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A neural network evaluation model for individual thermal comfort

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Abstract

An evaluation model for individual thermal comfort is presented based on the BP neural network. The train data came from a thermal comfort survey. The evaluation results of the model showed a good match with the subject's real thermal sensation, which indicated that the model can be used to evaluate individual thermal comfort rightly. Taken a room air conditioner as an example, the application of the NNEM in creating a microenvironment for individual was discussed. The result showed that the NNEM can play an important role of connecting individual thermal comfort with the control on the air conditioner.

Keywords: Thermal comfort; Neural network; Individual; Room air conditioner

1. Introduction

A comfortable indoor thermal environment is favorable for occupants' health and helps improve working efficiency, which is attached more and more attention. Human thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" [1]. In order to establish a favorable indoor thermal environment, first of all, human thermal comfort under an environment should be evaluated correctly. In the original studies on evaluation of thermal comfort, the boundaries between the scales of human thermal response, which are essentially fuzzy, were accurately defined by traditional math methods [2], which sometimes, however, led to imprecise results. Therefore, a more scientific evaluation system, the comprehensive fuzzy evaluation model, was developed based on the fuzzy mathematical theory [3]. And, a new approach based on fuzzy logic to estimate the thermal comfort level was presented in reference [4]. The common ground of all these methods was that they were used to evaluate a large group of persons' thermal comfort levels.

In general, different individual has different scale of thermal comfort, due to the physiological difference and the variety of subjective sensation. That means, in a comfortable thermal environment (based on the thermal comfort evaluation for most people), a single person may still feel uncomfortable. Therefore, a question arises: is it possible to establish an evaluation system of thermal comfort for individual? However, as mentioned above, these existing evaluation models were not fully suitable for individual. This paper attempts to develop an evaluation model of thermal comfort for individual based on the neural network theory and discuss about its application in thermal comfort control for an air conditioning environment.

2. A neural network thermal comfort evaluation model

Up to now, neural network models (NNM) were successfully applied in control of HVAC system and prediction of cooling/heat load in buildings [5–7]. However, only a limited number of studies were devoted to application of NNM in thermal comfort evaluation. Atthajariyakul and Leephakpreeda proposed a practical approach to determine the PMV index of thermal comfort via neural computing in a wide range of human variables and environmental variables for an HVAC control system [8]. Their thermal comfort model was developed for colony, not for individual.

In this paper, a neural network evaluation model (NNEM) of indoor thermal comfort is established based on the back propagation algorithm (BP neural network [9]), which can be fit for individual thermal comfort. The BP neural network has an important characteristic of predicting nonlinear systems and

Abbreviations: BP, back propagation; CC, comfort chooser; NNC, neural network controller; NNCS, neural network control system; NNEM, neural network evaluation model; NNM, neural network model

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Nomenclature

d	expected output of the output layer
H_j	output parameter of hidden layer
W_j	weight from hidden layer to output layer
W_{ij}	weight from input layer to hidden layer
X_i	input parameter of input layer
Y	output parameter

Greek symbols

θ	threshold value of input layer unit
θ_j	threshold value of hidden layer unit

Subscript

t	the *t*th learning sample

some tangible merits, such as fast convergence rate and strong false compatibility. Therefore, when applied to the thermal comfort domain, it can automatically learn according to variations of indoor environment parameters and evaluate thermal comfort levels.

2.1. Mathematical modeling

Numerous factors, such as physical factors, physiological factors and mental factors, affect the human thermal comfort. However, it is hard to consider all these factors when evaluating the human thermal comfort. Studies indicated that the thermal comfort evaluation index comprises of two human factors: human activity and clothing insulation and four environmental factors: air temperature, air humidity, air velocity and mean radiant temperature [10–13]. Because of the uncertainties of the human factors, the environmental factors are usually considered as the main factors affecting the human thermal comfort. Therefore, the NNEM in this paper chose the four environmental factors: air temperature, air humidity, air velocity and mean radiant temperature as input parameters.

