A Practical Application of Fuzzy Control for an Air-Conditioning System

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ABSTRACT

A practical application is given of a fuzzy control system for an air-conditioning system, and the results of simulation and practical use are presented. Air-handling units are widely used for central air-conditioning systems. The control system has two controlled variables (temperature and humidity) and three final controlling elements (cooling, heating, and humidifying valves). In order to achieve high efficiency and economical control, the two kinds of requests (temperature and humidity requests) must be adequately allotted to the three final controlling elements. The fuzzy control system infers two kinds of requests and the allotment. The results of simulation and practical use show that this design is effective.

In the fuzzy control system, the hardware of a fuzzy inference engine is used. Using this hardware it will be possible to make the necessary inference in less time than is needed with only the software system. This paper introduces the hardware system.

KEYWORDS: ***air-conditioning system, air-handling unit, fuzzy inference engine, membership function, fuzzy sets, fuzzy production rules***

INTRODUCTION

Various methods are used for air conditioning, depending on the application, for example keeping occupants comfortable or meeting industrial process requirements. Recently, because of industrial growth, the requirements of

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air-conditioning systems have been high grade and high quality control. In addition to constant temperature, constant humidity is required through the year for some industrial processes. In this case, an all-air, single-zone central air-conditioning system is generally used, and the air-handling unit is used as a central unit.

The control system is not a single-input, single-output system but a multivariable control system of two inputs and three outputs, which influence each other. Following fuzzy production rules that sum up people's common sense and experience, a fuzzy control system is able to manage the multivariable system. This paper presents the fuzzy control system and the results of simulation and practical use.

AIR-CONDITIONING SYSTEM AND EQUIPMENT

To achieve constant temperature and constant humidity throughout the year, an air-handling unit must include air-cooling, air-heating, dehumidifying, and humidifying equipment. An air-handling unit that consists of an air-cooling and dehumidifying coil, an air-heating coil, and a humidifier to condition the air is used in this design. Each piece of equipment has an automatic valve that varies the flow of the control agent. (See Figure 1.) These equipments and automatic valves work as follows:

1. *Air-cooling and dehumidifying coil.* The air-cooling and dehumidifying coil is used for the process of cooling and dehumidifying. When the temperature of the air leaving the coil is higher than the dew point of the air entering the coil, it will work almost entirely for cooling, and when it is lower, it will work for both cooling and dehumidifying. The cooling valve varies the flow of the chilled water that flows through it.
2. *Air-heating coil.* The air-heating coil is used for the process of heating or reheating. When the air-cooling and dehumidifying coil is used for

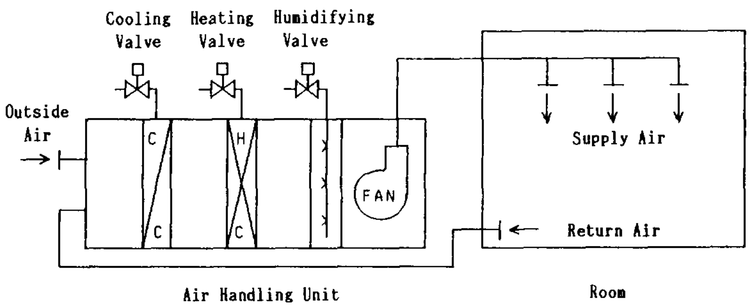

Figure 1. Outline of the air-conditioning system.

dehumidifying, the air-heating coil will work for reheating; otherwise it will work for heating. The heating valve varies the flow of the hot water (or steam) that flows through it.

3. *Humidifier*. In this design, a steam jet humidifier is used for the process of adiabatic humidification. The humidifying valve varies the flow of the steam that flows through it.

Thermodynamics for Air Conditioning

In most air-conditioning processes, the air can be considered to be a mixture of water vapor and dry components. The psychrometric chart (Figure 2) is used as a graphical representation of the thermodynamic properties of moist air.

A schematic solution for the process of the air-cooling and dehumidifying coil is shown in Figure 3., When the temperature of the air leaving the coil is lower than the dew point of the air entering the coil, some moisture removal has transpired, and the final point of the moist air must lie on a curve that goes along the saturation curve on the chart.

A schematic solution for the process of the air-heating coil is shown in Figure 4. The final state of the moist air leaving the coil must lie on a constant humidity ratio line drawn through the initial state point on the chart.

A schematic solution for the adiabatic humidifying process of the steam jet humidifer is shown in Figure 5. On the chart, the final state point of the moist air leaving the humidifier must lie on a straight line whose direction is fixed by the specific enthalpy of the injected water, drawn through the initial state point of the moist air. To say steam jet humidifier, the line is considered near the constant dry-bulb line.

When these three equipments are used properly, constant temperature and constant humidity will be economically achieved throughout the year. For example, a schematic solution for summer conditions of dehumidifying and reheating heat load is shown in Figure 6. The schematic solution for winter conditions of heating and humidifying heat load is shown in Figure 7.

THE ORDINARY CONTROL SYSTEM

The control system is a two-input, three-output control system. One of two representative control systems is generally used for control of the air-handling unit. These are the dew-point control system and the control system with a relay that selects the higher signal of two requests (temperature and humidity) for the cooling valve. The former has three closed-loop control systems, and the latter has two closed-loop control systems. These control systems usually obey the proportional action with automatic reset.

