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Procedia Engineering 41 (2012) 904 – 910
Engineering Procedia
www.elsevier.com/locate/procedia

International Symposium on Robotics and Intelligent Sensors 2012 (IRIS 2012)

Fuzzy-based Temperature and Humidity Control for HVAC of Electric Vehicle

B.S.K.K.Ibrahim[1,2], N.Aziah.M.A[1], S. Ahmad[3], R. Akmeliawati[3], Nizam H.M.I[1], A.G.A.Muthalif[3], S.F.Toha[1,3] and M.K.Hassan[1,4]

[1]PROTON Professor Office, Engineering Division,HICOM Industrial Estate, Batu 3, P.O Box 7100, 40918 Shah Alam, Selangor, D.E, Malaysia,
[2]Dept of Mechatronic and Robotic,Faculty of Electrical and Electronic Eng, Universiti Tun Hussien Onn Malaysia, 86400, Batu Pahat, Johor
[3]Department of Mechatronics, Faculty of Engineering, International Islamic University Malaysia,Kuala Lumpur, Malaysia
[4]Department of Electrical and Electronic, Faculty of Engineering, Universiti Putra Malaysia, 43400, UPM Serdang,

Abstract

Vehicles are the people's main means of transportation and thermal comfort in the vehicle cabin plays an important role. The heating, ventilating, and air-conditioning (HVAC) operation system in the vehicle cabin decides the degree of comfort, traffic safety as well as health of the occupants. The challenge of designing the HVAC control is to automatically achieve the thermal comfort, regardless of time varying weather conditions. Since most HVAC systems are complex with nonlinearity, distributed parameters, and multivariable therefore many classical controls do not necessarily yield a satisfactory control performance. This paper presents the development of temperature and humidity control strategy for HVAC based on Fuzzy Logic Control (FLC). The goal of the FLC-based temperature control is to satisfy the convergence and equilibrium property. The simulation test results have been shown a satisfactory to control the temperature and humidity.

Keywords: HVAC, Fuzzy Logic, Elctric Vehicle, Temperature, Humidity

Nomenclature

K_2 conductive heat transfer coefficient for insulation, $\mathrm{kJ/(m^2 \cdot {}^\circ C)}$, $= 2.98\times10^{-3}$
$\dot{m}_a$ air mass flow rate, kg/sec, $0.01 \sim 0.18\,(\mathrm{kg/sec})$
n number of people
$\dot{Q}_{room}$ compartment heat gains, kJ/sec
$\dot{Q}_e$ cooling capacity, kJ/sec
$RSHF$ room sensible heat factor
RH air relative humidity level, %
S the gap for insulation, m, $\approx 1.5\times10^{-3}\,\mathrm{m}$
T dry-bulb temperature, °C
T_a an average temperature amplitude, °C
V car compartment displacement, $\mathrm{m^3}$, $\approx 3\times1.5\times1.5 = 6.75m^3$
α the percentage of heating air flow rate, %

* Corresponding author. Tel.: +603-50392822; fax: +603-51026146
E-mail address: babul@uthm.edu.my

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doi:10.1016/j.proeng.2012.07.261

1. Introduction

Electric vehicles (EVs) are promising candidates to replace cars including Internal Combustion Engine (ICE) drive trains in the coming years especially in urban regions in order to reduce vehicular emissions. Up to now the EV's drawback is the battery system which is able to store only a very limited amount of energy on board [1]. Hence, it is necessary to use the energy in the most efficient way especially for heating, ventilating, and air-conditioning (HVAC) system. The purpose of the HVAC system of a car cabin is to provide complete thermal comfort for its occupants by controlling the temperature and humidity [2]. The challenge of designing the HVAC control is to automatically achieve the thermal comfort, regardless of time varying weather conditions. In fact, HVAC system is complex as the existence of severe nonlinearity and time varying characteristic [3].

