Investigation and Analysis of the Indoor Air Environment of a Large-scale Art Exhibition Hall in Beijing

Xuejun Hao Guotao Cao Yahui Wang Jian Wang
Associate Professor Postgraduate Associate Professor Postgraduate
Beijing Institute of Civil Engineering and Architecture
Beijing China, 100044
HXJ@bicea.edu.cn

Abstract: Adopting the method of locale measurement and subjective appraisal, this paper presents a synthesized investigation and analysis of both the indoor thermal and humid indices and the air quality of a specific exhibition hall in Beijing. Indoor air environment is analyzed according to the needs of the art exhibitions and collections and the personal feelings of subjects' thermal comfort and health within that environment. Finally, the paper provides advice regarding existing problems with the building's environment and equipment.

Keywords: Thermal and humid environment, IAQ, Subjective appraising

INTRODUCTION

With the development of the state economy and society, people's physical and cultural living standards are continuously enhanced. Buildings constructed for artistic display and museums are rapidly developing in China. Simultaneously, the emphasis on transformation, extension, equipment renewal and environmental promotion is also influencing these types of construction projects. The indoor environmental index of this kind of building must not only satisfy audience comfort and health, but also the precious exhibition articles' needs. So, a more demanding request is put forth regarding indoor air environment quality, making effective operation of the constructed environment and equipment system considerably more important. Supported and subsidized by the Beijing Municipal Commission of Education, the Beijing Institute Of Civil Engineering And Architecture and many cooperating organizations have begun the task of researching synthetic optimization control of air conditioning construction's indoor environmental quality as well as its running energy consumption.

In order to accumulate the first data concerning the indoor environment quality of a modern artistic exhibition hall and, further, propose synthetic optimization control technology measures for the air conditioning construction's indoor environmental quality and running energy consumption, the topic group has first chosen Beijing's national large-scale art exhibition hall for on-site testing and subjective quality investigation on the thermal and humid environment indices and indoor air quality in the main exhibition room. We hope to provide the model as a reference for the quality control of the indoor environments of similar construction projects.

1. CONSTITUTION OF INDOOR AIR ENVIRONMENT

Heat environment, humid environment and indoor air quality are three qualitative indices that make up the indoor air environment in construction. A proper indoor air environment should include both comfortable thermal and humid environments which are approved by majority of the members, and provide high quality air which is fresh and not detrimental to people's health. [1]

1.1 Indoor thermal and humid environment

The influence of indoor thermal and humid environment on a person's health, living quality and work efficiency cannot be neglected. People regard bodily thermal comfort as the standard for indoor thermal and humid environment. The ASHRAE standard has made the explicit definition of body thermal comfort: “the satisfactory state of consciousness that people express to the heat environment.” According to a study of the human body's subjective thermal reaction to a given heat environment, the best allowable scope of environmental parameters considers both the influence of the heat environment on the body and the control and adjustment method to implement a given condition.

Temperature, relative humidity, air velocity and surface temperature of surrounding objects are environmental factors that influence body thermal comfort. These are explained as follows:

(1)Temperature: A major criterion that characterizes indoor heat environment. It is high or low, affecting people's personal feelings of heat and cold. There is some research that has indicated: when air temperature is about 25 ℃, the working efficiency of brain is highest; when it is lower than 18℃ or higher than 28℃, the working efficiency drops drastically.

(2)Relative humidity: If temperature is set, air relative humidity indicates the degree of water vapor saturation content in the air. If relative humidity is higher, capacity to evaporate perspiration decreases. If relative humidity is increased, the human body feels warmer in increasingly high temperatures; feelings of cold are often intensified in low temperature.

(3)Air velocity: If indoor wind velocity can be controlled appropriately, it may promote heat convection from the body and increase individual comfort. But when air temperature is higher than an individual’s skin temperature, indoor air flow will cause the human body to absorb more heat from the external environment, producing negative physiological effects.

(4)Surface temperature of surrounding objects: Surface temperature of surrounding objects determines the intensity of radiating convection on the body. If this temperature is high, people will feel increased heat given the same indoor parameters. If temperature is low, people will conversely feel cooler.