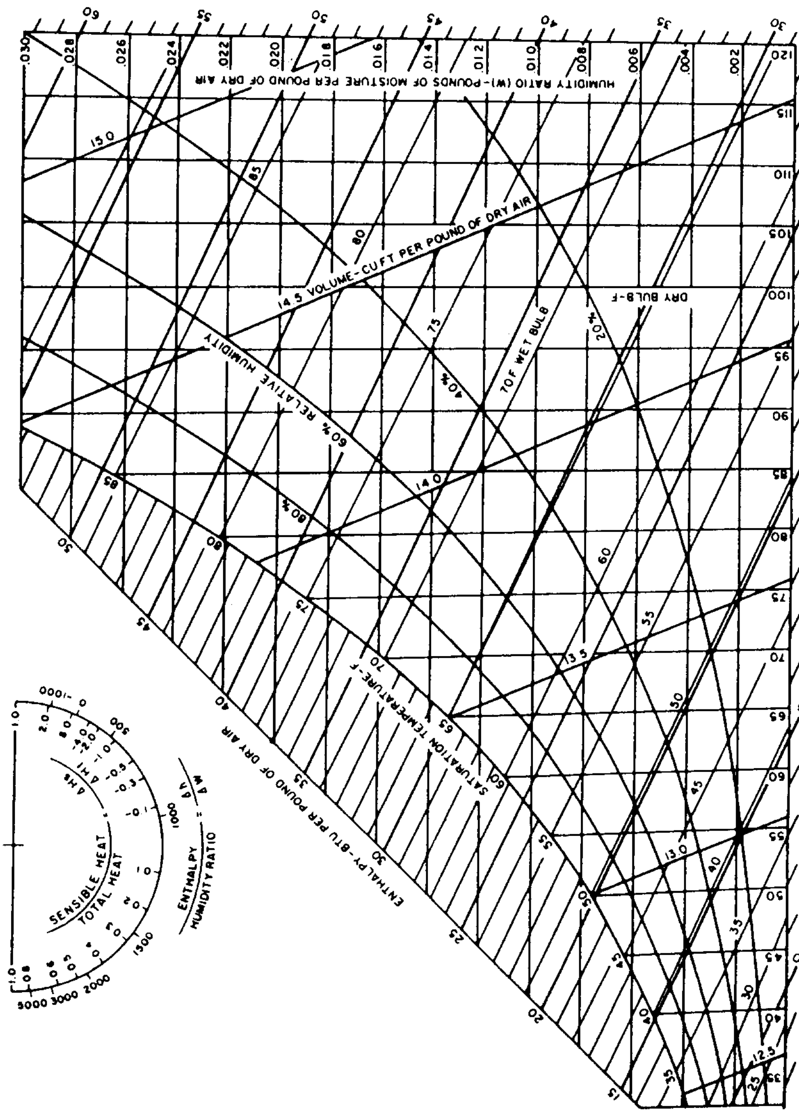

Figure 2. Abridgment of psychrometric chart. (Reproduced from *ASHRAE Handbook* [1] by permission of American Society of Heating, Refrigerating and Air-Conditioning Engineers.)

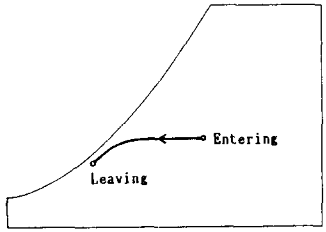

Figure 3. Schematic solution for air-cooling and dehumidifying coil.

The Dew-Point Control System

The dew-point control system takes the dew point of the air leaving the air-cooling and dehumidifying coil as another control variable. Therefore, the dew-point control system has three closed-loop control systems (temperature loop, humidity loop, and dew-point loop). The cooling valve controls the dew point, the heating valve controls space temperature, and the humidifying valve controls space humidity.

This control system is efficient, but it is not economical in some cases, because all three control valves will operate independently to achieve each objective, and all of them might open at the same time. The diagram of the dew-point control system is shown in Figure 8.

Control Systems with Relay

The control system with a relay has two closed-loop control systems: a temperature loop and humidity loop. Temperature requests are allotted to the cooling valve and the heating valve, because both of them can control temperature. Humidity requests are allotted to the cooling valve and the humidifying valve, because both of them can control the moisture in the air. Thus, the cooling valve can control both temperature and humidity, so it takes both temperature requests and humidity requests and then selects the higher signal.

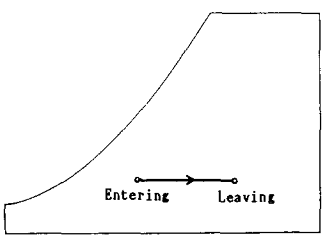

Figure 4. Schematic solution for air-heating coil.

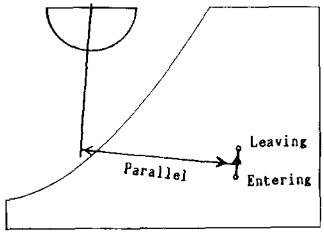

Figure 5. Schematic solution for steam jet humidifier.

