PROCESS CONTROL FOR THERMAL COMFORT MAINTENANCE USING FUZZY LOGIC

Zoran L. Baus * — **Srete N. Nikolovski** ** — **Predrag Ž. Marić** **

This paper presents the application of fuzzy process control and maintenance of thermal comfort in a measurement laboratory. A new systemic approach to process control is described with special emphasis on the human factor, the measurer, who is a constituent part of the feedback loop. For the conventional thermal comfort maintenance process control a correction is provided in accordance with personal experience, while retaining reference values within margins permissible by the applicable standard. Based on the research results, it has been decided, as well as implemented, to incorporate the personal feeling of comfort by applying the fuzzy sequence control. During research, for the needs of thermal comfort control, a linguistic deductive model has been developed whereby all possible linguistic demands for thermal comfort changes are described. Apart from this model, a model of heat and material accumulation in the observed space has been developed, aimed to confirm the applicability of the proposed theory of thermal comfort process control. The present paper is a new contribution to the theory of thermal comfort control, which has so far solely relied on the stabilization of thermodynamic variables.

K e y w o r d s: thermal comfort, thermo dynamical variables ergonomics, process control, fuzzy logic

1 INTRODUCTION

So far a lot of papers on thermal comfort have been published in the world. The start of research in that area coincides with the construction of multistoried, residential and air-conditioned buildings. P.O. Fanger in [1] defines thermal comfort as: "That condition of mind which expresses satisfaction with the thermal environment". He was the first to quantify thermal comfort by presenting a thermal comfort equation defined by the following parameters: air temperature and relative humidity, mean radiant temperature, relative air velocity, metabolic rate for different typical activities and clothing ensemble data. All three first factors ought to be measured to determine thermal comfort, whereas other parameters are evaluated. The automated control of maintaining the thermal comfort process has been based so far on a thermodynamic description of the process and occurs as automated temperature and humidity stabilization with reference values being determined by pertaining standards [5]. However, even the most rigorous standards cannot wholly meet different perceptions of thermal comfort in a certain ventilated environment, because they vary from person to person. Therefore, the thermal comfort process control based on information provided by an "average person" is not correct, and this notion will be a starting point in our further consideration [1], [2] and [12]. The human body has the natural ability of keeping its temperature at a practically constant temperature of 37C (thermoregulation). The human body is keeping that temperature quite easily if the heat production and loss equilibrium in the body is maintained in a stable environment. This would mean that air temperature, velocity and humidity in a human environment are well adjusted. Otherwise the human body will try to restore the thermal balance by means of metabolic functions using two action modes: chemical and physical [1] and [2].

2 RANGE OF DESIRED THERMAL COMFORT

A person can adapt to outdoor conditions within certain limits, but there is a certain ”range of comfort” within which one feels best. No precise boundaries can be defined here, because many factors are at work, both actual and subjective. That is why only approximate air data can be given where a person feels comfortable. Four parameters are crucial in this respect: air temperature and humidity, wall temperature and air velocity. The other characteristic factors are not so crucial, such as air composition, smells, electricity conditions, and may sometimes be ignored as less influential [1], [2] and [3].

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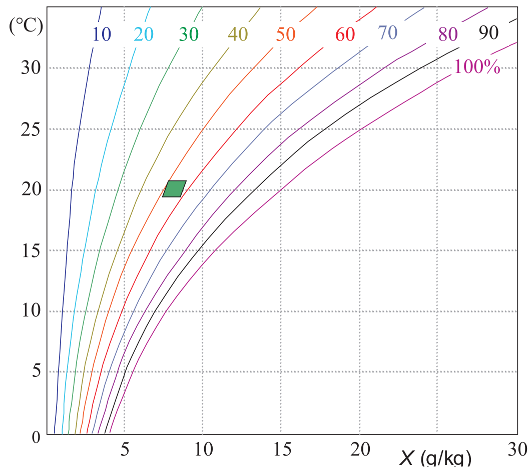

Fig. 1. Determining the thermal comfort range in Mollier h-X humidity diagram

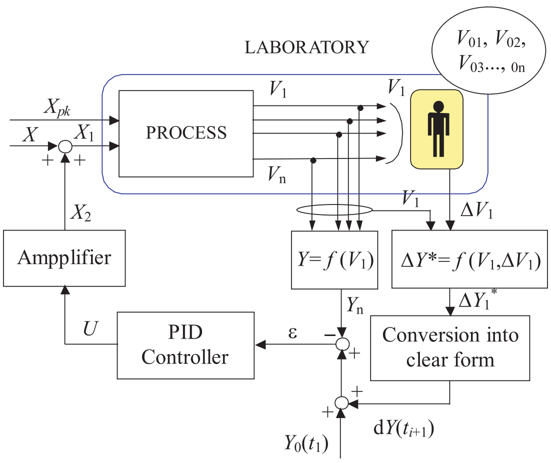

Fig. 2. Fuzzy process control of keeping thermal comfort.