Moreover, the air environment index of an air-conditioning system should regard satisfying technical requirements as its main goal. Although air-conditioning of an art exhibition hall is not typically technical, its indoor thermal and humid environment indices must not only conform to the people’s individual thermal requirements, but must also satisfy the thermal prerequisites of exhibit articles and collections. For example, canvases that are displayed and collected at the Orsay Museum in France require an environmental air temperature kept to 22±2℃, relative humidity 50±5%. Its temperature and humidity also happen to fall well within the range of thermal comfort for people. However, because the control precision that must be used is higher and the request of relative humidity must be specially achieved, the standard of constant humidity air conditioning may be difficult to carry out.

1.2 Indoor air quality

Indoor air quality is the important gauge of indoor environmental quality. Massive domestic and foreign research has indicated: IAQ has a decisive influence on people's health and work efficiency. Additionally, the WHO also has confirmed that bad indoor air quality could induce Sick Building Syndrome, Building Related Illness, and Multiple Chemical Sensitivity. [2]

Considering whether indoor air quality is acceptable, many scholars and research institutions have given more specific definitions. Among them, the ASHRAE standard 62-1999 defines “acceptable indoor air quality” as the condition in which any known pollutant density has not achieved the harmful level determined by given authority organizations, and, additionally, that the majority of personnel (>80%) breathing the air has not felt it to be unsatisfactory. Indoor air quality is not merely a series of pollutant density targets, after all. General health and people's subjective sensations are also very important factors. Organic combination of the pollutant density target and people's subjective feelings delineate the significance of indoor air quality. [2]

2. ANALYSIS ON INDOOR AIR ENVIRONMENT OF INVESTIGABLE

OBJECT

2.1 Construction survey

The exhibition hall is located in a flourishing area of Beijing. Its covered area is approximately 17,000 square meters, and the total area of exhibition room is approximately 6,000 square meters within it. Exhibition rooms are mainly distributed on floors one through five in the exhibition hall and the area of each room is about 500 square meters. The exhibition hall carried out a comprehensive rebuilding several years ago. Interior ornaments are all new and include the use of upscale decorative materials, such as marble, precious ceramic tile, etc. Its air-conditioning system has variable air volume and is a centralized system. Air conditioner units that use variable fan-speed control are located underground. The layout of flow distribution in the exhibition rooms takes into account that winds blow from the ceiling and return from the lower side of a wall. The terminal device is a line diffuser.

2.2 Investigation content and method

The test and investigation were carried out on June 10, 2005 8:00-17:00 and employed the method in which measuring on scene and subjective investigation are combined.

2.2.1 Locale measuring

Because the test day occurred during transition season and the outside temperature was not too elevated, the main measures of thermal and humid environment parameters, such as temperature, relative humidity and wind velocity, are derived strictly according to the objective condition of the exhibition hall.

Because the decoration period of the exhibition hall was not long, indoor management is strict, smoking or burning items are prohibited, specialists promptly clean air conditioning units, and each air conditioner unit has primary and middle two-stage filters, the main items tested included: CO_2, HCHO, NH_3 and R_n, as well as TVOC when indoor pollutants were tested.

The measuring instruments include: TsingHuaTongFang self-recording thermo hygrometer, SWEMAAIR300 universal instrument(draught probe and CO_2 probe), 4260-2 formaldehyde analyzer, RAD7 emanometer, TP2020 thermal analyzer, UV-9200 spectral photometer,GC14 and GC7890 gas chromatographic analyzers.

2.2.2 Subjective investigation

The subjective investigation directly uses crowd material. Using a person's own organic sense, indoor air environment quality was judged and recorded。

This subjective investigation uses the method of questionnaire surveys. These chiefly addressed the indoor personnel's subjective feelings. Five levels of standards were employed in ranking individual feeling.

