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Supervised fuzzy control for zone temperature and relative humidity

Mohamed Mahmoud Gouda, Ayman Haggag

Faculty of Industrial Education, Helwan University, Cairo, Egypt.

Abstract

An important aspect of the building services system which can have a major effect on the provision of occupant comfort within a building is the adopted control strategy. This paper investigates the use of a supervised fuzzy controller as a means of achieving good standards of comfort provision for occupants while maintaining or improving energy and cost efficiencies for the operation of the building heating, ventilation and air conditioning (HVAC) services. This represents a multi-variant controls objective which is capable of being fulfilled by a fuzzy controller. Simulation results shows that the proposed controller is able to improve the comfort conditions provided as well as the energy and cost efficiencies of the operation of the HVAC plant when compared with normal plant considering PID controller. This benchmark comparison is used to assess the benefits of using the supervised fuzzy control strategy.

Keywords: HVAC – Zone Temperature – Humidity – PID – Fuzzy Control – Supervised Fuzzy Control

1. Introduction

The main objective of control systems in buildings for heating, air conditioning and ventilation is to ensure certain indoors climate comfort and a minimum of energy consumption. Indoor air quality and energy use in buildings has been of considerable interest for several decades. The main advantages of improving indoor environmental quality include: more contented and satisfied employees, less absenteeism and fewer accidents [1-6].

Ventilation control system strategies such as sensible temperature-based air-side economizer, enthalpy-based airside 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, USA [7, 8]. 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.

Fuzzy logic offers an alternative to conventional ventilation controllers [9]. 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.

The results of the simulations with the pure fuzzy controllers indicated that comparable performance was achieved with PID controllers in terms of response time, overshoot, stability and energy consumption [10, 11]. Gouda has been described the use of fuzzy ventilation controllers to control the fresh air ventilation strategy [12]. This aims of utilizing favorable ambient air energy and moisture contents to conserve energy and provide improved environmental conditions through variation of the fresh air supply rates to the zone. However, the simulation results indicated that scope existed to improve upon the fuzzy ventilation control strategy.

This paper describes the theory and results of the use of a supervised fuzzy controller to improve the performance of the fuzzy ventilation control strategies described by Gouda [12]. Supervised fuzzy control builds on the theory of the fuzzy ventilation control strategy. It aims of further improving environmental conditions within the zone and hence occupant comfort while improving the energy and cost efficiencies simultaneously. This is achieved by supervising the fuzzy ventilation controllers to ensure they do not undermine the objective of their use under certain circumstances that arise due to specific ambient and zone environmental conditions. Results from simulations using the supervised fuzzy control strategy were compared with normal plant operation using PID controller. This benchmark comparison was used to assess the benefits of using the supervised fuzzy control strategy.

2. Supervised fuzzy controller operation

A. General aims of the supervised fuzzy controller

The supervised fuzzy control strategy builds on the use of the fuzzy ventilation control strategy described by Gouda [12]. Although the fuzzy ventilation control strategy, overall, was more energy efficient and provided better comfort provision within the zone during simulation, it was felt that the strategy could still be improved. Supervised fuzzy control uses the fuzzy decision making capabilities of fuzzy logic to improve the use of the fuzzy ventilation strategies further.

The fuzzy ventilation control strategy only operates the HVAC plant heating, cooling, humidification and dehumidification components. This happens when a specific controlled zone parameter could not be maintained within the defined control bands by the fuzzy ventilation control strategies alone [12]. Where possible the fuzzy ventilation strategies attempted to converge zone conditions to the preferred set point as these were considered the most desirable conditions from a comfort perspective. It was possible for operational conflicts to arise due to the control strategies for each controlled parameter operating independently. For example, a small improvement in the humidity condition within the zone may have been achieves by the fuzzy ventilation dehumidification controller at the expense of a large energy penalty for heating the cooler outside air introduced as a result.

The supervised fuzzy controller uses the fuzzy ventilation controllers described by Gouda [12], as the basic controllers within the supervised fuzzy controller. Temperature, humidity and CO2 concentrations are the zone controlled parameters considered for improvements in terms of energy consumption and the provision of indoor environmental quality. Set points defined for the supervised fuzzy control strategy simulations were the same as those described by Gouda [12].

