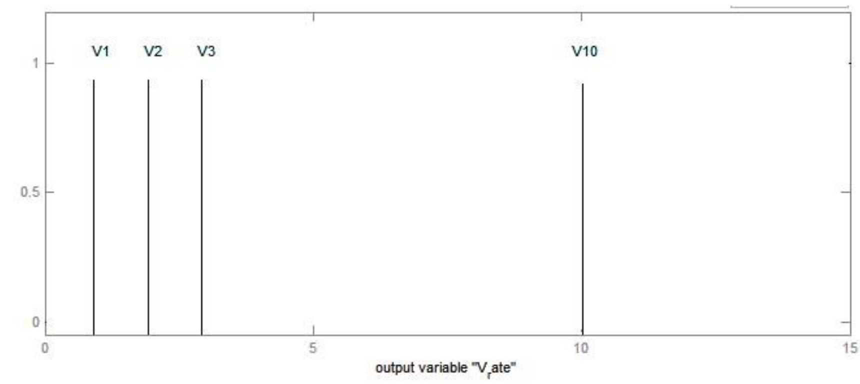


Figure 9. Output membership functions of the fuzzy ventilation rate controller.

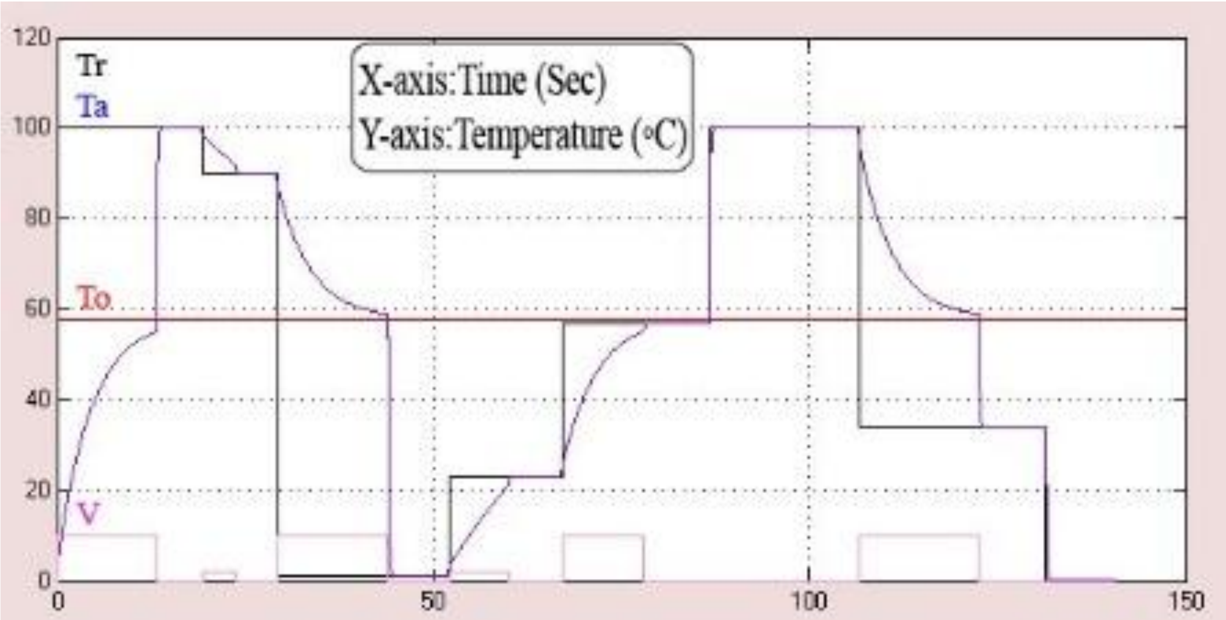


Figure 10. Ventilation effect on system temperature for M=1 and different T_r values.

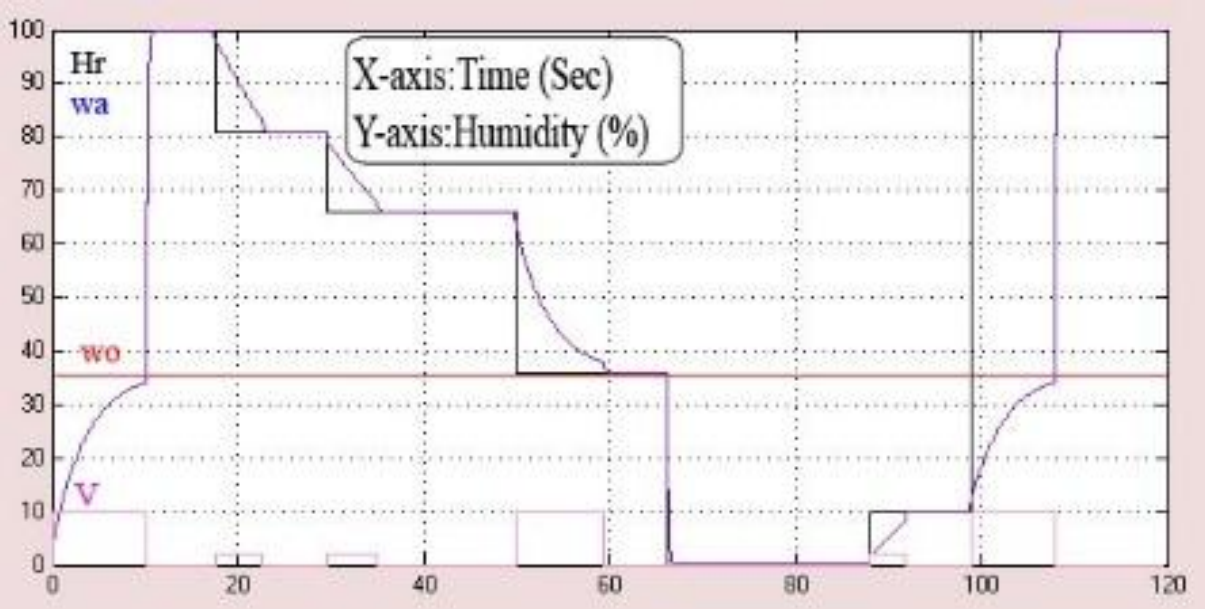


Figure 11. Ventilation effect on system humidity for M=2 and different H_r values.