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ORIGINAL ARTICLE

Management of air-conditioning systems in residential buildings by using fuzzy logic

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Abstract There has been a rising concern in reducing the energy consumption in buildings. Heating, ventilation and air-conditioning system is the biggest consumer of energy in buildings. In this study, management of the air-conditioning system of a building for efficient energy operation and comfortable environment is investigated. The strategy used in this work depends on classifying the rooms to three different groups: very important rooms, important rooms and normal rooms. The total mass flow rate is divided between all rooms by certain percentage using a fuzzy-logic system to get the optimum performance for each room. The suggested Building Management System (BMS) was found capable of keeping errors in both temperature and humidity within the acceptable limits at different operating conditions. The BMS can save the chilled/hot water flow rate and the cooling/heating capacity of rooms.

1. Introduction

Building Management System (BMS) is a high-technology system installed in buildings that controls and monitors the building's mechanical and electrical equipment such as air handling, fan-coil unit, cooling plant systems, lighting, power systems, fire systems, and security systems. The objective of a BMS is to achieve more efficient building operation at reduced labor and energy costs and to provide a safer and more comfortable working environment for building occupants [1–6]. Modern buildings and their heating, ventilating and air-conditioning (HVAC) systems are the biggest consumers of energy [7–10]. These buildings are required to be more energy efficient, while considering an ever-increasing demand for better indoor air quality, performance and environmental issues. Building automation systems have a hierarchical structure consisting of field, automation and management layers [10]. Energy management is achieved by means of schemes such as the duty-cycling of loads to conserve energy; peak load management to regulate total power consumption during peak hours; scheduled start/stop of building HVAC systems at the beginning and end of each day; and real-time control of building systems in response to occupancy detection [11–17]. However, most of existing supervisory and optimal control strategies are either too mathematical or lacking generality.

HVAC system must be complemented with an efficient control scheme to maintain comfort under any load conditions. Efficient control will also reduce energy use by keeping the process variables (temperature, humidity, etc.) to their set points. Fuzzy logic control (FLC) is designed on the basis of

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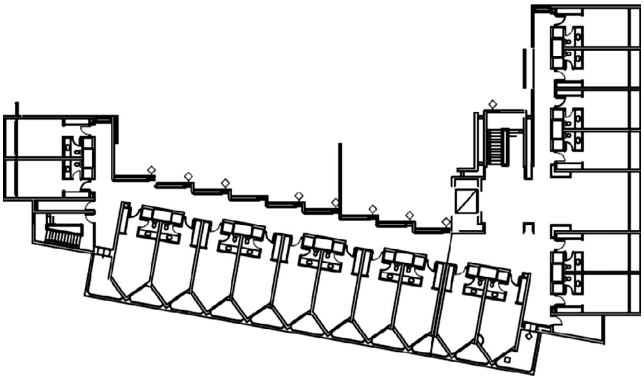

Figure 1 The five similar floors of academy building.

human experience, which means that a mathematical model is not required for controlling a system. Fuzzy logic-based control schemes were implemented for many industrial applications and HVAC systems [18–24]. Huang et al. [18] presented a robust model predictive control for improving the robustness of the temperature control of air-conditioning systems by taking account of the process gain and time-delay uncertainties as well as the constraints on the control input. This strategy was evaluated in a dynamic simulation environment of a typical AHU VAV system. Intelligent controllers, optimized by the use of evolutionary algorithms were developed for the control of the subsystems of an intelligent building [19]. A fuzzy controller for the regulation of indoor temperature of a discontinuously occupied building is compared with a classical controller by Fraisse et al. [22]. Kolokotsa et al. [23] designed and installed a fuzzy logic controller of indoor thermal and visual comfort as well as indoor air quality, using the European Installation Bus (EIB) system through interconnection with Matlab. It was found that fuzzy logic control was not applied to the management of air conditioning systems of buildings which have several rooms.

The objective of this paper was to investigate the management of air-conditioning systems in buildings using fuzzy logic technique. A building management strategy is suggested in an attempt to improve energy efficiency and occupant comfort for different loading conditions. The proposed strategy is taking into consideration any fault in temperature or flow rate either in chilled water during summer or in hot water during winter. The study is limited to the application in residential buildings.

