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Study on indoor air quality evaluation index based on comfort evaluation experiment

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Abstract

Based on the Weber/Fechner's law and PMV, the study puts forward the composition principle of indoor air quality evaluation index, and defines carbon dioxide sub-index PMV_{CO2}, respirable suspended particulate sub-index PMV_{PM10}, formaldehyde sub-index PMV_{HCHO}, and indoor air quality index PMV_{IAQ}. On the basis of indoor air quality comfort evaluation experiment and literatures，the rationality of these models is verified. Compared with the environmental parameters, the new defined comfort evaluation index models establish the link between the objective environment parameters and subjective comfort evaluation and unify the metrics of indoor environmental factors. If other environmental parameters are involved in the evaluation, the corresponding index can be built in the same way.

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Keywords: Indoor air quality, evaluation index, comfort evaluation;

1. Introduction

Comfort and health problems due to poor indoor air quality are becoming increasingly prominent. According to toxicology and epidemiology, many countries determine the threshold values of the indoor environmental parameters on the health point of view. It is also found that the indoor environment parameters of civil buildings, such as office buildings, meet the requirements of environmental quality standards, but occupants are not completely satisfied with the environment. This non-pollution environment will not have a significant and long-term impact on

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human health, in fact, mainly reflects the comfort aspect of indoor environment. In order to reflect the present situation of indoor air quality, the representative indoor air pollutants concentration can be measured and compared with the relevant control limits. However, there is a great difference in the values of the environmental parameters, which cannot express the comfort feeling of occupants directly, and it is not convenient to compare between the different indicators. Therefore, in the evaluation of indoor air quality, it is necessary to convert each environmental parameter value into a sub-index. Based on sub-indices which have the same scale of comfort level, comprehensive evaluation index of indoor air quality can be induced.

At present, based on the values of environmental parameters, the commonly used models to establish evaluation index are standard index method, piecewise linear interpolation method and comprehensive evaluation method. Law compares the concentration value of a certain indicator pollutant with the selected standard value, and obtains the evaluation index [1]. This method is simple and can directly express the relationship between indoor environmental quality and environmental standards. However, due to the different mechanism of the human body, the increment of 1 unit values of each index hasn't the same meaning. Sofuoglu determine the dividing value of the sub index and its corresponding value of pollutant concentration, and then the corresponding index was induced by the piecewise linear interpolation method [2]. Wargocki et al. use olf to measure sensory pollution loads from other pollution sources [3]. In order to express to total feeling of indoor air quality, the comprehensive evaluation index constructed from sub-indices is usually based on the linear synthesis model, the P root mean square model, the root mean square model and the maximum value model. The above-mentioned models of sub-index and comprehensive index are not well connected with the occupants' comfort feeling of indoor air. Moreover it is not convenient to compare between different environmental parameters. Based on the Weber-Fechner law and PMV, a new method which link environmental parameters well with subjective evaluation of indoor air is put forward in this paper.

2. Comfort evaluation experiment of indoor air quality

In order to study the effect of low concentration or near normal indoor environment parameters on human comfort, Zhu created 9 kinds of indoor environment parameters combination schemes and made the subjective comfort survey, according to orthogonal method [4]. In terms of indoor air quality, CO_2, PM_{10} and HCHO were chosen as the control parameters of indoor air environment, and the 9 parameter combination schemes are shown in the table 1. The environmental parameters of scheme 1, 4, and 7 are generally the background concentration and are suitable for human survival. The values of scheme 2, 5 and 8 are close to the control limits of the relevant environmental standards (such as GB/T18883-2002, ASHRAE 62-2013). Indoor pollutant concentration of scheme 3, 6, 9 will generally cause indoor personnel adverse reactions, but will not cause permanent damage.

Table 1. Indoor air quality parameters under nine schemes

Scheme	1	2	3	4	5	6	7	8	9
CO_2[ppm]	680	905	1345	720	885	1338	800	875	1361
PM_{10} [mg/m^3]	0.07	0.14	0.26	0.11	0.15	0.24	0.12	0.16	0.25
HCHO [mg/m^3]	0.03	0.07	0.21	0.04	0.07	0.2	0.04	0.07	0.21

