



Research Journal of  
**Information  
Technology**

ISSN 1815-7432



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## **Intelligent Humidity Control for Healthy Home to Wealthy Industry: A Review**

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### **ABSTRACT**

Humidity plays a vital role in the industrial spheres where there is an imminent needs to control the humidity to appraise the product quality. Among the industries are pulp and paper, sugar, textiles, pharma, air conditioner, food processing and formation of photonic band gap films. Essentially control of humidity in the above areas in the associated manufacturing industries attracts the researchers in recent days to develop latest techniques to implement control techniques effectively. Use of effective methods and to promote scopes for research oriented program for further developments in the field of computer based control of humidity to archive the goal of product quality. This is an honest attempt to review some papers published in various international journals which address the critical influences of humidity and its control strategy. To that account a brief survey on the papers titled on humidity control in various journals is also done.

**Key words:** Humidity, controller, product quality, human comfort

### **INTRODUCTION**

Humidity is defined as the partial pressure of water vapor which is present in the air. The definition of absolute and Relative Humidity (RH) slightly deviates. The former is the actual amount of water vapor present in the air, rather the later is the ratio of quantity of water vapor present in the air to the amount of water vapor that would saturate the air. The temperature and relative humidity are interrelated variables. As the temperature increases, the amount of water vapor present in the air decreases. So the numerator quantity in the ratio decreases as well as the denominator increases for the same temperature. As a whole the RH decreases as temperature increases.

Humidity plays vital role in almost all the industries in order to maintain the desired product quality (Ballaney, 2002). The strength of yarn produced in the textile industries deteriorate if the RH level is not maintained. The quality of drugs produced in the pharmaceutical industries will not meet the requirement of the patients if the proper humidity level is not matched. In food processing industries also, proper humidity ratio is to be maintained in order to achieve the desired food quality. Humidity plays vital role in human comfort also.

Hence, study of this humidity and maintaining its level is of prime importance in industrial sector as well as for human-comfort. For measurement of humidity variety of conventional meters are available. Mechanical hygrometer, chilled mirror hygrometer, wet and dry bulb psychrometer, IR hygrometer is some of the instruments to measure humidity

(Wiederhold, 1997). Yeo *et al.* (2008) have suggested optical fiber based sensor technologies for measurement of humidity. They concluded that this technology overcomes all the disadvantages with conventional methods. Young *et al.* (2007) investigated the effect of storage RH in finding the efficiency of aerosolisation. They also tested the effect of RH in formulations of dry powder inhaler based on triboelectrification *in vitro* methodology by means of the Electrostatic Low Pressure Impactor (ELPI) and Next Generation Impactor (NGI). They reported that both in aerosolisation and formulation of dry powder inhaler, humidity is a dominating factor. In power generation, humid air turbine which utilizes humidification process attracted the scientist because of its eminent performance of low heat recovery (Rao, 1989). Humidification of air by using water spray was tested experimentally and theoretically by Xu *et al.* (2007). Liao and Huang (2008) have concluded that minimum time and best quality films can be achieved for photonic band gap crystal films under RH controlled environments. Annual heating or cooling energy consumption is influenced by outside air humidity (Enshen, 2005). For real time operation of drying machine, high performance non linear based fuzzy controller has been proposed to control the humidity by Santos *et al.* (2010).

