Journal of Southeast University (English Edition) Vol. 26, No. 2, pp. 292 – 296 June 2010 ISSN 1003—7985

Field measurements on thermal comfort of a building with double-skin façade in winter

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Abstract: Field measurements on thermal comfort were carried out in a building with double-skin façade from January 14th to 16th, 2009. Data are obtained by measurements of physical parameters and a questionnaire survey is conducted at the same time in 27 offices of the building. The subjective survey involves questions on demographic information of the occupants, health status, environmental comfort conditions and acceptance. A total of 150 occupants are investigated and 131 questionnaires are completed. The statistical data presents the distributions of predicted mean vote, mean thermal sensation vote, mean thermal comfort vote, thermal acceptability, etc. The results show that low relative humidity is the main reason causing thermal discomfort. The greatest discomfort is dry mouth and eye dryness which are caused by low relative humidity. The females are verified to be more sensitive than the males. Meanwhile, a double-skin façade represents a good noise insulation effect while the glare problem is still unresolved.

Key words: thermal comfort; field measurement; double-skin façade

Double-skin façade is a multiple layer skin construction with an external skin, an intermediate space and an internal skin. The external and internal skin can be of either single-glazed or double-glazed pane. An adjustable sun-shading device is usually installed in the intermediate space for thermal control. The double-skin construction can be generally grouped into box window façade, shaft-box façade, corridor façade and multi-story façade[1]. It is quite suitable in moderate weather and enjoys popularity throughout the world for aesthetics, thermodynamics, acoustical and optical reasons.

Many studies have investigated the thermal performance and comfort of double-skin façade with experimental, numerical and theoretical methods. With TAS and CFD software, Wong et al.[2] verified that double-skin façade construction with natural ventilation could conserve energy and enhance thermal comfort in summer compared with single-glazed construction in a tropical humid climate. Kuchen and Fisch[3] conducted thermal comfort investigations on 25 office buildings in winter, in which 22.3% had double façade. However, energy conservation cannot be observed by the detriment of thermal comfort.

Received 2009-11-17.

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Foundation item: The National Key Technology R&D Program of China during the 11th Five-Year Plan Period(No. 2008BAJ12B05).

Citation: Wang Fang, Zhang Xiaosong, Li Shuhong, et al. Field measurements on thermal comfort of a building with double-skin façade in winter [J]. Journal of Southeast University (English Edition), 2010, 26(2): 292 – 296.

In recent years, double-skin construction has been pursued in rebuilt and newly built buildings in China. Further investigation on thermal comfort of existing double-skin façade buildings with field experiments is urgent in order to guide development of future applications, especially for hot-humid climates. Nanjing is located at east longitude 118°50′ and north latitude 32°02′ and characterized as a developed economy in Jiangsu province, China. It is hot-humid in summer and cold-humid in winter. Double-skin façade buildings in this region should resolve the energy consumption conflict between hot summer and cold winter. This study focuses on the investigation of thermal comfort of an existing office building with double-skin façade in winter in Nanjing.

1 Methodologies

Field measurements were conducted in the Silver City Building constructed with double-skin façade. Both questionnaire investigation and physical parameters measurements are carried out to collect subjective sensation responses and physical parameter levels concerning thermal comfort and air quality in the offices with double-skin façades.

The Silver City Building was erected in 2007, Nanjing, China. The total covered area is 3 534.08 m^2 with a height of 77.9 m. It includes 19 stories above the ground and 3 stories underground with a 3.6 m height of standard layer. The total façade area of this building is 1.3×10^4 m^2, of which about 63% is double-skin glazed façade. Double-skin façade is of box-window type and each box consists of three floors in vertical and one room in horizontal with an air cavity of 530 mm. Electric aluminum alloy louvers are installed in the cavity as solar shading devices. The exterior material of the double-skin façade is single ferrule of 10 mm width while the interior material is insulating glass 6 + 12A + 6 with low-ε coating. Each floor is fitted with two individual VRV systems and one electricity powered fresh air conditioning system. Temperature can be set at 24 ℃ in the office and 20 ℃ in the chamber hall in winter if air conditioning is needed. The windows of the exterior envelope are controlled by a centralized control centre and remain closed in winter while the windows of the interior envelope can be opened freely. Staff members can select their clothing except for some service personals. The 3rd to the 7th floor were unused when this building came into service.

