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Exploring the “black box” of thermal adaptation using information entropy

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Abstract:

Thermal adaptation has been interpreted well by behavioral, physiological, and psychological factors, but the mechanism and interaction between the three factors remain in the “black box”. This paper aims to apply the theory of general system and information entropy to investigate the quantitative relationships of the three thermal adaptation processes. Based on the database from the field survey and laboratory experiments conducted in the hot summer and cold winter climate zone of China, three typical adaptive indices: clothing insulation (Clo), thermal sensation votes (TSV) and sensory nerve conduction velocity (SCV) were selected to calculate Clo entropy, TSV entropy, SCV entropy and total entropy. The regression models were developed between these entropies and the indoor air temperature to quantify the weights of the three adaptive categories. The models were used to compare the differences between China and Pakistan as well as between adaptive approaches and climate chamber experiments. The thermal comfort and acceptable temperature ranges were obtained using the entropy models. Our findings propose a new perspective using entropy to quantify the behaviorally, physiologically, and psychologically adaptive approaches, which contribute to a better

understanding of opening the "black box" of thermal adaptation.

Keywords:
Thermal adaptation; Information entropy; General system theory; Free running buildings; China

1. Introduction

1.1. Research backgrounds

The occupants' thermal comfort directly influences the building energy consumption and greenhouse gas emissions [1–3]. Extensive studies have been conducted worldwide to reveal the mechanism of thermal comfort [4–6]. They emphasize two main research paradigms: the heat balance model and the adaptive model [4,7].

Based on the heat balance model, Fanger developed the Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) methods [8], which assessed human thermal sensation in terms of the physical and physiological heat transfer between the human body and the environment [1]. While the PMV-PPD model predicts thermal sensation well in steady-state air-conditioned buildings, many field studies have shown that the PMV model failed to predict thermal sensation in a naturally ventilated environment as is found in free-running buildings [1,4,9]. This theory is based on the reductionist premise, which could essentially a reductions disregards some important but ill-understood factors affecting comfort [10,11].Hence, the assumption that people are just passive recipients of their thermal environment has been challenged by the adaptive thermal comfort point of view [7,12].

The adaptive model states that occupants could react positively to the thermal environment through adaptive methods, rather than passively tolerating the conditions to which they are exposed [13,14]. The thermal adaptive theory proposes three categories of adaptation: behavioral, physiological, and psychological [15]. With the growing attention focused on sustainable building technology, adaptive thermal comfort has received more attention from researchers worldwide [4,7,16]. However, the adaptive models proposed by different researchers give inconsistent outcomes, even for the same indoor thermal environment [17,18]. The discrepancies in these results need to be explained by exploring the "black box" of thermal adaptation [1]. Therefore, it is necessary to interpret in-depth findings from both heat balance models and adaptive models to promote an understanding of thermal comfort research [7,19,20].

In order to investigate the discrepancies and relationship between the PMV model and adaptive models, Yao *et al*. [1] proposed a theoretical adaptive predicted mean vote (aPMV) model based on the "black box" theory. In the aPMV model, the effect of three thermal adaptive processes was evaluated by introducing an adaptive coefficient λ; however, the weights of each thermal adaptive process remained unknown [19]. In order to quantify the significance of the three categories, Liu *et al*. [19] came up with a method to weight the three adaptations respectively by applying the analytic hierarchy process (AHP), based on the subjective questionnaire surveys conducted in the UK and China. The study concluded the different weighting factors of three thermal adaptations

[19] but objective evidence is expected in contrast to the occupants' subjective judgment.

To date, the adaptive theory has advanced the generalized mechanism of human thermal adaptation from some views of the heat balance model. The adaptive studies by different researchers have shed some light on the 'black box' of thermal adaptation and proposed some "grey box" conceptual models [4,7,9,19]. Although numerous illustrations of thermal adaptation have been indicated by these studies, there is a paucity of models to quantify the three categories of thermal adaptation. Without the quantitative analysis, the relations between thermal adaptations and environment cannot be obtained. On the other hand, with progress in green building technology, developing quantitative model-based control strategies is an increasing challenge for building designers and facilities managers in the context of achieving thermal comfort and energy efficiency [19,21]. Hence, how to open the "black box" of thermal adaptation provides the initial impetus for this study [19].

