2005 American Control Conference
June 8-10, 2005. Portland, OR, USA

Fuzzy Ventilation Control for Zone Temperature and Relative Humidity

Mohamed Mahmoud Gouda, *Member, IEEE*, *Member, IEE*

***Abstract*— Many non-domestic and domestic buildings, built recently around the world, use natural means to provide ventilation for indoor air quality and thermal comfort. The fuzzy ventilation control strategy aims to use the free cooling and dehumidification available due to differences in zone and ambient conditions. This can achieve by changing the proportion of fresh air entering the heating, ventilation and air conditioning (HVAC) system and hence the controlled zone. The fuzzy ventilation controllers also aim to maintain the zone conditions at a preferred set point which lies between the upper and lower set points. The upper and lower set point limits and the preferred set point for fuzzy ventilation control purposes are set to ensure occupant comfort. Hence when the fuzzy ventilation control strategy is not capable of maintaining the zone conditions within the upper and lower set-point limits the HVAC plant become active. Simulations results using the fuzzy ventilation control strategy are compared with normal plant considering PID controllers with upper and lower set point limits for each controlled parameter. This benchmark comparison is used to assess the benefits of using the fuzzy ventilation control strategy.**

I. Introduction

Ventilation is a method to maintain good indoor air quality. The more fresh air is brought into the indoor environment, the better the indoor air quality can be achieved if the fresh air comes from non-polluted ambient source. However, conditioning fresh air can consume a lot of energy, especially in the areas where the humidity is high in summer. It has been noticed that 30% or more of the annual heating and cooling cost is spent in handling the fresh air in a typical office building [1, 2].

Over-ventilation may lead to a significant waste of energy. Therefore, an operationally cost-effective ventilation control system is very important in domestic and non-domestic buildings. Ventilation control system strategies such as sensible temperature-based air-side economizer, enthalpy-based air-side economizer and demand control ventilation (DCV) have been demonstrated in buildings all over the world. The sensible temperature-based air-side economizer uses the outdoor air temperature (dry-bulb temperature) as the control signal to adjust the fresh air supply to the prescribe supply rate. It usually reduces the annual cooling energy by around 30% in moderate climates such as in Columbia, MO, and US [3, 4]. The enthalpy-based air-side economizer considers the total heat of the outside, re-circulated and mixed air to determine the fresh air supply rate. It achieves a better performance than the sensible temperature-based air-side economizer in terms of energy saving because it traces both the sensible and latent heat of the dry-air and moisture, especially in highly humid climates. On the other hand, the enthalpy sensor is much more expensive and it usually needs a semi-annual calibration.

The main advantages of improving indoor environmental quality include: more contented and satisfied employees, less absenteeism and fewer accidents [5-10].

Fuzzy logic offers an alternative to conventional ventilation controllers [11]. By suitable selection of input/output linguistic variables and a rule base, a broad range of desirable control outcomes can be achieved. Possible features might include user-specified overall control 'tightness' analogous to a control range, closer adherence to set point conditions if desired, and the ability to explicitly set the trade-off between energy costs and interior environment.

This paper investigates the use of fuzzy logic controllers for controlling of the re-circulation air damper in the Simulink model as a means of adjusting the zone temperature and humidity. Results from simulations using the fuzzy ventilation control strategy were compared with normal plant operation using PID controllers. This benchmark comparison was used to assess the benefits of using the fuzzy ventilation control strategy.

II. Fuzzy Ventilation Controller Operation

A. General Aims of the Fuzzy Ventilation Controllers

The fuzzy ventilation controllers primarily aim to improve energy consumption and comfort conditions with respect to cooling, dehumidification and air quality. It is possible to use ambient cooling because zone temperatures often rise above outside temperatures due to solar and occupant gains within the zone. This allows the zone temperature to decrease by introducing cooler fresh outdoor air. Situations rarely occur when the outdoor temperature is above that of the zone and HVAC plant is required to be operational due to the zone temperature

Manuscript received September 15, 2004. M. M. Gouda is with the Industrial Education College, Cairo, Egypt (e-mail: mohamedgouda1967@yahoo.com).