2. Case study

In this study, the Arab Academy Student Housing is considered as a case study for building management system. It is in Alexandria, Egypt, at Latitude of 31.2. The building consists of five floors (zones). Each floor has eighteen rooms, three paths and one hall as shown in Fig. 1.

The central air-conditioning system consists of the following:

1. Two chillers, each has 100 ton refrigeration capacity with cooling tower to supply the cooled water to the cooling coils.
2. A boiler to supply the hot water to heating coils and to supply steam to the steam humidifier.
3. In each floor, there are 18 fan-coil units (FCU); one for each room. The fan-coil unit compact option simulates a four-pipe fan coil unit with hot-water heating-coil, chilled-water cooling-coil, and an outside-air mixer. The fan-coil units are zone equipment units which are assembled from other components. Fan coils contain an outdoor air mixer, a fan, a simple heating-coil and a cooling-coil. The fan-coil unit is connected to a hot-water loop (demand side) through its hot-water coil and to a chilled-water loop (demand side) through its cooling coil. The unit is controlled to meet the zone heating or cooling demand as shown in Fig. 2.
4. In the addition of the FCU, there is a steam humidifier in each room to control the humidity ratio in winter.

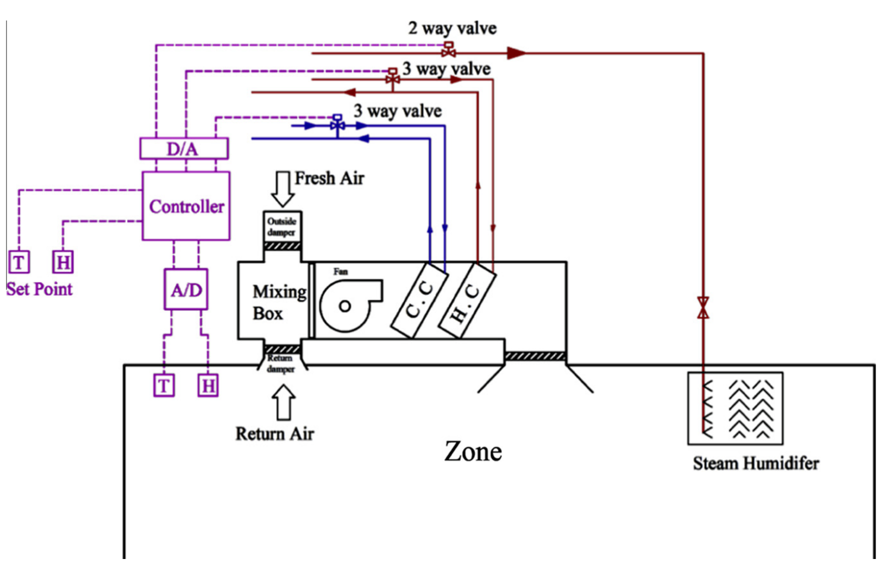

Figure 2 Schematic of control FCU with control signal.