2.3 Test, investigation results and analysis

2.3.1 Indoor thermal and humid environment test analysis

Measuring points were evenly arranged outdoors and in the test exhibition rooms. For the hanging self-recording thermo hygrometer，the time-gap was 30 minutes. Temperature and humidity changes in the outside rooms

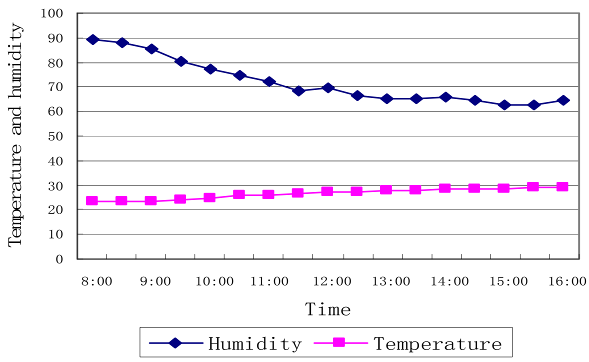


Fig.1 Fluctuating of outdoor temperature and Humidity

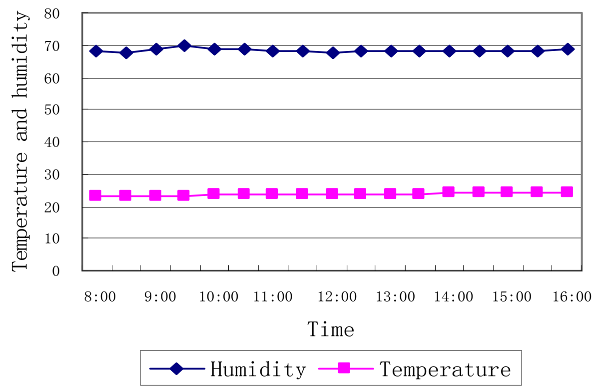


Fig.2 Fluctuating of temperature and humidity in the NO.1 exhibition room

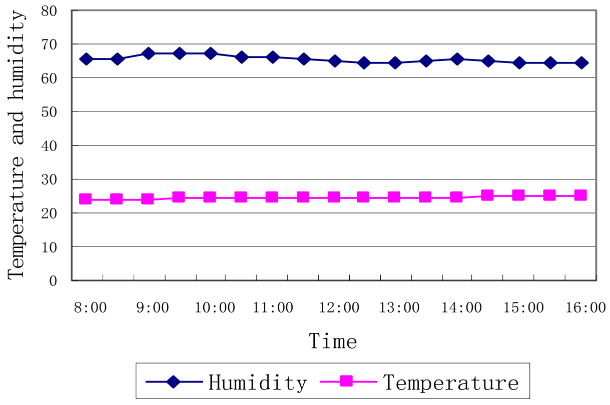


Fig.3 Fluctuating of temperature and humidity in the NO.3 exhibition room

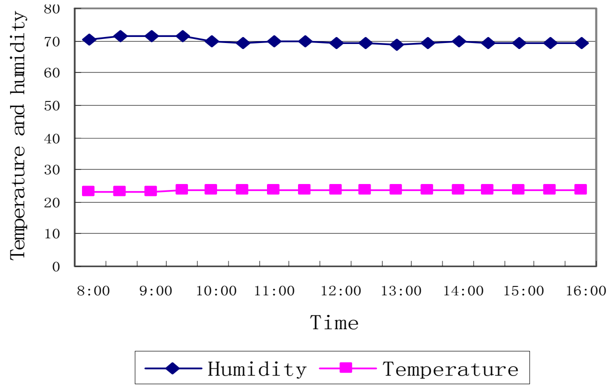


Fig.4 Fluctuating of temperature and humidity in the NO.8 exhibition room

and test exhibition halls over time can be seen from figure 1 to figure 4.

From figure 1， one can see that during testing time, outdoor temperature distribution fell within the range of 23.3 ~ 28.9 □ and the relative humidity in the 62.5 ~ 90.0% range. Outside temperature was not severe, yet the humidity is high compared to average humidity of approximately 72%.

Contrasting with outdoor temperature, the overall tendency of every test exhibition room to change is the same as outside. Temperature generally remained constant as time passed, but gradually rose. Within this rise, the temperature fluctuation scope of No.1 exhibition room was biggest (23.1～24.2□); following was No.3 exhibition room (23.9～24.8□); the range of fluctuation of the No.8 exhibition room was smallest (23.2～23.9□). As shown in figure 2 ~ 4, concerning the relative humidity fluctuation in these test exhibition rooms over time, the No.1, No.3, and No.8 exhibition rooms respective humidity scopes are 67.7 ~ 69.7%, 64.2 ~ 67.2% and 68.9 ~ 71.3%. The only case in which the maximum value of humidity has surpassed was 70% in the No.8 exhibition room. The main reason for this is the No.8 exhibition room has a door which is opened frequently by personnel passing in and out and outdoor air has a considerable influence on indoor environment.

