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INVESTIGATION ON OCCUPANTS' INTERACTION WITH WINDOWS IN UNIVERSITY BUILDING IN ZUNYI, CHINA

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ABSTRACT

Adaptive action in terms of window operation has closely correlation with indoor air quality and building energy performance. Guizhou is as a traditional undeveloped area in China, even though the GDP growth rate in recent 5 years is remarkable, very few studies on adaptive behaviours in context of built environment are conducted. In this paper, an investigation on window operation considering the influence of subject type was carried out in HVAC-system-equipped university building during winter in Zunyi, China. Due to out of service of HVAC system, indoor thermal conditions are relative poor and not in the ASHRAE's winter comfort zones. Outdoor air temperature is identified to be the only physical environmental variable driving window-opening behaviour in this study. Active occupants would like to adjust indoor thermal condition or to improve indoor air quality by means of operating windows. On contrary, passive occupants are reluctant to adjust windows during survey period. But overall, more surveyed windows are opened with the rising in outdoor air temperature. The mathematic models predicting the probabilities of window-opening occurrence are also developed based on logistic regression analysis. The predictive accuracy is 69.65%. This is the first time performing a study on interaction between occupants and window adjustments in Zunyi, China. The developed predictable models also fill in the blank the no quantitative models are available in this area. Therefore, the results concluded from the field study are helpful of providing unprecedented guidelines on improvement of indoor thermal environment and building energy efficiency in Zunyi, China. In addition, by integrating into simulation software the accuracy of dynamic simulation of building energy consumption can also be improved.

Keywords: field study, window operation, predictive model, thermal environment

NONMENCLATURE

T_{in}	Indoor air temperature (℃)
RH_{in}	Indoor relative humidty (%)
T_{g-in}	Indoor globe temperature (℃)
V_{a-in}	Indoor air velocity (m/s)
T_{out}	Outdoor air temperature (℃)
RH_{out}	Outdoor relative humidity (%)
T_{g-out}	Outdoor globe temperature (℃)
V_{a-out}	Outdoor air velocity (m/s)

1. INTRODUCTION

Building energy conservation attracts international attentions in recent twenty years. In China, more than 30% of total energy consumption is consumed by public buildings [1]. Improving HVAC system's energy efficiency attributes significantly to building energy reduction. On the other hand, occupants' behaviours are also playing a vital role of improving building energy performance [2], e.g. HVAC system utilization in a proper way (e.g. set-up temperature, air changes and fresh air volume, etc.) and window operation, et al.

Window is as the one of the most popular environmental control measures, the corresponding researches in built environment aspect mainly focus on

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the mechanism of interaction between occupants and windows, which are embodied by the studies on influence factors and mathematic models development. As the pioneers who investigated the window-opening behavior in residential buildings, Dick and Thomas found outdoor air temperatures were positively correlated with window operation [3]. The similar positive correlations were also identified between window-opening behaviour and the factors of indoor air temperature [4] and outdoor relative humidity [5]. The negative correlation was noticed between wind speed and window opening events [4][6-7]. In addition, the time of a day [4][8-9], occupancy pattern [4][8] and orientation [6], etc. were also identified to be factors influencing window opening behaviour. The model, which was established by Fritsch and Kohler et al. [10] was the first mathematical model predicting the transitions between different window opening angles. By applying different statistic methods, such as logistic regression[5][8][11-12], Markov chain [4] and survival analysis [4], etc., various models predicting the probability of window opening behavior, or the transition probability of the window state changing from closed to open or from open to closed, and estimating the duration distributions of windows being open or closed were developed.

However, the similar investigations are seldom performed in Guizhou province, which is located in south-west in China and is traditional undeveloped area. Since the non-physical factors such as social, economic and cultural issues also impact the interaction between environmental control utilization and occupants [13-14], the findings obtained from similar researches which were carried out in other countries and regions with different climatic characteristics may not be applied directly to Guizhou without modification. Therefore, with the aims to understand occupants' interaction with window control and to develop mathematic model for window-opening probability prediction and for dynamic simulation of building energy consumption, a field study on window opening behaviour of occupants in HVAC-system-equipped university building in Zunyi, a typical hot summer and cold winter city in Guizhou province, was first time conducted in winter covering the period from November to January. The findings gathering from this study will supplement the knowledge concerning subjects' adaptive actions, which were usually obtained from field experiments performed in relative developed areas in China, by carrying out investigation in undeveloped area and taking non-physical factors into account.