The questionnaire is designed according to the ISO 10551 and ISO 7730 standards[4–5]. Four sections are included as follows: First, demographic information (e. g. sex, age, height, weight, race, native place, occupation and the living time in Nanjing) is investigated. In order to calculate thermal comfort indices, quantitative data about activities during a 30 min period and clothing information of participants are collected. Secondly, evaluation and acceptability of participants on thermal aspects are observed. Participants mark with a cross at any point on the axis, which is set according to Fanger's scale to represent their thermal and comfort sensations, evaluations of air movement, humidity and quality, preference and acceptance of current environments. Thirdly, checklists of health discomfort are designed with the ratings of "never", "occasionally", "often" and "severely". Health complaints may be linked to sick building syndrome (SBS). Finally, occupants are required to give a comment of "very poor", "poor", "neutral", "good", or "very good" to indoor environments from the following aspects: acoustical environment, visual environment, comfort of furniture, mental state and work efficiency.

A total of 150 questionnaires were delivered in 27 offices and 131 were completed, which made the statistical results more representative. The statistical results of the samples show that the number of male workers is slightly greater than that of females. The average age of the participants in this investigation is 34 years old, and no significant difference is found in the age distribution between the males and the females. All people are of Han nationality except for one Moslem and the majority of workers are from Jiangsu province, China. About 87% of the occupants have lived in Nanjing more than five years. Approximately 88% of the occupants had stayed in the offices for more than one hour before the field experiment began. According to the research of Yu et al. [6], human responses reach a steady state within 20 min during each exposure ($p > 0.05$). These make the subjective and objective observations in this survey natural. It is reasonable to assume that all the responses in this survey are of a steady state for the air-conditioned environment, and Fanger's thermal comfort theory is applicable.

The physical measurements are administered with the questionnaire survey simultaneously in each room. Considering the staff's seating status, all the indoor parameters are collected at a height of 1.1 m. Four sampling points are chosen in each office, and parameters are recorded four times at each point to reduce errors. Three thermal parameters (air temperature, relative humidity and air velocity) and carbon dioxide concentration are collected. The apparatuses used are a TSI IAQ-CALC 8762 portable indoor air quality meter and a TSI 8346 portable air velocity meter. Black globe temperature is measured by a black ball thermometer. Instruments are calibrated before the experiments. The meteorological data are taken from the weather station which is located on the roof of the building. A team of six assistants perform the field survey. One team member registers the usage status of air conditioners, fans, shading devices, windows of interior façade, and the number of plants at workstations. The field investigation was commenced in each room from January 14th to 16th, 2009 to obtain typical cold season data. All the air conditioners keep working during spot monitoring.

2 Results and Discussion

During the experiments, outdoor climate parameters reflect typical sunny winter days in hot-summer and cold-winter areas: cold, some wind, and high solar radiation. The daily mean temperature of outdoor air is 2.47 ℃, with the lowest being −3.1 ℃ at 06:15 and the highest being 10.3 ℃ at 14:45. The daily average relative humidity (RH) is 51.24% while the lowest is 30% and the highest is 68%. The mean solar radiation during work time is 363 W/m^2 from 8:30 to 17:00 with the highest value being 573 W/m^2 at 12:30 on January 15th. The mean wind speed is 0.91 m/s, while the dominant wind direction is east and southeast. There is no rain for three days.

Indoor micro-climate is described by air temperature, relative humidity and velocity. Indoor air temperature in the surveyed spaces is (22.1 ± 2.1) ℃ which falls within the scope of a recommended temperature interval (20 to 24 ℃) of ISO 7730 with an 80% acceptability for the occupants who are engaged in light activities of sitting with air heating in winter. According to the limit values proposed by ISO 7730, a mean air velocity of 0.10 m/s is favorable. The recommended comfort zone of ISO 7730 for relative humidity in winter is 30% to 70%. A relative humidity of (20.2 ± 2.8)% in the surveyed building is unacceptable according to the criteria above. No apparent temperature or relative humidity differences are found between different orientations and floors.

With the investigation of the occupants' subjective feelings and objective measurements, indices in Tab. 1 are obtained to indicate people's sensations and preferences. They are valued on a visual-analogue scale, and the representative points of each index are chosen according to an ASHRAE 7-point or 5-point scale. The corresponding meaning is elaborated in Tab. 1. Occupants may mark a cross on any place of the axis to represent their sensations. At the same time, people are asked to describe their preferences of air temperature, relative humidity and velocity with "higher", "changeless" or "lower".

