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Fuzzy Control of the Air Conditioning System at Different Operating Pressures

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Abstract**—**The present work demonstrates the design and simulation of a fuzzy control of an air conditioning system at different pressures. The first order Sugeno fuzzy inference system is utilized to model the system and create the controller. In addition, an estimation of the heat transfer rate and water mass flow rate injection into or withdraw from the air conditioning system is determined by the fuzzy IF-THEN rules. The approach starts by generating the input/output data. Then, the subtractive clustering algorithm along with least square estimation (LSE) generates the fuzzy rules that describe the relationship between input/output data. The fuzzy rules are tuned by Adaptive Neuro-Fuzzy Inference System (ANFIS). The results show that when the pressure increases the amount of water flow rate and heat transfer rate decrease within the lower ranges of inlet dry bulb temperatures. On the other hand, and as pressure increases the amount of water flow rate and heat transfer rate increases within the higher ranges of inlet dry bulb temperatures. The inflection in the pressure effect trend occurs at lower temperatures as the inlet air humidity increases.

Keywords**—**Air Conditioning, ANFIS, Fuzzy Control, Sugeno System.

I. INTRODUCTION

THE comfortable environment provided by air conditioning systems is highly appreciated. Homes, offices and commercial facilities would not be comfortable without all year around control of the indoor environment. Air conditioning systems are essential in most of our daily life. Our expectations of such systems have been raised to demand more than just temperature control, and it is increasingly desirable to apply these systems in varying situations and environments. A comfortable and safe environment is often difficult to define and affected by sometimes-contradictory factors.

The main objectives of any heating, ventilating, air conditioning and refrigeration systems are to maintain the proper comfort or artificial environmental conditions with the minimum possible of energy consumption. The controller parts of these HVAC and refrigeration systems are the most important elements since they are essential in attaining the primary objectives of these systems with the minimum energy consumption.

In the literature, there are three well known controlling approaches numerously used to control HVAC and refrigeration systems [1]-[24]. These are the traditional Controllers, advanced controllers and intelligent controllers. Traditional control consists of two types which are the On/Off control and the Proportional, Integral and Differential (PID) control. The main advantages of the traditional control systems are their simplicity and low initial cost but their main disadvantages are their high maintenance cost and low efficiency [1]-[4]. The advanced controllers consist of three types which are the auto-tuning PID, modern and nonlinear controllers and optimal controllers [5]-[8]. The main disadvantages of the advanced controllers are their high initial cost but they have better performance than the traditional controllers [5]-[11]. Other advantages or disadvantages depend on each specific type of the advanced controllers. As an example, auto-tuning controllers may be applied on limited number of applications because auto-tuning controllers must recognize the operating model before being applied. The nonlinear controllers are most suitable for all nonlinear systems which are the case of all HVAC and refrigeration systems. The optimum controllers are excellent in situations require any sort of optimization [11]-[17] and this yields energy saving in case it applied on HVAC and refrigeration systems. The intelligent controllers consist of neural network and fuzzy logic controllers. These controllers are suitable for nonlinear and transient systems which are the main characteristics if all HVAC and refrigeration systems. As a result, the intelligent controllers are the excellent choice to control such systems. Fuzzy logic has an additional advantage over neural network when the system behavior is associated with a sort of uncertainty as in the case of thermal comfort conditions associated with HVAC systems [13]-[15]. As mentioned previously, HVAC and refrigeration systems have transient and nonlinear behavior with a certain uncertainty in the inputs and required outputs. In air systems, it is enough to fix two thermodynamics properties to identify the air status. Air dry bulb temperature and humidity are the most common chosen parameters. The main task of the controller is to add (or absorb) specific amount of thermal energy and to inject (or absorb) specific amount of water to provide the outlet air at the required comfort or design conditions. Although most of the commercial HVAC and refrigeration systems do not pay great intention to the addition or removal of water (humidity control) but the control of these two parameters are investigated in the literature [1]-[24]. However, all controlling approaches do not pay any attention to an important parameter which is the pressure of the heated, ventilated and conditioned air. There are wide range of applications that involve the HVAC and refrigeration of gases that are not maintained at

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atmospheric pressure [26]-[31]. Examples of these systems are conditioning systems that operate at high altitudes or below sea level or systems that have to cool certain products maintained at high pressures as in many industrial applications. Even in normal operating conditions the air pressure vary within a certain relatively significant range below and above sea level.