The comfort sense of occupants on indoor air environment is usually based on odor and sensory stimulation. Odor stimulation and stagnant sense lead to an increase in complaints about indoor air quality, and also are the main cause of many adverse symptoms. Therefore the intensity of odor, stagnant sense of indoor air and overall comfort evaluation on IAQ were surveyed in the comfort evaluation experiment. According to the intensity of the feeling, the corresponding subjective comfort vote raise from 0, 1, 2 to 3 (corresponding to comfort, a little discomfort, discomfort and extreme discomfort respectively). In order to study the effects of low concentration environment on human comfort, each experimental condition was kept stable for at least 20 minutes, and then subjective comfort survey of IAQ was carried out. The average vote values under 9 schemes are shown in Table 2. The experimental results show that the indoor environmental parameters will significantly affect the comfort of indoor personnel. It is particularly important that the comfort of occupants does be satisfied when the indoor air pollutants meet control

limits recommended by IAQ standards. It is necessary to establish the comfort evaluation method of IAQ which can establish the link between the objective environment parameters and subjective comfort evaluation.

Table 2. Average vote values of indoor air quality

Scheme	1	2	3	4	5	6	7	8	9
Odor	1	1.38	2.5	1.77	1.63	2.25	1.78	1.63	2.38
Stagnant	1	1.13	2.5	1.11	1	2.25	1.22	1.5	2.38
overall comfort evaluation on IAQ	0.89	1.38	2.38	1.67	1.38	2.38	1.78	1.75	2.25

3. Indoor air quality comfort evaluation method

The comfort feeling of occupant to indoor air quality should mainly be described by the human body's response to environmental stimuli. Based on psychophysical experiment, Weber-Fechner law indicates that response is proportionate to the logarithm of the stimulus, as showed in equation (1):

$$R = k \log S \tag{1}$$

where k is a constant, R is the response and S is the stimulus. The Weber-Fechner law has been successfully applied to noise rating. The logarithmic dB scale also reflects subjective hearing perception better than the Pa scale. On the basis of the concept of decibel, Jokl proposed two new unit decicarbdiox (dCd), decitvoc (dTv) to evaluate indoor air quality [5]. As for thermal comfort, Fanger proposed thermal comfort model which is based on the regulation of body temperature and thermal equilibrium theory [6]. Comfort refers to the degree to which people wish to be satisfied. According to the intensity of bad feeling, the comfort evaluation vote value of IAQ rose from 0 to 3, corresponding to comfort, a little discomfort, discomfort and extreme discomfort respectively.

It is evident that at least two points are necessary to determine the constant k for each stimulus: (a) minimum threshold value, i.e. the weakest odor that can be detected, (b) any second point can be chosen. As for indoor air quality, when the air pollutants are in the background concentration, people feel comfortable and have a high satisfaction with the environment. Therefore, it can be used as the starting point for the comfort evaluation of IAQ, and the corresponding value of sensation is 0, which is the same as the thermal neutral point of PMV=0 in the study of thermal environment. According to the experimental results and the relevant literature or standards, the representative point of indoor comfort evaluation can be selected as another reference point. For example, in a certain concentration of indoor air pollutants, occupant felt obvious discomfort; the corresponding value of sensation is 2 which mean that evaluation of the IAQ is discomfort. This reference point has the same meaning as "warm" and "cool", which is represented by PMV= ±2 in the study of thermal environment.

4. Models of IAQ sub-index based on comfort

Carbon dioxide, respirable suspended particulate, formaldehyde usually be selected as the representative pollutants for evaluation of indoor air quality in civil building. Based on the Webb–Fechner law and PMV, carbon dioxide index PMV_{CO_2}, respirable suspended particulate index $PMV_{PM_{10}}$, formaldehyde index PMV_{HCHO}, and indoor air quality index PMV_{IAQ} are put forward.

4.1 Carbon dioxide index PMV_{CO_2}

The concentration of carbon dioxide in ambient air is 300 ~ 400ppm, and the minimum threshold value for CO_2 is 485 ppm. Experimental results of indoor environment quality evaluation showed that when CO_2 was 1000 ppm, occupants felt obvious discomfort and voted 2 for IAQ. And according to the IAQ Standard of China (GB/T18883-2002), 1000 ppm CO_2 is the upper limit for indoor spaces. So for CO_2, 485ppm and 1000ppm can be selected as the two key points to formulate the equation for comfort level，the sub-index for CO_2 can be defined as equation (2):

$$PMV_{CO_2} = 6.364 \log \frac{X_{CO_2}}{485} \tag{2}$$

PMV_{CO_2} is a new unit for comfort level caused by CO_2. When PMV_{CO_2} are 0, 1, 2 and 3, the corresponding CO_2 concentrations are 485ppm, 700ppm, 1000ppm and 1500ppm, respectively. When concentration is less than 485 ppm, occupants feel comfort and PMV_{CO_2} can be set to 1. If the concentration is higher than 1500ppm, it shows that there is serious pollution, which is harmful to people's health. In this situation the calculated PMV_{CO_2} can be set to 3 directly, because this paper focuses on the comfort of indoor personnel in low concentration environment.