If simply considering temperature as the primary factor that influences indoor personnel comfort, this exhibition hall’s environment completely conforms to the comfort requirements of air conditioning. If temperature and relative humidity are comprehensively considered, the thermal and humid environment of this exhibition hall appears barely satisfactory.

On the testing day, the thermal resistance of individual’s clothing and activity is simple, an experimental condition that the ASHRAE 55-74 comfort standard requires. Contrasting the data of figure 2~4 with the comfort zone[3] (temperature 21.5～26.5℃ and relative humidity of 20%～70%) that ASHRAE provides, one may inquire as to whether the temperature and humidity indices of these test exhibition rooms are generally near the critical line of comfort or not. Hygienic standard value from 《Health Standard of Library, Museum, Art museum, Exhibition Hall》 is: temperature of 18 ~ 28 □ and relative humidity of 40 ~ 65%. Compared with that, the humidity of this exhibition hall is obviously high. The main reason is as follows: the test day is in the transition season and the air-conditioning system of this exhibition hall employs the method of using fresh air to carry on. However, there was high humidity on the testing day and without units that can get rid of unwanted humidity on the fresh air duct of the air-conditioning system. Depending only upon an external surface cooler to remove humidity resulted in higher indoor relative humidity.

Indoor air flow also has a significant impact on comfort. The average indoor air velocity and thermal comfort sensation measured by the Sweden SwemaAir300 universal instrument can be seen in Table 1.

Table.1 Indoor average air velocity and thermal comfort sensation of test exhibition hall

exhibition room / test item	No.1	No.3	No.8
Indoor average air velocity （m/s）	0.155	0.134	0.11
Draught rating	20.7%	14.9%	8.9%

Here, it is needed to specially explain that the index which appraises thermal comfort sensation is the DR. This index is proposed by Professor Fanger of the Danish Technology University. It is defined as the percentage of people who feel uncomfortable with indoor air quality due to air flow. Definition formula is as follows:

$$DR = (34-t_a)\ (v-0.05)^{0.62}\ (0.37\cdot v\cdot Tu+3.14) \quad (1)$$

In formula: t_a—indoor temperature

v—wind speed

Tu—turbulent coefficient

The test result shows that the average indoor air velocity of each test exhibition room is within the required range for comfortable air conditioning provided by the Code for Design of Heating Ventilation and Air Conditioning》 (GB50019-2003). They are not definitively different and fall within 0.05m/s. But, thermal comfort sensation provided by various exhibition rooms actually has very obvious disparity. This is expressed by the sensitivity of a person's reaction to the size of air flow velocity given a set room temperature and relative humidity.

Also consider the analysis of the requirements of artwork exhibits and collections. According to the design of this exhibition hall, the indices of the indoor thermal and humid environment are the same as the requests of the Orsay Museum in France: air temperature kept to 22±2□, relative humidity 50±5%. Contrasting the measurement of the thermal and humid indices, the temperature index of the No.8 exhibition room can satisfy the request and No.1 and No.3 are above satisfactory in the three test exhibition rooms. As for relative humidity, all of them can not meet. On the basis of comprehensive analysis, the most important reason that relative humidity can not be controlled effectively is the design of the air-conditioning system: the hall's system is designed as a general comfort air conditioner. The creators of this system do not consider the requirements of constant temperature and humidity.

2.3.2 Test analysis of indoor air quality

2.3.2.1 Analysis of indoor pollutant density

These test results of CO_2、HCHO、NH_3 and Rn、TVOC are shown at Table 2:

Table.2 Pollutant concentration of test exhibition hall

exhibition room / test item	No.1	No.3	No.8
CO_2 (%)	0.05	0.08	0.08
HCHO (mg/m^3)	0.07	0.10	0.08
NH_3 (mg/m^3)	0.1	0.1	0.1
Rn (Bq/m^3)	16.7	49.9	16.7
TVOC (mg/m^3)	0.1	0.1	0.1