To give the reader an idea of the expert knowledge incorporated within the supervised fuzzy control strategy, a design philosophy example is given: The zone temperature, zone humidity and ambient moisture content are high. Simultaneously, the ambient temperature is below that of the zone temperature. As a result the fuzzy cooling ventilation strategy can see an opportunity to cool the zone air towards the preferred (middle) set point by increasing the fresh air re-circulation and using ambient cooling. This works satisfactorily if zone temperature control is considered in isolation. However, if the zone humidity is taken into account the following situation may result. The zone air is cooled slightly by increasing the fresh air ventilation rate in order to improve thermal comfort conditions within the zone. By cooling the air the dew point temperature of the air is decreased and the relative humidity rises. The zone humidity was initially close to the upper set point limit before fuzzy ventilation cooling commenced. This scenario is likely to result in the zone relative humidity rising above the higher dehumidification plant operating set point. As a result the cooling coil becomes operational and the air is cooled. Consequently, the re-heated resulting in the zone temperature being at least heated to the zone temperature lower set point. Hence, energy has been expended with little overall gain in the comfort conditions within the zone in order to keep the humidity below the upper zone humidity set point. This situation can be undesirable in terms of energy consumption and fluctuations in the zone conditions.

The supervised fuzzy controller attempts to avoid situations such as the one described in the above paragraph by incorporating expert knowledge into its control structure and supervising the fuzzy ventilation control strategy.

B. Supervised fuzzy controller structure

The structure of the supervised fuzzy control system incorporating the fuzzy ventilation controllers described in [12] and the fuzzy supervisor is shown schematically in Fig. 1. The fuzzy ventilation dehumidification and cooling strategy controllers are shown as the components B and C, respectively. Controllers A, B and C return incremental values which alter the desired re-circulation damper position. The re-circulation damper position is referred to as "desired" as it is being controlled by three controllers. The fuzzy PDFC (Proportional + Derivative Fuzzy Control) air quality controller (A) is shown as a component of the fuzzy ventilation control strategy as it represents the overriding ventilation controller with respect to the recirculation damper position. The supervised fuzzy controller, component D, is used to control the overall controller output by the use of the weighting factors alpha, beta and gamma. This controller operates by determining the most appropriate use of the plant and ventilation strategy by considering the current zone temperature, relative humidity and CO_2 concentration and suppressing the outputs from controllers A, B and C when necessary.

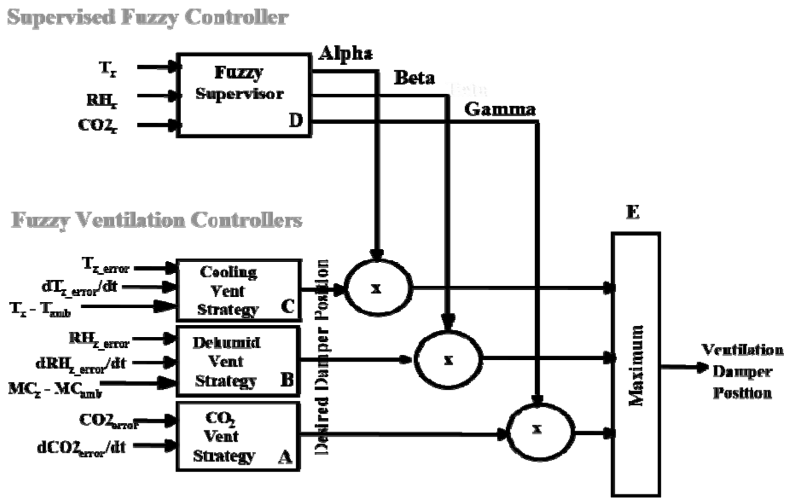

Fig 1: Supervised Fuzzy Controller Structure

This is achieved by multiplying the desired re-circulation damper positions by the weighting factors returned by the supervised fuzzy control. The maximum of the desired recirculation damper positions, calculated by component E in Fig. 1, was then used to represent the actual re-circulation damper position.