0-7803-9098-9/05/$25.00 ©2005 AACC

being below the required set point. Therefore ambient heating is not considered within the fuzzy ventilation control strategy.

Dehumidification using the ambient air can be achieved where humidity levels rise to undesirable levels due to occupant or process gains within the zone. It is considered as part of the fuzzy ventilation control strategy. By introducing outside air to the controlled zone with lower moisture content than the zone air, the zone relative humidity can be reduced. In contrast, humidification as part of the fuzzy ventilation control strategy was in practice unlikely to be feasible. Even though high humidity levels may exist outside while indoor levels are low, the moisture content of the air needs to be considered. A nominally high relative humidity in the outdoor air does not mean that it has high moisture content. For example air at 5^{o}C and 80% RH has a moisture content of 0.0044kg per kg of dry air. If this air were to be heated to 20^{o}C without the addition of moisture its relative humidity would be 30%. Consequently, ventilating the ambient air directly into the zone will not increase the relative humidity when the air temperature needs to be raised to a comfortable level. Thus ambient humidification is not considered as part of the fuzzy ventilation control strategy.

The indoor air quality was controlled in the same way when the (Proportional + Derivative Fuzzy Control) PDFC control strategy with the CO_2 concentration of the air is used as an indicator of indoor air quality. Introducing fresh outdoor air into the zone is the only method of controlling the air quality by practical means.

With respect to zone temperature control, a fuzzy controller considers the differential between zone and ambient temperatures. With respect to zone relative humidity control, a fuzzy controller considers the differential between the zone and ambient air moisture contents. The fuzzy ventilation controllers decide whether it is preferable to cool or dehumidify using ambient fresh air. Then it controls the fresh air re-circulation damper to achieve the preferred set point as possible. The preferred set points for temperature and humidity are 22^{o}C and 45% RH. This temperature humidity combination results in a 5% PPD (Predicted Percentage Dissatisfied) level, while the minimum PPD achievable according to Fanger [12].
During simulations, the zone parameters were allowed to drift between the upper and lower set point limits unless the fuzzy ventilation controllers took advantage of the opportunity to bring a zone parameter towards its preferred set point. Zone air quality considerations always took priority over temperature and humidity considerations for the control of the re-circulation damper when the desired re-circulation damper position value of the air quality controller was the largest.

B. Fuzzy Ventilation Controller Structure

A schematic of the structure of the fuzzy ventilation controllers is shown in Fig. 1. The basic principle of operation of the fuzzy ventilation controller is that of a PDFC controller but with the extra input of the ambient to zone parameter differential. The parameter differential is used to make a decision on whether it is possible to cool or dehumidify using the ambient air. Referring to Fig. 1, the principle of operation of a fuzzy ventilation controller is as follows:-

- The error, the rate of change of error and the difference between the ambient and zone condition under consideration are used as the three inputs to the fuzzy controller.
- PDFC with the extra input information of the difference between the ambient and zone conditions assesses the current zone condition under consideration and decides whether any benefit can be gained from altering the position of the re-circulation damper for the purposes of free cooling or dehumidification.
- PDFC controllers control the HVAC plant components as normal and are operational when the controlled zone parameter drifts beyond the upper and lower set point limits.
- The air quality requirements of the zone controlled by a separate controller have priority over the cooling and dehumidification ventilation controllers.

The membership functions for the normalized error and the rate of change of error are shown in Fig. 2. The membership functions for the zone-ambient parameter value difference are shown in Fig. 3. The normalized output membership functions for the fuzzy ventilation strategy controllers are shown in Fig. 4. The 75 (5x5x3) rules can be reduced to 27 rules by removing redundant rules. For the fuzzy ventilation controllers under consideration increased ventilation is not required when the ambient condition is higher than the zone condition. The control rules relating the fuzzified input values to the fuzzy output are:-