Figure 1 shows the range of thermal comfort in the Mollier h-X humidity diagram. The range of thermal comfort is bounded by the area of isotherms $19 < T < 21$ °C and relative humidity $0.52 < \varphi < 0.58$. The basic fuzzy subsets have thus been defined, used in our further research in developing a fuzzy multi-value controller.

Therefore, in the traditional approach to the A/C process control it was enough to automatically stabilize temperature in the set point (working environment), which led to a varying degree of discontent among A/C users [4], [5] and [10]. Each of them came up with different demands concerning the operation of A/C systems, actually with thermal comfort demands. This paper presents a new approach to indoor air-conditioning process control, automated, and computerized, with the process state being adjusted in interaction with the individual user currently occupying the observed space. The process control unit is thereby learning from the user! [1], [10] and [11]. Each end user is enabled to meet his or her specific thermal comfort requirements.

The paper follows up the thermal comfort maintenance process in a single space occupied by one person. However, an extension of this basic concept would lead to further development of the process and its application to far more complex cases involving more spaces and more persons in non-stationary conditions.

3 THE IDEA OF RESEARCH STUDY

The control task is defined as follows: It is required to maintain the total energy content, which means that it is required to automatically stabilize the enthalpy. Optimum values of temperature and humidity, T_0 and X_0, are assumed, and so is assumed that the process takes place at a constant pressure, $p =$ const. The choice of optimum temperature and humidity values is limited either by current regulations or by experience, but what applies is $X_{\min} < X_0 < X_{\max}$ and $T_{\min} < T_0 < T_{\max}$, where $T_{\min}$, $T_{\max}$, $X_{\min}$ and $X_{\max}$ are marginal values of working areas laid down by regulations, a standard or other conditions. Reference enthalpy value, i_0, is defined as a function of selected state values T_0 and X_0, $i_0 = f(T_0, X_0, p = \text{const})$. The initial reference enthalpy value is thus defined [1], as follows:

$$h_{1+x} = \sum_{i=1}^{2} g_i \left[c_{pi}\right]_0^T T + X_d\left(2500\times 10^3 + \left[c_{pd}\right]T\right)\left(\tfrac{\text{J}}{\text{kg}}\right). \quad (1)$$

Based on acquired experience and according to a need for changing certain state values, man acts on the process state by changing a reference value. Furthermore, the personal command for a change in the process state should be formalized, which result in a changed reference enthalpy value, will *ie*, mathematically describe the process with a view to making it automatic. Therefore, the solution to the set task lies in achieving a fuzzy adaptive process control of maintaining thermal comfort in a measurement laboratory. The idea of the process is shown in Fig. 2.

A new approach to indoor air-conditioning process control is motivated by the need for a system capable of online correction of its characteristics in interaction with the user, a human individual currently occupying the observed space [1], [4] and [7].

Particularly explored are all those parameters that influence the sensation of thermal comfort in the observed space, with special emphasis on the use of the personal perception of the thermal system obtained from the user. In the traditional approach to the A/C process control it sufficed to automatically stabilize temperature in the set point, which led to a varying degree of discontent among A/C users. The present work aims to develop a control system which learns from the user. This project task is motivated by the fact that the A/C system is not well designed or that its operation is not sufficiently known. Consequently, each end user has been coming up with varying demands placed on A/C system operation and thermal comfort respectively. It should be pointed out that this approach enables every end user to satisfy his or her demands in terms of thermal comfort quality. In