This control system is economical, but it is not efficient in some cases, because all three control valves will not open at the same time. A diagram of the control system with a relay is presented in Figure 9.

FUZZY CONTROL SYSTEM

The fuzzy control system for this design is shown in Figure 10. The fuzzy inference board is the hardware for the fuzzy inference engine. The CPU will get measured signals from the temperature and humidity sensors through an analog-to-digital converter and calculate each error and change in error from these signals.

Following the fuzzy production rules, the fuzzy inference board will execute the fuzzy inference from the information on errors, changes in error, and last manipulated variables, and it will send the final conclusion sets to the CPU. Then the CPU decides changes in the manipulated variable by the center-of-gravity method and sends the decided manipulated variables to each final controlling element through the D/A converter.

The Fuzzy Inference Method

In the fuzzy control system, the control algorithm is described using IF · · · THEN fuzzy control rules. The fuzzy inference method is shown as

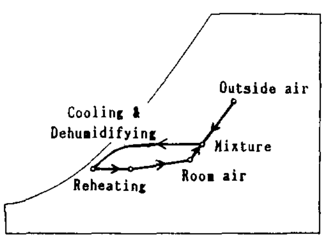

Figure 6. Schematic solution for summer conditions.

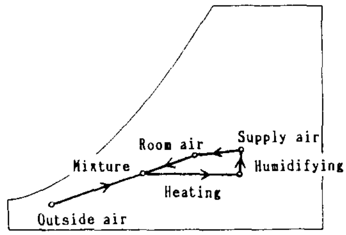

Figure 7. Schematic solution for winter conditions.

follows:

$$\text{Rule 1: IF } x_1 \text{ is } A_{11},\ x_2 \text{ is } A_{12}, \cdots, x_j \text{ is } A_{1j} \text{ THEN } y \text{ is } \mathrm{B}_1.$$
$$\text{Rule 2: IF } x_1 \text{ is } A_{21},\ x_2 \text{ is } A_{22}, \cdots, x_j \text{ is } A_{2j} \text{ THEN } y \text{ is } \mathrm{B}_2. \vdots$$
$$\text{Rule } i\text{: IF } x_1 \text{ is } A_{i1},\ x_2 \text{ is } A_{i2}, \cdots, x_j \text{ is } A_{ij} \text{ THEN } y \text{ is } B_i.$$

where A_{ij} is the antecedent fuzzy set and B_i is the conclusion fuzzy set. x_j is not a fuzzy set but a matter of fact in the fuzzy control.

Let x_j^* be the fact value for the matter x_j, ${}^hA_{ij}(x)$ a membership function, and ω_i the fitness grade of rule i. Then ω_i is expressed as

$$\omega_i = {}^hA_{i1}(x_1^*) \wedge {}^hA_{i2}(x_2^*) \wedge \cdots \wedge {}^hA_{ij}(x_j^*)$$

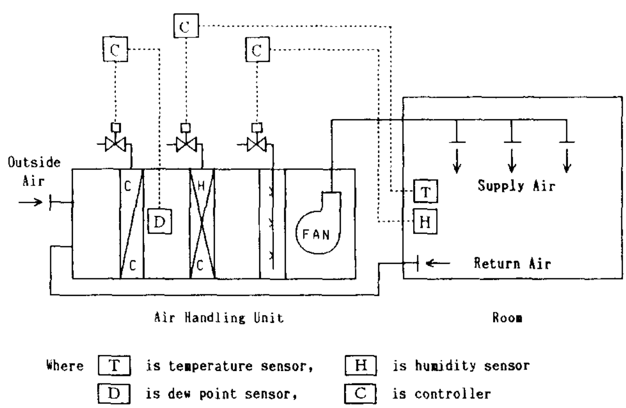

Figure 8. Diagram of the dew-point control system. T, temperature sensor; H, humidity sensor; D, dew-point sensor; C, controller.

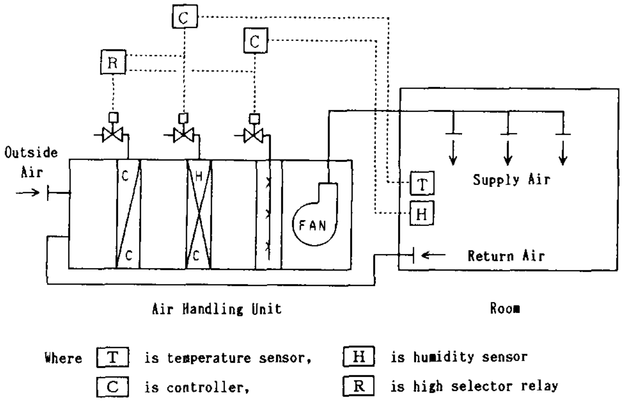

Figure 9. Diagram of the control system with a relay. T, Temperature sensor; H, humidity sensor, C, controller; R, high selector relay.

and the conclusion of the inference for rule i is expressed as

$$y \text{ is } \omega_i B_i, \qquad \text{where } {}^h\omega_i B_i(y) = \omega_i \times {}^hB_i(y)$$

Let B^* be the conclusion set of all the rules; then B^* is expressed as

$$B^* = \omega_1 B_1 \cup \omega_2 B_2 \cup \cdots \cup \omega_i B_i$$

Let the conclusion of fuzzy inference be y^*; then y^* is calculated as the center of gravity of ${}^hB^*(y)$.