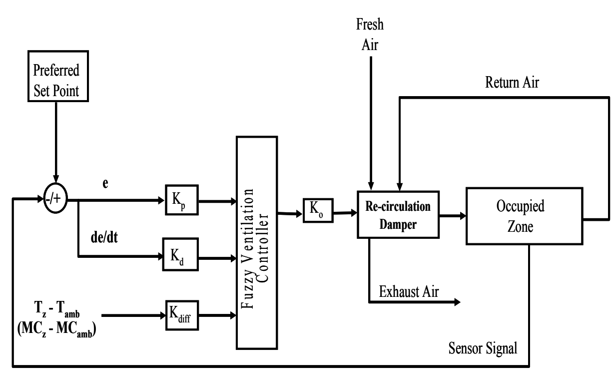

Fig. 1. Fuzzy Ventilation Controller Structure

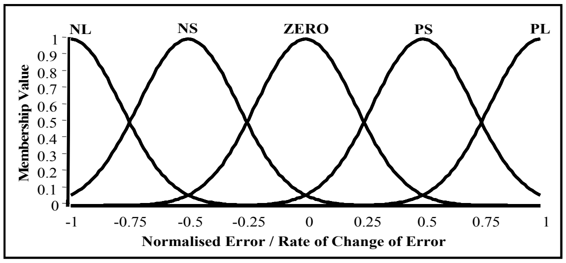

Fig. 2. Normalized error and rate of change of error input membership functions for the fuzzy ventilation controller.

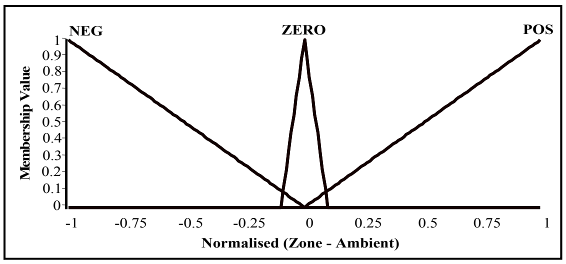

Fig. 3. Normalized membership functions for the difference between the zone and ambient condition under consideration.

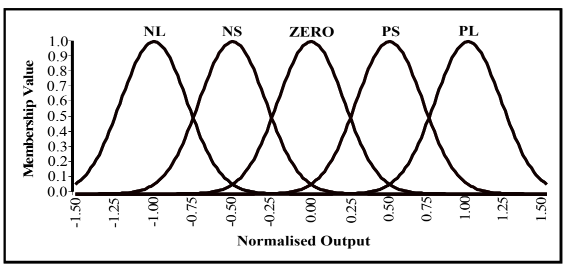

Fig. 4. Normalized output membership functions for the fuzzy ventilation strategy controller.

1. **IF** (Error is PL) **AND** (Rate is PL) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
2. **IF** (Error is PL) **AND** (Rate is PS) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
3. **IF** (Error is PL) **AND** (Rate is ZERO) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
4. **IF** (Error is PL) **AND** (Rate is NS) **AND** (Zone-Amb is POS) **THEN** (Damper is NS)
5. **IF** (Error is PL) **AND** (Rate is NL) **AND** (Zone-Amb is POS) **THEN** (Damper is ZERO)
6. **IF** (Error is PS) **AND** (Rate is PL) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
7. **IF** (Error is PS) **AND** (Rate is PS) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
8. **IF** (Error is PS) **AND** (Rate is ZERO) **AND** (Zone-Amb is POS) **THEN** (Damper is NS)
9. **IF** (Error is PS) **AND** (Rate is NS) **AND** (Zone-Amb is POS) **THEN** (Damper is ZERO)
10. **IF** (Error is PS) **AND** (Rate is NL) **AND** (Zone-Amb is POS) **THEN** (Damper is PS)
11. **IF** (Error is ZERO) **AND** (Rate is PL) **AND** (Zone-Amb is POS) **THEN** (Damper is NL)
12. **IF** (Error is ZERO) **AND** (Rate is PS) **AND** (Zone-Amb is POS) **THEN** (Damper is NS)
13. **IF** (Error is ZERO) **AND** (Rate is ZERO) **AND** (Zone-Amb is POS) **THEN** (Damper is ZERO)
14. **IF** (Error is ZERO) **AND** (Rate is NS) **AND** (Zone-Amb is POS) **THEN** (Damper is PS)
15. **IF** (Error is ZERO) **AND** (Rate is NL) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
16. **IF** (Error is NS) **AND** (Rate is PL) **AND** (Zone-Amb is POS) **THEN** (Damper is NS)
17. **IF** (Error is NS) **AND** (Rate is PS) **AND** (Zone-Amb is POS) **THEN** (Damper is ZERO)
18. **IF** (Error is NS) **AND** (Rate is ZERO) **AND** (Zone-Amb is POS) **THEN** (Damper is PS)
19. **IF** (Error is NS) **AND** (Rate is NS) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
20. **IF** (Error is NS) **AND** (Rate is NL) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
21. **IF** (Error is NL) **AND** (Rate is PL) **AND** (Zone-Amb is POS) **THEN** (Damper is ZERO)
22. **IF** (Error is NL) **AND** (Rate is PS) **AND** (Zone-Amb is POS) **THEN** (Damper is PS)
23. **IF** (Error is NL) **AND** (Rate is ZERO) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
24. **IF** (Error is NL) **AND** (Rate is NS) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
25. **IF** (Error is NL) **AND** (Rate is NL) **AND** (Zone-Amb is POS) **THEN** (Damper is PL)
26. **IF** (Zone-Amb is NEG) **THEN** (Damper is NS)
27. **IF** (Zone-Amb is ZERO) **THEN** (Damper is NS)