"Relative humidity in habitable spaces should be preferably maintained between 30 and 60%, to minimize growth of allergenic or pathogenic organisms". Humidity control is important in air conditioning to maintain the indoor air quality. Subramanyam *et al.* (2004) utilized desiccant wheel for dehumidification of supply air to improve the low humidity air conditioning system. Heat pipe heat exchangers were used in air conditioning system to control the humidity (Wu *et al.*, 1997). These heat exchangers are the best replacement for conventional reheat coils which enhances energy saving and cooling capability of cooling coils. Guo *et al.* (2009) proposed a intelligent control technique in industrial workshops for controlling humidity and temperature. The other conventional methods need mathematical model of the controlled object where as their control technique does not require the model. A miniature room structure of a industrial workshop is taken for this study. The actual error and change-in-error are taken as the parameters for designing the control algorithm. An independent humidity control is designed for Heating, Ventilating and Air Conditioning (HVAC) system which uses liquid desiccant system which operates throughout the year instead of only in the summer (Liu *et al.*, 2006). In this method of humidity control the operating cost and energy consumption were 57 and 62%, respectively compared with 75 and 78% with conventional HVAC system. Composite material was developed to control the humidity by Yang *et al.* (2011). Different control schemes were proposed for temperature and humidity to improve energy efficiency (Nagaya *et al.*, 2006; Han and Zhang, 2011; Xu *et al.*, 2008). Zhao *et al.* (2011) presented a non linear control method based on adaptive neuro fuzzy inference system. Neural network based control was discussed for neutralization process (Balasubramanian *et al.*, 2008, 2009; Jarmulak *et al.*, 1997). Vijaya-Selvi *et al.* (2006) suggested internal model control (IMC) based controller design for a conductivity process and compared its performance over the conventional controller. IMC based proportional integral derivative controller (IMCPID) was implemented in MATLAB environment by Madhavasarma and Sundaram (2008) for a non linear process of spherical tank with large dead time and compared with conventional Proportional Integral Derivative controllers (PID) and smith predictor controller. IMCPID outperformed the other controllers in terms of time domain specifications. Fuzzy based PI controller was realized for a non linear hemispherical process in which the former controller resulted with better performance compared with conventional PI controller in terms performance indices such as integral squared error, rise time, peak time and peak overshoot (Madhavasarma and Sundaram, 2007). Sumathy and Sundaram (2011) designed

IMC based controller to oxygenate the bone wash effluent. They developed a model and implemented several controllers such as conventional PI, Smith predictor, Skogestad and IMC based controller. The performance was better in IMC based controller. Vijaya-Selvi *et al.* (2007) developed IMC based controller for a delayed mixing process which showed better setpoint tracking as well disturbance rejection. They analyzed the controller for robustness which resulted in better robustness measure in terms of sensitivity and complementary sensitivity functions. Nithya *et al.* (2008) implemented Mamdani and Takagi-Sugeno (TS) based Fuzzy logic controller (FLC) for two different non linear processes such as conical tank and spherical tank. TS based FLC outperformed both Mamdani based FLC and conventional controllers in terms of integral squared error and integral absolute error. Hardware for PID controller was designed and realized using current feedback technique by Erdal *et al.* (2001) which produced optimum performance tolerance. Abiyev (2001) suggested and implemented a Genetic Algorithm (GA) based approach for conventional PID controller and neural network controller. The GA based approach did not require depth knowledge of the process. A novel approach for neural PID and feed forward controllers based on GA was designed and simulated (Ajlouni and Al-Hamouz, 2004). The controllers designed on GA based approach resulted with good tracking of setpoint changes for known uncertainties of the process. Durmus and Yumusak (2008) realized Generalized Predictive Controller (GPC) and neural based GPC for a robot manipulator and concluded that neural based GPC outperformed GPC.

To heighten the importance of the proposed work a survey has been conducted on the number of paper published under the title 'humidity control' in the science direct journals is given in Fig. 1. The journal titled 'Energy and buildings' have published a maximum of 11 journals, followed by 'Applied thermal engineering' of 5. The journals titled 'Building and environment' and 'Computers and electronics in agriculture' published 4 each. From the above discussion we infer that the journals related to air conditioning for human comfort, heat transfer for cold storage are addressing more on humidity control. The survey also showed the number of papers in the area of humidity control from the year 2000. From Fig. 2, it is clear that papers published in the current year are high. The next highest number of publication was during the year 2006.