Fuzzy Inference Board

The fuzzy inference board is the digital hardware of the fuzzy inference engine. The outline of the fuzzy inference board is shown in Figure 11.

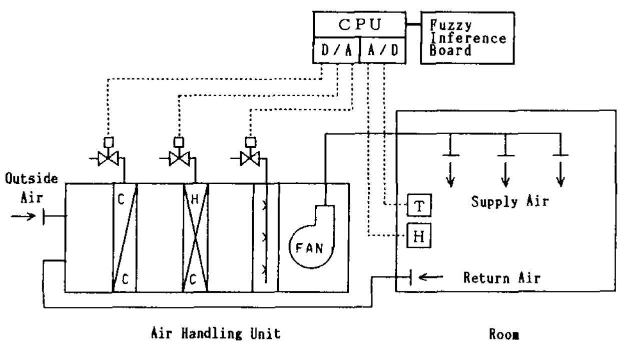

Figure 10. Outline of the fuzzy control system.

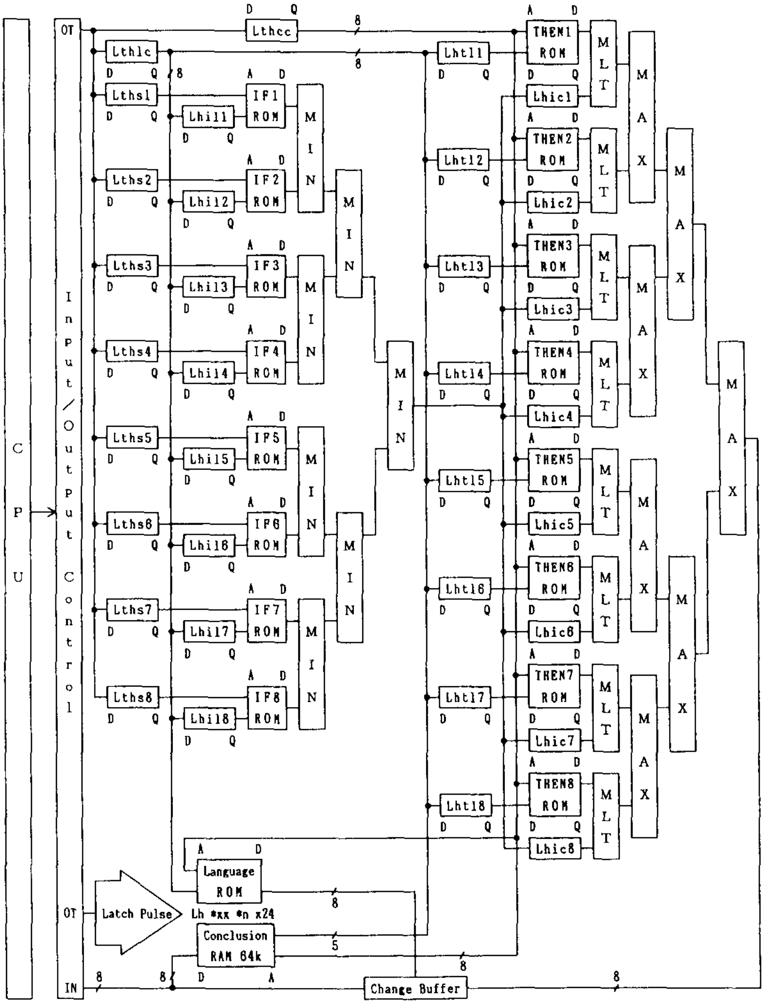

Figure 11. Outline of the fuzzy inference board. IF*nROM = antecedent fuzzy sets loading; THEN*nROM = conclusion fuzzy sets loading; MIN = MIN (minimum) arithmetic circuit; MLT = MLT (algebraic product) arithmetic circuit; MAX = MAX (maximum) arithmetic circuit; Lthcc = data latch circuit: address counter for deriving conclusion set of 256 bytes; Lthlc = data latch circuit: address counter for switching fuzzy set block; Lths*n = data latch circuit: input of defined information to support set of antecedent; Lhil*n = data latch circuit: setting antecedent fuzzy set block; Lhtl*n = data latch circuit: setting conclusion fuzzy set block; Lhic*n = data latch circuit: setting fitness grade for antecedent fuzzy set of control rule; Latch pulse = data latch pulse generating circuit to Lh*xx*n latch circuit **n* is a variable and takes 1 to 8; **xx* is a character variable and takes il, tl or ic); Language ROM = loading the message for printer output; Conclusion RAM = storing 32 conclusion sets; Change buffer = switching the line for conclusion set or printer output message.