The main objective of the present work is to apply fuzzy control on an air conditioning system that cool, heat, humidity and dehumidify the air at different operating pressures. The main three thermodynamic properties of the gas (air) are the dry bulb temperature, humidity and pressure. The study will consider how to apply fuzzy controller to control the required heat transfer (heating or cooling) and the water vapor transfer (humidification and dehumidification) to bring air from known inlet condition to the required outlet temperature at different pressures. The focus will be on the additional effects that will be brought by considering air pressure as an additional variable parameter. It will be assumed that the flowing air through the air conditioner will have constant pressure but not necessary the atmospheric one. In classical air conditioning, systems are only controlled at certain pressure. We modified the controller to compensate for any variation in pressure. In (HVAC) systems, most work applies fuzzy logic control to solve simple problems such as thermal regulation and maintaining a temperature set point. Therefore, a more general case of air conditioning system at different pressures has been considered. The pressure variation problem has not been generally investigated before which makes our work to be original.

II. FUNDAMENTAL CONCEPT OF AIR CONDITIONING SYSTEM

The most important processes conducted to bring air to the comfort or design conditions are:

1- Heating: it is the transfer of energy to a space or to the air in a space by virtue of a difference in temperature between the sources and the space or air.
2- Humidifying: the transfer of water vapor to atmospheric air and the heat transfer is associated with this mass transfer; however, the transfer of mass and energy are manifested an increase in the concentration of water in the air-water vapor mixture.
3- Dehumidification: it is the transfer of water vapor from atmospheric air. The transfer of energy is from the air in the form of enthalpy of condensation; as a consequence, the concentration of water in the air-water vapor mixture is lowered.
4- Humidification: it is the transfer of water vapor to atmospheric air. The transfer of energy is to the air in the form of enthalpy of evaporation; as a consequence, the concentration of water in the air-water vapor mixture is lowered.

III. FUZZY LOGIC

Fuzzy logic is a powerful problem-solving methodology with a myriad of applications in embedded control and information processing. Fuzzy provides a remarkably simple way to draw definite conclusions from vague information. In a sense, fuzzy logic resembles human decision making with its ability to work from approximate data and find precise solutions. Fuzzy Logic has been gaining increasing acceptance during the past few years. There are over two thousand commercially available products using fuzzy logic, ranging from washing machines to high-speed trains. Nearly every application can potentially realize some of the benefits of fuzzy logic, such as performance, simplicity, lower cost, and productivity.

Fuzzy logic is the extension of the Boolean logic that has been proposed to handle the concept of partial truth-truth values between "completely true" and "completely false". Dr. Lotfi Zadeh introduced it in the 1960's. He says that rather than regarding fuzzy theory as a single theory, we should regard the process of " fuzzification " as a methodology to generalize ANY specific theory from a crisp (discrete) to a continuous fuzzy form. On the other words the fuzzy logic is the extension of classical two-valued logic by using the truth set [0, 1]. In fuzzy reasoning, the most important fuzzy implication inference rule is the generalized modus ponens (GMP), which uses an IF-THEN rule that implicitly represents a fuzzy relation. The use of fuzzy rules is important when the causal link between domains is not known. Usually partial knowledge about the relation between these domains exists in the form of fuzzy rules. The fuzzy rules define the connection between input and output fuzzy (linguistic) variables. The rule consists of two parts: an antecedent and a consequence part. A typical rule, which describes this simple fact, is

IF *X* is *A* AND Y is B THEN *Z* is *C*

in the above fuzzy rule X, Y and Z are called fuzzy variables, and *A*, *B* and C are linguistic values, the operator **AND** is a fuzzy connective. It aggregates the results within the premise part. The other common connectives are union **OR** and complement **NOT**.

IV. MATHEMATICAL FORMULATION OF AIR CONDITIONING SYSTEMS

This section describes the mathematical model that describes the thermodynamic behavior of the air conditioning system **(ACS)**. The governing equations that relate pressure, elevation above sea level, dry bulb temperature, relative humidity, humidity ratio, vapor partial pressure, air partial pressure, air enthalpy, water enthalpy, specific volume, heat transfer rate and water mass flow rate will be considered.