Tab. 1 Meaning of representative points corresponding to each index

Level	PMV	MTSV	MTCV	VV	AFV	RHV	TA
−3	Cold	Cold					
−2	Cool	Cool		Very draughty	Very stale	Very wet	
−1	Slightly cool	Slightly cool		Draughty	Stale	Wet	Clearly unacceptable
0	Neutral	Neutral	Comfortable	Neutral	Neutral	Neutral	Just unacceptable(−0) Just acceptable(+0)
1	Slightly warm	Slightly warm	Slightly uncomfortable	Stuffy	Fresh	Dry	Clearly acceptable
2	Warm	Warm	Uncomfortable	Very stuffy	Very fresh	Very dry	
3	Hot	Hot	Very uncomfortable				
4			Intolerable				

Note: MTSV represents mean thermal sensation vote; MTCV represents mean thermal comfort vote; VV represents velocity vote; AFV represents air freshness vote; RHV represents relative humidity vote; TA represents thermal acceptability.

Personal styles in clothing and metabolic rates are important parameters for calculating the PMV index using Fanger's comfort formula. With the spot measurements of indoor air and the statistical results of the personal clothing insulation and the metabolic rate, the PMV index can be calculated. In the questionnaire, a detailed list of common clothing is given according to ISO 7730. The overall clothing insulation for a given person can be calculated using the standard value of assigned clothing piece with the unit of clo (clothing). One clo is equivalent to 0.155 $m^2 \cdot K/W$. The average clothing insulation value of the surveyed occupants is (1.17 ± 0.35) clo without regard to the insulation contribution value of the work post chair. The metabolic rate is another crucial parameter influencing the PMV value. Different activities match different generations of internal heat in the body. A list of possible activities is given in the questionaire, and people are asked to list their activities for 30 min before the test. The unit of the metabolic rate is met, and 1 met represents the generation of a metabolic rate of 58.2 W/m^2 per body skin surface. The metabolic rate for a given person is the average of activities. For example, for a person performing sedentary activity (1.2 met) and collating documents standing activity (1.4 met) for 30 min before filling in the questionnaire, then, the mean metabolic rate is 1.3 met. The mean metabolic rate for all the surveyed people is 1.41 met, while the values for females and males are 1.53 and 1.28 met, respectively. The proposed value for office work by ISO 7730 is 1.2 met. There are four individual companies in this building. Each company occupies three or four stories and different departments of the same company are scattered on adjacent floors. People go upstairs and downstairs on foot due to the needs of work, which causes an increase in energy production. No significant correlation is found between age and metabolic rate. With the measured black globe temperature, indoor air temperature and air velocity, the mean radiant temperature and the operative temperature can be calculated.

Fig. 1 provides the statistical results of MTSV, MTCV, VV, AFV, RHV, and PMV. All the people feel warm with reference to the PMV index, which deviates from the statistical results of MTSV and MTCV. The main reason may be the occupants' high metabolic rates. The mean metabolic rate for all the surveyed people is 1.41 met which means more energy production. According to Fanger's thermal comfort formula, people prefer a lower temperature with a high metabolic rate. With the combination of people's vote on thermal sensation, comfort and the PMV index, it can be seen that people in hot-humid summer and cold-humid winter zones are fond of higher temperatures in winter. By the analysis of MTSV, 57.3% of the occupants show their thermal sensations to be neutral, which means that more than half of the the people are satisfied with the current thermal environment. The majority of people (76.9%) express their satisfaction regarding air velocity, which is in accord with the objective measurement results, where the mean air velocity of 0.1 m/s conforms to the "good" level.

People express their dissatisfaction regarding air humidity and freshness as more than 70% of the people assess the air to be dry and one half of the people regard air to be stale. About half of the occupants think the indoor air stale, although the air velocity and the concentration of carbon dioxide reach the standard. Carbon dioxide consistency of all

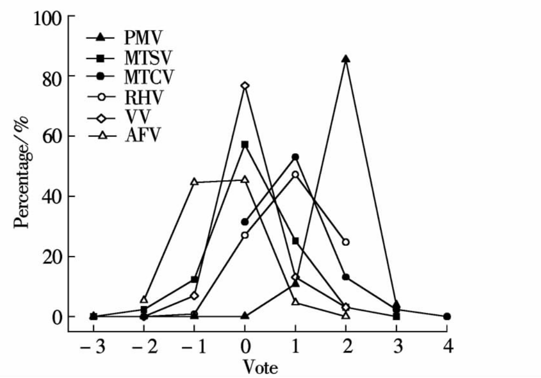

Fig. 1 Frequency distribution of PMV, MTSV, MTCV, RHV, VV, and AFV

the surveyed offices, which is less than 900×10^{-6}, complies with the standard on the basis of objective investigation. So the complaints of stale air are questionable. As mentioned above, the exterior windows are closed centrally and the terminal temperature of the air conditioning can be set at one unchanged value throughout the winter. During the field interviews, occupants also show their inclination to control the temperature and air velocity operated centrally. One possible reason is related to the complaints about air freshness, which may express people's wishes to contact nature. The high percent usage of venetians may be another reason for the feeling of stale indoor air. Further study is needed to emphasize the influence of the ventilation rate and air flow organization on air freshness.