In general, indoor CO_2 is a metabolic product of human, and room temperature, humidity and odor also increase with CO_2 emission. Table 3 shows the effect of CO_2 concentration on human comfort under low and medium concentration [7]. In order to analyze the relationship between the new carbon dioxide index and human comfort, the corresponding calculated index PMV_{CO_2} is also listed in the Table 3.

Table 3. Effect of CO_2 on human comfort.

CO_2[ppm]	PMV_{CO_2}	Effect of CO2 on human comfort
700	1	Smell sensitive people can feel
1000	2	More people feel uncomfortable
1500	3	Dyspnea and increased respiratory rate
2000	3	Poor indoor air

Also we can calculate the PMV_{CO_2} of each experimental scheme, and Figure 1 presents average vote values of odor, stagnant, overall comfort evaluation on IAQ and the corresponding calculated PMV_{CO_2} under the CO_2 concentrations of 9 schemes. Literature and comfort evaluation experimental show that when carbon dioxide is 1000ppm, occupants feel uncomfortable obviously. We can see more clearly the relationship between the carbon dioxide evaluation index and the results of the indoor subjective investigation in Figure 1. Therefore, PMV_{CO_2} can be a good expression of people's comfort in the air environment. In order to obtain an excellent indoor air environment, PMV_{CO_2} should be below 1, and the corresponding carbon dioxide concentration should be 700 ppm.

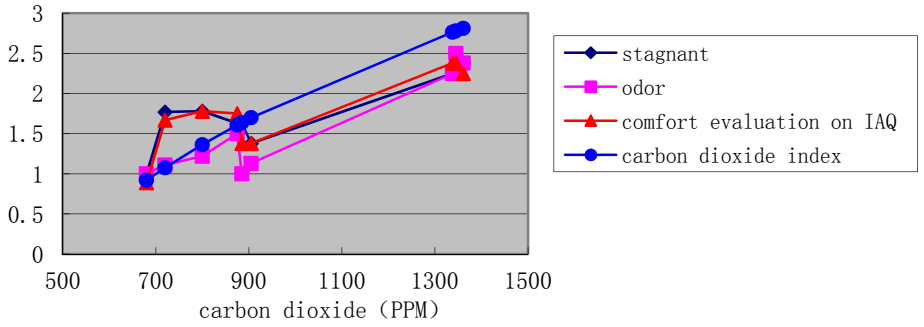

Fig. 1. Carbon dioxide index and comfort vote values.

4.2 Respirable particulate index $PMV_{PM_{10}}$

The background concentration of respirable particle is about 0.02 mg/m^3 in the atmosphere. When the indoor PM_{10} concentration is 0.18mg/m^3, occupants will feel uncomfortable obviously and vote 2 for IAQ. Therefore, the

two key points of 0.02mg/m^3 and 0.18mg/m^3, can be used to establish the sub-index for PM10. The mathematical model of $PMV_{PM_{10}}$ is shown in equation (3):

$$PMV_{PM_{10}} = 2.096 \log \frac{X_{PM_{10}}}{0.02} \tag{3}$$

$PMV_{PM_{10}}$ is a new unit for impact of respirable particle on human comfort, and value 0,1,2 ,and 3, correspond to 0.02mg/m^3, 0.06mg/m^3, 0.18mg/m^3 and 0.54mg/m^3, respectively. The calculated $PMV_{PM_{10}}$ can be set 0 when the concentration is less than 0.02mg/m^3. If the concentration is higher than 0.54mg/m^3, the comfort evaluation index $PMV_{PM_{10}}$ can be directly set to 3. The effect of respirable particle on human comfort is shown in Table 4 [8]. In order to analyze the relationship between the new evaluation index and human comfort, the corresponding calculated $PMV_{PM_{10}}$ is also listed in the table.

Table 4. Effect of PM_{10} on human comfort.