This board can memorize 256 fuzzy inference rules, 32 units of eight rules each. Each rule can take eight inputs for the antecedent and eight outputs for the conclusion. Thus, the maximum capacity of each unit consists of eight rules expressed as follows:

Rule 1: IF x_1 is $A_{11}, \cdots, x_8$ is A_{18} THEN y_1 is $B_{11}, \cdots, y_8$ is B_{18}.
Rule 2: IF x_1 is $A_{21}, \cdots, x_8$ is A_{28} THEN y_1 is $B_{21}, \cdots, y_8$ is B_{28}.
⋮
Rule 8: IF x_1 is $A_{81}, \cdots, x_8$ is A_{88} THEN y_1 is $B_{81}, \cdots, y_8$ is B_{88}.

The fuzzy set of A_{i1} for the antecedent is memorized in IF1ROM, A_{i2} is in IF2ROM, and so on. The fuzzy set of B_{1i} is memorized in THEN1ROM, B_{2i} is in THEN2ROM, and so on. Each fuzzy set is described in 256 bytes. For these IF*nROM and THEN*nROM, 512K C-MOS EP-ROM is used, and the fuzzy sets can easily be reloaded. MIN means minimum arithmetic circuit, MLT means algebraic product arithmetic circuit, and MAX means maximum arithmetic circuit.

It is possible to operate each eight rules (eight-inputs for the antecedent and one output for the conclusion) in parallel at once. After operating each eight rules, the board sends the conclusion set to the CPU. The CPU can operate maximum calculation with other conclusion sets, if necessary. Then the CPU has to calculate the conclusion value by the center-of-gravity method.

The Structure of Fuzzy Inference

In this design, the control system is not described simply as a single-input, single-output control system but as a multivariable control system of two inputs and three outputs, which influence each other in some cases. In an air-conditioning system, "humidity" refers to relative humidity, so a change in temperature will influence the humidity. For example, when the humidity ratio (pounds of moisture per pound of dry air) is constant, a rise in temperature will cause a drop in relative humidity. When the air-cooling and dehumidifying coil is used for the dehumidifying process, it works not only for dehumidifying but also for cooling. So when the cooling valve is controlled by the humidity request, it will influence the temperature control.

Using a fuzzy control system, integrated inference makes it possible to control the system with high efficiency and economy. The diagram of the structure of the fuzzy inference is shown in Figure 12. In this control system, there are two steps of fuzzy inference, the (1) temperature request inference and humidity request inference and (2) integrated inference of economical allotment to three final controlling elements used in the conclusion of the first

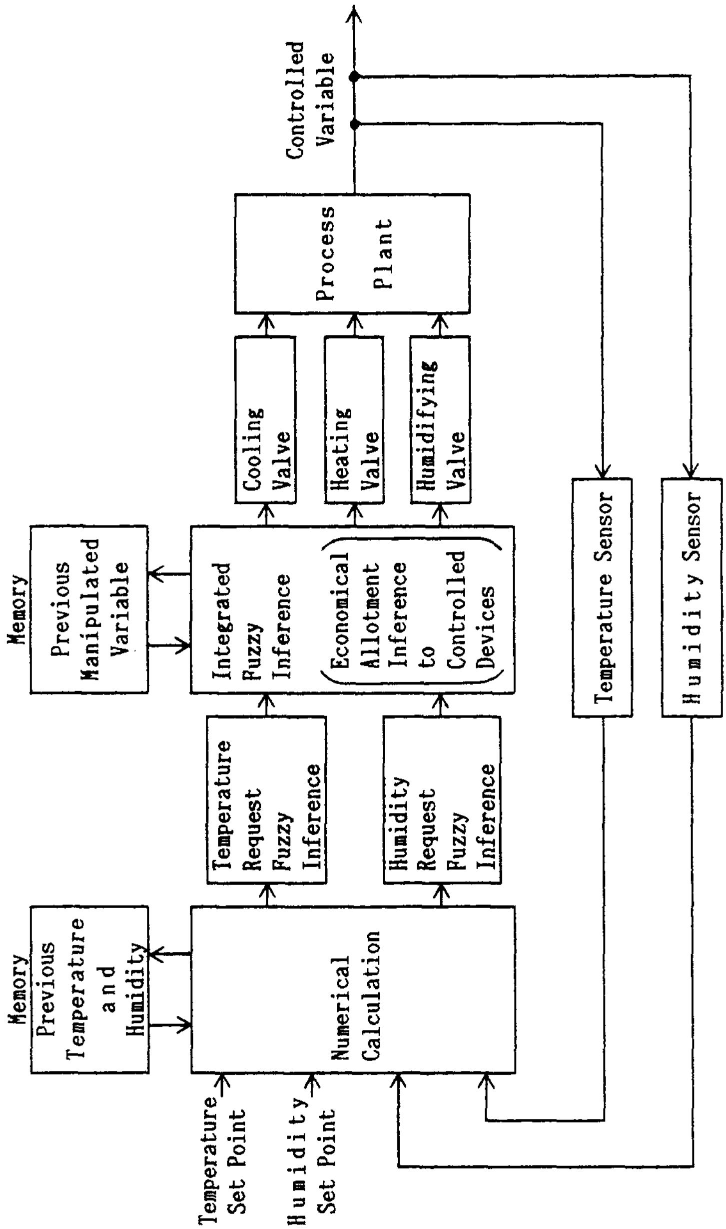

Figure 12. Structure of fuzzy inference.

step. These steps of fuzzy inference are organized as follows:

STEP 1 Temperature request and humidity request inference. The temperature request is inferred from its error and change in error compared to measured temperature with temperature set point and last temperature. The humidity request is not inferred from its error and change in error compared to measured humidity with humidity set point and last humidity, because relative humidity is influenced by temperature. The humidity request is inferred from its foreseen error and change in foreseen error considered together with the temperature error.