There was one output parameter in the NNEM, indicating the thermal comfort level. This parameter had three different values: 0, 0.5, and 1, where 0 stands for cool, 1 for warm, and 0.5 for comfort. Here the thermal sensation was not divided into the seven stages proposed by P.O. Fanger, because the seven stages were developed based on a large group of human thermal feeling, while the NNEM is expected to evaluate individual thermal comfort, and as to each individual, he need not distinguish cool or warm from slightly cool or warm. Certainly, the actual outputs of the NNEM were close to the three values (0, 0.5, and 1). For example, an output parameter of 0.99 represents a warm environment and 0.51 means comfort.

According to the output (one parameter) and the input (four parameters), five hidden layer nodes were selected. The NNEM is shown in Fig. 1.

2.2. Arithmetic

In the NNEM, there were 4 input layer units and 5 hidden layer units. The transfer from input layer to hidden layer is as follows:

$$H_j = f\left(\sum_{i=1}^{4} W_{ij}X_i - \theta_j\right), \quad J = 1,2,3,4,5 \tag{1}$$

$$f(s) = \frac{1}{1+\mathrm{e}^{-s}} \tag{2}$$

The transfer from hidden layer to output layer is as follows:

$$Y = f\left(\sum_{j=1}^{5} W_jH_j - \theta\right) \tag{3}$$

After entering the four environmental factors, Y is output by the NNEM. There is an error between Y and the target value before modifying the weights W_{ij} and W_j, which is used to modify the weights. The calculation of weights was repeated until the error fell into the range of the desired tolerance.

The gradient descent method is adopted as the learning algorithm, and the square error function is applied as,

$$E^t = \tfrac{1}{2}(d^t - Y^t)^2 \tag{4}$$

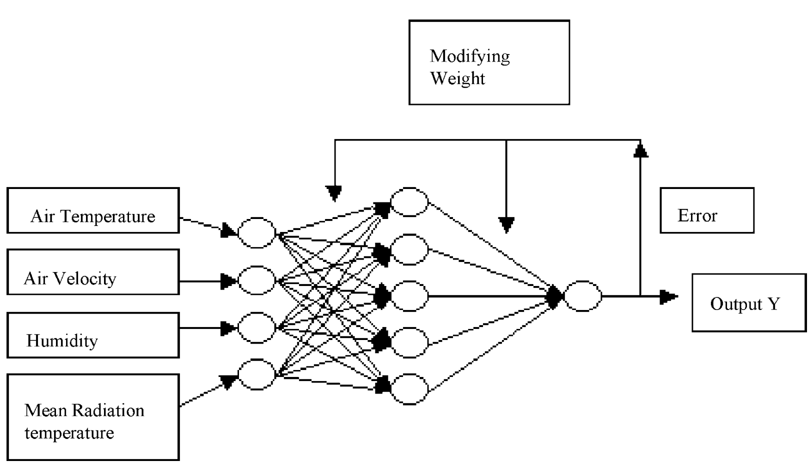

Fig. 1. Diagrammatic sketch of neural network evaluation model of indoor thermal comfort.

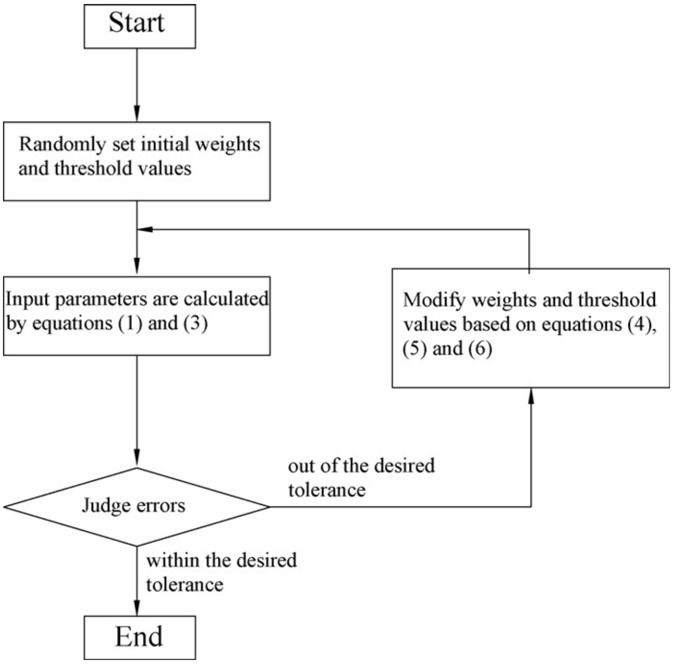

Fig. 2. Arithmetic process of the NNEM.