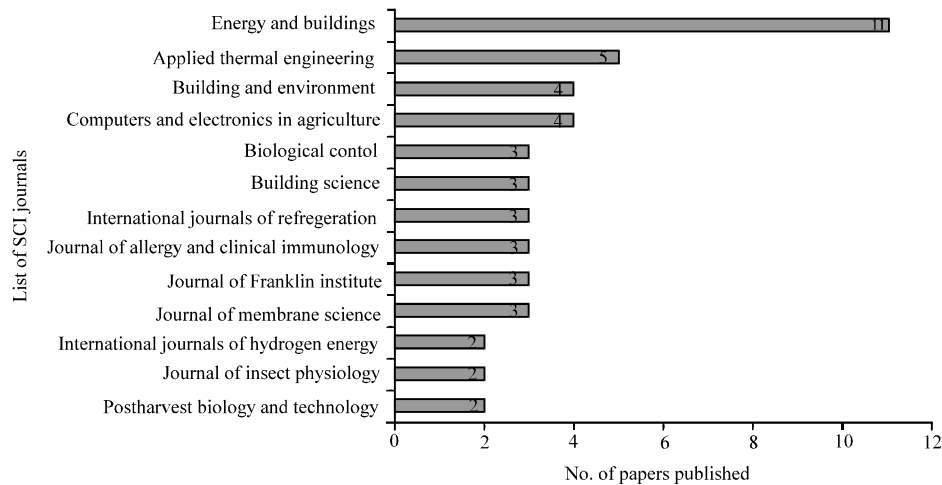


Fig. 1: Chart showing the numbers of papers published under the title humidity control in SCI journal

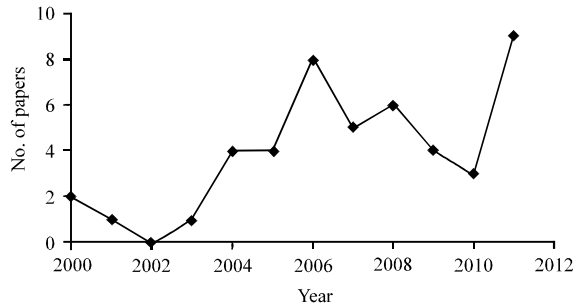


Fig. 2: The number of papers published titled humidity control in various SCI journals at different years

Table 1: Level of RH to be maintained in various process environments

| Process environment and product                 | RH level (%) |
|---|--------------|
| Cable wrapping                                  | 15-25        |
| Transformer winding                             | 15-30        |
| Sugar and milk powder storage                   | 20-35        |
| Capsule and powder storage, chemical laboratory | 30-45        |
| Books, paper archives, leather product          | 40-55        |
| Laboratory electronics                          | 45-60        |
| Computer peripherals                            | 50-60        |

### EFFECT OF HUMIDITY

The quality of product is getting affected in industries like textiles, food processing, pharmaceuticals and leather factories if a proper humidity level is not maintained. Human being also feel discomforted if a proper humidity is not maintained for a particular room temperature. The RH levels to be maintained in the process of different products are shown in Table 1.

**Crystal film formation with experimental design:** A study was conducted by Liao and Huang (2008) to obtain the effect of RH in the formation of the opal Photonic Band Gap (PBG) crystal films and concluded that the quality of PBG films were very high under RH controlled environment. For PBG crystal fabrication, three stages of silica particle deposition were done. The experimental procedure and artificial neural network were proposed to obtain the process model related to the film quality and RH environments for all the three stages. The experimental design showed that the structure of crystal deposition pattern of PBG film was random and disorder under low RH environment. Moreover the stop band intensities are also less under low RH. In higher RH environment, the stop band intensities are higher compared with lower RH. Out of three stages in the formation of PBG film, higher stop band intensities can be achieved as the RH level is increased from first stage to third stage. If RH level is reduced from second stage to third stage, the stop band intensities obtained also reduces.

**Use of artificial neural network (ANN):** ANN methodology was adopted for formation of PBG films. In this ANN approach also the RH level at the final deposition stage was influencing the stop band intensities. As compared with the first two stages, the higher RH level in the third stage produced the quality film in terms of stop band intensity. Liu *et al.* (2006) discussed that in the

PBG film deposition process which was divided into three stages, the third stage was critical with respect to level of RH both in stop band intensity as well as structure of the pattern.