Classical control techniques, such as on–off switching controller (thermostats), proportional–integral (PI) [4] and proportional–integral–derivative (PID) [5] controllers are still widely used in practice as they can be easily implemented, are low cost, and reliable in harsh field conditions. Since most HVAC systems are complex with nonlinearity, distributed parameters, and multivariable therefore many classical controls do not necessarily yield a satisfactory control performance. Commonly classic control schemes use the first order or second order plus time delay models to represent process dynamics [3]. The performances of these control schemes are limited due to their inherent nonlinearity and time varying nature. To overcome these drawbacks, applications of intelligent control to HVAC systems have drawn some interests [6], [7], and [8]. In recent years, the various studies using intelligent and soft computing methods were presented in the area of HVAC systems. One of these intelligent methods is artificial fuzzy method. There are many advantages of fuzziness, one of which is the ability to handle the complex system. Fuzzy controllers can control nonlinear process model and time-delay process model significantly better than classical controller [9].

The fuzzy control is a method to replicate and execute a (smart) human's knowledge about how to control a system [9]. Fuzzy controllers demonstrate models or knowledge using IF–THEN rules in the form of ''if X and Y, then Z''. A fuzzy inference system mainly consists of fuzzy rules and membership functions and fuzzification and de-fuzzification operations. By applying the fuzzy inference, an ordinary crisp input creates an ordinary crisp output, which is easy to be interpreted and understood. A fuzzy controller consists of simple rules such as:

' if temperature is high and humidity is normal , then AC is high '

where temperature, humidity, and AC are linguistic variables; high and normal are linguistic values that are characterized by membership functions. According to the nonlinearity and complexity of HVAC system, a fuzzy controller has been developed and used in this study.

The ultimate aim of this research work is to indentify an intelligent control strategy based on Fuzzy Logic Control (FLC) to reduce the electric energy consumption of the HVAC system depending on the driving situation. In this paper the initial finding of the FLC development of temperature and humidity control of HVAC is presented.

2. HVAC Model

In this work, the complete mathematical model of the HVAC system has been developed mainly based on [10]. This model is chosen as it provides a mathematical model which describes the HVAC system based on thermodynamics. The model is considerably complete and easy to understand. It is shown in Fig. 1. In general, an automobile HVAC system consists of a vehicle air-conditioning apparatus model, a car compartment model, outdoor environment model and an automatic climate control. Passenger comfort depends very much on the compartment temperature T_R and humidity ratio, ω_r, which is often represented by relative humidity, RH_R.

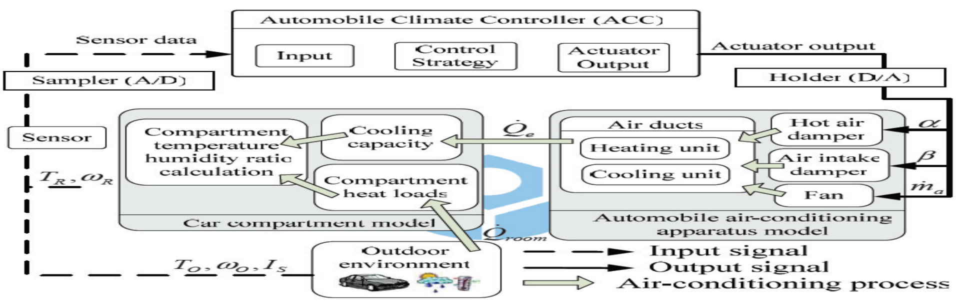

Fig. 1 General structure of automobile HVAC system [10]

In order to derive the mathematical model, a complete process and heat flow in the system needs to be understood well. The process consists of four stages [10]:

i. Ventilation, in this process, the air in the car compartment is mixed with the outdoor air. The percentage of outdoor air is defined by the opening of air circulation valve, β.
ii. Chilling, in this process, the air is cooled by air-conditioning apparatus. A fan pumps mixing air to the evaporator to chill the air to dew-point temperature. This process depends on the airflow rate, $\dot{m}_a$, which determines the speed of the fan and later the compartment temperature.
iii. Heating, this process involves the heating-up of the chilled air in order to achieve the desired compartment temperature. The amount of heating used for the supplying air depends on the heater valve, α.
iv. Heat absorption, in this process, the supplied air will enter the car compartment and absorb the heat and the humidity of the compartment and will be recirculated, and ventilation process will be repeated.

The whole process is shown in Fig. 2 and Fig. 3.