The variety in the weights from hidden layer to output layer is:

$$\Delta W_j = -\eta \frac{\partial E}{\partial W_j} = \frac{\partial E}{\partial Y}\frac{\partial Y}{\partial W_j}$$
$$= \eta(d-Y) f'\left(\sum_{j=1}^{5} W_j H_j - \theta) H_j\right) \qquad (5)$$

And the variety in the weights from input layer to hidden layer is:

$$\Delta W_{ij} = -\eta \frac{\partial E}{\partial W_{ij}} = -\eta \frac{\partial E}{\partial Y}\frac{\partial Y}{\partial H_j}\frac{\partial H_j}{\partial W_{ij}}$$
$$= \eta(d-Y) f'\left(\sum_{j=1}^{5} W_j H_j - \theta\right) W_j f'$$
$$\times \left(\sum_{i=1}^{4} W_{ij} X_i - \theta_j) X_i\right) \qquad (6)$$

Fig. 2 depicts the arithmetic process of the NNEM.

3. Human thermal comfort survey

In order to provide data for training the NNEM, an experiment was carried out in the manner of thermal comfort survey.

3.1. Subjects and instruments

Sixty five male and 48 female volunteers with the following characteristics (mean) accepted the survey: age: 26.7 years, height: 165 cm, weight: 55 kg. All the volunteers were in good health.

Four basic environmental parameters (air temperature, air velocity, relative humidity and mean radiant temperature) were measured while the subjects were completing their questionnaires. The measurement instruments are shown in Table 1. The accuracy of the instruments met the requirement of ASHRAE Standard 55 [10] and ISO 7726 [14].

3.2. Thermal comfort questionnaire

Subjects were asked to complete a questionnaire during the survey. The questionnaire was based on four sections: personal information, clothing and activity, thermal sensation and thermal comfort level, environmental parameters. The personal information included gender, age, height and weight. The section of clothing and activity required the subjects to carefully record what they dress and what they are doing during the survey. The subjects' thermal sensation was tested using 7-point ASHRAE scale, as shown in Fig. 3, and the thermal comfort was only divided into two levels: comfortable and uncomfortable. The environmental parameters near the subjects were also recorded in the questionnaire.

3.3. Protocol

The survey was carried out in 20 offices and 10 computer rooms in Shanghai of China during June–October 2004. In the survey, the subjects' thermal sensation and thermal comfort level was inquired under various combinations of air temperature and velocity. The air temperature and the air velocity were not restricted in some given values, but changed in a range, randomly, in order to bring the subjects different thermal sensation. The air temperature was controlled in 20–35 °C by room air-conditioners (Sometimes, nature ventilation was chose). At the same time, the air velocity was regulated in almost 0–0.8 m/s by the room air-conditioners or fans.

Usually, thermal comfort experiments require fixed clothing and activity level. However, the survey allowed the two human factors to change, which means that the subjects can wear different clothes and do different work under various thermal environments. By doing so, the survey can provide training data of human thermal comfort with different clothing and activity for the NNEM.

Table 1
Location of measurements point and accuracy

Parameter	Accuracy	ASHRAE or ISO standard	Measurement instrument
Air temperature	±0.2 °C (−25 to +75 °C)	±0.2 °C	TESTO 110
Air velocity	±2% full scale	±0.05 m/s	EY3-2A
Relative humidity	±0.5 °C	±0.5 °C	WS508D
Mean radiant temperature	±0.1 °C	±0.2 °C	150 mm black-bulb

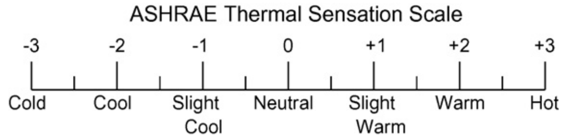

Fig. 3. Seven grades of human thermal sensation.

The subjects were asked to learn the questionnaire before the survey. And, after staying for at least 30 min in an experimental condition, the subjects began to fill the questionnaire. Every subject accepted 20–40 tests under different combinations of air temperature and velocity.