2. METHODOLOGY

2.1 Environmental Variables Measurement

Indoor air temperature (T_{in}), globe temperature (T_{g-in}), air velocity (V_{a-in}) and relative humidity (RHin RH_{in}) were measured as indoor physical environmental parameters in this study. Indoor air temperature and air velocity were collected by using hot wire anemometer (TESTO 425). Globe temperature and relative humidity were evaluated by a heat stress WBGT meter (HT30) from Extech Instruments. Both indoor air temperature and air velocity were measured at three vertical levels, 0.1m, 0.6m and 1.1m, respectively, representing the positions of ankle, waist and neck for a seated person. The data were then averaged as corresponding values of indoor environmental parameters for further analysis. Globe temperature and relative humidity were acquired at the height of 1.1m. With respect to outdoor meteorological parameters, such as outdoor air temperature (T_{out}), globe temperature (T_{g-out}), air velocity (V_{a-out}) and relative humidity (RH_{out}), were gathered by using the instruments as the same as those employed by indoor environmental parameters measurement. Outdoor environmental variables were measured at the end of each field study session on the survey day. No less than 3-min measurement period was applied to all environmental variables at an interval of 1s. The instruments' technical indexes, measurement position and duration meet the corresponding requirements specified in ASHRAE 55 standard and ISO 7726 [15].

2.2 Questionnaire Survey

Questionnaire here was designed to collected subjective information on respondents' background information, thermal perceptions and adaptive responses. Section one comprised questions which were used to collect respondents' background information in terms of age, gender, the length of living in Zunyi, activity level and clothing assembles. Section two was mainly used to quantify occupants' thermal sensation, thermal preference, thermal acceptability, thermal satisfaction and thermal expectation by applying various scales, e.g. ASHRAE's 7-point scale. The questions, which asked occupants to provide information on subjects' perceived environmental control level, the purpose of utilizing certain environmental control, use frequencies of various environmental controls and other adaptive actions which could be as supplementary strategies, were included in section three. The questionnaire survey was performed 3-4 days per week, twice on each survey day, morning session and afternoon session, respectively. Environmental parameters measurement and questionnaire survey were conducted simultaneously.

2.3 Subject Type

In order to improve the predictive accuracy of window opening events, the subjects were divided into two categories, passive and active subject, respectively, according to the answers to the question of 'How often do you close or open window?'. 5-point scale ranging from 0-never, 1-rarely, 2-sometimes and 3-frequently to 4-always was adopted to quantify the answers. Occupants who gave answers of 'never' or 'rarely' were classified into 'passive' category. 'Active' category included answers of 'frequently' and 'always' to that question. Therefore, the influence of subject type on window operation was considered in this study.

3. RESULTS

3.1 Surveyed building

This field study was conducted in a HVAC-system-equipped, five-floor building with flat roof, which is located in Zunyi Normal University, Zunyi, China. The surveyed building is multi-functional with a south-north orientation. The surveyed building was building in 2015 with concrete and brick structure. All windows in this building are double-glazed operable windows with plastic-steel frame. For the internal space, a west-east corridor divides each floor into two parts. Classrooms, offices and labs are distributed in both parts. Since classrooms and labs sometimes are sometimes not occupied by subjects, the windows in 6 offices, which distribute in each orientation from second floor to four floor, are investigated in this study. A total of 2177 datasets are collected. Figure 1 demonstrates the façades of the surveyed buildings.

Fig 1 Surveyed building

3.2 Indoor and Outdoor Thermal Conditions

Table 1 shows the statistics of indoor and outdoor environmental variables. Although the HVAC system was installed in surveyed building, they were not in use due to some technical problems during survey period. Thus subjects sometimes turned on fan heaters to compensate for the discomfort caused by lower indoor air temperatures. Even though, the mean indoor air temperature was still not in ASHRAE's winter comfort zone [15]. The indoor relative humidity levels were varying from 65% to 80.51% with mean value of 72.50%. The indoor globe temperatures were similar with the values of indoor air temperatures but overall lower than air temperatures. The air velocities were quite small. The outdoor meteorological parameters followed the patterns that were presented by indoor environmental variables. The significant discrepancy between indoor and outdoor thermal conditions was the air velocity. The mean value of outdoor air speed was nearly five times than indoor air velocity average value. The indoor and outdoor thermal conditions were in agreement with climatic characteristics of hot summer and cold winter region.