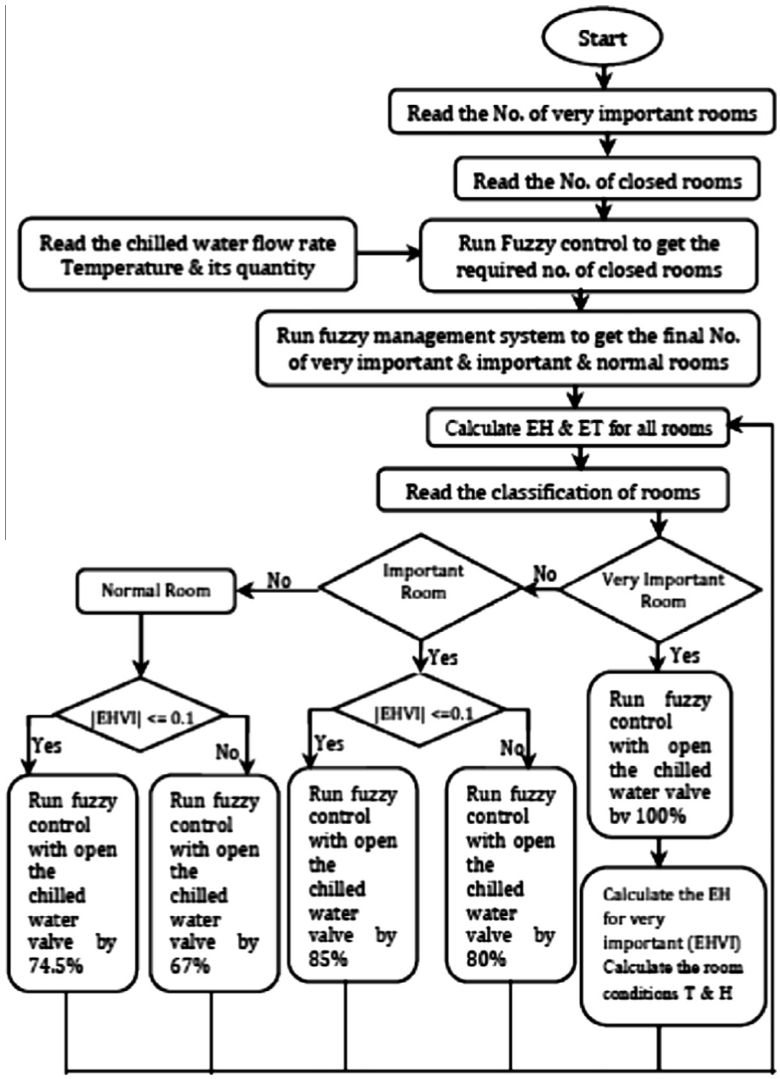

Figure 3 Flowchart of building management strategy.

The analysis of the finned-tube heat exchanger is conducted provided that the variation of the film heat transfer coefficient on the air side of the coil is expressed as a function of the air Reynolds number. The coil is divided into loops. Each loop can be one column or multi-columns, with the tubes of each loop connected to each other. For such coil arrangement, the hot air and the chilled water temperatures will vary through the row and over the rows of the loop. Moist air is treated to flow either in cross–counter flow with chilled water or in cross–parallel flow arrangement. At steady-state conditions, a heat and mass balance on the control volume of an elementary area leads to the governing equations for the cooling coil.

Heating coil is used to adjust the sensible heat only (increases the temperature only, while the absolute humidity remains constant). The process of humidification can be simplified by adding steam directly into the air. This method is an isothermal process because the temperature of the air remains almost constant as the moisture is added. For this type of humidification system, the steam source is usually a central steam boiler at low pressure. When steam is supplied from a source at a constant supply pressure, humidification responds quickly to system demand. A control valve may be modulating or two-position in response to a humidity sensor/controller. Steam can be introduced into the air stream through one of the following devices. Steam is injected to heated air at winter to maintain space relative humidity within desired values.

3. Building management system strategy

The management for the air-conditioning system is developed for only one floor with 18 rooms. The main goal of BMS is to save the energy used in the air-conditioning system by managing the chilled or hot water flow in both cooling and heating coils, respectively. The optimization of the previous flow rates will reduce the cooling and heating capacity and will also reduce the power consumption in the pumps feeding the fan-coil units. The BMS will also be useful in case of any soft fault. The fault may be in either the temperature or quantity of the chilled water or both.

The management strategy of these rooms depends on two main factors:

1. Classifying the rooms to three groups; each has six rooms:
   - The first group includes the most important rooms (VI type) where it is required to achieve to the desired condition at all different conditions with almost 0.1 absolute errors in both humidity and temperature.
   - The 2nd group is called important rooms (II type) where it has a settling time longer than that acquired in the first group. The absolute errors allowed in the second group are 0.5 °C in temperature (ET) and 0.6 g/kg in humidity (EH).
   - The 3rd group named as normal rooms (NN type) which have an absolute error equal to 1 °C in temperature and 1 g/kg in humidity and the settling time is longer than that of the 2nd group. Although the errors in the 2nd and the 3rd groups are larger than the first group, they still in the human comfort region as determined by ASHRAE Standard 55[25]. The owner or the management person must specify the numbers of closed rooms and the rooms that will be considered as ''very important'' ones.
2. The chilled water flow rate in summer or hot water flow rate in winter is distributed between the three groups according to the BMS flowchart shown in Fig. 3.