Identical controllers were used for both fuzzy ventilation cooling and fuzzy ventilation dehumidification but with different input and output gain factors. The fuzzy ventilation controllers were tuned using an iterative process of trial and error until satisfactory performance was obtained.

III. Fuzzy Ventilation Controller Simulation Results

The fuzzy ventilation control strategy was compared with the conventional PID strategy controlling to upper and lower set points. Simulations were initially carried out for a one week period to tune and assess the operation of the fuzzy ventilation controllers. Once their performances were considered adequate, one week simulations were carried out for each of the 52 weeks of one year based on a given weather data. This enabled a comprehensive assessment of controller performance based on provided zone conditions and energy consumption over a realistic time period while being subjected to various ambient weather conditions. The occupancy pattern profile used for the simulations is shown in Fig. 5. The HVAC plant is able to operate between 05:00 and 17:00.

A. Fuzzy Ventilation Cooling Control Strategy - One Week Trial Simulation

The fuzzy ventilation cooling control strategy is compared with a normal PID control strategy operating between upper and lower control set points for the week April 23-29 to give the reader a graphical view of the way in which the controller operates. Fig. 6 shows the zone temperature and cooling valve operation for the two control strategies. Fig. 6 shows by using the fuzzy ventilation cooling control strategy a significant reduction in the need for plant cooling operation is achieved. Further, it can be seen that the fuzzy control strategy maintains the zone temperature closer to the preferred set point during the occupied periods. The fuzzy control strategy improves temperature conditions within the space through the use of the re-circulation air damper for ambient cooling purposes, see Fig. 7. The fuzzy ventilation cooling strategy further aimed to maintain the zone temperature at the preferred set point (broken line, Fig. 6).

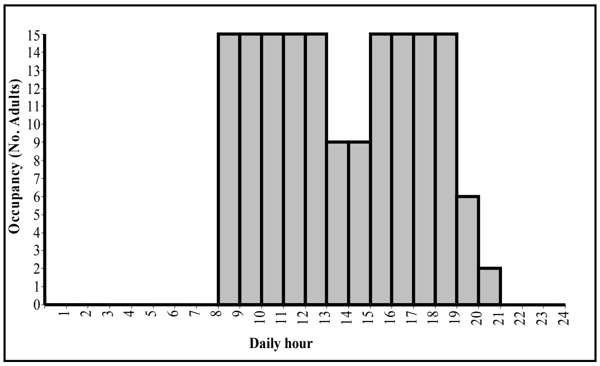

Fig. 5. Occupancy pattern used for the fuzzy ventilation control simulations.