The supervised fuzzy controller, component D in Fig. 1, has 3 inputs and 3 outputs. Each of the inputs and outputs consists of 3 membership functions, see Fig. 2, to Fig. 5.

The fuzzy supervisor component of the fuzzy high level controller returns an absolute output rather than an incremental one.

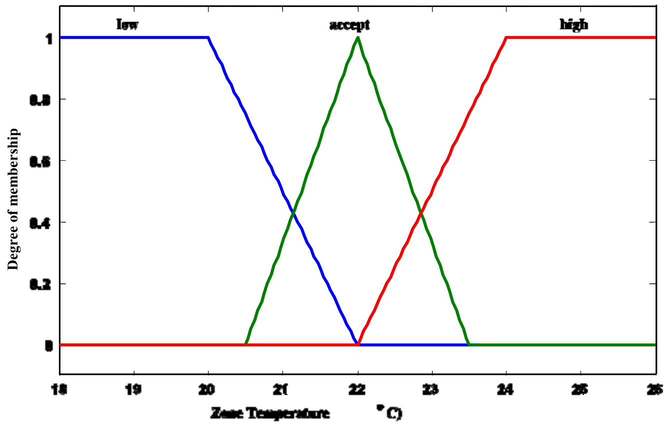

Fig 2: Supervised Fuzzy controller membership functions for the input zone temperature.

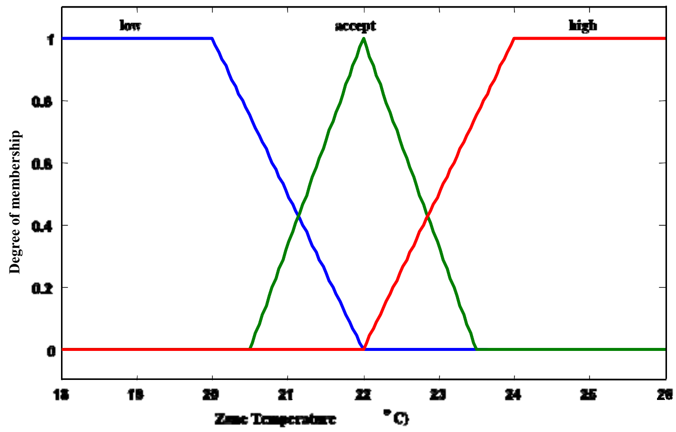

Fig 3: Supervised Fuzzy controller membership functions for the input zone relative humidity.

The membership functions shown in Fig. 5, for alpha, beta and gamma are defined on the universe of discourse {-0.5, 1.5}. This effectively gives a controller output of 0 - 1 when the centroid method is used as the defuzzification method.

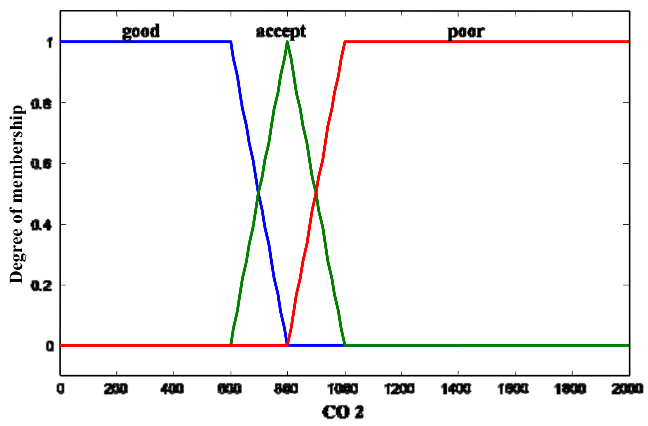

Fig 4: Supervised Fuzzy controller membership functions for the input zone air quality, CO_2 (ppm).