Two fuzzy systems are developed for building management:

- The first fuzzy system calculates the number of rooms that must be closed in case of an increase in the chilled water temperature (T_{win}) or a decrease in the chilled water flow rate (MW). The inputs here are the flow temperature (T_{win}) and the available flow rate (MW) while the output is the number of closed rooms (CC). The membership functions of the fuzzy system are shown in Figs. 4a–4c.
- The second fuzzy control determines the number of rooms in each group. The inputs are the number of closed and very important rooms with flow temperature, while the output is the number of very important (NVI), important (NII), normal (NNN) and closed rooms (CC). The membership functions of the fuzzy systems are shown in Figs. 5a–5d.

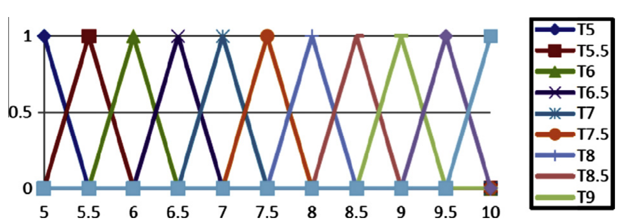

Figure 4a Membership functions of the T_{win} input for 1st fuzzy management.

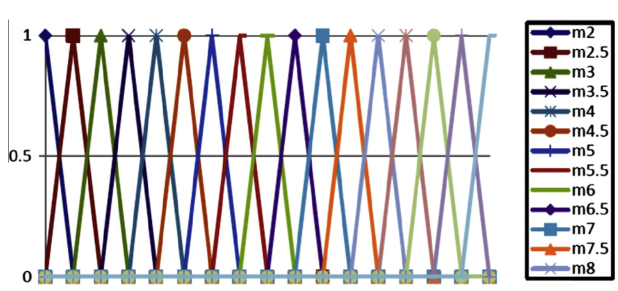

Figure 4b Membership functions of the MW input for 1st fuzzy management.

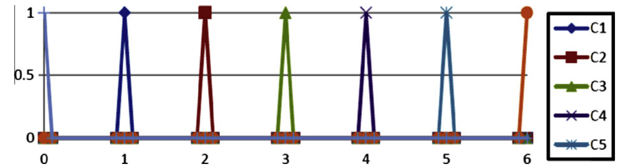

Figure 4c Membership functions of the CC output for 1st fuzzy management.

After trials, it was found that the membership functions with the triangular shape give the best response and results

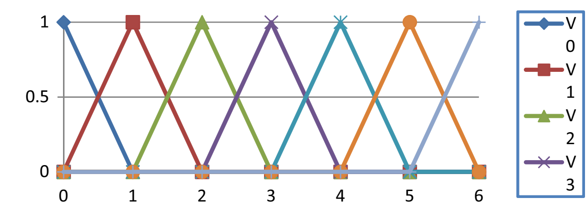

Figure 5a Membership functions of the NVI for 2nd fuzzy management.

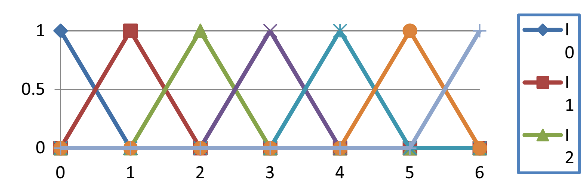

Figure 5b Membership functions of NII output from 2nd fuzzy management.

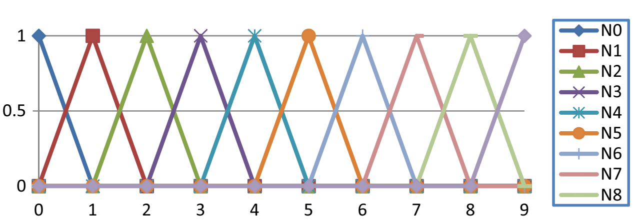

Figure 5c Membership functions for NNN output from 2nd fuzzy management.

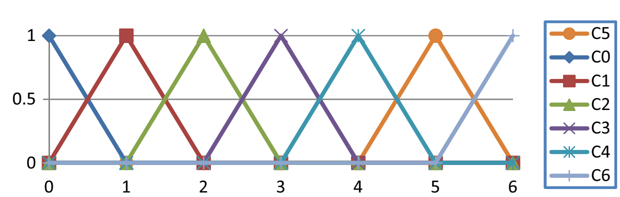

Figure 5d Membership functions for NCL output from 2nd fuzzy management.