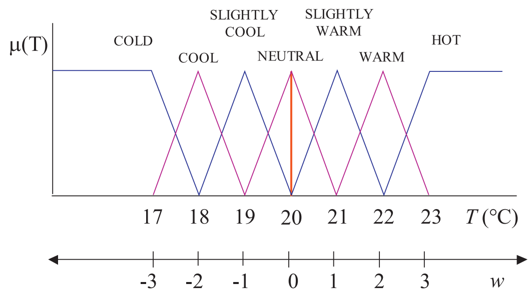

Fig. 3. Basic fuzzy sets of thermal comfort for temperature

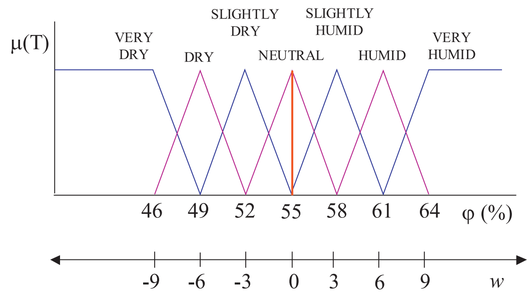

Fig. 4. Basic fuzzy sets of thermal comfort for humidity

developing an intelligent or learning system an algorithm must be considered which is able to learn or adopt all offered relevant knowledge. Possible sources of knowledge presentation are physical system models, knowledge bases with rules, neural networks or appropriate addressable memories.

The present paper explores presentations of knowledge base models due to the physical process which plays a key role and which by now is well known through intense research work. The approach is presented through the existing basic model for which a new control system is used, one adapted to highly efficient parameters of state evaluation algorithms. The present paper is confined to a one-space one-man set-up. However, an extension of this basic concept would lead to further development of the process and its application to far more complex cases involving more spaces and more persons in non-stationary conditions.

4 MAINTENANCE OF THERMAL COMFORT BY USING FUZZY LOGIC

Under consideration is the thermal state maintenance process control in a test laboratory with a view to attaining adaptability to the measurer's perception of thermal comfort. Process control is based on personal demands of the measurer working in the test laboratory, which is achieved by the use of fuzzy logic. Our starting point is the fact that man is an integral part of the process in that with his presence in the process space he participates in the matter and energy exchange and in the heat and material equilibrium changes. At the same time, the measurer subjectively perceives the process state (as a fuzzy sensor of thermal comfort) and compares it with his/her subjective perception of the control task, thereby deciding on a change in the process state, which is possible to attain by changing the reference values [8], [11],. Thus the measurer plays a dual role in a process space, as a heat generator and as an intelligent sensor. The measurer subjectively perceives the thermal accumulation state in the measurement laboratory and communicates that sensation in the form of a linguistic expression "neutral ... ", "warm ... ", "cold ... ". Such a linguistic expression is converted into a fuzzy value and assumes one of the values of the associated thermal comfort functions, as illustrated in Figs. 3. and 4.

For thermal accumulation process control or adaptive maintenance of thermal comfort we have developed a thermal model of man-measurer by using experiences acquired over more years of research in human perception of heat in air-conditioned spaces. The thermal model allows quantifying human perception of heat and thereby defining the so-called "thermal index". The human thermal model is a result of solving the thermodynamic equations, whereby a certain quantitative value is obtained (ranging from -3 to $+3$). The thermal index is defined on the basis of the results obtained from the human thermal model and empirical decisions made on the basis of thermal sensation (one of linguistic values ranging from "cold" to "hot"). That is how we have arrived at a scale of thermal perception, as shown in Fig. 8.

The thermal index value may also be numerically quantified: -3; -2; -1; 0; $+1$; $+2$; $+3$. Each of these numbers from a set of real numbers may be empirically associated with a corresponding linguistic value as follows:

− **3** – COLD
− **2** – COOL
− **1** – SLIGHTLY COOL
0 – NEUTRAL
+ **1** – SLIGHTLY WARM
+ **2** – WARM
+ **3** – HOT

Man-measurer perceives the state of thermal accumulation and passes a judgment on thermal comfort, as well as evaluates a change in the state in the form of linguistic information. The person's linguistic information is converted into a linguistic relation in the following form:

"*If* SLIGHTLY COOL .. *then a* SLIGHTLY WARM *state is required*."

"*If* COOL .. *then a* WARM *state is required*."

"*If* COLD .. *then a* HOT *state is required*."

Such a linguistic relation in the form of fuzzy information (demand) is compared with a fuzzy reference value obtained from the thermal model. Obtaining the controller's operating point is based on a fuzzy theory. Man-measurer, depending on his individual feeling of thermal comfort, gives a verbal command, *eg*: "I am cool". This command triggers a transformation based on the temperature scale division into fuzzy sets as shown in Fig. 5.