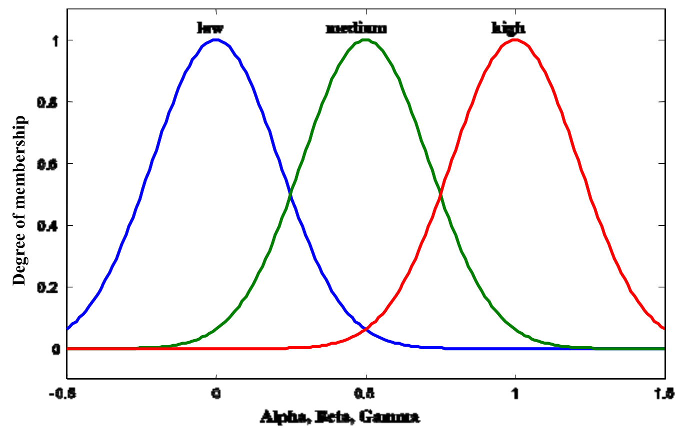

Fig 5: Supervised Fuzzy controller membership functions for the outputs alpha, beta and gamma.

Twenty seven rules (3^3) were developed and used to map the fuzzy supervisors 3 sets of input membership functions to the 3 output sets of output membership functions alpha, beta and gamma. The 27 control rules for the supervised fuzzy controller are given below:-

1. If (T Is Low) and (Rh Is Low) and (Co_2 Is Good) then (Alpha Is Low)(Beta Is Low)(Gamma Is Low)
2. IF (T is low) and (RH is accept) and (CO_2 is good) then (alpha is low)(beta is low)(gamma is low)
3. IF (T is low) and (RH is high) and (CO_2 is good) then (alpha is low)(beta is med)(gamma is low)
4. IF (T is low) and (RH is low) and (CO_2 is accept) then (alpha is low)(beta is low)(gamma is med)
5. IF (T is low) and (RH is accept) and (CO_2 is accept) then (alpha is low)(beta is low)(gamma is med)
6. IF (T is low) and (RH is high) and (CO_2 is accept) then (alpha is low)(beta is med)(gamma is med)
7. IF (T is low) and (RH is low) and (CO_2 is poor) then (alpha is low)(beta is low)(gamma is high)
8. IF (T is low) and (RH is accept) and (CO_2 is poor) then (alpha is low)(beta is low)(gamma is high)
9. IF (T is low) and (RH is high) and (CO_2 is poor) then (alpha is low)(beta is med)(gamma is high)
10. IF (T is accept) and (RH is low) and (CO_2 is good) then (alpha is high)(beta is low)(gamma is low)
11. IF (T is accept) and (RH is accept) and (CO_2 is good) then (alpha is med) (beta is med)(gamma is low)
12. IF (T is accept) and (RH is high) and (CO_2 is good) then (alpha is low)(beta is high)(gamma is low)
13. IF (T is accept) and (RH is low) and (CO_2 is accept) then (alpha is high)(beta is low)(gamma is med)
14. IF (T is accept) and (RH is accept) and (CO_2 is accept) then (alpha is high)(beta is high)(gamma is med)
15. IF (T is accept) and (RH is high) and (CO_2 is accept) then (alpha is med)(beta is high)(gamma is med)
16. IF (T is accept) and (RH is low) and (CO_2 is poor) then (alpha is high)(beta is low)(gamma is high)
17. IF (T is accept) and (RH is accept) and (CO_2 is poor) then (alpha is high)(beta is high)(gamma is high)
18. IF (T is accept) and (RH is high) and (CO_2 is poor) then (alpha is med)(beta is high)(gamma is high)
19. IF (T is high) and (RH is low) and (CO_2 is good) then (alpha is high)(beta is low)(gamma is low)

20. IF (T is high) and (RH is accept) and (CO_2 is good) then (alpha is high)(beta is med)(gamma is low)
21. IF (T is high) and (RH is high) and (CO_2 is good) then (alpha is med)(beta is high)(gamma is low)
22. IF (T is high) and (RH is low) and (CO_2 is accept) then (alpha is high)(beta is low)(gamma is med)
23. IF (T is high) and (RH is accept) and (CO_2 is accept) then (alpha is high)(beta is med)(gamma is med)
24. IF (T is high) and (RH is high) and (CO_2 is accept) then (alpha is med)(beta is high)(gamma is med)
25. IF (T is high) and (RH is low) and (CO_2 is poor) then (alpha is high)(beta is low)(gamma is high)
26. IF (T is high) and (RH is accept) and (CO_2 is poor) then (alpha is high)(beta is med)(gamma is high)
27. IF (T is high) and (RH is high) and (CO_2 is poor) then (alpha is med)(beta is high)(gamma is high)