The assessments of male and female health status in the subjective survey are summarized in Fig. 2 and Fig. 3. The percent of "uncomfortable" means the percent of people puzzled by such symptoms "often" and "severely". The incidences of dry mouth and eye dryness are the highest for both males and females (29.6% of males feel dry mouth and 26.8% feel eye dryness; 45.0% of females feel dry mouth and 40.0% feel eye dryness, respectively). These symptoms are predominantly caused by the low RH level of indoor air. It can be concluded that the main reason causing high thermal discomfort in winter is low relative humidity. This conclusion aligns with the results drawn from Refs. [3,7]. Kuchen and Fisch[3] concluded that low RH could cause dryness and irritation in the eyes and the respiratory tract. Wagner et al. [7] pointed out that the perception of humidity, especially in winter, had a high and significant effect on the ratings of satisfaction with room temperature and perceived indoor air quality. Despite this, males are irritated by a sleepy and tired feeling and the discomfort caused by the smell of cigarettes and glare whose corresponding uncomfortable vote is in excess of 10%. It should be mentioned that more than 30% of the females are bothered by dysphoria and glare. It can be inferred that females are more sensitive than males because of the mean female discomfort vote value of 17%, approximately doubling that of the male by 9%. This conclusion is supported by Karjalainen's research[8]. Karjalainen revealed that females tend to be more critical of their thermal environments and are more sensitive to both cold and hot room temperatures according to quantitative interview surveys and controlled experiments[8].