A consequence of this is that after working hours, i.e. 5:00 p.m., the zone temperature reaches the lower limit of the control band more quickly for the fuzzy ventilation cooling strategy than for PID due to the building fabric being cooler at the time when temperatures start to decrease. The consequence of this is that the heating plant is operational for longer and hence heating energy usage is greater for the fuzzy ventilation cooling strategy than the PID. This is confirmed in Fig. 8. However, the resulting higher energy use for the fuzzy ventilation cooling strategy is more than offset by the decreased energy consumption for cooling purposes.

Dehumidification via the use of cooling coil was not required during the simulation period considered for either the PID control strategy or fuzzy cooling strategy for the week under consideration. However, a result of using ventilation cooling in the simulation week considered is the requirement for some humidification during the 132 - 144 hour period, see Fig. 9. An additional benefit of using the fuzzy ventilation cooling control strategy can be seen in Fig. 10. Due to the increased fresh air ventilation rates associated with the fuzzy cooling ventilation strategy for free cooling purposes, the CO_2 concentrations are also reduced in the occupied zone.

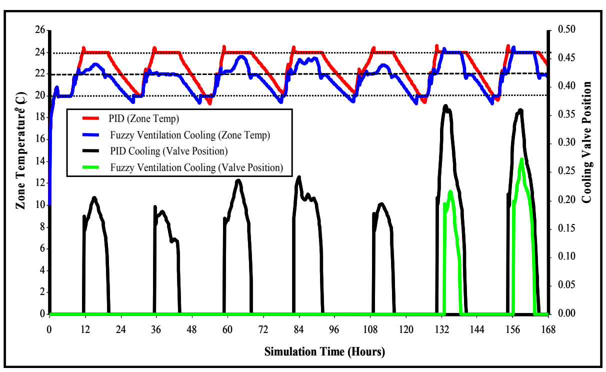

Fig. 6. Zone temperature and cooling valve positions for the normal PID and the fuzzy ventilation control strategy.

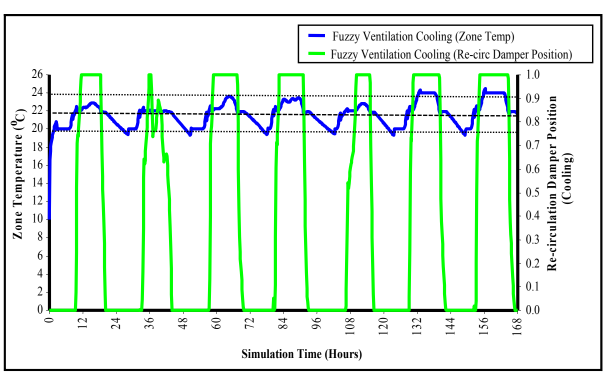

Fig. 7. Zone temperature and damper (cooling) position for the fuzzy ventilation cooling strategy control simulation.

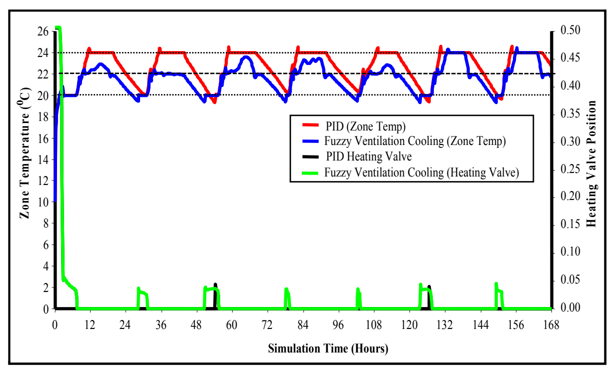

Fig. 8. Zone temp. and heating valve positions for PID and fuzzy ventilation cooling control.