3. Supervised fuzzy ventilation controller simulation results

The supervised fuzzy controller membership functions and control rules were developed heuristically from operator knowledge and intuition regarding the manner in which the controller was expected to operate. The operation of this controller assesses the multivariant interaction of several differrent parameters, i.e. cooling, heating, humidification, dehumidification and air quality. Zone temperature, relative humidity and CO_2 concentration are used as the inputs to the controller to assess the supervisory action that should be taken with regard to the fuzzy ventilation controllers.

It was not possible to test the performance of the controller over short time periods, due to the complexity of the interactions taking place. Assessment of the performance of this control strategy required longer term simulations to allow the occurrence of various combinations of zone and ambient conditions. However, tuning was not critical for the supervisory component of the controller as this part of the system was unlikely to become unstable. The stability of the system was ensured by the correct tuning of the fuzzy ventilation controllers. Tuning of the fuzzy ventilation controllers was already completed [12]. The main aspect of the control system considered in this paper is the control strategy implemented by the control rules within this controller.

In order to describe the operation of the supervised fuzzy controller to the reader, a single week is considered. The plant was operated between the hours of 5:00 a.m. and 5:00 p.m. with the exception of the air re-circulation fan and air quality control for the re-circulation damper which were operated 24 hours. Occupancy patterns were the same as for the simulations for the fuzzy ventilation controllers [12].

The dynamic zone temperature, humidity and CO_2 concentrations for selected week with the supervised fuzzy control strategy are shown in Fig. 6, Fig. 7 and Fig. 8.

To examine the operation of the supervised fuzzy controller in more details, the 7 days simulation is considered for the 96 - 168 hour simulation time, i.e. the final three days of the simulated week. The zone temperatures for the three control strategies for this period are shown in Fig. 9. The broken lines 1, 2 and 3 refer to the upper, preferred and lower temperature set points, respectively. Similarly, the zone humidity and CO_2 concentrations are shown in Fig. 10 and Fig. 11 respectively.

Plant dehumidification was not required during the occupied periods of the 120 - 168 hour simulation for the simulated week. Heating, cooling, humidification and recirculation damper operation were required in order to maintain environmental conditions within the desired set point limits. The valve positions are shown in Fig. 12 and Fig. 13 for the heating and cooling plant components respectively during the simulation period week 96-168 hour simulation period.

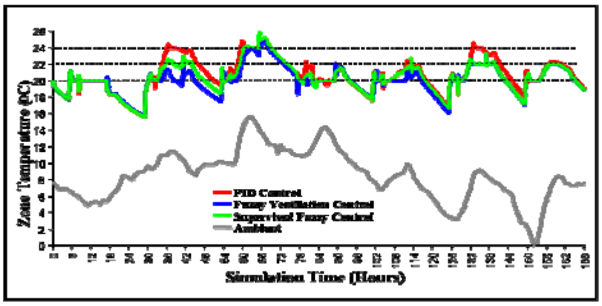

Fig 6: Zone and ambient temperatures. Broken lines indicate the upper, lower and preferred set points.

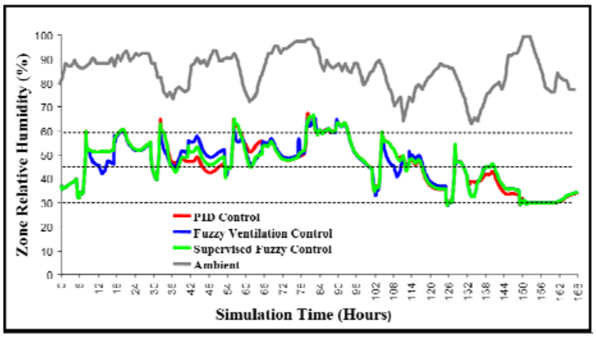

Fig 7: Zone and ambient relative humidity Broken lines indicate the upper, lower and preferred set points.

