A Field Study of Thermal Comfort in Open-plan Office Buildings during Transition Seasons in Harbin

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Abstract

The field study was conducted during transition seasons in Harbin to investigate thermal comfort of open-plan office in severe cold region, covering deficiency of related works for open-plan office. Questionnaire survey and field measurement proceeded simultaneously. Correlation between environmental parameters, MTS and PMV were analysed to distinguish different effect of environmental factors on MTS and verify precision of PMV-PPD model. Results showed that indoor air temperature was the primary influence factor of MTS and the existence of thermal adaptation to outdoor climate affected precision of PMV model. Subjects have higher thermal acceptability in ES period than LS period with limited preference for cooler environment during transition seasons. Further research may figure out an actual thermal comfort range for staff in each specific period in severe cold region to improve thermal performance and energy efficiency at the same time.

Introduction

Severe cold region has an obvious climate characteristic which is quite different from other regions. Harbin, as a typical city in severe cold region, has a rather short transition seasons lasting no more than 2 months while the daily average temperature changes from 1℃ to 21℃ during transition seasons. Due to the dramatic fluctuation of temperature and limited precipitation during transition seasons, there exist large amount of thermal discomfort condition in transition seasons, which emphasizes the significance of relating studies. Besides, the open-plan office begins to gain popularity among intensive and high-density office buildings of China for its high space-utilization and flexibility in recent years. Hence, the thermal comfort research of open-plan office during transition seasons is significant to the well-being of staff and building energy efficiency in severe cold region.

The PMV-PPD model proposed by P. O. Fanger (1970) is widely used to predict human thermal sensation. However, the related works have found considerable deviation between PMV-PPD predicted results and mean thermal sensation (MTS) caused by individual, region and season. The field measurement is a promising method for thermal comfort study as it could explore the subjects' thermal response in their usual working conditions to avoid the test subjects perceives the thermal condition atypically. M. S. Mustapa (2016), R. J. De Dear (2016) and M. Indraganti (2011) carried out field studies on thermal comfort effect factors in Japan, Australia and India respectively. Most of the thermal comfort field studies were conducted in the tropical and temperate regions instead of severe cold region. In severe cold region, Z. Wang has conducted thermal comfort field studies in naturally ventilated residential buildings during summer 2009 (2010), residential buildings during the winter from 2009 to 2010 before and after space heating (2011), classrooms and offices in winter and spring (2014), residential and office buildings from September 2013 to May 2014 (2015), typical university dormitories from late autumn to early spring (2016). It can be obviously found that Z. Wang's works mainly focused on unit-typed office space and were carried out in heating and cooling seasons. The field study of thermal comfort in transition seasons for open-plan office in severe cold region has not been found. Moreover, the thermal comfort effect factors and thermal neutral temperature study in transition seasons in severe cold region is still deficient. This paper aims to propose the regression equations between indoor air temperature, relative humidity, clothing insulation and thermal expectation and MTS and verify precision of PMV-PPD model, which would support the thermal environment design for open-plan office building in severe cold region.

Experiment

The experiment consisted of field measurement of outdoor meteorological parameters and indoor physical environmental parameters, subjective questionnaire investigation of subjects' background and thermal condition and correlation analysis of experimental data with SPSS 22.0 three parts.

The research site was an open-plan office unit with unilateral western orientation in Harbin. The building uses 24h-boiler as heating system with 20℃ as the set point temperature from 15 October to 15 April. The ventilation was conducted mainly by opening windows for a short time before the staff came. The western exposure can be relieved by inner curtain, so the effect of direct sunlight in afternoon can be neglected.

Field measurement and subjective questionnaire investigation of thermal environment were conducted simultaneously from 25 March to 20 May during work time with all windows closed and there were no available personal control measures. The field measurement schedule was divided into two periods of late spring (LS) and early summer (ES) by the last day using heating facilities so as to analyse thermal response of subjects to indoor environment, among which LS period lasted from 25 March to 20 April while ES period lasted from 21 April to 20 May. After removing holidays, the field measurement time included 25 days altogether. Details of the experiment were introduced as follows.