4. Realization of the NNEM

In this section, trained by data from the human thermal comfort survey, the NNEM can be used to evaluate individual thermal comfort.

4.1. Method

Considering the change of the environmental factors and the human factors in actual circumstances, the NNEM adopts the following method to deal with the experimental data. First, the NNEM learns one subject's thermal comfort scale with one kind of clothing and activity level. And then, adapt the NNEM to the same subject's new thermal comfort scale with another kind of clothing and activity level. Finally, make the NNEM fit different subjects' thermal comfort scale.

As mentioned above, subjects' thermal sensation was assessed using 7-point ASHRAE scale in the thermal comfort survey. However, when training the NNEM, only three levels need to be considered: uncomfortable cool (including cool or cold), comfort (including cool, slightly cool, slightly warm and warm) and uncomfortable warm (including warm or hot).

4.2. Fixed subject, clothing and activity

Taking a subject as an example, his thermal comfort levels (fixed clothing and activity) in 20 different indoor circumstances were chosen as the training data of the NNEM, as shown in Table 2. The subject wore short-sleeved clothing, thin trousers, silk stockings and slippers. During the experiment, he did office work, such as writing or reading.

Table 2
The training samples of the NNEM

No.	Air temperature (°C)	Air velocity (m/s)	Air relative humidity (%)	Mean radiant temperature (°C)	Thermal comfort level
1	27	0.25	50	27	0.5
2	22	0.38	64	22	0
3	29	0.28	45	30	1
4	25	0.06	44	27	0.5
5	26	0.2	80	27	0.5
6	33	0.09	75	33	1
7	25	0.12	40	28	0.5
8	29	0.18	90	32	1
9	30	0.3	60	32	1
10	27	0.1	50	33	1
11	21	0.03	32	20	0
12	25	0.02	37	26	0
13	22	0.04	50	23	0.5
14	22	0.32	60	26	0
15	26	0.08	60	26	0.5
16	34	0.05	80	35	1
17	27	0.13	75	29	1
18	26	0.14	70	26	0.5
19	27	0.11	60	30	1
20	30	0.21	80	33	1

In Table 2, every row is a training sample. The four environmental factors of each sample were linearly mapped to zone $(-1,1)$ as the input of the NNEM. The number of the training samples was 20. The learning rate took 0.01. When the error was 0.1 and the weights and thresholds were set randomly, the NNEM converged after 3000 operations. By learning, the weights were modified, and then the NNEM can evaluate the subject's thermal comfort scale.

Table 3 illustrates the comparison between the output values of the NNEM and the actual values, from which it can be seen that the evaluation results matched the subject's real thermal comfort level very well. For example, in the sample of No 21, the subject's actual thermal comfort level was 0.5, which means that he felt comfortable. The output of the NNEM was 0.5065. The two values agreed pretty well. So, according to the output of the NNEM, 0.5065, the subject's thermal comfort can be obtained.

In actual application, with rational initialization of weights and thresholds, the error can be properly broadened, so that the NNEM can converge rapidly.

4.3. Fixed subject, variable clothing and activity

As described in Section 4.2, the subject's thermal comfort level with one kind of clothing and activity level (circumstance A) can be rightly evaluated by the NNEM. Here, the NNEM was required to be effective for another kind of clothing and activity level (circumstance B). Therefore, the samples under circumstance B was input to the NNEM one by one. Modified by n samples, the NNEM can also rightly evaluate the subject's thermal comfort level under circumstance B. The number n of samples was determined in the learning process. For example, $n = 3$ means that the NNEM can fit the subject's thermal comfort scope under circumstance B after being modified by three samples.

Fig. 4 shows the curvy of number of new samples—veracity, as error was 0.01 and 0.1 respectively. The abscissa of Fig. 4 denotes the number of the new samples (under circumstance B) added to the NNEM after the NNEM learned all the 20 samples under circumstance A. When a new sample was added, an old sample under circumstance A was deleted. Therefore, the total number was always 20. The ordinate denotes the veracity of evaluation on the subject's thermal comfort level under circumstance B via the NNEM, which varied with the number of new samples.

As shown in Fig. 4, the veracity of evaluation rose with the increasing number of new samples. The NNEM had a veracity of about 80% when the number of new samples reached 20.