(1) CO_2 concentration analysis: Indoor CO_2 mainly comes from the human body's metabolic function and is influenced by construction volume, ventilation condition, crowd activity, etc. Under usual conditions, when indoor CO_2 concentration is 0.07%, air quality is clean, and people are subjectively comfortable. When CO_2 concentration is 0.07 ~ 0.1%, air quality is ordinary and some people may feel uncomfortable. When CO_2 concentration is 0.1 ~ 0.15%, air quality is critically deteriorated, and other characteristics of indoor air quality start to decline.[4] The healthy and appropriate level of CO_2 concentration, which is also defined by 《Health Standard of Library, Museum, Art museum, Exhibition hall》, is not higher than 0.1 ~ 0.15%. The CO_2 test concentration of this exhibition hall is approximately 0.07-0.08%. Only considering in terms of CO_2, its air quality may be satisfactory. At time of testing, the building's air-conditioning system operates using all fresh air. It is estimated that if this test is carried on using a mixture of return air and fresh air during summer or winter, the CO_2 pollution situation may be more serious.

(2)Other pollutant concentration analysis: As mentioned above, this exhibition hall has been recently repaired and decorated. Decorative material includes stone, primarily in the form of tile, massive wooden building materials, and other upscale decorative materials. Moreover, no exhibition rooms in this exhibition hall have windows, only several doors. Ventilation depends primarily on mechanical ventilation. HCHO、NH_3、Rn, TVOC are pollutants commonly found in decorated buildings. As the source of common pollutants, their potential harm to indoor air quality of the exhibition hall is apparent.

According to fourth item of 2.4.1 general principles of《Code for Pollution Control of Indoor Environment of Civil Building》, the exhibition hall belongs to type II of civil building engineering. Limited value of pollutant concentration of indoor environment is shown at Table 3:

Table.3 Limited value of pollutant concentration of indoor environment

pollutant	□ type civil building engineering
HCHO (mg/m^3)	≤0.12
NH_3 (mg/m^3)	≤0.5
Rn (Bq/m^3)	≤400
TVOC (mg/m^3)	≤0.6

Comparing the data of table 2 with table 3, test results of various pollutants' densities are limited in value. In the light of the above code, we may consider indoor environment quality of this exhibition hall to be acceptable.

2.3.2.2 Rank appraisal of indoor air quality

Actually, indoor pollution is often in low concentration. It may require a long period to do harm to one's body. Large amounts of date from previous testing indicate that these long-term low concentration pollutions seldom exceed permissible standards, even if the condition of IAQ gets worse and complaints are registered. Therefore, it is necessary to put up the rank appraisal of indoor air quality.

At present, there are many evaluation rules about indoor air quality, such as comprehensive index evaluation, fuzzy comprehensive evaluation and gray comprehensive evaluation, etc. We decide to use comprehensive index evaluation after synthesis comparison because this method was developed earlier and is applied more often.

The main principle of the method is: Actual obtained pollutant concentration (Ci) is taken as the objective evaluation target. Ratio of pollutant concentration to standard upper limited value is defined as a fractional exponent and reciprocal value of S_i is regarded as weight coefficient. This method vividly expresses the range of some pollutant concentration and the standard upper limit value. The comprehensive index with which fractional exponents combine reflects indoor air quality.[5] The comprehensive index formula is shown as follows:

$$I = \sqrt{\left(\max\left|\frac{C_1}{S_1}, \frac{C_2}{S_2}, \ldots, \frac{C_n}{S_n}\right|\right) \bullet \left(\frac{1}{n}\sum \frac{C_i}{S_i}\right)} \qquad (2)$$

In accordance with the comprehensive index obtained, indoor air quality is divided into five levels. See Table 4:

Table.4 Rank of indoor air quality

Comprehensive index	Rank	Rank evaluation
＜0.49	□	Clean
0.49～0.99	□	Low clean
1.00～1.49	□	Light pollution
1.50～1.99	□	Middle pollution
＞2.00	□	Heavy pollution

Take the mean value calculated with the tested pollutant concentration of each exhibition room as the mean index of pollution of this exhibition hall and compute the fractional exponent. See table 5:

Table.5 Rank evaluation value of indoor air quality of the exhibition hall

Index value	Mean value	Fractional exponent
CO_2 (ppm)	730.3	0.73
HCHO (mg/m^3)	0.08	0.67
NH_3 (mg/m^3)	0.1	0.2
Rn (Bq/m^3)	27.8	0.07
TVOC (mg/m^3)	0.1	0.17

The last counted comprehensive index obtains 0.52. Compared with table 4, we can draw a conclusion that indoor air quality of this exhibition hall belongs to□level, namely low clean rank.