STEP 2 Integrated inference (economical allotment inference) When the temperature request is to raise the temperature, there are two ways to raise the temperature: close the cooling valve, or open the heating valve. It will be considered by operators that closing the cooling valve is economical, but if it is closed perfectly or is used for dehumidifying, then the heating valve must be opened.

When the temperature request is to lower the temperature, there are two ways to lower the temperature: close the heating valve, or open the cooling valve. Closing the heating valve is economical, but if it is closed perfectly then the cooling valve must be opened.

When the humidity request is to raise the humidity, there are two ways to raise the humidity: close the cooling valve, or open the humidifying valve. Closing the cooling valve is economical, but if it is closed perfectly or is used for cooling, then the humidifying valve must be opened, and if the cooling valve is closed according to the humidity request, then the temperature will be raised.

When the humidity request is to decrease the humidity, there are two ways to decrease the humidity: close humidifying valve, or open the cooling valve. Closing the humidifying valve is economical, but if it is closed perfectly then the cooling valve must be opened, and if the cooling valve is opened according to the humidity request, then the temperature will drop.

Thus, it is considered that temperature- and humidity-integrated inference of economical allotment could perform better and more economical control than temperature- and humidity-independent control systems. Integrated fuzzy inference rules are described as follows:

Rule 1: IF x_1 is $A_{11}, \cdots, x_5$ is A_{15} THEN y is B_1.

Rule 2: IF x_1 is $A_{21}, \cdots, x_5$ is A_{25} THEN y is B_2.

$\vdots$

Rule i: IF x_1 is $A_{i1}, \cdots, x_5$ is A_{i5} THEN y is B_i.

where x_1 is the last manipulated variable for the cooling valve; x_2, the last manipulated variable for the heating valve; x_3, the last manipulated variable for the humidifying valve; x_4, the temperature request (decided in the first step

Table 1. Fuzzy Production Rules for Heating Valve Operation

	Antecedent					Conclusion
	Cooling Valve Condition	Heating Valve Condition	Humidifying Valve Condition	Temperature Request	Humidity Request	Heating Valve Operation
Rule 1	NCL	CL	NCL	NR	NR	ZO
Rule 2	NCL	NCL	NCL	DP	NR	NB
Rule 3	NCL	NCL	NCL	ZO	NR	NS
Rule 4	NCL	NCL	NCL	RS	NR	ZO
Rule 5	CL	NR	NCL	DP	NR	NS
Rule 6	CL	NR	NCL	ZO	NR	ZO
Rule 7	CL	NR	NCL	RS	NR	PS
Rule 8	NR	NR	CL	DP	ZO	NS
Rule 9	NR	NR	CL	ZO	ZO	ZO
Rule 10	NR	NR	CL	RS	ZO	PS
Rule 11	NOP	NR	CL	DP	DP	ZO
Rule 12	NOP	NR	CL	ZO	DP	PS
Rule 13	NOP	NR	CL	RS	DP	PB
Rule 14	OP	NR	CL	DP	DP	NS
Rule 15	OP	NR	CL	ZO	DP	ZO
Rule 16	OP	NR	CL	RS	DP	PS
Rule 17	NCL	NR	CL	DP	RS	NB
Rule 18	NCL	NR	CL	ZO	RS	NS
Rule 19	NCL	NR	CL	RS	RS	ZO
Rule 20	CL	NR	CL	DP	RS	NS
Rule 21	CL	NR	CL	ZO	RS	ZO
Rule 22	CL	NR	CL	RS	RS	PS

of fuzzy inference); x_5, the humidity request (decided in the first step of fuzzy inference); y, the change in manipulated variable for the cooling, heating, or humidifying valve; each antecedent fuzzy set of A_{i1}, A_{i2}, and A_{i3} is CL (closed almost perfectly), NCL ($\overline{\text{CL}}$), OP (opened almost perfectly), NOP ($\overline{\text{OP}}$), or NR (no relation); each antecedent fuzzy set of A_{i4} and A_{i5} is RS (raise), DP (drop), ZO (do nothing), or NR (no relation); and each conclusion fuzzy set of B_i means PB (open much), PS (open a little), ZO (do nothing), NS (close a little), or NB (close much).

For example, the production rules for the heating valve are shown in Table 1.