Field measurement

The measured physical environmental variables included outdoor and indoor air temperature, globe temperature, relative humidity and air velocity. According to ISO 7726-1998, 5-points method was used to measure the indoor air temperature (T_{in}) and relative humidity (RH) at the height of 0.1m, 0.6m and 1.1m with globe temperature measured at central point 0.6m in height to avoid the asymmetrical distribution of physical environment caused by sun exposure and air infiltration. The layout of office staff and test points was shown in Figure 1.

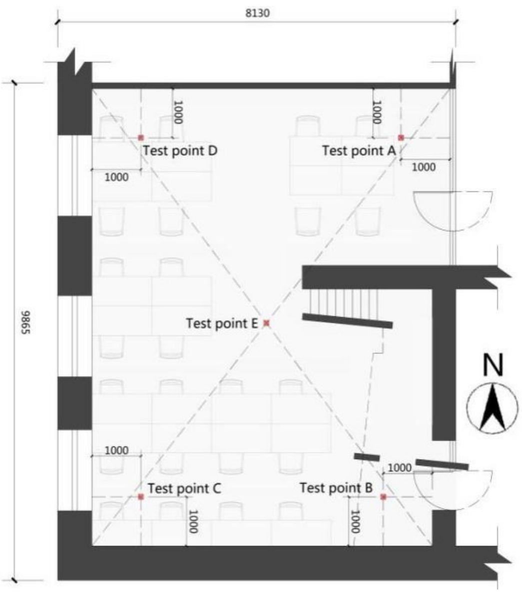


Figure 1: Layout of office staff and test points.

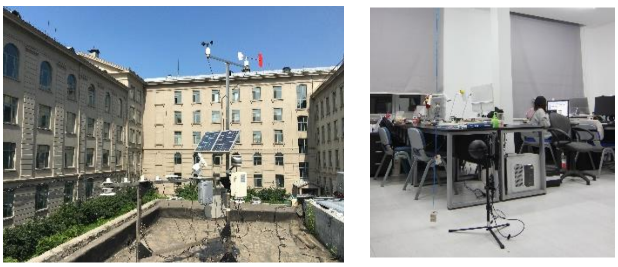


Figure 2: Meteorological station, Testo480 and thermo-hygrometer.

During the process of experiment, outdoor air temperature was recorded by meteorological station located on the roof nearby every 30 minutes, indoor air temperature and relative humidity were continuously recorded by BES-02B thermohygrograph every 5 minutes and globe temperature and air velocity were measured by Testo 480 every ten minutes. The test instruments and accuracy were shown in Table 1. The scene of actual measurement was shown in Figure 2.

Table 1: Test instruments and accuracy

Name	Type	Parameter	Accuracy	Range
Thermo-hygrometer	BES-02B	Air temperature Relative humidity	±0.5℃ ±3%	-30-50℃ 0-99%
Globe thermometer	Testo 480	Globe temperature	±1%	0-+120 ℃
Vane anemometer	Testo 480	Air velocity	±0.03m/s +4% measured value	0-20m/s

Subjective questionnaire investigation

22 primary office staff working in the office were chosen as subjects, who were evenly distributed within the open-plan office. All of the subjects have lived in Harbin for more than 2 years. According to Z. Wang (2003), subjects were assumed to well adapt to the climate of Harbin and deviation caused by climate acclimatization among individuals can be ignored. The information of age and living years in Harbin of subjects was shown in Table 2.

Table 2: Subjects' basic information

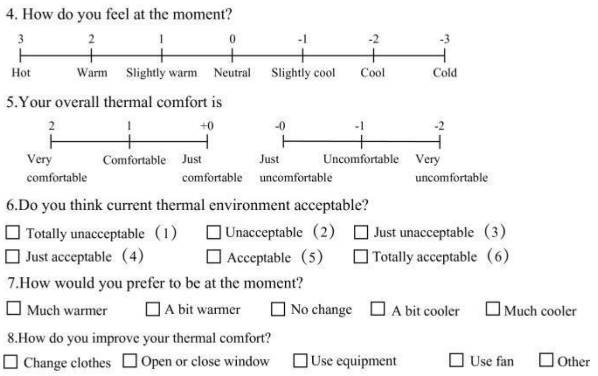
Total number	Data statistic	Age	Living years in Harbin
22 (14 male/ 8 female)	Average	26	16.45
	Std.dev.	1.93	13.42
	Maximum	30	30
	Minimum	22	2

Investigation of subjects' background, objective questions and subjective questions composed three main parts of subjective questionnaire survey, which was conducted twice each workday among subjects who have been working continuously for more than 30 minutes.