The atmospheric pressure varies with the elevation above sea level in the following form:

$$P = a + bH \qquad (1)$$

where *a* and *b* are constants given in Table I and *H* is the elevation above sea level in meters.

TABLE I
THE PARAMETERS *a* AND *b* USED IN PRESSURE-ELEVATION RELATION

Constants	$H \leq 1220 \ m$	$H > 1220 \ m$
a *(Kpa)*	*101.325*	*99.436*
b *(Kpa/m)*	-0.01153	-0.010

Other thermodynamics relations are given as:

$$P\upsilon = n\bar{R}T \tag{2}$$

$$P = P_a + P_v \tag{3}$$

$$W = \frac{m_v}{m_a} \tag{4}$$

$$W = 0.622\,\frac{P_v}{P_a} \tag{5}$$

$$\phi = \frac{W\left(P - P_v\right)}{0.622\,P_{vs}} \tag{6}$$

$$\ln\left(\frac{P_{vs}}{2337}\right) = 6789\left(\frac{1}{293.15} - \frac{1}{T}\right) - 5.031\ln\left(\frac{T}{293.15}\right) \tag{7}$$

$$h = \left(T - 273\right) + W\left[2501.3 + 1.86\left(T - 273\right)\right] \tag{8}$$

$$\frac{\dot{q}}{\dot{m}_w} + h_w = \frac{h_2 - h_1}{W_2 - W_1} \tag{9}$$

$$\dot{q} = \dot{m}_a\left(h_1 - h_2\right) - \dot{m}_a\left(W_1 - W_2\right)h_w \tag{10}$$

in order to find the theoretical heat transfer rate and water mass flow rate at any pressure, temperature and relative humidity a computer program is developed for this purpose. The numerical code will be used to solve the set of coupled nonlinear algebraic equations (1-10) to estimate the required heat transfer and water mass flow rate that must be added or removed from the air conditioning system in order to bring the inlet air from a known set of thermodynamics properties to another set of known properties. At the air conditioning inlet or outlet it is enough to know three parameters, normally dry bulb temperature, relative humidity and total pressure. All other properties and heat and water mass fluxes will be estimated using the listed governing equations. It is worth mentioning that equation 2 will be applied to both air and water vapor that are treated as ideal gas. In addition, the enthalpy of saturated liquid water is assumed to be known from steam tables. All plotted figures will focus on estimating the required heat transfer rate and water mass flow rate that are required to bring air from inlet to outlet conditions at different operating air total pressure. In all plots, the outlet conditions are assumed to be the average human comfort conditions at both summer and winter depending on the considered case unless mentioned otherwise.

V. FUZZY LOGIC CONTROL

According to the form of the consequent of the fuzzy control rules, we can usually distinguish two main different types of fuzzy logic controls **(FLCs)** in the specialized literature, Mamdani **FLCs** [32] and Takagi-Sugeno-Kang **FLCs** [33] and [34]:

Mamdani-type rules are composed of input and output linguistic variables taking values on a linguistic term set with a real-world meaning:

R_i: *If* X_1 *is* A_{i1} **and . . . and** X_n *is* A_{in} **then** Y *is* B_i

Where X_n and Y are the input and output linguistic variables and the A_{in} and B_i are linguistic labels for the fuzzy sets.

Takagi-Sugeno-Kang-type rules are based on the division of the input space into several fuzzy subspaces in which each rule defines a linear input-output relationship by means of the real-valued coefficients ($p_{i\,n}$):

R_i: *If* X_1 *is* A_{i1} **and . . . and** X_n *is* A_{in} **then** $Y = p_{i1}X_1 + \ldots + p_{in}X_n + p_{i0}$

Where X_n and Y are the input and output linguistic variables and the A_{in} are linguistic labels associated with fuzzy sets specifying their meaning.

The method of Mamdani inference is to expect all output membership functions to be fuzzy sets. It is intuitive, has widespread acceptance, is better suited to human input, but its main limitation is that the computation for the defuzzification process lasts longer. While, the Sugeno-style inference has a computational efficiency, works well with linear techniques, works well with optimization and adaptive techniques, guaranties continuity of the output surface and it is better suited to mathematical analysis. Also, Mamdani and Takagi-Sugeno (TS, for short) types mainly differ in the fuzzy rule consequent: a Mamdani fuzzy controller utilizes fuzzy sets as the consequent whereas a TS fuzzy controller employs linear functions of input Variables [35].