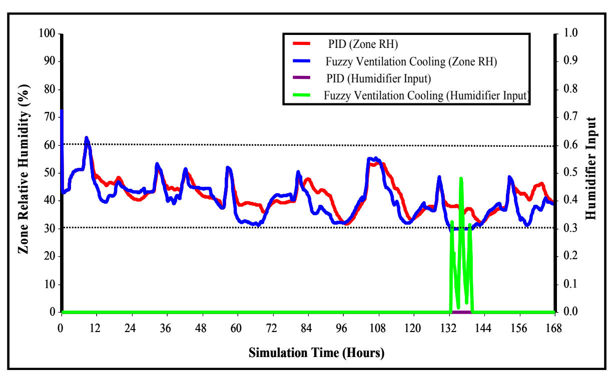

Fig. 9. Zone relative humidity and humidifier input for PID plant operation and fuzzy ventilation cooling strategy control.

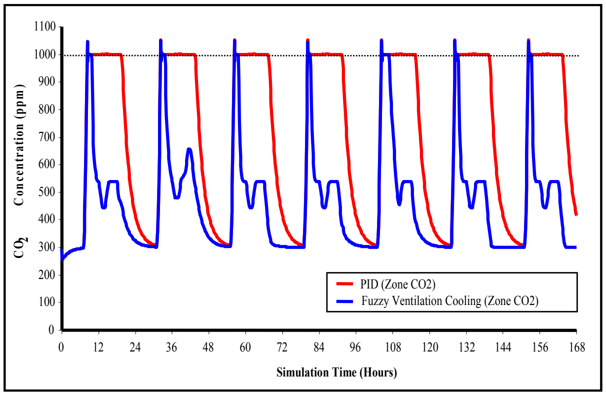

Fig. 10. Zone CO2 concentrations for PID plant operation and fuzzy ventilation cooling strategy control.

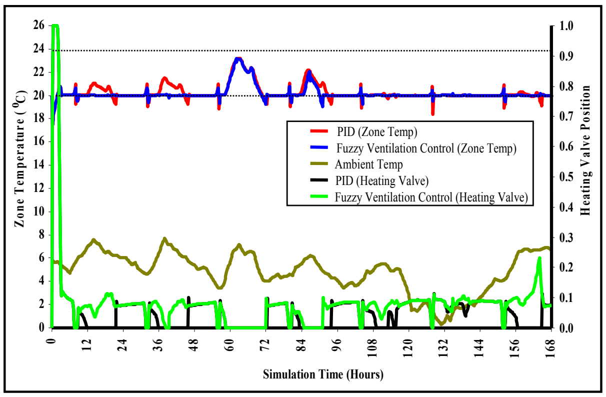

Fig. 11. Zone temperature, ambient temperature and heating valve position for PID control and fuzzy ventilation dehumidification control.

B. *Fuzzy Ventilation Dehumidification Control Strategy - One Week Trial Simulation*

Using a similar methodology to fuzzy ventilation cooling this strategy attempted to utilize the free dehumidification available where the zone moisture content was higher than the ambient moisture content and the zone relative humidity was above the preferred set point. Again, the occupancy pattern shown in Fig. 5 was used and repeated for all seven days of the simulated week.

Fig. 11 shows the zone temperatures and heating valve positions for the simulation of the chosen week. No plant cooling was required for the simulation period due to the zone temperature remaining below the upper set point limit. However, the cooling plant is operational where plant dehumidification is required in order to reduce the air temperature to below its dew-point temperature for the removal of moisture. Fuzzy ventilation cooling was not operational for this simulation. Fig. 11 shows that the zone temperature using the fuzzy ventilation strategy often remained close to the lower set point limit. The desired re-circulation air damper position for dehumidification purposes is shown in Fig. 12.

Fig. 12 shows how the fuzzy ventilation controller attempted to bring the zone relative humidity closer to the preferred set point when humidity levels rise above the preferred set point. Zone and ambient moisture contents are shown graphically in Fig. 13 for the simulated week for the PID and fuzzy ventilation dehumidification strategies. The zone/ambient differential value for the moisture contents was used as an input to the fuzzy ventilation dehumidification controller. Superimposed over these values is the moisture content value of the zone air for normal PID control during the same simulated week which show what the moisture content values would be if the fuzzy ventilation strategy was not operational. The zone/ambient moisture content differential value used as an input to the fuzzy ventilation dehumidification controller allows the controller to decide whether dehumidification is possible using increased fresh air ventilation rates when required.