PM_{10}[mg/m3]	PMV_{PM10}	Effect of PM_{10} on human comfort
0.025~0.05	0~0.83	Background concentration
0.075~0.10	1.20~1.47	Most people are satisfied
0.10~0.14	1.47~1.77	Visual range decreases
0.15~0.20	1.83~2.10	Most people feel dissatisfied
>0.2	>2.10	Most people feel completely dissatisfied

Similarly, we can calculate the $PMV_{PM_{10}}$ in each experimental scheme, and Figure 2 presents average vote values of odor, stagnant, overall comfort evaluation on IAQ and the corresponding $PMV_{PM_{10}}$ under PM_{10} concentration. It can be seen from Figure 2 and Table 5 that $PMV_{PM_{10}}$ can better express the effect of respirable particle on comfort of occupants, and is closely linked with stagnant sense of indoor air.

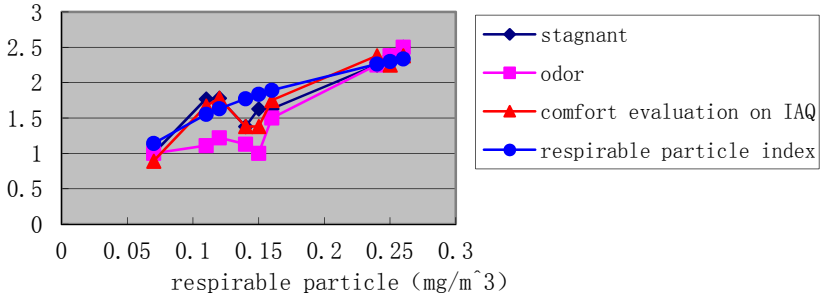

Fig. 2. Respirable particle index and comfort vote values.

4.3 Formaldehyde index PMV_{HCHO}

Generally, the threshold of formaldehyde odor is 0.06-0.07mg/m^3, and the threshold of eye irritation can be as low as 0.01mg/m^3. According to the IAQ Standard of China (GB/T18883-2002), 0.1mg/m^3 is the upper limit of formaldehyde for indoor spaces. And indoor environment comfort experiment showed that when the indoor formaldehyde concentration was 0.1mg/m^3, the occupants felt uncomfortable and set the comfort rating to 2. So we can choose 0.01mg/m^3 and 0.1mg/m^3 as the two key points to formulate the sub-index model formaldehyde:

$$PMV_{HCHO} = 2\log\frac{X_{HCHO}}{0.01} \quad (4)$$

PMV_{HCHO} is a new unit for impact of formaldehyde on human comfort, and value 0,1,2 ,and 3, correspond to 0.01mg/m^3, 0.03mg/m^3, 0.1mg/m^3 and 0.32mg/m^3 respectively. The calculated PMV_{HCHO} can be set 0 when the concentration is less than 0.01mg/m^3. If the concentration is higher than 0.32mg/m^3, the comfort evaluation index PMV_{HCHO} can be directly set to 3. Literature has given the relationship between the concentration of formaldehyde and the health effects on human body in Table 5 [9]. In order to analyse the relationship between the new index and human comfort, the corresponding calculated PMV_{HCHO} is also given in the table.

Table 5. Effect of HCHO on human comfort.

HCHO[mg/m^3]	PMV_{HCHO}	Effect of HCHO on human comfort
0.0~0.05	0~1.4	No irritation or discomfort
0.06	1.56	Eye irritation
0.06~0.22	1.56~2.68	Olfactory stimulation
0.12	2.16	Upper respiratory tract irritation
0.45	3	Chronic respiratory disease, lung function decreased
1.0	3	tissue damage

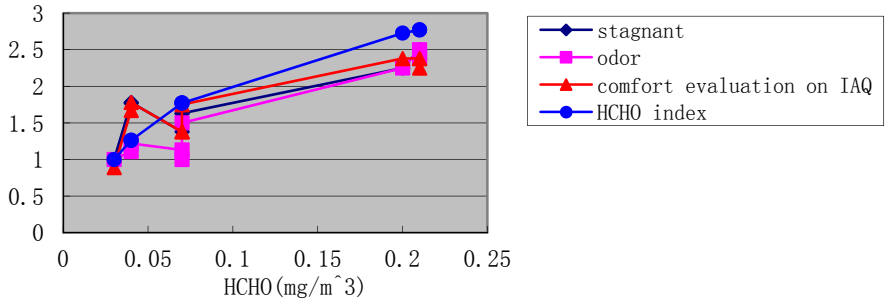

Fig. 3. HCHO and comfort vote values.