THE RESULT OF THIS DESIGN

A lot of work has been done to investigate the performance of a fuzzy control system and an ordinary control system with a relay by using the

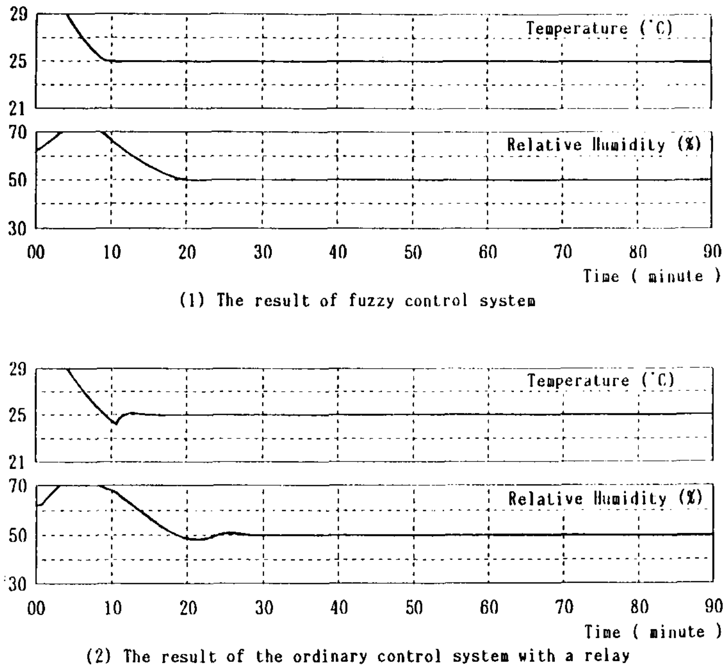

Figure 13. Results of simulation in the case of starting under summer conditions.

method of simulation. The fuzzy control system can be practically used for air-conditioning systems to meet industrial process requirements. We present briefly some results of simulation and practical use.

The Result of Simulation

The results in the case of starting under summer conditions are shown in Figure 13. In this simulation, summer conditions means the state of 33°C outside temperature and 63% outside humidity, and the initial state of space is the same. In this case, the set point of temperature is 25°C, and the set point of relative humidity is 50%.

Temperature and humidity obtained with the ordinary control system with a relay overshoot each set point, but not those obtained with the fuzzy control system. The fuzzy control system has been able to achieve the state of constant temperature and constant humidity in a shorter time than the ordinary control system.

The results in the case of a change in temperature set point, from 25°C to 23°C, from 23°C to 25°C, from 25°C to 27°C, and from 27°C to 25°C, under summer conditions are shown in Figure 14.

The ordinary control system with a relay causes a change in humidity,

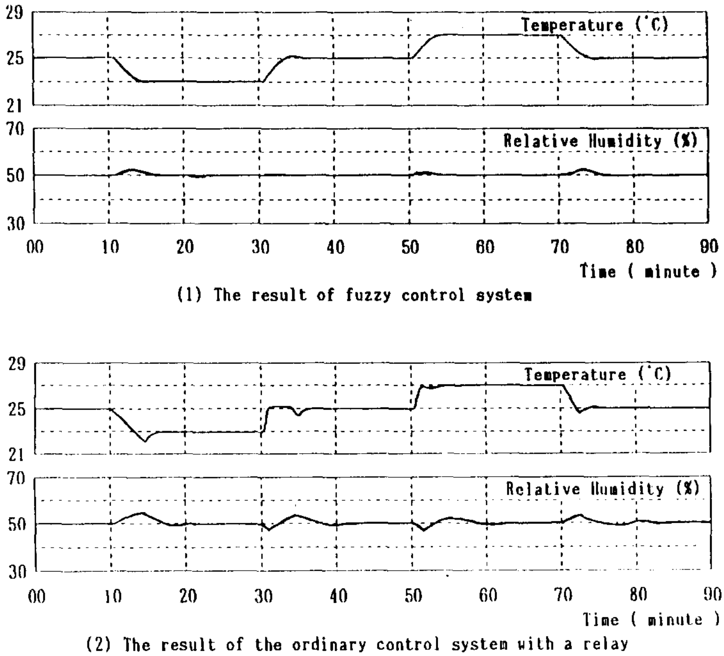

Figure 14. Results of simulation in the case of change in temperature set point under summer conditions.

because a change in temperature influences relative humidity. And then the humidity control causes a change in temperature, because the cooling valve works for both cooling and dehumidifying under summer conditions. But the fuzzy control system does not cause them to such a degree because the fuzzy control system infers temperature and humidity together according to the fuzzy production rules.

The results in the case of a change in humidity set point, from 50% to 40% and from 40% to 50%, under summer conditions are shown in Figure 15.

Humidity control by the ordinary control system with a relay causes a change in temperature, because the cooling valve works for both cooling and dehumidifying under summer conditions. And then the change in temperature causes a change in humidity, because temperature influences relative humidity. But the fuzzy control system does not cause them to such a degree in this case either.

Results of Practical Use

This fuzzy control system is practically used for clean rooms for industrial processes and for biotechnology equipment or rooms. We present briefly the results of practical use of the fuzzy control system for a clean room.