Table 3
Validation of the NNEM

No.	Air temperature (°C)	Air velocity (m/s)	Air relative humidity (%)	Mean radiant temperature (°C)	Subject's thermal comfort level	Output of the NNEM
21	25	0.18	60	27	0.5	0.5065
22	29	0.15	67	30	1	0.9904
23	25	0.5	50	26	0	0.0218
24	22	0.25	45	24	0	0.0132

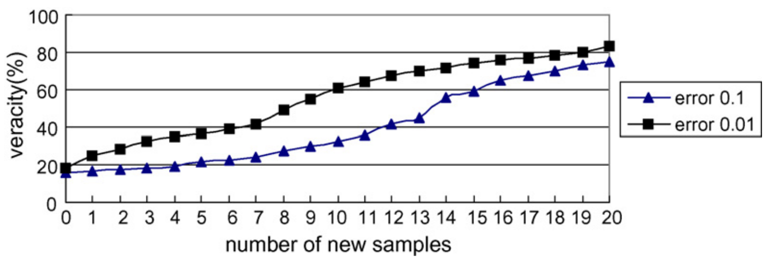

Fig. 4. Curvy of number of new samples—veracity with variable clothing and activity.

4.4. Variable subjects

When evaluating different subjects' thermal comfort, subject B's samples were added to the NNEM one by one, like dealing with the problem of variable clothing and activity in Section 4.3. At the same time, the veracity of evaluation on the subject B's thermal comfort level via the NNEM was verified. It can be predicted that the condition of variable subjects exerted the same influence on the NNEM as that of variable clothing and activity. Fig. 5 illustrates the curvy of number of new samples—veracity based on two subjects' samples, whose thermal feelings were distinct. The curvy in Fig. 5 demonstrates the same trend as in Fig. 4, which indicates that the NNEM can also adapt to the new subject's thermal comfort scope very well.

5. Discussion on application of the NNEM

When creating a microenvironment for individual, such as room air conditioners, how to control the environment factors to bring an occupant comfortable feelings is especially important. As mentioned before, the comfortable conditions obtained according to a large group of persons' thermal feelings may not be suitable for every person. Because the NNEM directly evaluates individual thermal comfort, it seems that the NNEM can achieve good effects in creation of comfortable environment for individual.

5.1. A neural network control system for a room air conditioner

In China, room air conditioners are broadly used in personal offices and families. Generally, a room air conditioner only controls indoor temperature, which can be easily realized, but always lead to unsatisfied indoor environment. If the room air conditioner can automatically judge the owner's thermal comfort and determine the comfortable environment parameters, it will be more significative to improve thermal comfort level for individual. In this section, the room air conditioner was taken as an example to discuss the application of the NNEM.

Here, a neural network control system (NNCS) of a room air conditioner was designed, which is shown in Fig. 6. For the room air conditioner, indoor air temperature and velocity can be controlled by regulating frequency of the compressor, angle of vanes in the airflow outlet and speed of the fan. Therefore, the three parameters were adopt as control variables. The neural network controller (NNC) was desired to output a reasonable combination of the three controlled variables according to the

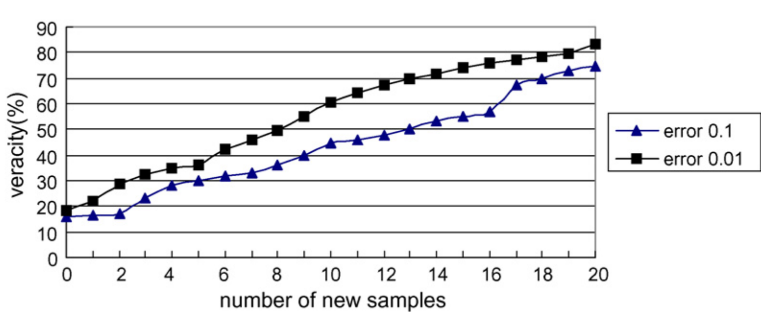

Fig. 5. Curvy of number of new samples—veracity with variable subjects.