To avoid remarkable deviation between individuals, background investigation included gender, age and living years in Harbin. Objective questions investigating self-status and surroundings of subjects while filling in the questionnaire were dress condition, activity level and number of current working staff. Quantitative information of subjects' thermal sensation, thermal comfort, thermal acceptability and thermal expectation and adapted thermal measures were surveyed through subjective questions. Abstract of questionnaire was shown in Figure 3.

277 and 238 questionnaires were collected during LS and ES period respectively. Values more than or less than 1.5 times QR (quartile range) apart from upper or

lower quartile or 3 times QR apart from the median were regarded as invalid values during data processing (Z. Wang, 2015). And questionnaires with incomplete information were also annulled. After screening, there were 164 and 167 valid questionnaires left of LS and ES period.


4. How do you feel at the moment?

3 Hot | 2 Warm | 1 Slightly warm | 0 Neutral | -1 Slightly cool | -2 Cool | -3 Cold

5.Your overall thermal comfort is

2 Very comfortable | 1 Comfortable | +0 Just comfortable | -0 Just uncomfortable | -1 Uncomfortable | -2 Very uncomfortable

6.Do you think current thermal environment acceptable?

☐ Totally unacceptable (1) ☐ Unacceptable (2) ☐ Just unacceptable (3)
☐ Just acceptable (4) ☐ Acceptable (5) ☐ Totally acceptable (6)

7.How would you prefer to be at the moment?

☐ Much warmer ☐ A bit warmer ☐ No change ☐ A bit cooler ☐ Much cooler

8.How do you improve your thermal comfort?

☐ Change clothes ☐ Open or close window ☐ Use equipment ☐ Use fan ☐ Other

Figure 3: Abstract of questionnaire.

Discussion and result analysis

The thermal comfort field study of open-plan office in severe cold region was conducted under non-natural ventilation condition in Harbin, which was applicable for PMV-PPD thermal comfort model. Experimental results were analysed from aspects of influence factors of MTS and precision of PMV-PPD thermal comfort model.

Physical parameter measurement results

During the field measurement period, daily outdoor air temperature ranged from 25.41℃ to -0.14℃ with an average of 11.08℃ and a standard deviation of 5.53℃. Daily outdoor relative humidity ranged from 86.33% to 22.37% with a mean of 46.39% and a standard deviation of 17.03%.

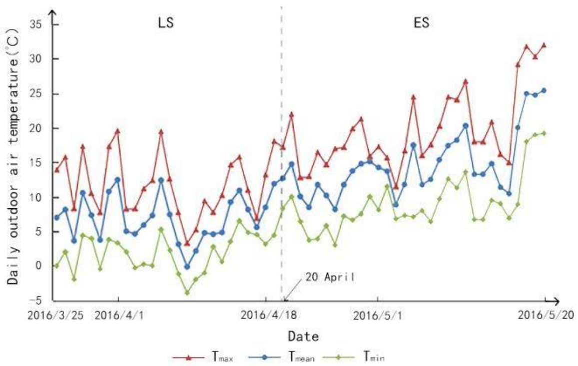


Figure 4: Fluctuation of daily outdoor air temperature during field measurement period.

Figure 4 showed the fluctuation of daily outdoor air temperature. It was observed that the maximum, mean and minimum of daily outdoor temperature changed with a similar tendency during field measurement period. Daily outdoor temperature was above -5℃ all the time with some occasions exceeding 30℃ later in May. In LS period, average daily outdoor air temperature mainly fluctuated around at the temperature of 10 ℃ and no obvious uptrend was seen in temperature in overall. In ES period, average outdoor temperature changed around at the temperature of 15 ℃ except for a sharp rise in outdoor temperature in 16 May. Fluctuating continuously as the outdoor temperature, it climbed up steadily from general aspect.