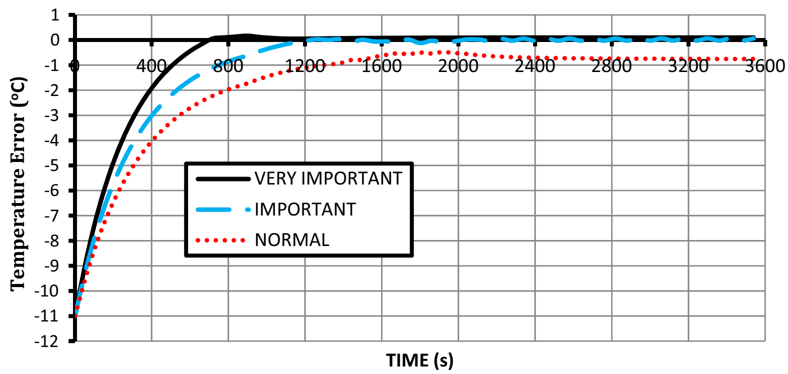

Figure 6a Temperature Error Variation with time for 3-groups rooms at normal condition with BMS.

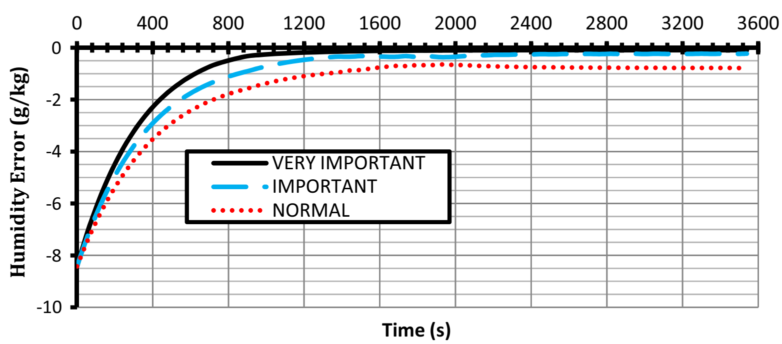

Figure 6b Humidity Error Variation with time for 3-groups rooms at normal condition with BMS.

Table 1 BMS results at different temperatures and flow rate of chilled water at summer season.

T_{win} (°C)	M_{wmax} (kg/s)	M_{wused} (kg/s)	No. of rooms in each group			Temperature error (°C)			Humidity error (g/kg)			Flow rate saved (%)	Cooling capacity saved (%)
			VI	II	NN	VI	II	NN	VI	II	NN		
5	10	6.64	6	6	6	0.09	0.06	−0.75	−0.09	−0.23	−0.78	17.3	2.2
5	6	6	6	6	5	0.09	−0.02	−1.17	−0.09	0.23	−1	–	2.4
5	5.5	5.5	6	6	3	0.09	0.06	−0.75	−0.09	−0.23	−0.78	–	1.7
5	5	5	6	6	1	0.09	0.06	0.075	−0.09	−0.23	−0.22	–	0.94
6	10	7.75	6	6	6	0.1	0.04	−0.57	−0.08	−0.19	−0.6	17.3	1.95
6	7	7	6	6	4	0.1	0.012	−0.63	−0.08	−0.2	−0.7	–	1.78
6	6	6	6	6	1	0.1	0.01	−0.06	−0.08	−0.2	−0.33	–	0.94
7	10	9.84	6	6	6	0.1	≈0.0	−0.37	−0.08	−0.2	−0.56	17.3	1.7
7	9	9	6	6	4	0.1	≈0.0	−0.09	−0.08	−0.2	−0.4	–	1.3
7	8	8	6	6	2	0.1	≈0.0	−0.16	−0.08	−0.22	−0.44	–	1.34
8	10	10	6	6	3	0.1	– 0.4	−0.85	−0.08	−0.56	−0.83	38.54	2.54
8	9	9	6	6	1	0.1	– 0.4	−0.66	−0.08	−0.56	−0.73	–	2.14

for this management. It can be noted that: T5 means that the inlet chilled water temperature has 5 °C while T6 means that the chilled water temperature has 6 °C and so on. The symbol m10 means that the available chilled water flow rate is 10 kg/s while m9 means that the available chilled water flow rate is 9 kg/s and so on. The symbol V0 means that the number of very important rooms is zero while V1 means that the very important rooms are one and so on. The symbol I0 means that the number of important rooms is zero while I1 means that the number of important rooms is one and so on. The symbol N0 means that the number of normal rooms is zero while N1 means that the number of normal rooms is one and so on. The symbol C0 means that the number of rooms must be closed is zero while C1 means that the number of rooms must be closed is one and so on.