### **CONTROL OF TEMPERATURE AND HUMIDITY**

Since humidity plays an important role in industries to maintain the product quality as well as human comfort in air conditioning system, it is clear that controlling the same is of prime importance. Some of the control techniques in literature are discussed here.

**Controller design for humidifying process:** Humidity process with transportation lag in laboratory scale was studied experimentally. The set up comprises humidifying chamber filled with water. Air from the compressor was bubbled into the chamber and humidified. The flow rate of air was manipulated by suitable valves and measured using rotameter. The exit air coming from chamber was made to flow through the coils of different length to introduce time delay. This system was modeled using process reaction curve method and model parameters were found. The model was a best fit for first order with dead time (FOPDT). Dead time was introduced into the system purposely to steady the effect of transport delay on the process.

#### **Procedure for system modeling:**

- Introduce setpoint change in step magnitude by manipulating the air flow rate
- Record the response with respect to time until the steady state is reached
- From the 'S' shaped curve obtain the model parameters using process reaction curve
- Obtain the transfer function from the model parameter
- Find the response equation using the obtained transfer function
- Find the calculated response with respect to time till it settles
- Validate the model by plotting experimental response and calculated response with respect to time
- Calculate the error between the calculated and experimental response
- If error is tolerable the model obtained is perfect one else use different method to find the model

For the identified model, the following control schemes were implemented.

**Conventional proportional integral (PI) controller:** For PI controller number of classical methods is available. In Ziegler and Nichols tuning strategy the controller gain is varied keeping the integral term as zero to attain the sustained oscillation of the system. From the knowledge of the controller gain and period of oscillation the controller settings are obtained. Cohen Coon method is the open loop approach. In this work Cohen Coon tuning methodology is implemented in which proportional and integral terms are found and are substituted in the corresponding modules.

**Internal model control (IMC):** This procedure is based on the model of the process. The basic structure of IMC is shown in Fig. 3. The input to the plant is also given to the model of the process. The difference between the output of the process and model are given as one of the inputs for the comparator where as in conventional controller, the other input to the comparator is the output from feedback signal. This approach results in better performance of the controller since it uses present status of the outputs from both process and model. The disadvantage of this method is that

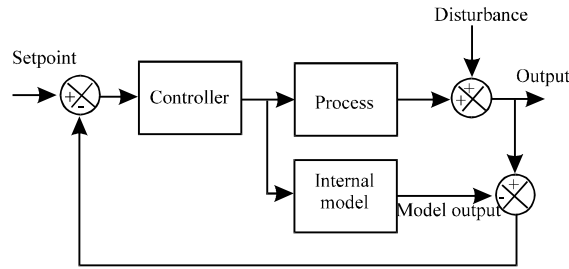


Fig. 3: Structure on IMC controller

the mismatch of the model with process. If both process and model are not matched, then the difference signal given to the input of the comparator will not be a right choice to perform the control action. Hence, the efficiency of the controller is based on the closeness of the model identified with the real process.

**IMC based PI controller:** This approach overcomes the difficulties of the IMC method and best suited for first order plus dead time process. The dead time is compensated with Pade approximation. A tuning filter factor is introduced in this approach and its value should not be too small. Hence it is approximately taken as dead time. The filter factor is a function of closed loop time constant. Rivera *et al.* (1986) suggested tuning rules for IMCPID which can be applied to first and second order systems with and without delay.

**Smith predictor compensator:** The dead time in the process is the most critical issue in designing the controller. Controller will not respond to any changes in the input until the dead time is elapsed. Hence the response of the system will be sluggish in nature. Smith compensator provides the useful attempt to rectify the effect of dead time. In this approach the dead time is isolated from the plant and the output signal from the plant bypasses the dead time component.