Measured indoor physical environmental parameters included air temperature, globe temperature, relative humidity and air velocity. Field measurement was conducted continuously during working hours. The air velocity remained stable at the level of zero all the time. Indoor air temperature ranged from 19.4℃ to 26.48℃ with an average of 21.82 ℃. Frequency of indoor air temperature was shown in Figure 5. Thermal environment in LS period had a relative low indoor air temperature and 87.69% of the indoor air temperature fell within 20 ℃ and 24 ℃ with no circumstances exceeding 22.91℃. When it comes to the ES period, the indoor air temperature ranged from 19.8℃ to 26.48℃ with 89.12% fell within 20℃ and 24℃.

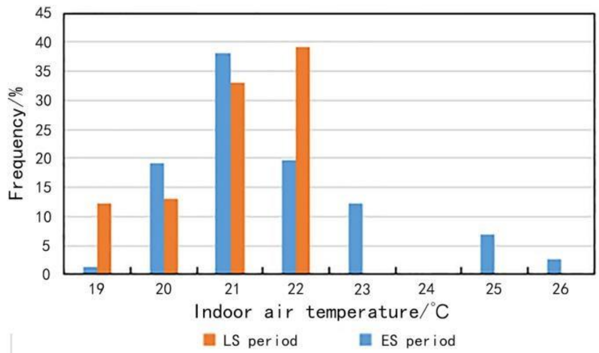


Figure 5: Frequency of indoor air temperature

The globe temperature ranged from 20.4 ℃ to 27.7 ℃ with a mean of 23.02℃. It can be inferred that globe temperature had a close relative with indoor air temperature, for the standard deviation of the two environmental parameters were similar in value and the difference between their average, maximum and minimum were all around 1℃.

The mean radiant temperature (MRT) was calculated based on globe temperature, expressed in Eq. (1), Z. Wang et al (2015).

$$T_r=[(T_g+273)^4+2.5\times 10^8\times v^{0.6}(T_g-T_a)]^{1/4}-273. \qquad (1)$$

where T_r represents the mean radiant temperature, ℃. T_g represents the globe temperature, ℃. T_a represents the air temperature, ℃. v represents the air velocity, m/s.

As the research was conducted under non-ventilation condition with air velocity of zero, MRT is equal to globe temperature in value. According to statistic results, MRT was apparently higher than air temperature with a deviation from 1℃ to 1.5℃ and Pearson correlation coefficient of 0.985. Therefore, indoor air temperature was used as evaluation index of indoor environment to represent MRT in value.

Affected by the utilization of humidifier, relative humidity changed with a wide range from 18.9% to 51.9% with an average of 31.98% and standard deviation of 7.23%. Figure 6 showed the frequency of indoor relative humidity distribution during both survey periods. The relative humidity was within the range from 10% to 50% in LS period while it was in the range from 20% to 60% in ES period. The relative humidity increased about 10% during ES period compared with that in LS period. 73.85% of the relative humidity in LS period ranged from 20% to 30% with no case over 50%. 74.15% of the relative humidity in ES period varied from 30% to 40% with no case under 20%.

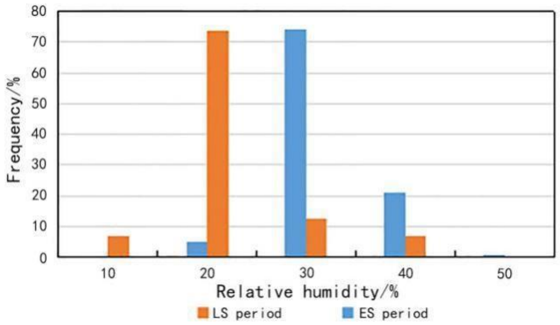


Figure 6: Frequency of relative humidity.