VI. FUZZY MODEL OF THE AIR CONDITIONING SYSTEM

The process of learning begun by using ANFIS to find the appropriate rules for the heat transfer rate and mass flow rate at different pressure. The system is composed of three-input (temperature, relative humidity and pressure) and one-output (the heat transfer rate or water mass flow rate). 75% of the data are used as training data, while the other 25% of the data is left as checking data. The process of modeling by fuzzy IF-THEN rules of the heat transfer rate and water mass flow rate, as well as for the air conditioning system at different pressures, were done by creating tables including three inputs and one output. After that, the training and checking data were obtained by means of previously generated input/output tables. Then the cluster centers were generated utilizing the subtractive clustering method. Finally, the rules were adapted and formulated by means of *ANFIS.* The control system implemented in the air conditioning system is a closed-loop system demonstrated throughout the simulation, using the appropriate fuzzy model.

VII. RESULTS AND DISCUSSION

Fig. 1 shows the effect of the inlet dry bulb temperature T_{db} on the heat transfer rate at different relative humidity of air that flows into the air conditioning system. As predicted, it is clear from this Figure that less heat is required to bring inlet air to the required outlet temperature when inlet air has higher temperature. Also, as inlet air becomes more humid less heat is required. This is due to the increase in the total enthalpy of the inlet air when it becomes more humid.

The effect of the inlet dry bulb temperature T_{db} on the water mass flow rate at different relative humidity for inlet air is shown in Fig. 2. It is clear from this figure that less water mass flow is required to bring inlet air to the required outlet comfort conditions as the inlet air dry bulb temperature and humidity increase. Humid and hot inlet air does not need too much heat and water to be brought to the required outlet comfort conditions.

Fig. 3 shows the effect of inlet air dry bulb temperature on the required heat transfer at different inlet relative humidity and at two low values of air total pressure. These two low values of air pressures are at 5 and 60 kPa. As explained previously, hotter and more humid inlet air needs less heat. Also, increase the system pressure within the low pressure range reduces the required heat. As the air pressure increases to higher levels different behavior will be observed as it will be shown later.

Fig. 4 shows the effect of inlet air dry bulb temperature on the required heat transfer at relative humidity $\Phi = 30\%$ and at two values of air total pressure. One of these values is low (P= 5kPa) and the other is high (P= 101 kPa). As observed previously, hotter inlet air needs less heat to be brought to the required outlet conditions. However, the trend of pressure effect on the required heat depends on the range of inlet dry bulb temperature. Inlet air with relatively low dry bulb temperatures (lower than 307 K) needs less heat as pressure increases. On the other hand, inlet air at higher temperatures (higher than 307 K) needs more heat as pressure increases.

Behavior similar to what appears in Fig. 4 is observed in Fig. 5. Fig. 5 shows the effect of dry bulb temperature on the heat transfer at relatively saturated air and at different three values of pressures (60, 101 and 120 kPa). Again, less heat is required to heat hotter inlet air. Also, as pressure increases less heat is required for relatively cool inlet air and more heat is required for relatively hot inlet air. The variation in the effect of pressure trend appears at dry bulb temperature 270 K. This implies that the change in the trend of air pressure appears at lower temperatures as the air humidity increases. For the dry inlet air case considered in Figure 4, the change in the effect of pressure trend appears at temperature 307 K but for this humid case the change appears at temperature equal to 270 K.

Fig. 6-8 show the effect of the inlet air dry bulb temperature on the water mass flow rate required to bring inlet conditions to the outlet ones. These figures show the effect at three different pressures (60, 101 and 120 kPa) and at three values of the inlet relative humidity (Φ = 10%, 50% and 99%). All these three figures show a similar trend regarding the effect of the inlet air dry bulb temperature on the required water injection (or withdraw) flow rate. As the inlet air becomes hotter less water flow rate is required to be injected (or withdrawn) in order to bring inlet air to the required outlet conditions. Regarding pressure effects on water flow rate different trends appear depending on inlet air dry bulb temperature and humidity. At low inlet humidity, and as clear from Fig. 6, less water flow rate is required as air total pressure increases over the entire range of inlet air dry bulb temperatures. However, at relatively higher inlet humidity the system needs less water flow rate as pressure increases within the lower range of inlet dry bulb temperatures and needs more water flow rate within the higher ranges of dry bulb temperatures. The inflection in the effect of pressure trend occurs at temperature 298 K at humidity 50% and at temperature 287 K at humidity 99%. This implies that as the inlet air humidity increases, the change in the effect of pressure trend occurs at lower inlet temperatures. Fig. 9-14 show the automatically generated fuzzy membership functions by ANFIS.