Figure 3 and Table 5 show that the new PMV_{HCHO} is more suitable to express the effect of formaldehyde on comfort of occupants. It also can be seen from Figure 3 that the calculated PMV_{HCHO} is closely linked with odor sense of indoor air, which is consistent with the olfactory stimulation effect of low concentration formaldehyde.

If according to the environmental characteristics of the building, it is necessary to choose other indoor air pollutants as evaluation indicators, the corresponding sub-index also can be set up in the same method.

5. Construction of indoor air quality index PMV_{IAQ}

The indoor air quality evaluation should not only reflect the indoor pollution level, but also reveal the subjective feeling of the indoor personnel. Based on comfort, the IAQ sub-index models have been used to standardize the concentration of pollutants. For different indoor air pollutants, when the value of the evaluation index is equal, human comfort is basically the same. PMV_{CO_2} , $PMV_{PM_{10}}$ and PMV_{HCHO} are good indicators of comfort sense caused by carbon dioxide, respirable particles and formaldehyde respectively. The interaction of a variety of pollutants determines the overall feeling on indoor air quality. Therefore, the indoor air quality evaluation index PMV_{IAQ} can be fined as follow:

$$PMV_{IAQ} = \max\left(PMV_{CO_2}, PMV_{PM10}, PMV_{IHCHO}\right) \quad (5)$$

The comprehensive evaluation value of the model takes the maximum value of the sub-indices, which represents the maximum impact of air pollutants on the comfort of indoor air environment. According to Indoor Air Quality Standard of China (GB/T18883-2016) and Code for Indoor Air Environmental Pollution Control of Civil Building Engineering of China (GB50325-2010), all the environmental parameters must meet the requirements. Therefore, the maximum synthesis model is suitable for indoor air quality evaluation. In order to verify the rationality of PMV_{IAQ}, we compared the calculated PMV_{IAQ} values and the IAQ comfort vote values under 9 schemes in Figure 4. It can be seen from Figure 4 that the indoor air quality evaluation index PMV_{IAQ} based on pollutants concentration values are in good agreement with the indoor air comfort vote. Because the sub-indices are the results of logarithmic processing of pollutants concentration, which reflects the relation between the sensation and stimulation, the same sub-index values signify the same comfort levels sensed by occupants. The indoor air quality evaluation index PMV_{IAQ} takes the maximum value of each sub index, so it can reflect the overall comfort evaluation of air environment.

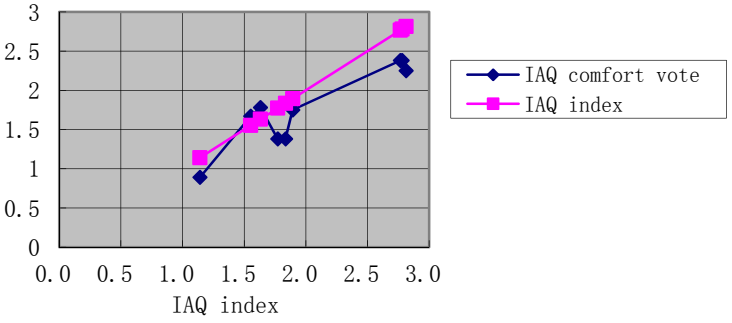

Fig. 4. IAQ index and IAQ comfort vote

6. Conclusions

In this paper, indoor air evaluation index models based on Webb's law and PMV are proposed and the rationality of the models has been verified by literatures and indoor air comfort evaluation experiment of indoor air quality. The new unit PMV_{CO_2} $PMV_{PM_{10}}$ PMV_{HCHO} can be estimated by the direct measurement of CO_2, PM_{10} and HCHO concentrations and gives a much better approximation of the human comfort perception of indoor air. The indoor air quality evaluation index PMV_{IAQ} takes the maximum value of the sub-indices, so it can reflect the overall comfort evaluation of air environment. Compared to the CO_2, PM_{10} and HCHO concentration scales, the new defined comfort evaluation index models establish the link between the objective environment parameters and subjective comfort evaluation and unify the metrics of indoor environmental factors. The new PMV_{IAQ} values fit also very well with the PMV values for thermal environment, e.g. the neutral values of 0 corresponds to the ASHRAE 55-2013 thermal neutrality 0, so they can be compared to each other. The developed method is universal; it can also be applied to other environment constituents.

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