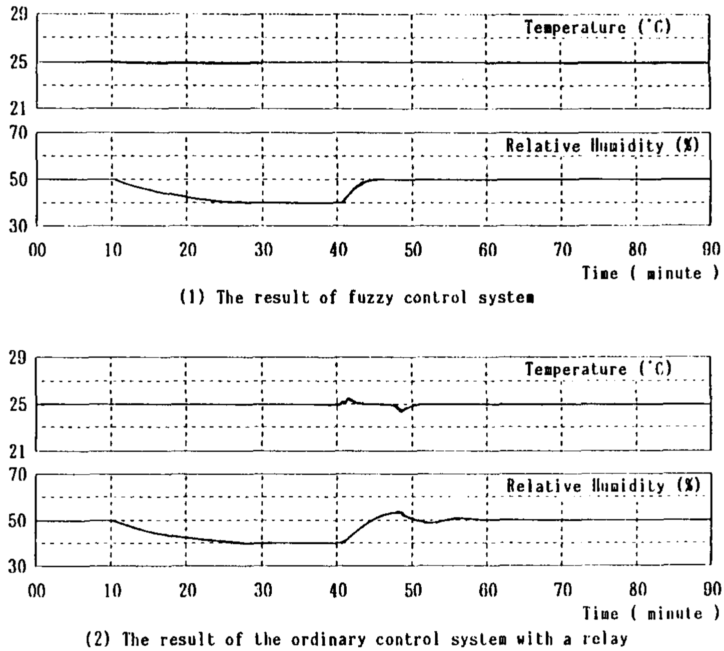

Figure 15. Results of simulation in the case of a change in humidity set point under summer conditions.

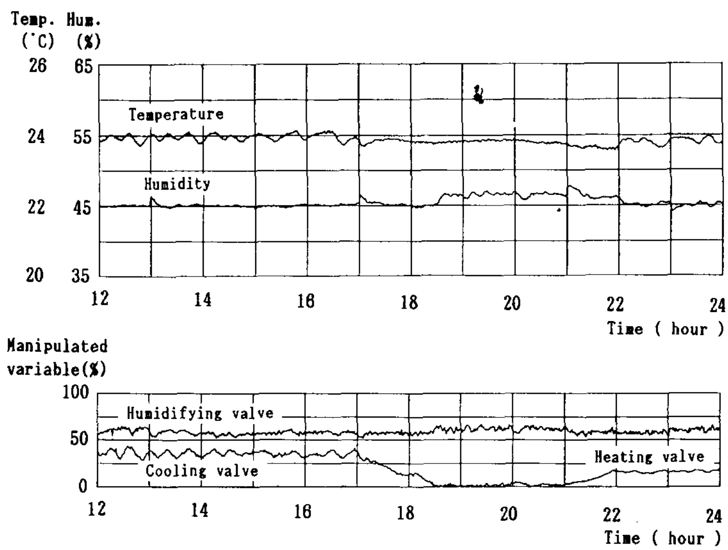

Figure 16. Results of practical use for a clean room (March 28, 1989).

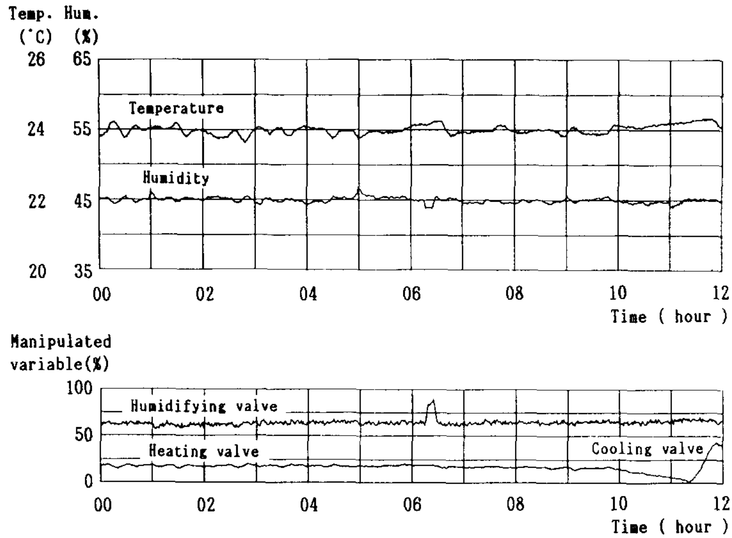

Figure 17. Results of practical use for a clean room (March 29, 1989).

In this control system, the temperature set point is 24°C and the humidity set point is 45%. These data for the fuzzy control system were measured from March 28, 1989 to March 29, 1989 (see Figures 16 and 17).

In this room, each process of industrial production is started between 6:00 and 10:00 a.m. and ended between 5:00 and 10:00 p.m. It is considered that the cooling load would be increased when industrial machines are started into operation. To meet changes in heat load, the fuzzy control system infers optimal and economical manipulated variables according to the fuzzy production rules. In these data, the heat load is cooling and humidifying when industrial machines are into operating, and it is heating and humidifying when they are not.

As the result of practical use, the biggest temperature error is about 0.4°C, and the biggest humidity error is about 2.0%. It is shown from the manipulated variables that the control system is economical because all of the control valves did not open at the same time.

CONCLUSION

In this design, the control system is not described simply as a single-input, single-output control system but as a multivariable control system of two inputs and three outputs. Using a fuzzy control system, integrated fuzzy interference of a two-input, three-output control system makes it possible to control the system efficiently and economically.

From the results of simulation and practical use, the fuzzy control system is demonstrated to be effective for this multivariable control system.

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1. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., *ASHRAE Handbook 1981 Fundamentals* 5.5, 1981.