**Decoupled control of temperature and humidity in industrial processes:** Both humidity and temperature are coupled thermodynamic variables. In some of the industrial processes such as chemical and biochemical processes, printed circuit board manufacturing and crystallization processes, temperature and relative humidity are influencing factors which affect the quality of product. For most of the industrial processes, it is essential to control temperature and RH independently. The conventional control techniques do not perform satisfactorily. Gomez and Reyes (2001) have presented a decoupled control technique for controlling temperature and RH. They designed a non interacting controller for variable-air-volume HVAC system as an inner loop and for outer loop they designed PD controller.

In simulation, two cases were studied. In the first case, temperature set point was changed keeping RH at a constant value. In the second case variation in RH set point for constant temperature was studied. In both the cases the non interacting controller for independent control of temperature and humidity outperformed the other conventional controller. They concluded that the behavior of the proposed controller for decoupled control of temperature and RH for industrial processes was attractive.

**Independent control in air conditioning system of a building:** In conventional HVAC system, air is cooled and moisture is removed by condensation. In almost all the cases of HVAC system, the sensible load of the building covers major portion of the cooling load whereas the latent

load (moisture load) is only a minor part. The source of cooling temperature required for latent load is much less compared to sensible load. But both sensible and latent loads use the same cooling coil for condensation which leads to lot of energy wastage (Waugaman *et al.*, 1993).

Zhao *et al.* (2011) proposed a methodology to control the temperature and humidity independently (THIC) which was tested in an office building at China. In their THIC system, they utilized two subsystems one for indoor temperature (sensible load) and other for humidity (latent load) for independent control. The heat pumps which drive the liquid-desiccant-fresh-air handling units were utilized as source for removal of latent load while for controlling the sensible load, chilled water at 17.5°C was used.

**Energy efficiency and energy consumption of the proposed system:** A field test was conducted to study the energy efficiency of the THIC system. The test was carried out under different environmental conditions in different occasions, like high temperature and low humidity and low temperature and high humidity environment. Their results indicate that the coefficient of performance (COP) of the humidity control subsystem obtained under different environmental condition was varying from 4.0 to 4.4 as cooling capacity changed from 773 to 915 kW. Similarly for the temperature control subsystem, the coefficient of performance varied from 3.7 to 4.1 as cooling capacity changed from 446.1 to 543.4 kW under different environmental conditions.

The energy consumption of this THIC system also varied from 22.6 to 32.2 kWh under different ambient conditions whereas for the conventional HVAC system it was around 42 kWh. Hence, the proposed system achieved better energy consumption as well as energy efficiency compared to conventional air conditioning system. Though the initial cost of the proposed THIC system for office building was 10 to 20% higher than the conventional system, the added cost can be regained within two years.

**Adaptive neuro fuzzy inference system (ANFIS) based control:** In HVAC system, the humidity and temperature are controlled using ANFIS. The damper gap rates for humidity and temperature were controlled by PID controller for the interested indoor volume. Soyguder and Alli (2009) have obtained PID parameters theoretically for controlling the damper gap rates using fuzzy sets. In their later work (Soyguder *et al.*, 2009) simulation of ANFIS based controller was carried out for damper gap rate. The experimental work was conducted using PID control algorithm.

ANFIS is the fuzzy inference system which uses the advantages of neural network and fuzzy system to perform control action. The Sugeno type fuzzy inference system parameters are identified using hybrid learning algorithm. The membership function parameters are trained with the help of back propagation and least squares technique.

The ANFIS structure (Fig. 4). Out of its five layers the first layer is the input layer receiving two different inputs. The nodes this layer is of square in shape and the number of nodes is equal to the number of membership function. The linguistic label of the fuzzy inference system is decided by this layer. Layer 5 is of single node which computes the overall output of ANFIS. Layers 2, 3 and 4 are the hidden layers which are responsible for multiplying the input signals and calculating the firing strength of the rules.