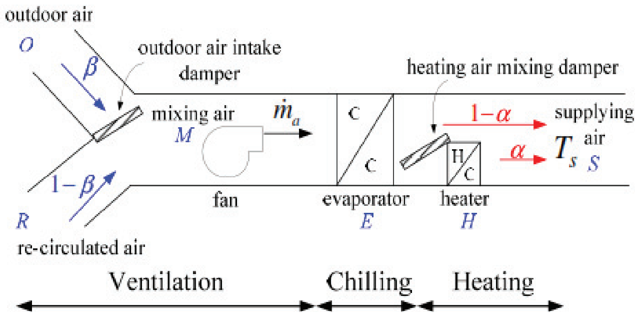

Fig. 2 Air distribution system [10]

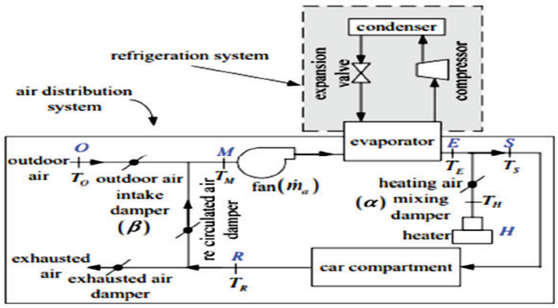

Fig. 3. Equipment of automobile air-conditioning system [10]

To achieve passenger comfort, the heat gains in the compartment, $\dot{Q}_{room}$, which is a function of time-varying outdoor environment must be regulated by sufficient cooling capacity, $\dot{Q}_e$, which is provided by air-conditioning apparatus.

The complete model (i.e. including the actuators, evaporator and fan models) is implemented in Simulink as shown in Fig. 4.

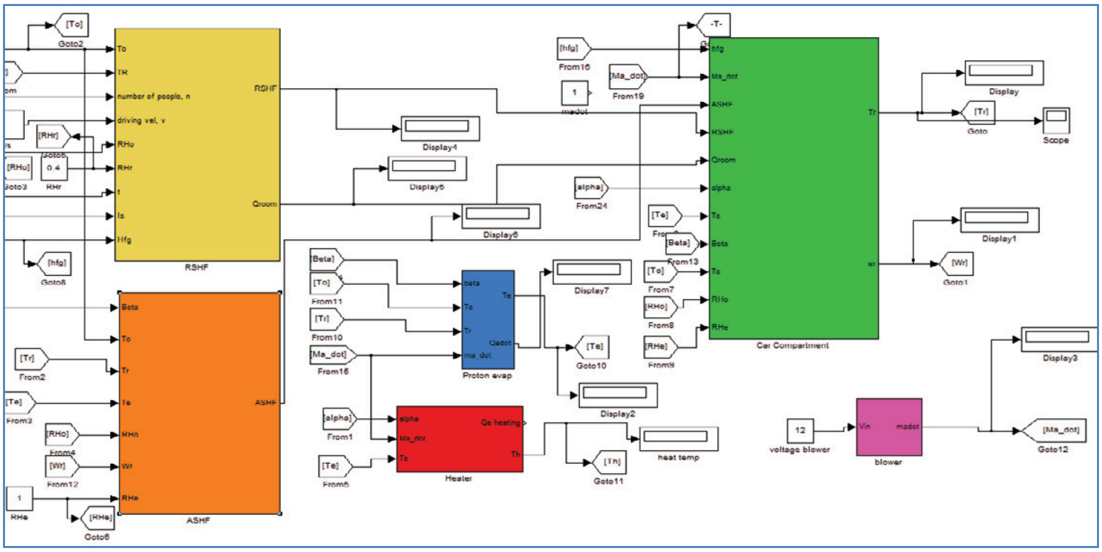

Fig. 4. Simulink implementation of HVAC system developed

3. HVAC Control Development

3.1 Definitions

Comfort zone as defined by ASHRAE standard 55 [11] is comprises of two conditions that are 1) temperature as 20°C to 27°C in dry bulb temperature (T_{db}) and 2) humidity as 30% to 60% in relative humidity (RH). The dry bulb temperature (T_{db}) is defined as the air temperature measured using a standard thermometer. Humidity is defines as water-vapor content of the air while relative humidity (RH) is the percentage of saturation. At a given temperature and pressure, air can hold a certain amount of water and no more. Air holding the maximum amount of water is saturated with the value of RH is 100%.