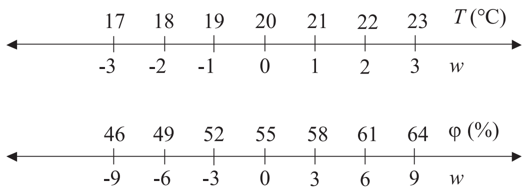

Fig. 5. Defining the thermal index scales for temperature and humidity

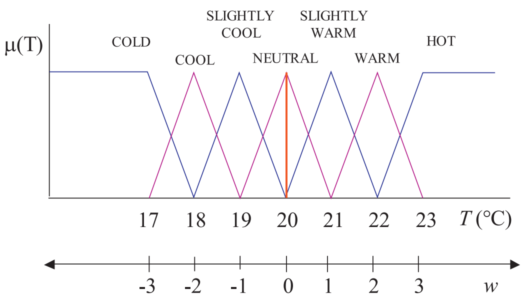

Fig. 6. Temperature scale divided into fuzzy sets and appropriate temperature index scale

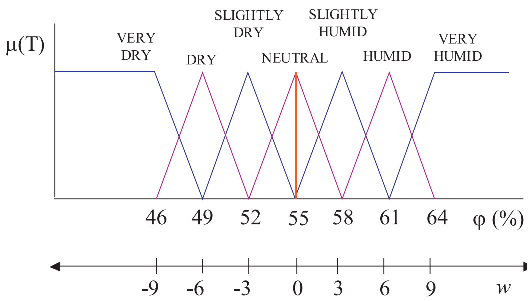

Fig. 7. Relative humidity scale divided into fuzzy sets and appropriate humidity index scale

Each fuzzy set has its weight factor w. Thus the command "I am cool" is converted into a numerical value on the temperature scale by subtracting the weight factor value of the given command from the reference temperature value.

$$T_{DESIRED} = T_{\mathrm{REF}} - w\,. \tag{2}$$

The arithmetic mean of the obtained numerical value and the current temperature value, obtained by lab measurement at a certain level, determines the set point of the temperature controller.

$$T_{SP} = \big(T_{DESIRED} + T\big)/2\,. \tag{3}$$

Now the reference scale shifts towards a temperature change in the laboratory, *ie*, the reference temperature assumes the value of the set point temperature:

$$T_{SP} = T_{REF}\,. \tag{4}$$

Analogous to the above said, calculation proceeds for the set point of the humidity controller, but the essential difference is that the weight factor values vary from −9 to +9, with step 3, Figs 6. and 7.

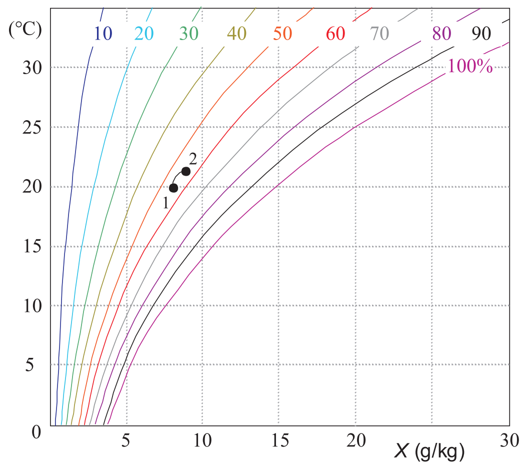

Fig. 8. Air state change at Command 1: "cool".

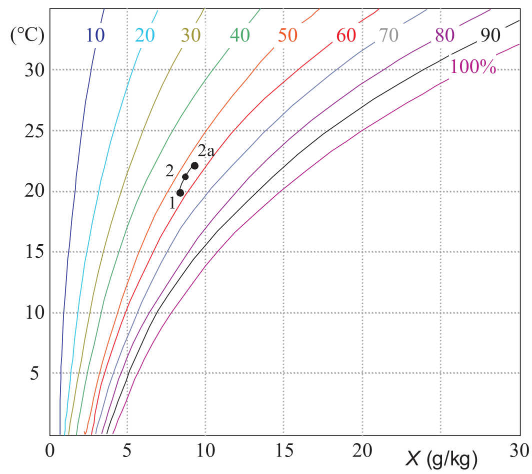

Fig. 9. Air state at Command 2a: "cool".