In this study, the ANFIS was used to predict and control the HVAC system. Different membership functions were tried to get the best model for damper system. For humidity control dampers 3 membership functions of triangular shape resulted with root mean square error (RMSE) of 16.6940 and of Gaussian shape with RMSE of 10.6950. The temperature control dampers produced RMSE of 34.8585 for Pi shaped 2 membership functions and of 0.7918 for 3 membership



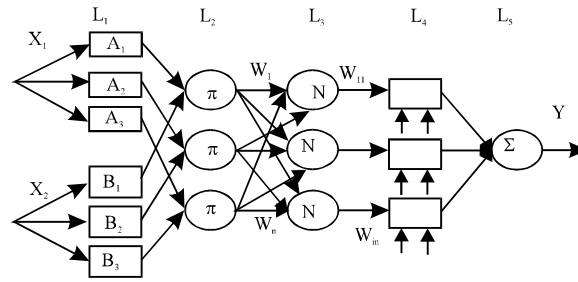


Fig. 4: ANFIS architecture (Soyguder and Alli, 2009). X<sub>1</sub>, X<sub>2</sub>: Input variable, A<sub>1</sub>, A<sub>2</sub>, A<sub>3</sub>: Linguistic label corresponding to input X<sub>1</sub>, B<sub>1</sub>, B<sub>2</sub>, B<sub>3</sub>: Linguistic label corresponding to input X<sub>2</sub>, L<sub>1</sub>-L<sub>5</sub>: Layers 1 to 5, W<sub>1</sub>-W<sub>n</sub>: Firing strength of rules from L<sub>2</sub>, W<sub>11</sub>-W<sub>1n</sub>: Normalized firing strength of rules from L<sub>3</sub>, Y: Overall output of ANFIS

function of generalized bell curve. The HVAC system was controlled using ANFIS approach with reduced steady state error and speedy settling time compared with other conventional techniques.

**Controller based on MIMO (Multiple-input-multiple-output):** Qi and Deng (2009) have proposed a multivariable control system using Linear Quadratic Gaussian (LQG) technique to control humidity and temperature in direct expansion air conditioning system. Simultaneous control signals are generated for both compressor speed and supply fan speed to regulate temperature and humidity, respectively.

The LQG controller is based on Kalman filter (Observer based compensator) which is estimating unmeasured state variables. The controller was tested for both set point tracking and disturbance rejection capabilities. In set point tracking, the controller forced the process to reach the new set point for either of the variable without affecting the other controlled variable. The new set point for humidity was reached without affecting the temperature and vice versa. Similar kind of results was obtained for disturbance rejection also. The proposed controller for direct expansion air conditioning system overcomes all difficulties in on-off control and conventional control techniques to control temperature and humidity with adequate control accuracy and sensitivity.

**Robust control technique:** For livestock building a non linear robust control technique was presented by Soldatos *et al.* (2005) to control the temperature and humidity. The farm animals inside the livestock buildings should be safeguarded with good environment to provide healthy condition as well as efficient animal production. The quality of environmental condition is influenced by many parameters such as temperature and humidity. In their work, they presented a non linear robust control technique for controlling the environmental condition. In this approach, unknown and bounded errors such as floor water evaporation in the building were considered. The proposed control scheme was simulated for a pig house which resulted accurate tracking of set point and excellent rejection of external disturbances. The technique can be applied for air conditioning system also.

**Design of control strategy:** Non linear robust control is based on the state equation shown below:

$$\frac{dx}{dt} = Ax + Bu + C_1 v_1 + Cv \quad (1)$$

$$x(t_s) = x_s \tag{2}$$

where,  $x$ ,  $u$ ,  $v_1$  and  $v$  are state vector, winter or summer control inputs, measured and unmeasured disturbance, respectively.

A, B,  $C_1$  and C are the matrices corresponding to state, input, measured and unmeasured disturbances.

The control equation derived is given in Eq. 3:

$$u_{a,w} = Kx + p_c(x) - F_1 v_1 + u_{s,w}^* \tag{3}$$

where, s and w stands for summer and winter.

The first two components constituting the feedback action of robust controller used to nullify the effect of unmeasured but bounded disturbances. The third and fourth part of the equation is governing the feed forward action and is used to suppress the measured disturbance.