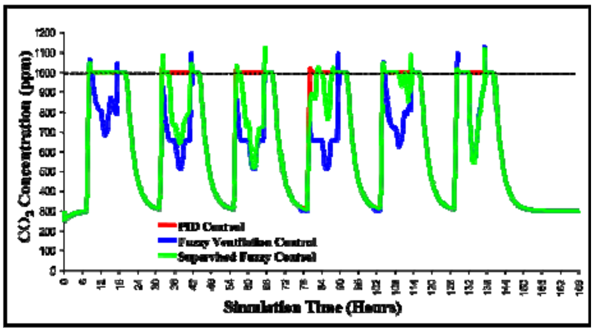

Fig 8: Zone CO_2 concentrations. The broken line indicates the higher set point.

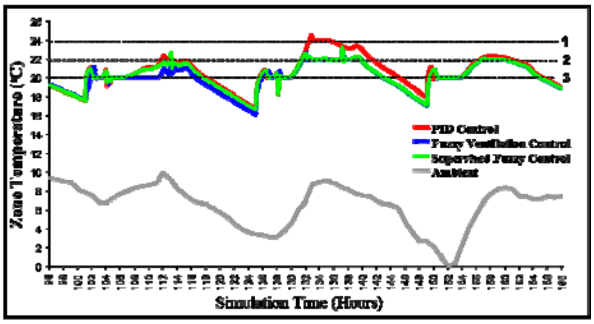

Fig 9: Zone and ambient temperatures for the 96 - 168 hour simulation period.

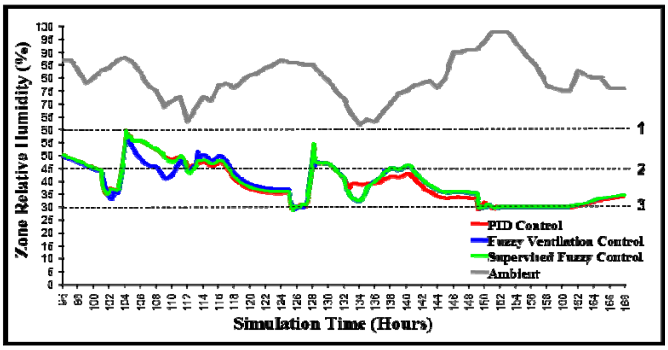

Fig 10: Zone and ambient relative humidity for the 96-168 hour simulation period.

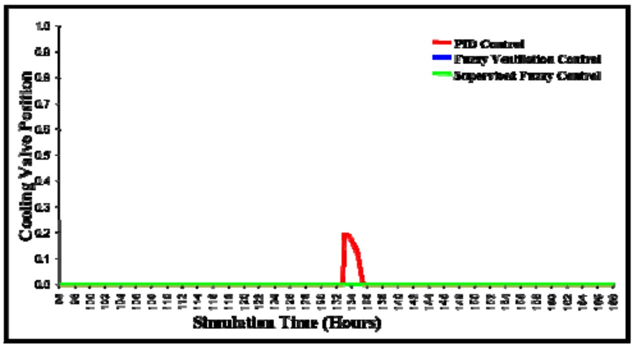

Fig 13: Cooling valve position for the 96-168 hour simulation period.

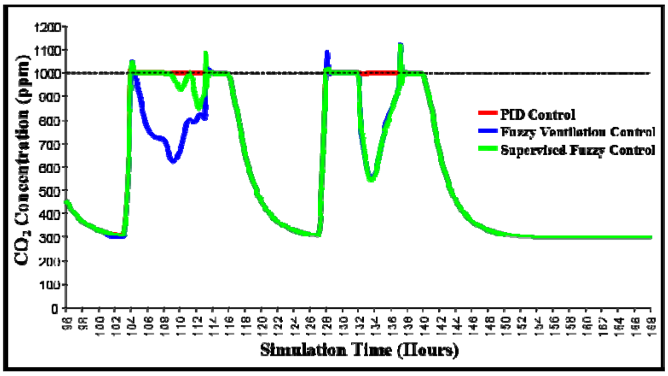

Fig 11: Zone CO $_2$ concentrations for the 96 - 168 hour simulation period.