The resulting zone humidity conditions resulting from the use of the PID control and fuzzy ventilation dehumidification control strategies are shown in Fig. 14.

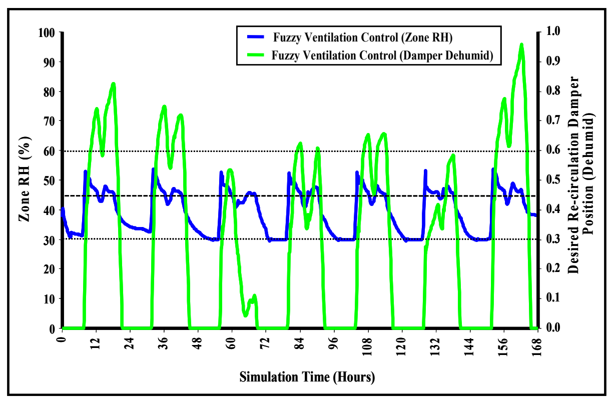

Fig. 12. Zone relative humidity and desired re-circulation damper position for the fuzzy ventilation dehumidification control strategy.

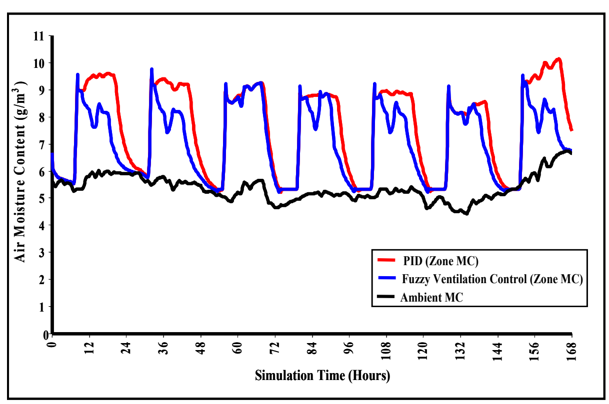

Fig. 13. Air moisture for normal PID plant operation, fuzzy ventilation dehumidification strategy control and ambient conditions.

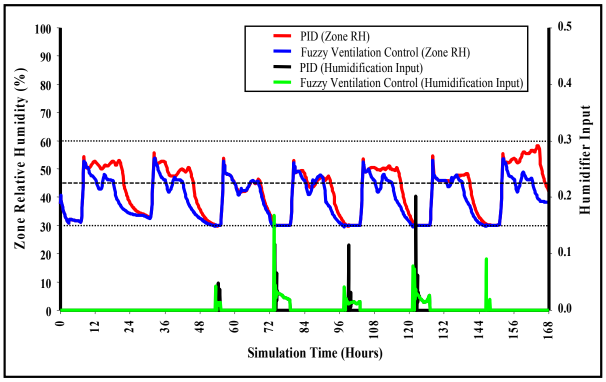

Fig. 14. Zone relative humidity and humidifier input positions for normal plants operation and fuzzy ventilation dehumidification strategy control.

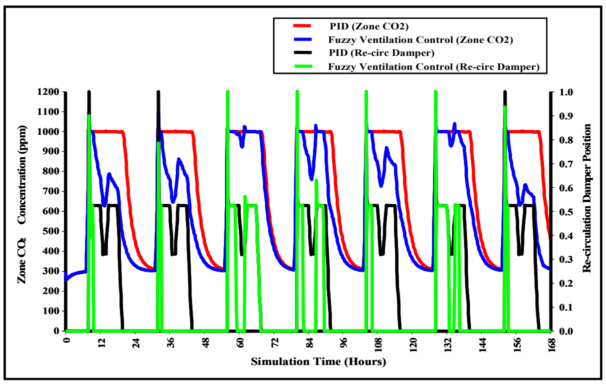

Fig. 15. Zone CO_2 concentrations and re-circulation air damper positions for normal PID plant operation and fuzzy ventilation dehumidification strategy control.

As a result of the use of the fuzzy ventilation dehumidification strategy there was a requirement for humidification using the plant slightly earlier than for the normal strategy towards the end of some days, see Fig. 14.