In winter, management strategy is similar to that described above for summer. The input to the fuzzy system, in winter, is the hot water temperature and hot water flow rate.

4. Results

4.1. BMS results for the summer season

Figs. 6a and 6b show the temperature and absolute humidity error response for the three groups of rooms (very important (VI), important (II) & normal (NN)) in the summer season. The responses are obtained using the model in [26].

At normal conditions, the maximum chilled water flow rate is 10 kg/s at 5 °C temperature. The BMS at this condition uses only 6.4 kg/s of available chilled water as compared to 7.74 kg/s without BMS. Accordingly, the cooling capacity is reduced by 2.2%. The figures indicate that the "VI" rooms reach its final value with zero error after only 600 s for temperature and 1000 s for humidity. The "II" rooms reach its steady state with zero error in temperature after 1200 s and an absolute error of 0.23 g/kg in humidity after 1400 s. Finally, the "NN" rooms have a final value of −0.75 °C error in temperature and −0.78 g/kg error for humidity after a transient period of 2000 s.

As the temperature of the chilled water rises above 5 °C due to any fault, it is necessary to increase the flow rate to obtain the same cooling capacity. If the required flow rate is more than the available flow rate due to any fault in the pumps or the chiller or both, the BMS strategy needs to close (discard) one or more rooms depending on the deficiency in the required flow rate. Collection of BMS results at different temperatures and flow rates of chilled water at the summer season are summarized in Table 1.

4.2. BMS results for the winter season

Figs. 7a and 7b show the response of temperature and humidity for "VI", "II" and "NN" rooms, during winter, at normal operating conditions. Normally, the maximum hot flow rate is 4.5 kg/s at 60 °C temperature when all rooms are open. By using BMS strategy, the required flow rate is reduced by 31.6% and the heating capacity is reduced by 1.78%. The temperature of the very important rooms reaches a steady-state value of 23.1 °C after 700 s while the final value of temperature for important rooms is 22.65 °C and is achieved after 1000 s. The normal rooms take 2000 s to settle down at a final temperature of 22 °C. There is no change in humidity response for all rooms.

Any decrease in the hot water temperature due to system faults, should be compensated by an increase in hot-water flow rate to obtain the required heating capacity. Meanwhile, if there is a fault in the feeding pumps, the quantity of hot-water

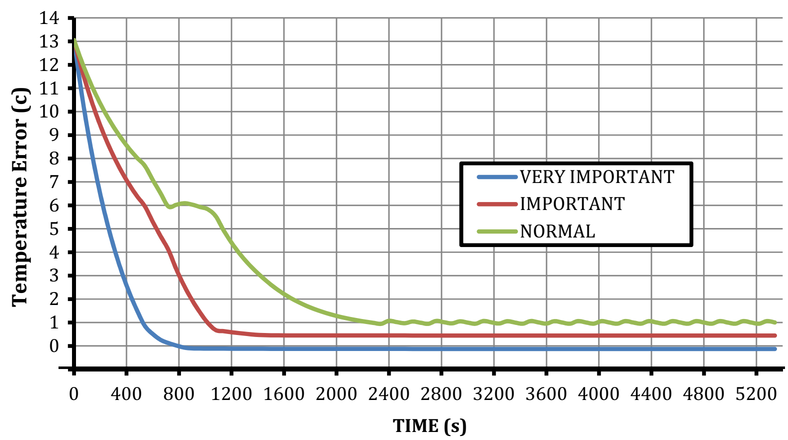

Figure 7a Temperature Error Variation with time for 3-groups rooms at normal condition with BMS in winter season.