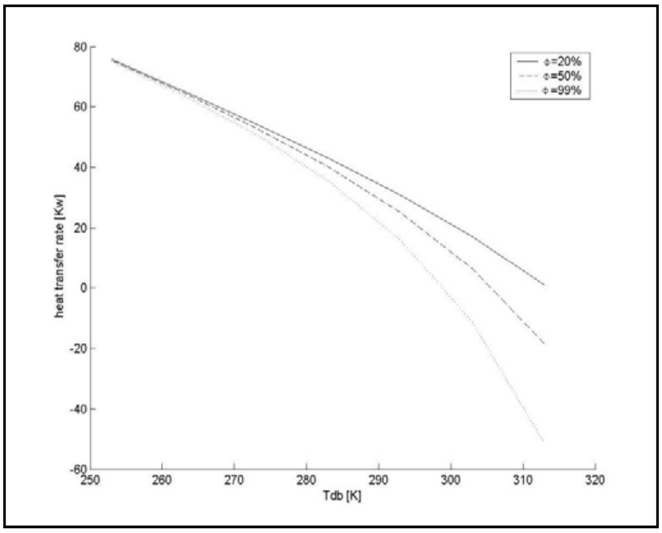

Fig. 1 Effect of the inlet dry bulb temperature and relative humidity on the heat transfer rate at 101 Kpa

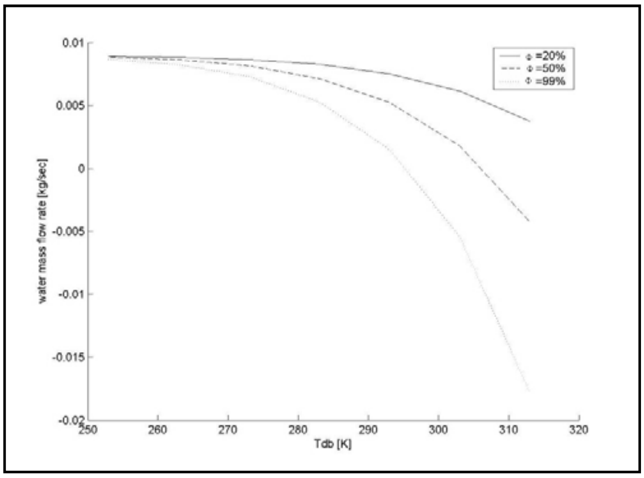

Fig. 2 Effect of the inlet dry bulb temperature and relative humidity on the water flow rate at 101 Kpa

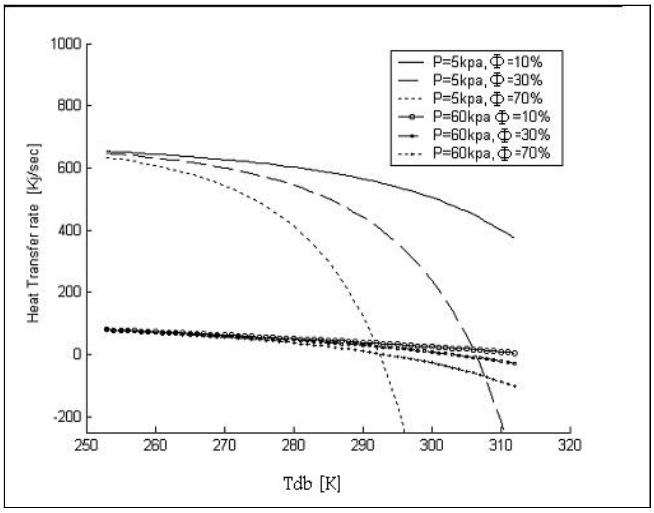

Fig. 3 Effect of inlet dry bulb temperature on heat transfer rate at different inlet relative humidity and pressures