Subjective questionnaire results

Subjects were under the condition of typing when filling in the questionnaires and their metabolic was assumed to be 1.1met. The clothing insulation was calculated by CBE, an online thermal comfort simulation software developed by UC Berkeley based on outdoor temperature at 6 a.m. and subjects' actual clothing level according to the questionnaires. Table 3 showed the statistical summary of clothing insulation during research time in LS and ES period, respectively. In LS period, the clothing insulation ranged from 0.6clo to 1.18clo with a mean of 0.945clo and standard deviation of 0.14clo. In ES period, the clothing insulation ranged from 0.6clo to 1.02clo with a mean of 0.848clo and standard deviation of 0.127clo. It can be found that despite the fact that clothing insulation had a wider range and indoor air temperature was more stable during LS period compared with ES period, subjects changed clothes more frequently in LS period.

Table 3: Statistical summary of clothing insulation

	Average /clo	Standard deviation /clo	Maximum /clo	Minimum /clo
LS period	0.945	0.14	1.18	0.6
ES period	0.848	0.127	1.02	0.6

Fluctuation of daily average clothing insulation was shown in Figure 7. Affected by outdoor climate, indoor temperature had a similar fluctuation tendency with outdoor air temperature but changed less dramatically and not always simultaneously and indoor air temperature was higher than outdoor temperature during the whole research period. It was seen that postpone of variation in indoor air temperature appeared during the period from around 18 April to 28 April and indoor air temperature may not increase or decrease with the rise or decline of outdoor temperature when the variation was not obvious. Clothing insulation tended to drop when outdoor temperature ascended most time. However, when a sharp ascendant of outdoor temperature arose, there was a lag in the variation of clothing insulation. When it comes to May, clothing insulation may not always increase with the decline of outdoor temperature due to the drastic change of outdoor temperature. It can be induced from the statistical results that subjects preferred to taking off their clothes once the outdoor temperature went up even it descended afterwards yet they still felt warm and continued to reduce their clothes especially when the outdoor temperature surpassed 15℃.

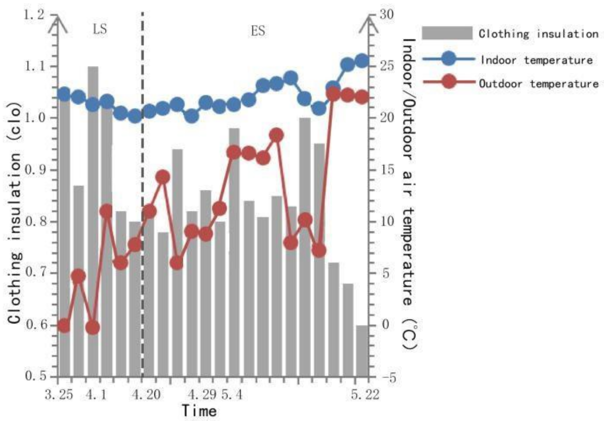


Figure 7: Fluctuation of daily average clothing insulation.

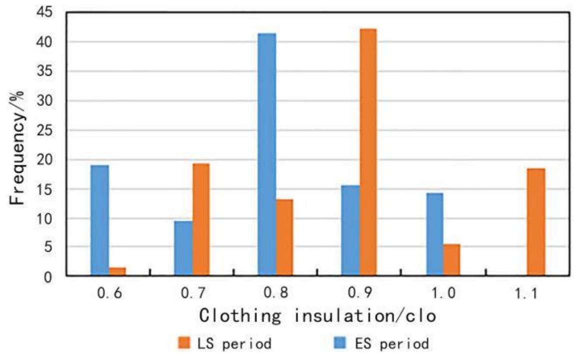


Figure 8: Frequency of humidity sensation.

Figure 8 revealed the frequency of clothing insulation in LS period and ES period. 41.5% of the clothing insulation was within the range between 0.8clo and 0.9clo during LS period while 42.31% of the clothing insulation ranged from 0.9clo to 1.0clo in ES period. As it could be seen that only 19.05% of the clothing insulation fell below 0.7clo, which not conformed to the application condition of ASHRAE 55-2013 standard in summer, the thermal comfort may not be simply evaluated by the indoor temperature range defined by ASHRAE Standard for summer during ES period. 18.46% of the clothing insulation exceeded 1.1clo in LS period, which was much higher than 0.9clo, the given clothing insulation proposed by ASHRAE Standard for winter condition. As a result, the utilization of the comfort zone defined by ASHRAE Standard to evaluate thermal environment during LS period may not be accurate to some extent, either.