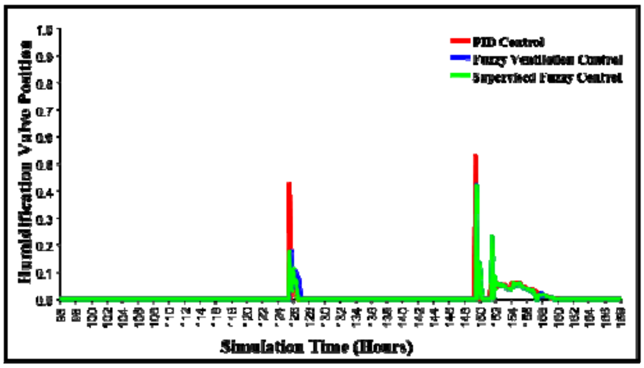

Fig 14: Humidification demand (0-1) for the 96-168 hour simulation period.

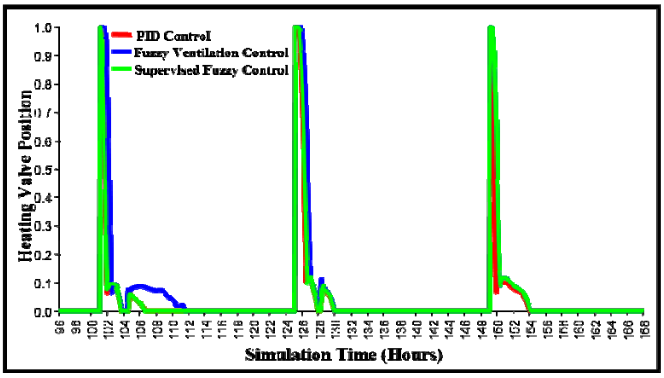

Fig 12: Heating valve position during the 96 - 168 simulation period.

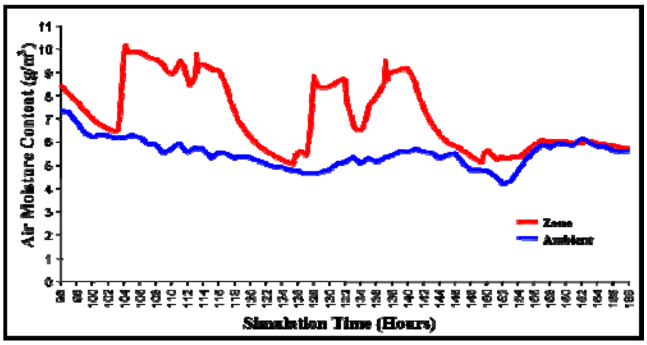

Fig 15: Zone and ambient air moisture content for the 96 - 168 hour simulation period.

In addition to HVAC plant operation, the fuzzy ventilation control strategy requested free ambient cooling and dehumidification during the simulation period under consideration [12]. The ambient temperature was lower than the zone temperature for the considered period as shown in Fig. 14. Hence it was beneficial to increase the fresh air ventilation rate when the zone temperature was above the preferred temperature set point. Similarly, the zone relative humidity was above the preferred set point during some of the occupied period, see Fig. 15, and the ambient air moisture content was lower than the zone air moisture content, see Fig. 16. Hence, an opportunity sometimes existed to carry out free ventilation dehumidification.

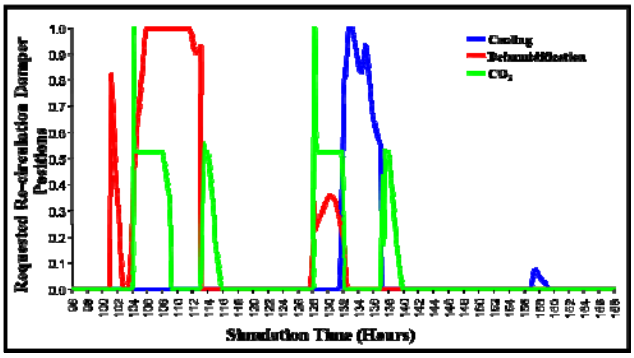

Fig 16: Fuzzy ventilation strategy desired re-circulation air damper positions for cooling, dehumidification and air quality purposes with supervised fuzzy control operational