3.2 Control Design Challenges

The challenge of designing the HVAC control is to automatically achieve thermal comfort, regardless of time varying weather conditions. In fact, human are more sensitive to temperature variation than tolerable to humidity variation [12], the main task is to bring the car compartment temperature, T_r to the setting temperature, T_{ss}, i.e.: ($T_r = T_{ss}$). Then the next task is to close the different between the measured value of the measured humidity, in this case the value of relative humidity (RHr) to be within the optimal range i.e.: (RH = [30% to 60%]). Thus, the goal of the FLC-based temperature control is to satisfy the following properties, [13]:-

a. Convergence property
- The control strategy must ensure that the climate is converged to a pre-set climate structure within the comfort zone.

b. Equilibrium property
- Once the set temperature has been achieved, the control must be robust to make sure the climate remains almost unchanged despite possible time-varying heat condition.

3.3 Fuzzy-based Temperature and Humidity Control for HVAC

The overall of the block diagram of PD-type Fuzzy-based Temperature Control for HVAC is shown in Fig. 5. There are 3 inputs to the controller that are temperature error (Terr), change of temperature error (TCerr) and relative humidity (RHr). Temperature error is defined as difference between the setting temperature (Tss) and measured temperature (Tr). The Mamdani-type fuzzy controller will regulate three components voltage such as voltage of heater damper motor (Vα), voltage of outside air damper (Vβ) and voltage of fan (Vf) according to these three inputs. Mamdani type fuzzy inference was used due to the simplicity to formulate the rules. Control Variables are such as Vα, Vβ and Vf, which are corresponding to α, β and Ma_Dot parameter respectively. The range of the 3-input and 3-output PD-type fuzzy control is tabulated in Table 1.

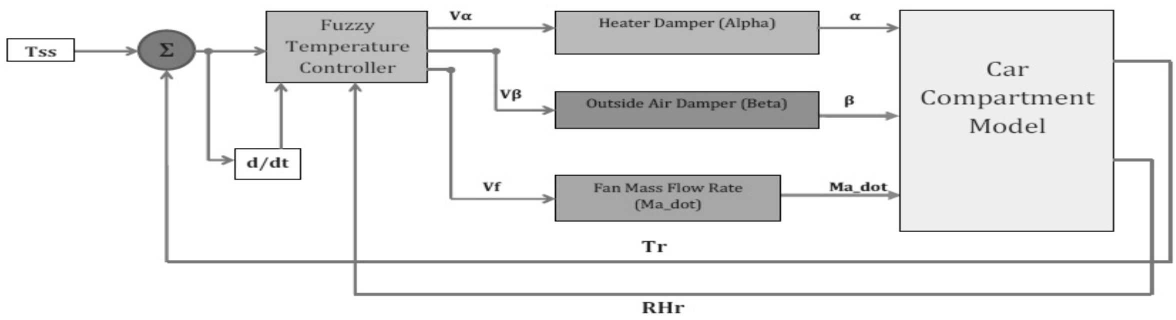

Fig. 5. Block diagram of Fuzzy-based Temperature Control for HVAC

Table 1. Range of inputs and outputs

	Parameters	Range
Inputs: -	Temperature error (Terr)	between -20 and 20
	Change of temperature error (TCerr)	between -200 and 200
	Relative Humidity (RHr)	between 0 and 1
Outputs:	Voltage of heater damper motor (Vα)	between 0 and 15
	Voltage of outside air damper (Vβ)	between 0 and 15
	Voltage of fan (Vf)	between 0 and 15

Fig. 6 shows the inputs and outputs membership functions (MFs) of the fuzzy controller. There are 3 MFs for inputs and 4 MFs for outputs have been used for this controller. Piecewise linear triangular and trapezoidal MFs are preferred, because of their simplicity and efficiency with respect to computation capability. The fuzzy rules of three inputs and three outputs are shown in Table 2.