Humidity sensation was investigated during research period, which was divided into 7 scales including very humid (-3), humid (-2), just humid (-1), neutral (0), just dry (1), dry (2), very dry (3). Figure 9 showed the frequency of humidity sensation distribution during both survey periods. It was seen that subjects tended to feel dry during both LS and ES period. 79.87% of the humidity thermal sensation votes were dry humidity discomfort in LS period compared with 60.48% in ES period. 18.29% humidity sensation was neutral during LS period instead of 33.53% in ES period with the utilization of humidifier, which implied that humidity sensation was dry in experimental time and humidity environment need to be improved.

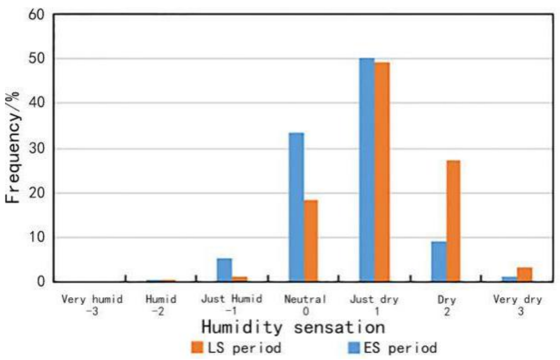


Figure 9: Frequency of humidity sensation.

Humidity sensation had a correlation coefficient with relative humidity of 0.357, which was lower than that between MTS and relative humidity. The result implied that subjects were not that sensitive towards humidity. According to statistic results of humidity acceptability and humidity sensation, only 18.29% subjects voted neutral in humidity sensation investigation while the humidity acceptability was 73.17% in LS period. When it came to the ES period, 33.53% subjects voted neutral with a humidity acceptability of 82.63%. It revealed that the subjects had a high tolerance to low humidity.

Figure 10 showed the percentage of thermal expectation distribution during both survey periods. Most subjects voted no change in thermal expectation with a percentage of 55.49% in LS period and 67.07% in ES period, respectively. Subjects preferred thermal environment to be cooler in LS period instead of ES period with a higher average indoor temperature, which may result from the higher clothing insulation and thermal sensitivity in LS period. It also revealed that subjects would not like a cooler environment under most conditions during research period.

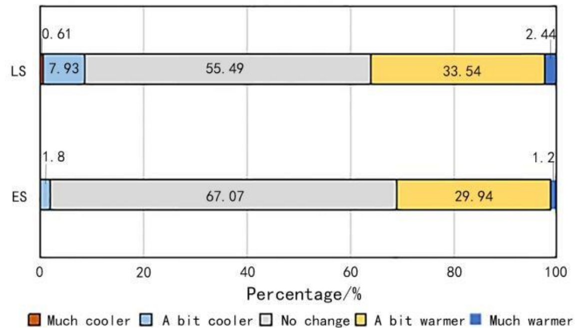


Figure 10: Percentage of thermal expectation.

Figure 11 revealed the analysis of the percentage of MTS, thermal comfort and thermal acceptability during experimental time. In the statistic process, the condition that thermal sensation vote of zero, thermal comfort vote of just comfortable and just uncomfortable and thermal acceptability vote of just acceptable, acceptable and totally acceptability were counted. It was seen that there existed a high percentage of thermal acceptability vote and low percentage of thermal comfort vote compared with MTS in both periods. During ES period, more percentage of zero vote for thermal sensation and vote for thermal acceptable with less percentage of thermal comfort compared with those in LS period, which implied that subjects had a higher standard for thermal comfort than other thermal evaluation index in ES period. In addition, subjects tended to be more thermal acceptable in ES period. The different results of the relative relation between MTS and thermal comfort compared with other related studies could be caused by the unique and changeable outdoor climate of the transition seasons in Harbin.