Let us see how the system behaves:

STATE 1: –
T – °C – temperature in the laboratory
$T_{\mathrm{Ref}} = 20\,$°C– starting reference temperature
$T_{\mathrm{SP}} = 20\,$°C – starting set point

<u>COMMAND 1: "cool":</u>
$T_{\mathrm{DESIRED}} = T_{\mathrm{Ref}} - (-2) = 20 + 2 = 22\,$°C
$T_{\mathrm{SP}} = (T + T_{\mathrm{Ref}})/2 = (20 + 22)/2 = 21\,$°C
$T_{\mathrm{Ref}} = T_{\mathrm{SP}} = 21\,$°C

STATE 2: –
a) $T = 21\,$°C – set point attained
b) $T = 20.1\,$°C– set point not yet attained

Air humidiy state can be observed in the Mollier diagram — Fig. 8.

a) <u>COMMAND 2: "cool":</u>
$T_{\mathrm{DESIRED}} = T_{\mathrm{REF}} - (-2) = 21 + 2 = 23\,$°C
$T_{\mathrm{SP}} = (T + T_{\mathrm{REF}})/2 = (21 + 23)/2 = 22\,$°C
$T_{\mathrm{REF}} = T_{\mathrm{SP}} = 22\,$°C

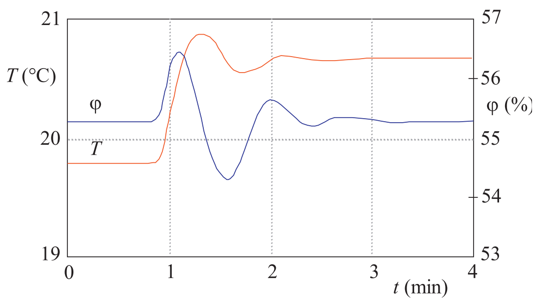

Fig. 10. Changes in temperature and relative humidity in the lab after Command "cool".

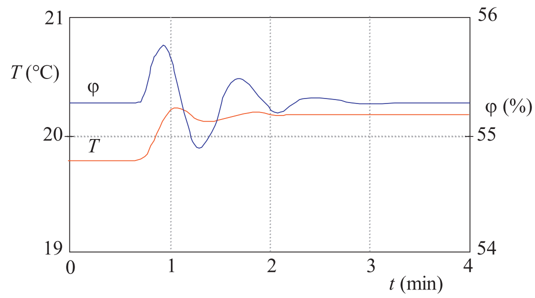

Fig. 11. Changes in temperature and relative humidity in the lab after Command "slightly cool".

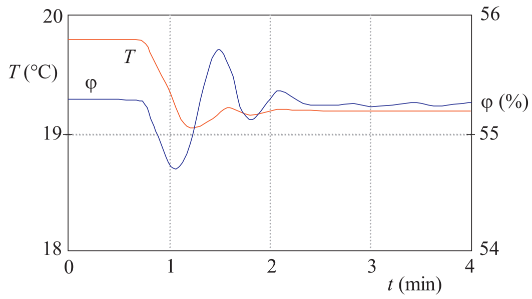

Fig. 12. Changes in temperature and relative humidity in the lab after Command "slightly warm".

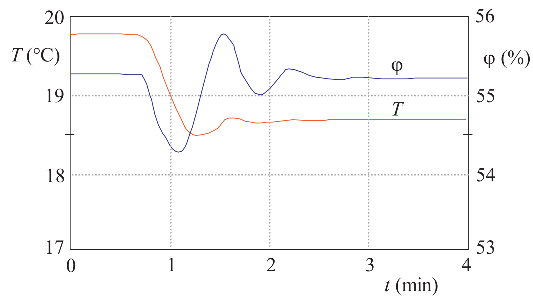

Fig. 13. Changes in temperature and relative humidity in the lab after Command "warm".

b) COMMAND 2: "cool":

$T_{\mathrm{DESIRED}} = T_{\mathrm{REF}} - (-2) = 21 + 2 = 23\,°\mathrm{C}$

$T_{\mathrm{SP}} = (T + T_{\mathrm{Ref}})/2 = (20.1 + 23)/2 = 21.55\,°\mathrm{C}$

$T_{\mathrm{REF}} = T_{\mathrm{SP}} = 21.55\,°\mathrm{C}$

As shown above, in case a (set point reached) the set point shifts by the same value as it did at Command 1, by 1 °C. In case b (the command is repeated before a new set point is reached) the set point shifts by a smaller value than in case a:

$\Delta 1 T_{\mathrm{SP}} = 21.55 - 20 = 1.55\,°\mathrm{C}$

Now let us assume a repetition of situation b. Over time, between two commands, temperature in the laboratory rises by 0.1 °C, and man-measurer is repeatedly giving Command "cool".