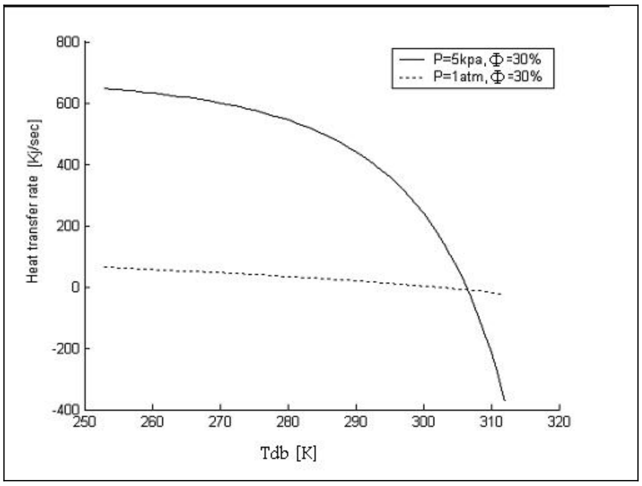

Fig. 4 Effect of inlet dry bulb temperature on heat transfer rate at different pressures and at relative humidity of 30%

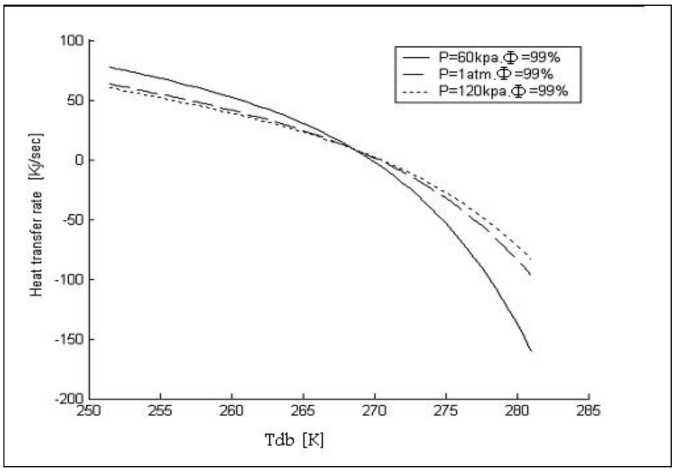

Fig. 5 Effect of inlet dry bulb temperature on heat transfer rate at different pressures and relative humidity of 99%

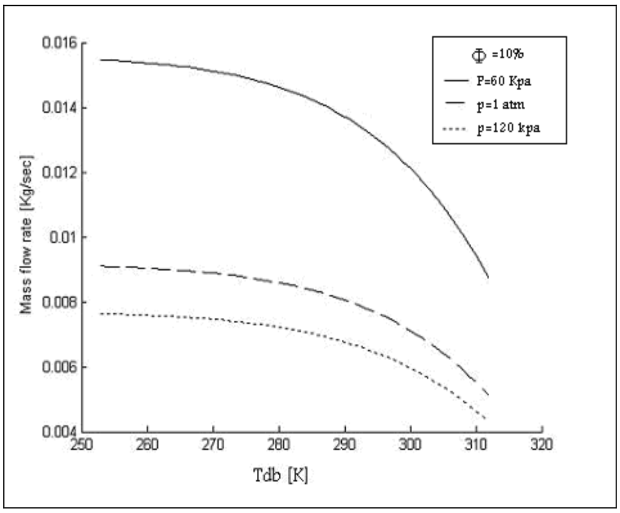

Fig. 6 Effect of inlet dry bulb temperature on water flow rate at different pressures and relative humidity of 10%

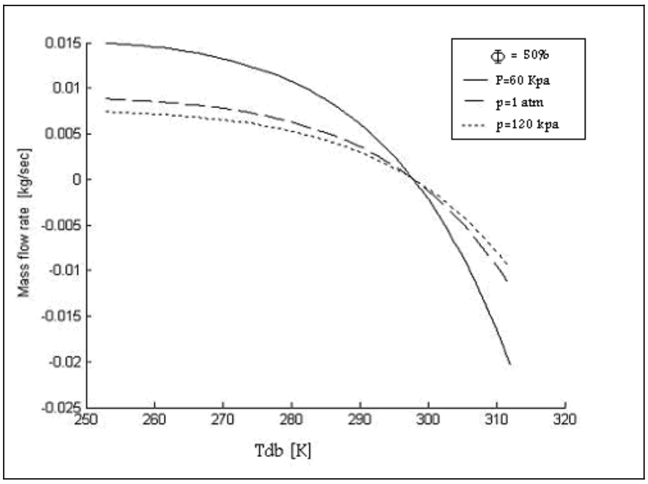

Fig. 7 Effect of inlet dry bulb temperature on water flow rate at different pressures and relative humidity of 50%