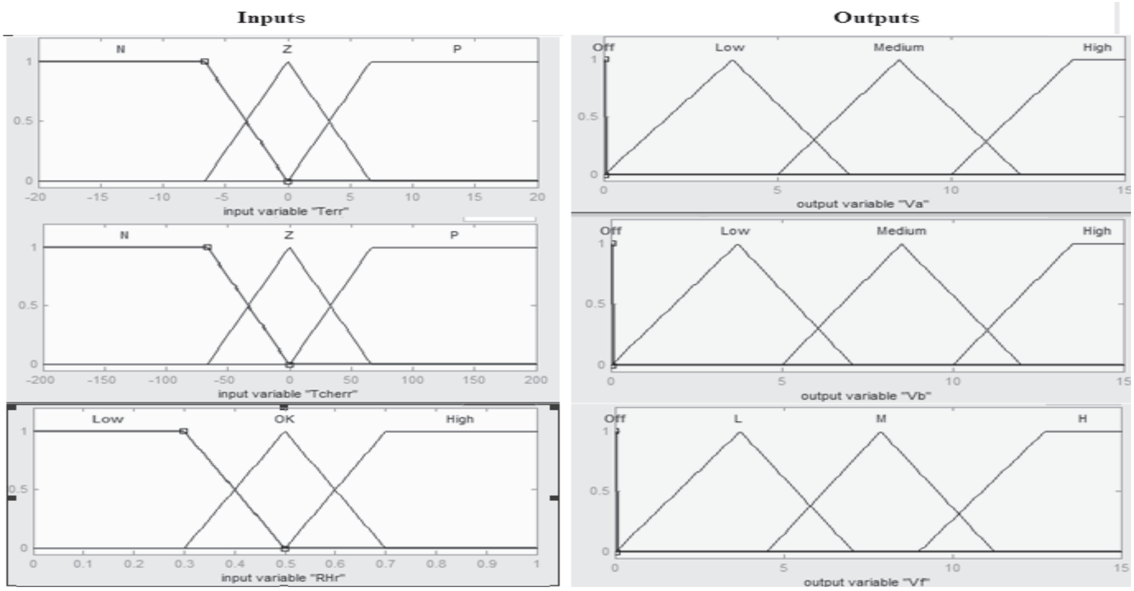

Fig. 6 Inputs and outputs MFs of the fuzzy controller

Table 2. Fuzzy rules

Vα

	RHr = L			RHr = OP			RHr = H		
e \ Δe	N	Z	P	N	Z	P	N	Z	P
N	O	O	O	H	M	O	H	M	O
Z	O	O	M	M	O	O	M	O	O
P	O	M	H	O	O	O	O	O	O

Vβ

	RHr = L			RHr = OP			RHr = H		
e \ Δe	N	Z	P	N	Z	P	N	Z	P
N	O	O	O	H	M	O	H	M	O
Z	O	O	M	M	O	O	M	O	O
P	O	M	H	O	O	O	O	O	O

Vf

	RHr = L			RHr = OP			RHr = H		
e \ Δe	N	Z	P	N	Z	P	N	Z	P
N	O	O	O	H	M	O	H	M	O
Z	O	O	M	M	O	O	M	O	O
P	O	M	H	O	O	O	O	O	O

4. Results and Discussion

Computer simulations are performed to assess the performance of the designed PD-FLC to control the desired temperature and humidity. The simulations were carried out using Matlab/Simulink with Fuzzy Logic Toolbox as a platform. Both simulation without the controller and simulation with PD-FLC controller have been performed within 500 seconds.

4.1 Simulation without controller

The simulation without controller has been performed by setting the constant voltages to the actuators such Vα = 12, Vβ = 12 and Vf = 12 with initial condition (32°, 0.6, 0.8 kW solar radiance). Figure 7 and 8 show the temperature and humidity behavior of the simulation without controller. Obviously the temperature and humidity were unable to be controlled as shown in these figures. The car compartment temperature, T_r tends to follow the exact temperature fluctuation in outside cabin temperature, T_o. This phenomenon also reflects the same behavior to relative humidity, RHr and Rho value.