2.3.3 Subjective investigation

In this investigation, subjective reflection of indoor people in the exhibition hall mainly is reviewed from three aspects: indoor temperature reflection, humidity, and air quality. On-site subjects investigated are shown in table 6:

Table.6 Effective investigation person of each exhibition room

No.1	No.3	No.8	Total number
35	28	24	87

Single statistic results of each exhibition are showed as picture 5 to picture 7:

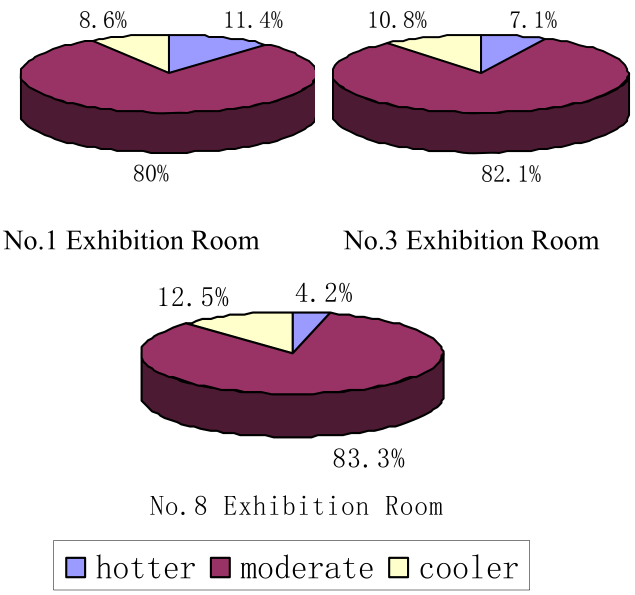


Fig.5 Reflection of indoor people to temperature

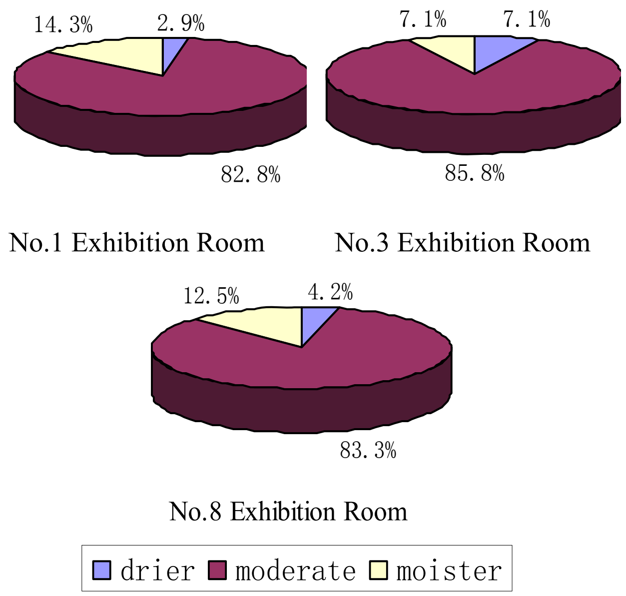
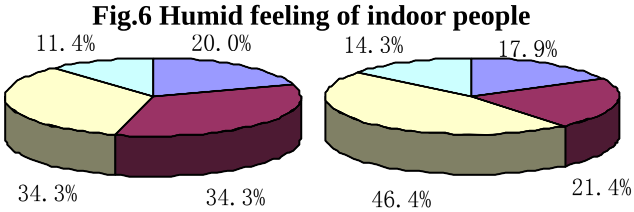