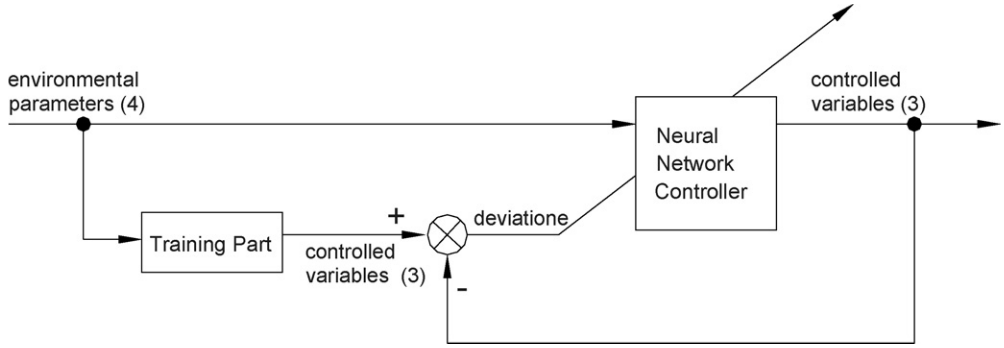

Fig. 6. A neural network control system of a room air conditioner.

four basic environmental parameters. The neural network was trained according to the deviation of output values between the NNC and the training part. By learning, the neural network can reflect the mapping relation between the environmental parameters and the controlled variables.

Finished training the NNC, the NNCS was an open loop control system without error, which can achieve better controlling results.

5.2. Training part based on the NNEM

According as Fig. 6, the training part directly provided the controlled parameters for the NNC, which can determine the indoor thermal comfort level. Considering the advantage of evaluating individual thermal comfort, the NNEM was applied in the training part as the core. The NNEM learnt the occupants' thermal comfort scope based on their thermal sensation and the four environmental parameters. The thermal comfort scope obtained by the NNEM provided a basis for the NNC to control the environmental parameters. Fig. 7 depicts the structure of the training part.

The four environmental parameters (air temperature, air velocity, air humidity, and mean radiant temperature) measured by sensors are input to the NNEM. The output of the NNEM means the thermal comfort levels, which is in the range of 0–1. During the training process of the NNEM, the output is given a factual meaning that $0.5 \pm \varepsilon$ stands for comfort, $0 + \varepsilon$ for cool, and $1 - \varepsilon$ for warm, with ε being the set error. The output value is compared with the preset value of 0.5 to get deviation 1. Deviation 1 is input to the comfort chooser (CC), which works like a trigger.

Signal 1 has three values: 0, 0.5 and 1, which corresponds to the occupant's actual thermal sensation of cool, comfort and warm, respectively. This signal is input by the occupant. In fact, if three keys (cool, comfort and warm) are set as the input of the signal 1 in the remote device of the room air conditioner, the occupant only needs to select the corresponding key according to his thermal feeling.

When the occupant inputs signal 1, the difference between signal 1 and the preset value 0.5 is deviation 2, and the difference between signal 1 and the output of the NNEM is deviation 3. Like deviation 1, deviation 2 is also input to CC.