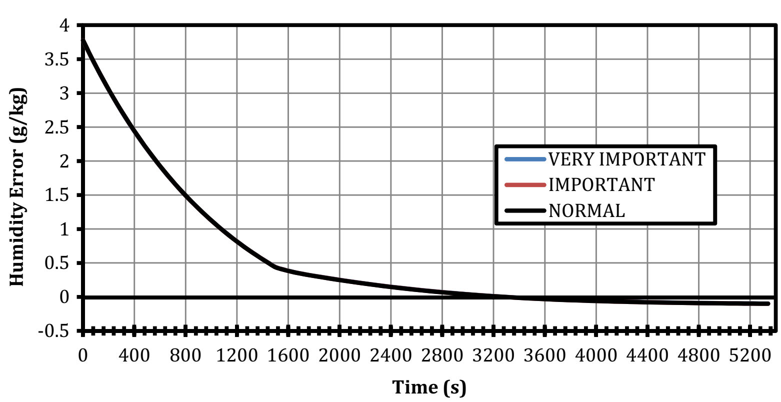

Figure 7b Humidity Error Variation with time for 3-groups rooms at normal condition with BMS in winter season.

Table 2 BMS results at different temperatures and flow rate of Hot water at winter.

T_{Hin} (°C)	M_{Hmax} (kg/s)	M_{Hused} (kg/s)	No. of rooms in each group			Temperature error (°C)			Flow rate saved (%)	Heating capacity saved (%)
			VI	II	NN	VI	II	NN		
60	4.5	2.4	6	6	6	−0.12	0.44	1	31.6	1.78
60	2	2	6	6	3	−0.01	0.42	0.96	–	1.6
60	1.75	1.75	6	6	1	−0.01	0.42	1	–	1.4
55	4.5	3.32	6	6	6	≈0.0	0.38	0.95	31.6	1.48
55	3	3	6	6	4	≈0.0	0.38	0.9	–	1.48
54	4.5	3.6	6	6	6	0.04	0.4	0.95	20	1.4
52	4.5	4.5	6	6	6	0.2	0.9	0.92	–	1.36
51	4.5	4.5	6	6	6	0.3	0.98	1.3	–	1.7
51	4	4	6	6	3	0.3	0.95	0.9	–	1.2
50	4.5	4.5	6	6	3	0.38	0.97	0.97	–	1.1
50	4	4	6	5	2	0.38	0.95	0.87	–	1

flow rate will decrease and the demand for hot-water flow rate will be more than the available flow rate. Consequently, BMS needs to close the air-supply to some normally-classified rooms to ensure the desired conditions for both "VI" and "II" rooms. Considering different scenarios for either the temperature or the flow rate of hot water, the results of BMS strategy are presented in Table 2. The results include the managed flow rate, numbers of closed rooms according to classification considered, the energy saved and the associated temperature error of each room classification.

5. Conclusions

Fuzzy logic controller has been synthesized to manage and control the temperature and humidity ratio for a building. The rooms are divided into three groups according to their importance. The management governor feeds the number of closed rooms and the required number of very important rooms. The output of the management controller is the final number of rooms in each group according to the classification of the management governor. The following conclusions are obtained:

1. In normal operations, the proposed BMS can save up to 17.3% of the flow rate during summer and 31.6% during winter. The cooling capacity saved is up to 2.2% in summer while the heating capacity saved is up to 1.78% in winter.
2. The very important rooms have the fastest final response while the normal room responses are the slowest.
3. In case of a temperature change of 3 °C of the chilled water or 6 °C of the hot water, the BMS was able to save the flow rate as the normally operated system.
4. In the case of extreme faults in the chilled (hot) water flow or temperature, and to keep the errors in the room temperature and humidity within the acceptable limits according to their classifications, the suggested BMS keeps the number of both very important and important rooms as specified by the manager. Meanwhile, a minimum number of the normally operated rooms are shut down.
5. From the practical point of view of the air-conditioning technology, two outcomes can be concluded. First, to control relative humidity during summer, the control system has to be prepared to activate a part of the heater to act as reheater. Second, to control relative humidity during winter, it has to add a steam humidifier inside the room or (may be inside the external unit) to add 1.5 kg/h of steam for a unit of 1000 m^3/h. Both of these approaches are controlled by using dry-mode control of the unit.

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