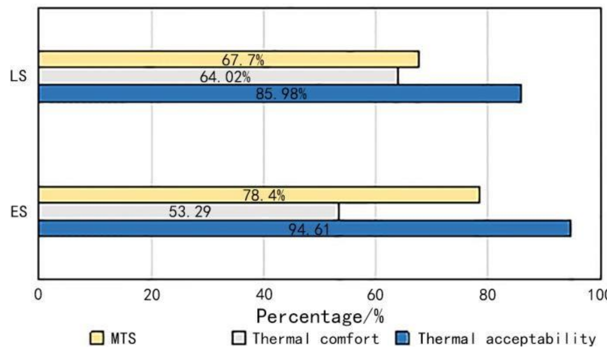


Figure 11: Percentage of MTS, thermal comfort and thermal acceptability

Correlation analysis

The study analysed the effect of environmental variables on MTS based on correlation coefficient with SPSS 22.0 as shown in Table 4. The results showed that indoor air temperature had the greatest effect on MTS then came the clothing insulation. Relative humidity had the least effect on MTS. Besides, the correlation coefficients of indoor air temperature, clothing insulation and relative humidity were higher in LS than ES period.

Table 4: Correlation coefficients of effect factors.

	Indoor air temperature	Clothing insulation	Relative humidity
Correlation type	Linear	Quadratic	Cubic
Correlation coefficient	0.449	0.358	0.155

Through the analysis of the correlation between indoor physical environmental parameters and MTS, indoor air temperature was proved to be the most important influence factor on MTS with the correlation coefficient of 0.449. The regressions between MTS and indoor air temperature during LS and ES period were shown in Eq. (2) and Eq. (3).

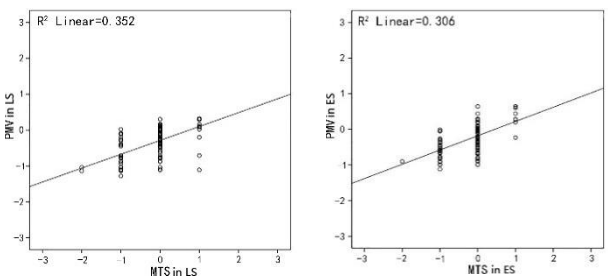
$$LS: MTS = 0.32T_a - 6.95, \quad R^2 = 0.288 \qquad (2)$$

$$ES: MTS = 0.16T_a - 3.61, \quad R^2 = 0.201 \qquad (3)$$

Where *MTS* represents mean thermal sensation, T_a represents indoor air temperature, ℃.

The paper used cubic correlation to calculate the correlation between relative humidity and MTS, which had a higher correlation coefficient and had passed significant test. The R^2 between relative humidity and MTS was 0.125 in LS period and 0.066 in ES period. Correlation coefficient between relative humidity and MTS was relatively low and a significant decrease was observed in ES period.

Clothing insulation, as the second important influence factor of MTS, was proved to be in quadratic correlation with MTS and had a higher correlation coefficient in LS period compared with ES period.



(a) (b)

Figure 12:(a) Correlation between PMV and MTS in LS period. (b) Correlation between PMV and MTS in ES period.

Subjects' overall thermal sensations were reported on ASHRAE 7-point continuous scale (ANSI/ASHRAE Standard 55-2013, 2013). Based on data statistic of indoor air temperature, mean radiant temperature, relative humidity and clothing insulation, PMV was simulated with the utilization of CBE, an online thermal comfort tool. Correlation analysis was conducted between PMV and MTS to verify the precision of PMV-PPD thermal comfort model during test time. The correlation PMV and MTS was shown in Figure 12. Equations between PMV and MTS during LS and ES period can be concluded as follows.

$$LS: MTS = 0.39PMV - 0.29, R^2 = 0.352 \qquad (4)$$

$$ES: MTS = 0.40PMV - 0.180, R^2 = 0.306 \qquad (5)$$

Findings can be drawn from the equations and Figure 12 that correlation coefficient between PMV and MTS was higher in LS period than ES period and subjects felt warmer in ES period even under similar condition, which proved thermal acclimation to outdoor climate. Subjects tended to feel cooler than PMV thermal comfort model assumed even under the same thermal environment.