## DISCUSSION

In the formation of PBG films RH level in third stage influences the stop band intensity. Table 2 is drawn taking 100% stop band intensity if the RH level in all the three stages is 90% for the first sample. From this it is inferred that stop band intensity becomes poorer as the RH level reduces from stage 1 to 3.

The decoupled non interacting control acted well for both temperature and humidity set point changes. At a constant RH of 80%, the change in set point from 50 to 70°F was introduced. The controller reduced the supply air rate as well as the flow rate of chilled water to maintain the RH to a set value. In similar way at a constant temperature of 75°F, a change in set point of humidity from 60 to 80% was introduced in which the controller performed well to maintain the temperature at constant value.

For THIC system the energy efficiency was calculated based on COP. The COP for this system was around 4.0. For the conventional air conditioning system which uses cooling coil and supply air the COP was only 3.0 which are very less compared with THIC system.

PID control algorithm was implemented experimentally to adjust the damper gap rates for the control of humidity and temperature. PID parameters were obtained using fuzzy modeling approach with optimization. Simulation results showed (Soyguder *et al.*, 2009) that the ANFIS is the best alternative for predicting and controlling the damper gap rate in HVAC system.

MIMO control regulated either humidity or temperature simultaneously without affecting the set point of the other variable in both set point tracking and disturbance rejection. The controller was tested for a smaller operating region but not for all operating conditions. The authors (Qi and Deng, 2009) did not address the energy efficiency.

Table 2: Showing reduction in stop band intensities for different RH level in different stages

| Sample | RH level I stage | RH level II stage | RH level III stage | Reduction intensity (%) |
|--------|------------------|-------------------|--------------------|-------------------------|
| 2      | 90               | 50                | 50                 | 78.7                    |
| 3      | 50               | 50                | 50                 | 54.0                    |
| 4      | 50               | 50                | 90                 | 24.7                    |

Table 3: Merits and demerits of various control schemes used in the literature

| S. No. | Schemes | Merits   | Demerits  |
|--------|---------|--|---|
| 1      | THIC    | Lesser energy consumption and better energy efficiency   | Simultaneous control of temperature and humidity is not possible                          |
| 2      | ANFIS   | Faster settling time and reduced steady state error  | Only simulation results were obtained. The controller was not tested in real time         |
| 3      | MIMO    | Adequate control accuracy and sensitivity both in set point tracking and disturbance rejection   | Applicable only for a specific operating point. Not implemented for wider operating range |
| 4      | Robust  | Cancelling the measured and unmeasured disturbances while tracking the set point. Does not require prior knowledge of uncertain inputs | Not implemented for drastic changes in weather conditions                                 |

Robust control applied the combination of both feedback and feed forward control. The unknown and external disturbances were cancelled out since it was using a non linear robust control technique. Unlike the non linear control that can be implemented for limited region, this approach (Soldatos *et al.*, 2005) is best suited for any kind of uncertainties.

From Table 3, it is evident that each control schemes are having its own merits and demerits. The real time implementation of ANFIS based controller can be performed by the researchers. Robust control scheme may be tested in a real farm house throughout the year to incorporate the external disturbances.

## CONCLUSION

Humidity affects not only the quality of the products in industries such as textile, pharmaceuticals, food processing, pulp and sugar industries but also the human comfort. Lots of humidity control techniques are available in literature and some them were reviewed in this paper. IMC controller produces faster settling time and less overshoot for a laboratory level humidity process. Since humidity and temperature are interrelated variables the researchers address the regulation of both the variables in majority of the papers. The independent control of humidity and temperature consumed lesser energy compared with other conventional HVAC system. ANFIS based control resulted with faster settling time and lesser steady state error. The MIMO control strategy which uses LQG controller based on Kalman filter algorithm and provided good control accuracy and sensitivity. Robust controller design performed well which nullified the measured and unmeasured disturbances.

## ACKNOWLEDGMENT

Authors are expressing sincere gratitude to Mr. Rengarajan Amirtharajan, Senior Assistant Professor, SASTRA University, who has been a source of encouragement and moral support throughout this work.

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