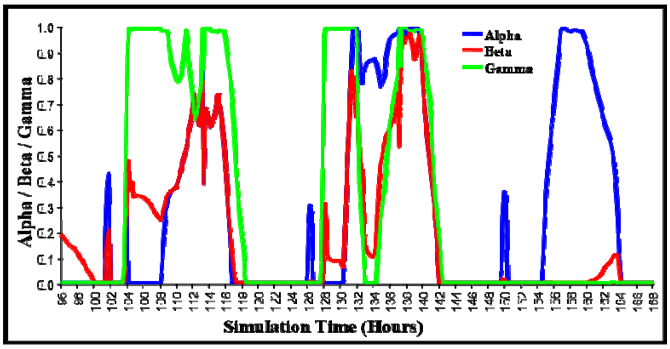

Fig 17: Supervised fuzzy controller weighting outputs alpha, beta and gamma

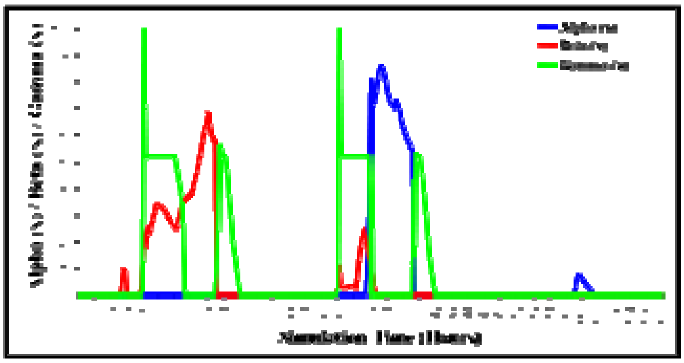

Fig 18: Requested fuzzy ventilation control re-circulation damper positions multiplied by the weighting factor for the supervised fuzzy controller.

During the simulation for the example under consideration the fuzzy ventilation control components aimed to converge the values of the environmental parameters towards the preferred set points. As a result, the requested positions of the re-circulation air damper for cooling, dehumidifying and air quality purposes before fuzzy supervisory control were implemented are shown in Fig. 17. The supervised fuzzy control strategy used the same control methodology as for the fuzzy ventilation control strategy up to this point. The inputs for this controller were the zone temperature, humidity and CO_2 concentration. This controller used these input values to determine whether the fuzzy ventilation strategy could be improved and assigned the weighting factors alpha, beta and gamma to the outputs from the fuzzy ventilation controllers prior to the maximum weighted desired re-circulation air damper position being selected.
The values for alpha, beta and gamma for the example under consideration are shown in Fig. 18. The values alpha (x), beta (x) and gamma (x) represent the weighted values alpha, beta and gamma multiplied by the desired recirculation damper position values obtained from the fuzzy ventilation component for cooling, dehumidification and air quality respectively.
For clarity, by compare Fig. 16 and Fig. 18, it can be seen how the desired re-circulation damper position requested by the fuzzy ventilation dehumidification controller has been suppressed during the 96-100 hour simulation period. This illustrates how each of the proposed outputs becomes dominant at some point during the simulation 96 - 168 hours of simulated week. The dominance of the fuzzy ventilation control component realises the potential to converge the zone temperature and humidity towards the preferred set points or the controller objectives with regard to energy efficiency.

Conclusion

In this paper, a supervised fuzzy ventilation controller has been developed to improve the environmental conditions and energy consumption inside the building. The supervised fuzzy used the inputs of zone temperature, relative humidity and CO_2 concentration to decide whether it was prudent to carry out the actions desired by the fuzzy ventilation control strategies.
This paper has been also described a supervised fuzzy control which takes advantage of the capabilities of fuzzy logic to deal with a multi-variant input / output control system. The simulation results indicate that improved control of the HVAC plant can be achieved when compared to normal PID control and fuzzy ventilation control.

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