Statistic results of thermal sensation vote were shown in Figure 13. During LS period, 62.2% questionnaires voted zero for thermal sensation with 70.73% circumstances satisfying thermal comfort when PMV was between -0.5 and 0.5, according to simulating results of CBE. While during ES period, 73.05% voted zero for thermal sensation with 72.46% satisfying thermal comfort standard. A declination in subjects' sensibility towards indoor thermal environment was observed.

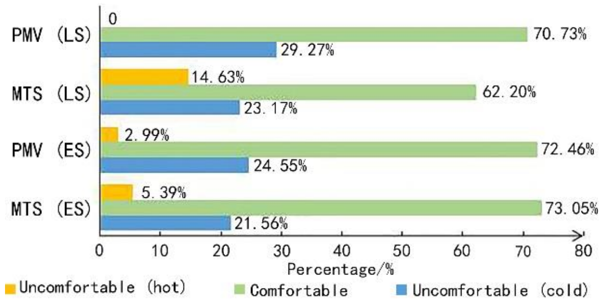


Figure 13:The statistic of thermal comfort condition.

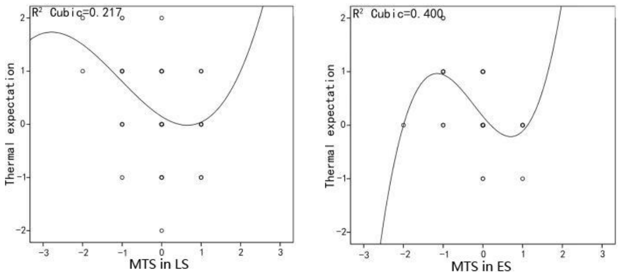
Through correlation analysis of clothing insulation and outdoor temperature, the regression between clothing insulation and outdoor temperature was shown in Eq.(6).

$$I_{cl} = -0.014t_{out} + 1.0353, R^2 = 0.4725 \qquad (6)$$

Where I_{cl} represented clothing insulation, clo. T_{out} represented outdoor temperature, ℃.

Compared with the regression between clothing insulation and outdoor temperature in university dormitories proposed by Z. Wang (2016), clothing insulation in this research also had a linear correlation with outdoor temperature yet with a lower correlation coefficient of 0.4725 instead of 0.9059 in Wang's research during the same experimental period. The deviation may be caused by the difference in subjects' age, building types and orientation of research site.

Through the regression and curve-fitting analysis of different correlation types, cubic correlation was revealed between thermal expectation and MTS with higher correlation coefficient and passed significant test. The correlation between thermal expectation and MTS in both periods was shown in Figure 14. It revealed that thermal expectation had a higher correlation coefficient of 0.632 with MTS in ES period compared with that of 0.466 in LS period.



(a) *(b)*

Figure 14:(a) Correlation between thermal expectation and MTS in LS period. (b) Correlation between thermal expectation and MTS in ES period.

Conclusion

A field experimental study was conducted in actual working condition to study thermal performance of open-plan office in severe cold region during transition seasons. The following conclusions were noteworthy:

(1) Pearson correlation coefficient between MTS and PMV was 0.352 in LS and 0.306 in ES, which implied that there existed deviation between predicted value of PMV model and mean thermal sensation during transition seasons in severe cold region. Subjects felt cooler than PMV thermal comfort model assumed even under the same thermal environment.

(2) Indoor air temperature had the greatest effect on MTS then came the clothing level. Relative humidity had the least effect on MTS.

(3) Subjects usually did not prefer a cooler environment with over half vote of no change in thermal expectation during research period and tended to be more thermal acceptable in ES period compared with LS period.

(4) 62.2% MTS were zero with PMV assuming 70.73% conditions thermal neutral in LS period while 73.05% voted for zero with 72.46% assumed thermal neutral, which revealed subjects were less sensitive to thermal environment in ES than LS period.

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