Table 1 Indoor and outdoor thermal environment

		Max	Min	Mean	Std.
Indoor	T_{in}	19.80	11.57	14.83	2.15
	RH_{in}	80.51	65.00	72.50	7.37
	$T_{g\text{-}in}$	18.20	10.10	12.45	2.42
	$V_{a\text{-}in}$	0.26	0.03	0.15	0.07
Outdoor	T_{out}	18.00	11.23	13.21	1.59
	RH_{out}	80.40	60.00	72.63	7.61
	$T_{g\text{-}out}$	17.90	10.10	11.80	1.75
	$V_{a\text{-}out}$	2.00	0.05	0.71	0.80

3.3 Driving force

Based on the literature review, both physical and non-physical factors influence the occurrence of window opening significantly. In this study, the influence of indoor air temperature, indoor globe temperature, indoor air velocity, indoor relative humidity, outdoor air temperature, outdoor globe temperature, outdoor air velocity, outdoor relative humidity were verified by applying multi-factor variance analysis. The results of multifactor analysis of variance showed that Sig. value of outdoor air temperature was less than 0.05, Sig. values of other variables were all more than 0.05. It indicates that outdoor air temperature is the influence factor predominating window-opening events in university building in winter. Therefore, outdoor air temperature in this investigation is determined as predictor of window operation. The chosen of outdoor air temperature as predictor is also confirmed by Li et al. [14] who studied window-opening behaviour of occupants in university's office building in Chongqing (another hot summer and cold winter city and adjacent to Zunyi city), China,.

3.4 Window-opening Observations

The window opening frequencies in response to variation of outdoor air temperatures are illustrated in figure 2. In general, with the increasing in outdoor air temperatures, more window-opening behaviours were observed during survey period. The window-opening behavior in this investigation was basically happened when the outdoor air temperatures exceeded 12℃. Once the outdoor air temperatures were over 15℃, half of surveyed windows were opened.

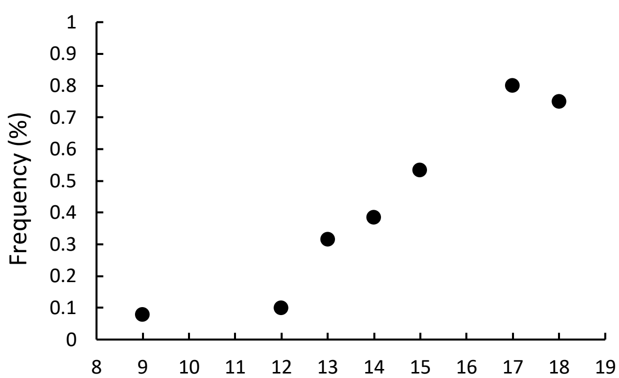

Fig 2 Observed window-opening frequencies

3.5 Model Development

As mentioned above, outdoor air temperature is determined as the sole physical environmental parameter impacting window-opening behaviour in this study. The outdoor air temperature is thus considered as predictor in window operation model. Meanwhile, the influence of subject type is also took into account in process of model development. Since the results of window operation could be regarded as binary data, binary logistic regression is employed to establish mathematic model predicting the probability of window opening in HVAC-system-equipped university building in Zunyi in a free-mode during wintertime. The established models considering factor of subject type are expressed as below:

For active subject: $$P = \frac{e^{-7.947+0.597t_{out}}}{1+e^{-7.947+0.597t_{out}}} \quad (1)$$

For passive subject: $$P = \frac{e^{-6.266+0.346t_{out}}}{1+e^{-6.266+0.346t_{out}}} \quad (2)$$

Based on the above equations, figure 3 illustrates the probabilities of window-opening behaviour for active and passive subjects, respectively. It is clear that active occupants prefer to open window either to adjust indoor thermal condition or to improve indoor air quality. Over 13.3℃, the probability of window-opening events would exceed 50%. Passive occuapnts during survey period were reluctant to adjust windows regardless of what the outdoor air temperatures were in winter.

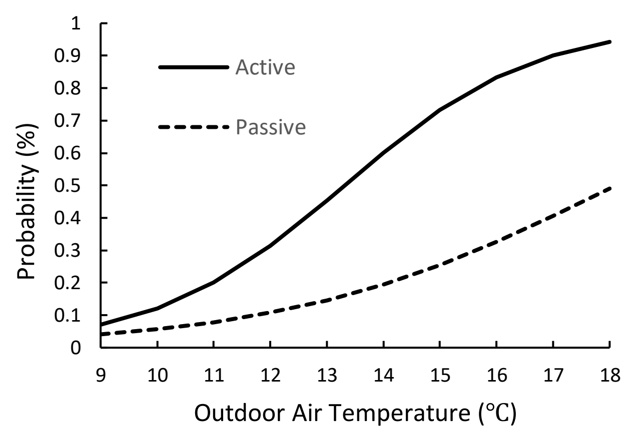

Fig 3 Window-opening probability

The variables in equations (e.g. standard error, Wald, degree of freedom, Significance, Exp (B)), which reflect the influence of outdoor air temperature on window-opening probability, are presented in table 2. For active subject case, the significance values of variables are all less than 0.05, which implies that window-opening behaviour is closely related to outdoor air temperature. But for passive subjects, the adaptive actions on window adjustment during the survey period are observed rarely, the data are consequently insufficient for further model establishment. This is why the significance values of variables for case of passive subject are more than 0.05.