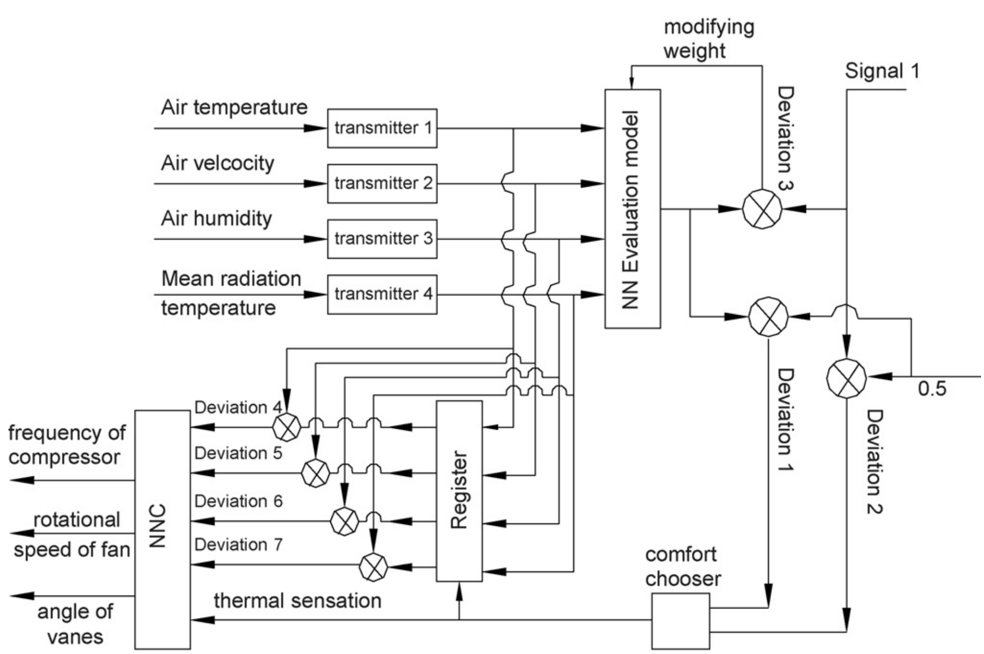

Fig. 7. Training part of the indoor air-conditioner control system.

Deviation 3 returns to the NNEM to modify the weights of the neural network, so that the NNEM can evaluate the occupant's thermal comfort scope better.

Under most time, the NNEM can rightly evaluate the occupant's thermal comfort level in current environment, therefore the occupant does not need to input signal 1. At this time, the output of the CC is only deviation 1, meaning that there is not deviation 2. However, when the NNEM does not entirely learn the occupant's thermal comfort scope or the occupant's thermal comfort scope changes due to different clothing or activity, there is an error between the output of the NNEM and the occupant's actual thermal sensation. Therefore, he needs to input signal 1 via the remote device, and the output of the CC is deviation 2 (deviation 1 does not act).

The signals of the four environmental parameters from the sensors are input to the register. However, the register only stores the latest favorable environmental signals. Hence, the register instruction is decided by the output value of the CC. Once the output of CC means comfort, the register will store the current four environmental signals and then output them.

Four deviations (deviation 4–7) are obtained by subtracting the output of the register from the signals of the four current environmental parameters. Thus, the four deviations represent the difference between the current four environmental parameters (measured by the sensors) and the latest four favorable values (stored in the register). They are input to the NNC. Here, considering the individual's diversity and simplify control, the four deviations instead of the current four environmental parameters are used as the input of the NNC. If the current four environmental parameters are directly input to the NNC, a control principle must be designed for each room air conditioner based on every owner's thermal sensation. However, when the four deviations used, a universal control principle can be designed.

At last, based on the four deviations (deviation 4–7), the NNC adopts appropriate control arithmetic to get right values of frequency of the compressor, angle of vanes in the airflow outlet and speed of the fan, and regulate them.

5.3. Key problems

With the application of the NNEM, the room air conditioner can be treat as ''individual air conditioner''. Obviously, in the NNCS, the NNEM plays an important role of connecting individual thermal comfort with the control on the air conditioner.

However, following two key problems must be solved in the future work, before the whole NNCS can be successfully realized:

(1) Determination on the optimal combination of environmental parameters. It is known that different combination of air temperature, air velocity, air humidity, and radiant temperature can lead to different thermal sensation, and the same thermal comfort level can also be achieved with various combination of environmental parameters, especially air temperature and air velocity. Thus, it is necessary to study how to design the optimal combination with the maximum benefit in terms of individual thermal comfort and energy utilization.

(2) Control principles of an individual air conditioner. Once the optimal combination of environmental parameters is determined, how to control the air conditioner to realize the combination, with high efficiency and low energy consumption, is another problem.

6. Conclusions

In the paper, a neural network evaluation model for individual thermal comfort was developed based on the back propagation algorithm. Compared with the experimental data from the human thermal comfort survey, the evaluation results of the NNEM showed a good match with the subject's real thermal sensation, which indicated this model can be used to evaluate individual's thermal comfort, rightly.

The application of the NNEM in creating a microenvironment for individual was discussed. Taken the room air conditioner as an example, a neural network control system was designed. In the system, the NNEM plays an important role of connecting individual thermal comfort with the control on the air conditioner. Therefore, with the application of the NNEM, the room air conditioner can be more significative to improve thermal comfort level for individual.

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