Fig.6 Humid feeling of indoor people



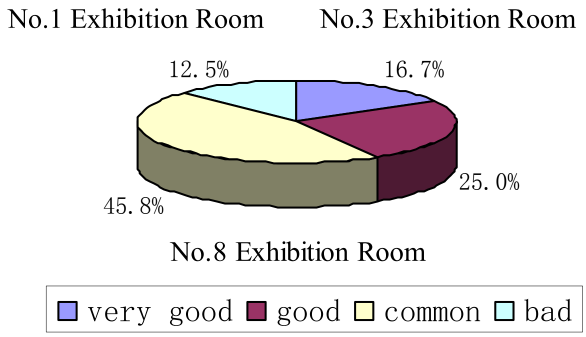


Fig.7 Subjective appraisal of indoor people to indoor air quality

In the No.1, No.3 and No.8 exhibition rooms, the majority of people felt the indoor thermal and humid environment was moderate, with only a few people feeling hotter, cooler, drier, or wetter. In the indoor air quality evaluation, the best results came from the No.1 exhibition room. In the effective survey of 35 individuals, 20% thought the indoor air quality to be very good and comfortable; 34.3% thought the indoor air to be good and fresh; 34.3% thought the indoor air to be common and acceptable, 11.4% thought the indoor air quality was bad. As their time remaining in the room lengthened, these people felt a choking sensation. The worst conditions were in the No.3 exhibition room. In the effective survey of 28 individuals, 46.4% thought the indoor air was common and 14.3% considered it to be bad. This is most likely the result of the way in which temperature, CO_2 and HCHO comprehensively operate. The concentration of CO_2 and HCHO in No.3 exhibition room was higher and the temperature in the three rooms was highest. People were more sensitive to subtle changes when in a higher temperature environment. When people were in an environment of higher concentration contamination, they also became uncomfortable quickly.

Surveys used the division of satisfaction or dissatisfaction to determine the subjective evaluation of indoor thermal and humid environment and air quality. The result is shown in Table.7:

The result shows the subjects' rates of satisfaction for thermal and humid environment and air quality are all above 80%. It could be concluded that indoor air environment is in accordance with personal demand.

Table. 7 The rate of satisfaction for audience towards indoor environment

Item \ Exhibition room	1	3	8	Average
Thermal	80%	82.1%	83.3%	81.8%
Humid	82.8%	85.8%	83.3%	83.1%
Air quality	88.6%	85.7%	87.5%	87.3%

3. CONCLUSION

Though the conclusions drawn from the survey infer that the air environment is satisfactory toward the comfort and health demands of an audience, this should not be considered the final conclusion regarding air quality. There are several reasons for this. First, the survey was held in the transitional season, with the air-conditioning system of the exhibition hall operating in all fresh-air mode. On the day of survey, the number of people at the site was not at its peak. This would likely lead to a decrease in the severity of potential problems. Second, through locale measuring and subjective survey, disadvantages of the indoor air environment of the exhibition hall were discovered. For example, the indoor relative humidity is higher than the standard, the fluctuation of indoor temperature and relative humidity is larger than the standard, and the concentration of CO_2 almost reaches the top allowable limit. Furthermore, the concentration of HCHO also almost reaches upper allowable limit value in some rooms.

Suggestions to rectify this, improve the indoor air environment of the exhibition hall, and stop any potential problems include:

(1) Precision control of constant temperature and humidity for air conditioning, especially in artwork exhibit areas. At present, the air-conditioning system of the building is a common comfort air conditioning system in which precision control of temperature and humidity is low. It can not satisfy the demands of constant humidity control and needs improvement.

(2) For the high demands of the indoor thermal and humid environment, some measures must be taken to intensify the anti-interference ability of indoor air environment towards outdoor conditions. The building is a large space exhibition hall. Because there are many exits and entrances and crowds are often dense, the indoor air environment is easily influenced by outdoor weather.

(3)In daily operations and managements, it is necessary to pay attention to the balance of mechanical exhaust and fresh air. One must ensure the positive pressure of indoor air and decrease the influence of outdoor air towards the quality of controlling indoor environment as much as possible.

(4) Because the location of temperature and humidity sensors influences the measuring precision of an auto-controlled air-conditioning system, accurate adjustment and modification are needed to improve its precision.

(5)The control of fresh air in this type of building in the transition season should be comprehensively considered from the perspectives of saving energy in operation, the sanitation demand, the positive press control, the organization of air flow and the quality control of the thermal and humid environment.

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