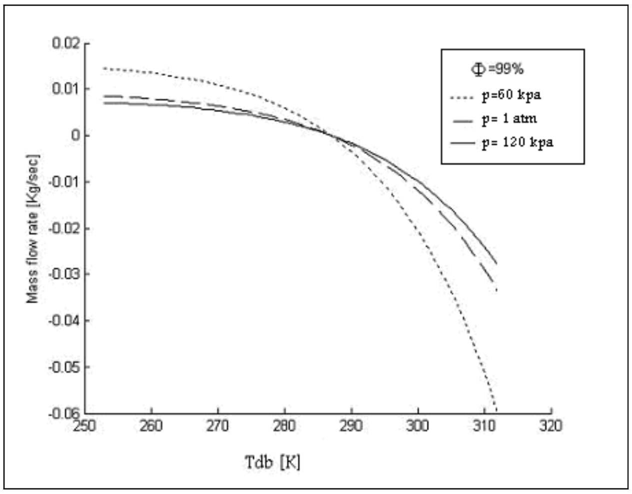

Fig. 8 Effect of inlet dry bulb temperature on water flow rate at different pressures and relative humidity of 99%

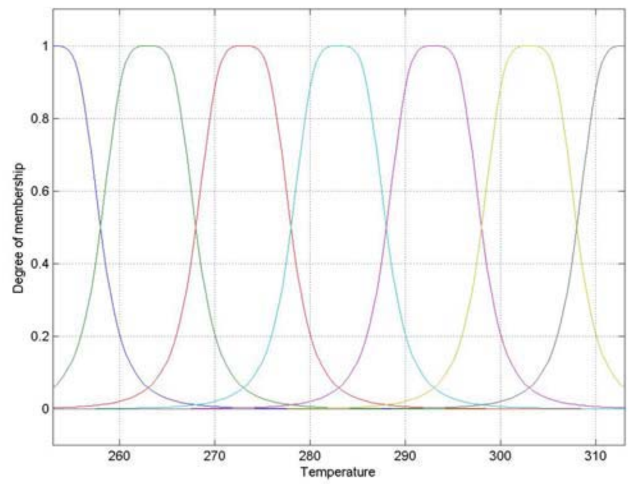

Fig. 9 Membership functions of the Temperature for Heat transfer rate

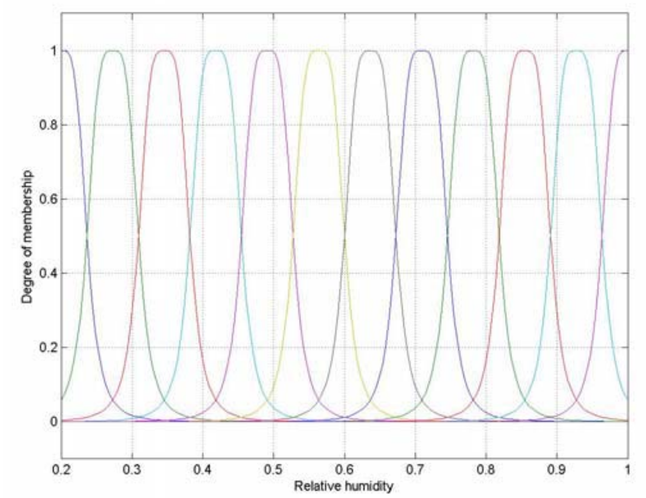

Fig. 10 Membership functions of the Relative Humidity for Heat transfer rate

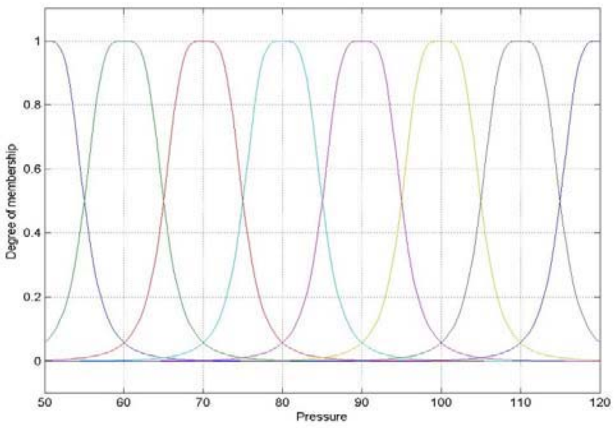

Fig. 11 Membership functions of the Pressure for Heat transfer rate

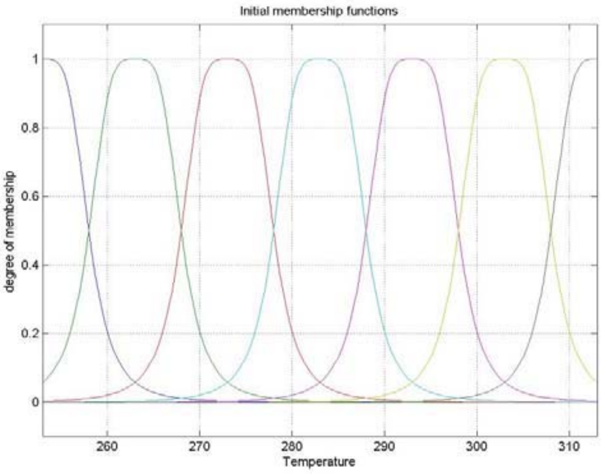

Fig. 12 Membership functions of the Temperature for water mass flow rate

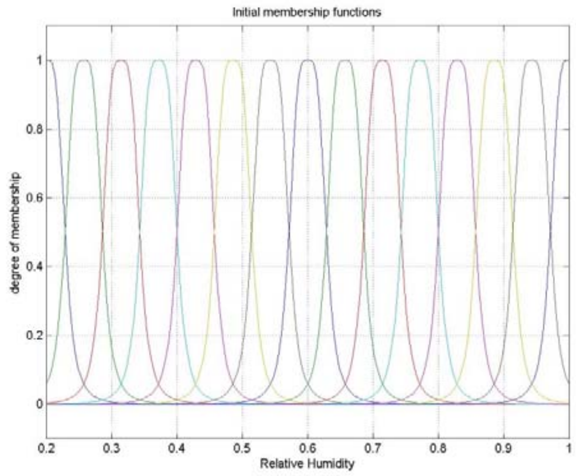

Figure 13 Membership functions of the Relative Humidity for water mass flow rate

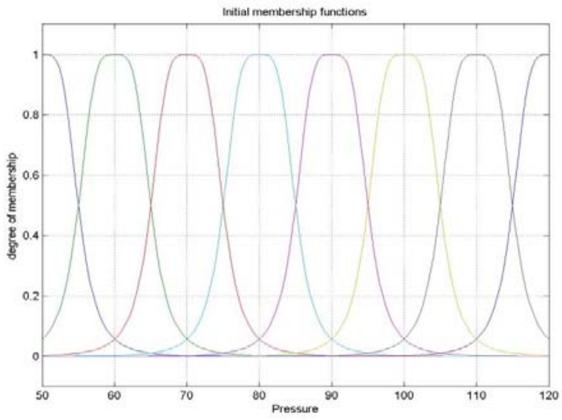

Fig. 14 Membership functions of the Pressure for water mass flow rate

VIII. CONCLUSION

This work discusses the design and simulation of fuzzy control of an air conditioning system at different pressures. The first order Sugeno fuzzy inference system is utilized to model the system and create a controller design. In addition, an estimation of the heat transfer rate and water flow rate injected into or withdrawn out of the air conditioning system is determined by the fuzzy IF-THEN rules. The results show that when the pressure increases the amount of water flow rate and heat transfer rate decrease within the lower ranges of inlet dry bulb temperatures. On the other hand, and as pressure increases the amount of water flow rate and heat transfer rate increases within the higher ranges of inlet dry bulb temperatures. The inflection in the pressure effect trend occurs at lower temperatures as the inlet air humidity increases.

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