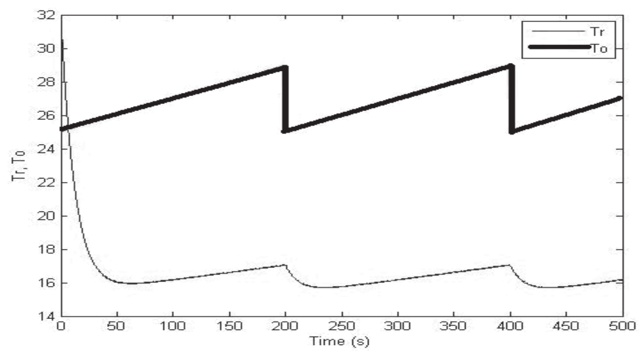

Fig. 7: Tr and To vs. time without controller

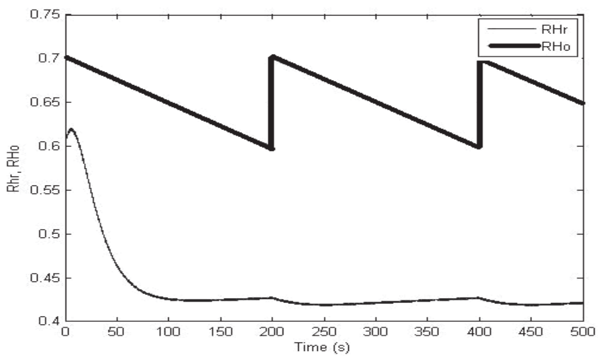

Fig. 8: RHr and Rho vs time without controller

4.2 Simulation with PD-FLC controller

In this test the outside temperature (To) and humidity (Rho) are set to be constant at 30°C and 0.7 respectively. Figure 9 and 10 show the temperature and humidity response of the simulation test with controller. The initial condition was 32°C and Tss was set to be 25°C. The controller able to regulate the temperature as desired within 10 seconds and maintains the desired temperature as shown in Figure 9. The initial humidity was 0.75 and the controller able to regulate to the optimal range which is between 0.3 and 0.6.

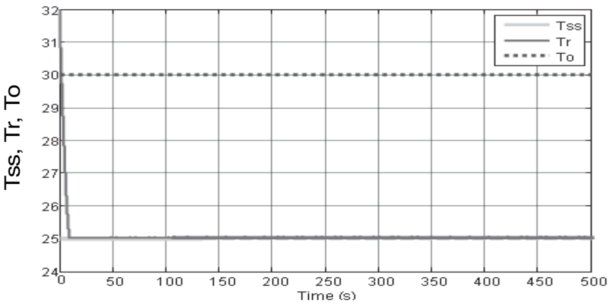

Fig. 9 Tss, Tr and To vs time with controller

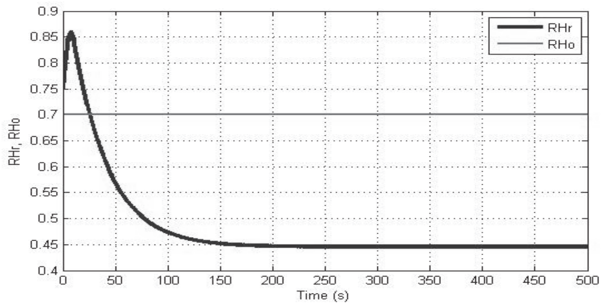

Fig. 10 RHr and Rho vs time with controller

Conclusion

The temperature control based on PD-fuzzy logic has been designed and developed to control the car compartment's temperature. The fuzzy rules are designed such that the actuators will settle when the set-point temperature has been achieved within the comfort zone region of the relative humidity and climate. The PD-Fuzzy logic based controller is able to work well regardless any car compartment initial conditions (Tr_init and RH_init) or at different outside conditions (To, Rho) achieving the targeted temperature within the comfort zone of RH. HVAC system in EV is required to be more energy efficient while adhering to an ever-increasing demand for better indoor air quality and comfort. Therefore this PD-Fuzzy control approach can be applied with consideration on the energy consumption by incorporating with optimisation tools such genetic algorithm in future control development. Thus a balance between indoor comfort and energy efficiency can be obtained.

Acknowledgements

The authors would like to express gratitude and acknowledgement to Perusahaan Otomobil Nasional Sdn. Bhd. under sabbatical program and group members in VeHiL Project at Research Department. The authors also would like to express appreciation to Advanced Engineering and Innovation Centre (AEIC), IIUM for the assistance and support given.

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