COMMAND 3:

$T = 20.2\,°\mathrm{C}$

$T_{\mathrm{DESIRED}} = T_{\mathrm{REF}} - (-2) = 21.55 + 2 = 23.55\,°\mathrm{C}$

$T_{\mathrm{SP}} = (T + T_{\mathrm{Ref}})/2 = (20.2 + 23.55)/2 = 21.875\,°\mathrm{C}$

$2T_{\mathrm{SP}} = 0.325\,°\mathrm{C}$

$T_{\mathrm{REF}} = T_{\mathrm{SP}} = 21.875\,°\mathrm{C}$

COMMAND 4:

$T = 20.3\,°\mathrm{C}$

$T_{\mathrm{DESIRED}} = T_{\mathrm{REF}} - (-2) = 21.875 + 2 = 23.875\,°\mathrm{C}$

$T_{\mathrm{SP}} = (T + T_{\mathrm{REF}})/2 = (20.3 + 23.875)/2 = 22.0875\,°\mathrm{C}$

$3T_{\mathrm{SP}} = 0.2125\,°\mathrm{C}$

COMMAND 5:

$T = 20.4\,°\mathrm{C}$

$T_{\mathrm{DESIRED}} = T_{\mathrm{REF}} - (-2) = 22.0875 + 2 = 24.0875\,°\mathrm{C}$

$T_{\mathrm{SP}} = (T + T_{\mathrm{REF}}/2 = (20.4 + 24.0875)/2 = 22.24375\,°\mathrm{C}$

$3T_{\mathrm{SP}} = 0.15625\,°\mathrm{C}$

$T_{\mathrm{REF}} = T_{\mathrm{SP}} = 22.24375\,°\mathrm{C}$

As can well be seen, if the set point from the foregoing command has not been reached, the new set point will be closer to the foregoing one, proportionately to the current room temperature and the reference temperature. What it means in practice is that through successive commands the user cannot adjust too high or too low the set point values of temperature and relative humidity. For example, if the user successively repeats Command "cool", the temperature set point value difference will be asymptotically nearing zero. This is graphically shown in Fig. 9.

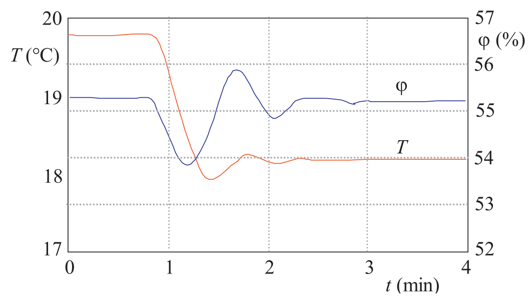

Fig. 14. Changes in temperature and relative humidity in the lab after Command "hot".

Experimental research results were presented on Figures 10–14

5 CONCLUSIONS

The present paper posits and elaborates a new approach to thermal comfort process control by applying the theory of fuzzy sets, the theory of approximate reasoning and the theory of linguistic modeling, involving multi-value fuzzy The present paper posits and elaborates a new approach to thermal comfort process control by applying the theory of fuzzy sets, the theory of approximate reasoning and the theory of linguistic modeling, involving multi-value fuzzy control. The previous approach to thermal comfort control has been confined to automatic control systems based on feedback principles, where the thermal comfort experience of the person currently occupying a space has never been taken into account. As a result of our research, a new systemic approach to control has been conceived and implemented, with special emphasis on man who is a constituent part of the feedback loop, to the effect that his personal feeling of comfort is incorporated by applying a fuzzy sequence control by a fuzzy controller. The previous approach to thermal comfort control has been confined to automatic control systems based on feedback principles, where the thermal comfort experience of the person currently occupying a space has never been taken into account. As a result of our research, a new systemic approach to control has been conceived and implemented, with special emphasis on man who is a constituent part of the feedback loop, to the effect that his personal feeling of comfort is incorporated by applying a fuzzy sequence control by a fuzzy controller.

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