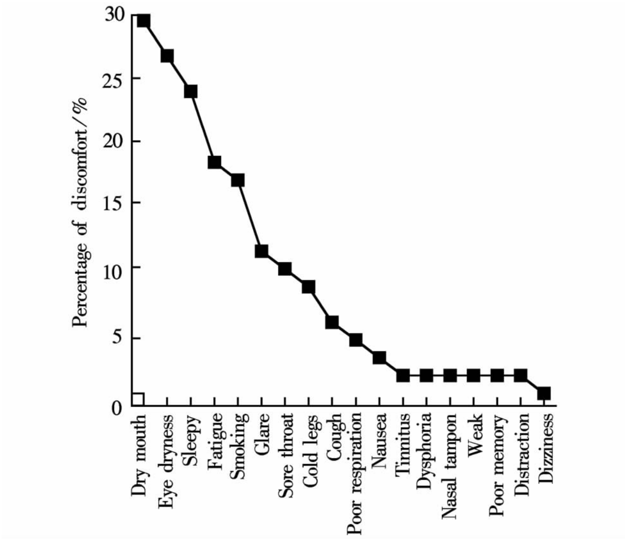

Fig. 2 Health status of males

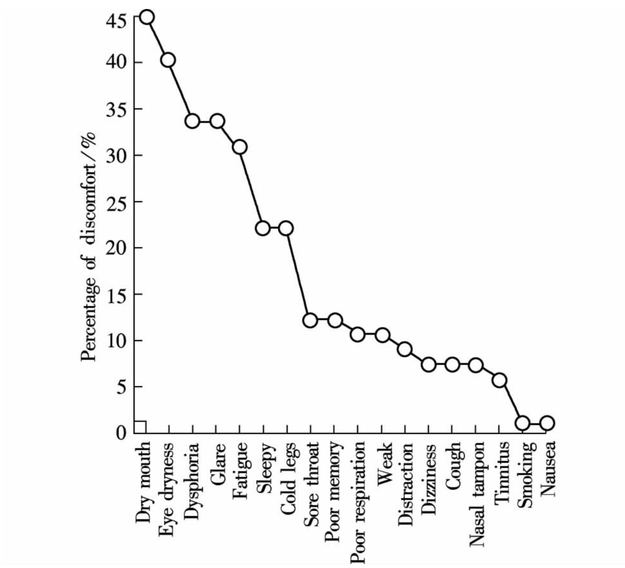

Fig. 3 Health status of females

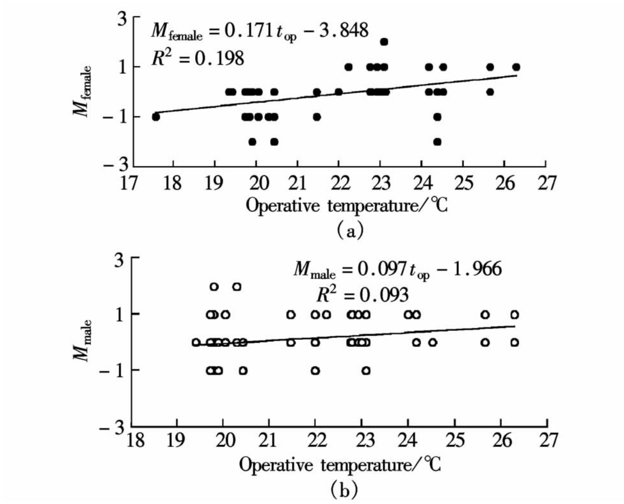

Fig. 4 Linear regressions of mean thermal sensation votes (M) vs. operative temperature. (a) Female votes; (b) Male votes

Considering the sensibility deviations between the sexes according to the subjective survey, the mean thermal sensation votes are linearly regressed against operative temperature by sex individually, as depicted in Fig. 4. The regression model is weighted by the number of votes falling into each of the temperature bins on the *x*-axis. The gradients of the regression models are apparently different: 0.171/℃ for females as opposed to 0.097/℃ for males(R^2 = 0.198 for females and R^2 = 0.093 for males). Moujalled et al. illustrated that the gradient of the regression models measures the thermal sensitivity[9]. This evident gradient difference verifies that females are more sensitive than males, which is in accordance with the subjective health status evaluation. Karjalainen[8] came to the same conclusion that females tend to be more critical of their thermal environments and are more sensitive to both cold and hot room temperatures.

The double-skin façade represents a good noise insulation effect while the glare problem is still unresolved. The investigation results imply that more than 95% of the people have good mental states and high efficiency. An overwhelming majority (95.4%) are satisfied with the auditory environments which reflects the advantage of double-skin façade on noise reduction although this building is located in the flourishing heart of the city and is beset with turbulence. Moreover, about 12.2% of the occupants are discontented with the visual environments. The analysis data indicate that 21.4% of the occupants are irritated with the glare, which may be a conceivable reason for displeasure regarding their visual environments.

3 Conclusions

In this study, winter thermal comfort conditions of a double-skin façade building are investigated in hot-summer cold-winter zones. Both a questionnaire survey and physical parameters measurements are conducted. The questionnaire collects the subjective responses and sensation votes from occupants, while the experiments collect the thermal and air parameters in all the offices. By analyzing the correlations between the subjective and objective data, the main conclusions from this paper are as follows:

1) Low relative humidity is the main reason causing thermal discomfort. The greatest discomfort is dry mouth and eye dryness, which are caused by low relative humidity.

2) Females are more sensitive than males. On the one hand, the overall discomfort value of the females is approximately double that of the males. On the other hand, that the gradient of regression models for female 0.171/℃ is higher than the gradient for male 0.097/℃ verifies this conclusion.

3) The double-skin façade represents a good noise insulation effect while the glare problem is still unresolved. People show their preferences to influence heating and ventilating control, which is centrally controlled in this building.

In summary, relatively small samples (131) are collected in a double-skin façade building in winter in this study. However, the general tendencies are useful for further experiments.

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双层幕墙建筑冬季热舒适性现场测试研究

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摘要:2009 年 1 月 14 ~16 日选取一栋双层幕墙建筑的 27 间办公室进行了热舒适性现场测试实验. 客观数据采集和主观问卷调查同时进行. 主观问卷调查主要从 4 个方面展开:个人基本信息、健康状况、当前环境的舒适性和可接受度. 共有 150 人次参加本次主观测试,回收有效问卷 131 份. 根据实验数据整理出预测平均评价、平均热感觉投票、平均热舒适投票、可接受度等指标分布. 实验结果表明,引起不舒适的主要原因是较低的相对湿度,由此引起的口干和眼涩成为最主要的不舒适症状,而且女性比男性更加敏感. 双层幕墙在隔音方面效果较好,但眩光问题仍然值得重视.

关键词:热舒适;现场测试;双层幕墙
中图分类号:TU-023