Table 2 The results of variables in equations

		B	Wald	df	Sig.	Exp (B)
Active	Tout	0.597	7.023	1	0.008	1.817
	Constant	-7.947	8.083	1	0.004	0.000
Passive	Tout	0.346	3.379	1	0.066	1.413
	Constant	-6.266	6.835	1	0.009	0.002

In addition, the results of variables representing the goodness of fit are listed in table 3. Similarly, the values of both Cox & Snell R^2 and Nagelkerke R^2 for case of active subjects demonstrate better data fitting the model predicts. The corresponding values of R^2 for passive subjects' case are just greater than zero, which indicates that the variation ratio of probability of window-opening cannot be explained well by outdoor air temperature to total variation.

Table 3 Model summary

	-2 log likelihood	Cox & Snell R^2	Nagelkerke R^2
Active	38.647	0.234	0.333
Passive	29.168	0.067	0.142

In order to assess the predictive accuracy, classification table is applied and the results are showed in table 4. Since the derived equation predicting window-opening probability for passive subject is identified to be dissatisfaction with the requirements of significance test, the predictive accuracy assessment for passive subject case is thus not included in table 4.

Table 4. Classification table[a]

Observed		Predicted: Window status 0	Predicted: Window status 1	Percentage correction
Window Status	0	94	16	85.5
	1	18	21	53.8
Total percentage				69.95

[a] The cutoff value is 0.500.

As shown in table 4, the accuracy for predicting window-closing behavior performed by active occupants is 85.5%. The figure turns to be 53.8% for window-opening probability. The overall prediction accuracy is 69.65%. Therefore, the model derived for active subjects is able to predict window operation behavior well.

4. DISCUSSION

Since the parameters representing outdoor climate are collected at the end of each field study session, not successively 24-hour measurement, the outdoor environmental variables seems don't fluctuate significantly. In fact, the climatic data which was provided by local weather station showed that the outdoor temperature during the survey period varied from -4℃ to 22℃. According the window-opening frequencies demonstrated in figure 1, the surveyed window are basically keep closed until the outdoor air temperatures exceeds 12℃. That is to say, even the outdoor air temperatures are sometimes below 0℃., it will not influence window-opening events in Zunyi during wintertime. It implies, the result that outdoor air temperature is good predictor of window-opening behaviour in this study is subjected to the condition that the outdoor air temperatures are over 12℃.

Which can be a good predictor for window-opening behaviour? To date, there is no agreement achieved. In this investigation, the outdoor air temperature is chosen as independent variable in derived equations mainly for two reasons. Firstly, in non-air-conditioned building the indoor air temperature is influenced significantly by outdoor air temperature. The indoor air temperature is consequently regarded as calculated result of outdoor air temperature. Based on such principle, in most circumstances particularly in naturally ventilated space outdoor air temperature is the most popular predictor adopted by many researchers [4][6][8]. Secondly, excluding the influence of independent variable's selection presented in literature, the results of multifactor analysis of variance confirm the chosen of outdoor air temperature as independent variable in this investigation.

5. CONCLUSIONS

A field study on occupants' interaction with window operation was first time carried out in university building during winter in Zunyi city, China. The conclusions obtained from this investigation are summarized as follows:

- The HVAC system is not in use during the survey period. The indoor thermal environmental conditions are poor in winter in Zunyi.
- The outdoor air temperature is identified to be the only physical environmental parameter stimulating window operation behavior in this study.
- In general, the window-opening probabilities follow the pattern that with the increasing in outdoor air temperatures, particularly the outdoor air temperatures exceed 15 ℃, the probabilities of window-opening behaviour will exceed 50%.
- The differences of window-opening probabilities between active and passive subjects are significant. During the survey period, active subjects are likely to open windows for fresh air or for thermal environment adjustment. No matter the outdoor thermal conditions are, passive respondents are not willing to open windows.
- A stochastic model for predicting probability of window-opening events is developed. The predictive accuracy of derived model for active occupants is 69.65%. But the model for passive subjects doesn't meet the requirements of significance test.

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