Fig. 14 shows graphically an improvement in provided relative humidity conditions for the fuzzy ventilation dehumidification control strategy during occupied period Due to the increased fresh air supply rates using the fuzzy ventilation control for dehumidification purposes the zone air quality is improved when compared to the normal PID strategy as shown in Fig. 15

IV. Conclusion

Fuzzy ventilation control strategies for ambient cooling and dehumidification have been developed in this paper. Combinations of the adaptive and steady state approaches to thermal comfort have been considered to define the set point ranges and preferred set points. Upper and lower set points have been defined such that combinations of zone temperature and humidity would not cause a Predicted Percentage Dissatisfied (PPD) value of greater than 10% using the steady state approach.

The temperature and relative humidity ranges defined using this criterion were 20^{o}C - 24^{o}C and 30% - 60% respectively. When the zone conditions drifted beyond these ranges the HVAC plant was used to bring the conditions within the range. Preferred set points of 22^{o}C and 45% RH were also defined and represented a PPD of 5% where both conditions were satisfied simultaneously. The fuzzy ventilation controllers attempted to converge the zone conditions towards these preferred set points when possible using free cooling and dehumidification through the use of the fresh air re-circulation damper. Overall, the yearly assessment of the fuzzy ventilation control strategies therefore have been showed a reduction in energy consumption and an overall improvement in the environmental conditions provided.

References

[1] B. A. Rock, and C. T. Wu, “Performance of fixed, air-side economizer, and neural network demand-controlled ventilation in CAV systems,” ASHRAE Transactions, vol. 102, part 2, 1998, pp. 234-245.

[2] B. F. Warren, “Energy saving in buildings by control of ventilation as a function of indoor carbon dioxide concentration,” Building Services Engineering Research & Technology, vol. 3, part 1, 1982, pp. 4-12.

[3] J. D. Spitler, D. C. Hittle, D. L. Johanson, and C. O. Perderson, “A comparative study of the performance of temperature-based and enthalpy-based economy cycle,” ASHRAE Transactions, vol. 93, part 2, 1987, pp. 13-22.

[4] D. K. Dickson, and S. T. Tom, “Economizer control systems,” ASHRAE Journal, vol. 28, part 9, 1986, pp. 32-36.

[5] J. M. Allison, J. M. White, J. W. Worley, and F. W. Kay, “Algorithms for microcomputer control of the environment of a production broiler house,” ASAE Transactions, vol. 34, part 1, 1991, pp. 313-320.

[6] G. Zhang, S. Morsing, and J. S. Astrom, “An airflow pattern control algorithm for livestock buildings,” In: E. Collins, and C. Boon, (Eds), "Livestock Environment IV," ASAE , St. Joseph, MI 49085, 1993, pp. 779-355.

[7] Y. Zhang, E. M. Barber, and H. C. Wood, “Analysis of stability of livestock building HVAC control systems,” ASHRAE Transactions, vol. 99, part 2, 1993, pp. 273-244.

[8] K. Chao, R. S. Gates, and H. C. Chi, “Diagnostic hardware/software system for environment controllers,” ASAE Transactions, vol. 38 part 3 1995 pp. 939-947.

[9] M. B. Timmons, R. S. Gates, R. W. Carter, T. A. Brake and M. J. Wineland, “Simulation analysis of a new temperature control method for poultry housing,” Journal of Agric. Eng. Res., vol. 62, 1995 pp. 237-245.

[10] K. Chao, and R. S. Gates, “Design of switching control systems for ventilated greenhouses,” ASAE Transactions, vol. 39 part 4 1996 pp. 1513-1523.

[11] R. S. Gates, M. B. Timmon, D. G. Overhults, and R.W. Bottcher, “Fuzzy reasoning for environmental control during periods of heat stress,” In: R. W. Bottcher, and S. J. Hoff, (Eds), "Livestock Environment V, vol I" ASAE , St. Joseph, MI 49085, 1997, pp. 553-562.

[12] P.O. Fanger, "Thermal Comfort – Analysis and Applications in the Environmental Engineering," Book, McGraw Hill, 1972.