1.2. General system theory

The conceptual frameworks of thermal adaptation [1,15,22] have identified the complex process of coupled human and building environment systems involved in the three adaptive categories. In order to explore the system characteristic of occupants' thermal adaptation and beyond the reductionism, the general system theory was adopted in our study, which was expected to lead to new general fundamental principles of thermal adaptation.

General system theory elaborates properties, principles and laws that are characteristic of "systems" in general, regardless of their particular type, the nature of their component elements, and the relations or "forces" between them [23]. The system theory has been proved in living systems by e.g. organismic biology and ecological systems [23–26]. Their systemic properties emerge at the whole system level, which cannot be reduced to those of smaller parts [27–29]. Hence, the behavior of large and complex aggregates of elementary parts could not to be understood in terms of a simple extrapolation of the properties of a sub-set of particles [30].

With the subsequently robust support from cybernetics, the concepts of system thinking and system theory have become integral parts of the established scientific language and led to numerous new methodologies and applications: systems engineering, systems analysis, systems dynamics, and so on [24,31].

1.3. Information entropy

In general system theory, the view that the components in a system are all interconnected and interdependent has been acknowledged throughout the history of philosophy and science. However, the detailed models of the nonlinear inter-connected characteristics of a system could been formulated when the mathematical theory of complexity became available [28,32,33]. Over the past three decades, a new set of concepts and techniques dealing with that enormous complexity have emerged, one of which is to form a coherent mathematical framework [24]. As there is no definitive name for this new mathematics, it is popularly known as the "mathematics of complexity" and technically as "dynamical systems theory, " "systems dynamics," "complex dynamics," or "nonlinear dynamics" [24].

Information entropy is defined by Shannon [34] to quantify the information. It has been used widely to measure the complexity in system theory [35–39]. The information composed by a set of possible events is measured by information entropy using the probabilities. If p_i is the probability at state i, the information entropy H is defined by following equation [34]:

$$H = -\sum_{i=1}^{n} p_i \ln p_i \tag{1}$$

Where H = information entropy, nat.

In order to apply the information entropy method to thermal adaptation, we made some assumptions as follows. The collections of occupants in building environments are the information source. The thermal sensation, physiological and behavioral data sets are the message from the information source. The information entropy of these thermal adaptive variables thus could be defined in Equations (2)-(3):

$$H_i = -\sum_{j=1}^{n} p_j \log p_j \tag{2}$$

$$\sum_{j=1}^{n} p_j = 1 \tag{3}$$

Where H_i is the information entropy of a thermal adaptive process within the binned temperature interval, Nat; n is the number of thermal adaptation categories; p_j is the occurrence probability of thermal adaptive parameters in each temperature bin.

1.4. Variables of thermal adaptations

Behavioral adjustment includes three categories [15]: personal adjustment; technological or environmental adjustment, and cultural adjustments. In un-air-conditioned building environments, clothing level adjustment (Clo) is a basic behavior in occupants' daily life [15,22,40]. Hence, the clothing was selected in our study to represent the behavioral adjustment.

The physiological adaptation was evaluated by sensory nerve conduction velocity (SCV). The thermal or cold environmental stimulus can cause changes in SCV [34]: due to a high degree of excitability, once the nerves are stimulated effectively by temperature to produce excitation, the generated action potential will conduct along the nerve with a certain speed. SCV has been identified as an indicator of physiological thermal adaptation [41,42], and was used in this study.

Psychological adaptation encompasses the effects of cognitive and cultural variables, describes the extent to which habituation and expectation alter one's perception and acts upon sensory information [43]. The thermal sensation vote (TSV) has been widely used in thermal adaptation to represent the occupants' psychological thermal adaptation [1,44,45]. In this study, TSV was applied to evaluate psychological adaptation.

1.5. Aims

As aforementioned, the TSV [1,46,47], Clo [15,48–51], and SCV [41,52] have been identified as parameters of physiological adaptation, behavioral adaptation, and psychological adaptation respectively. However, within the "black-box", there is an urgent need to understand the roles of these parameters in thermal adaptation and the interactions among them. Therefore, this research aims to investigate the quantitative relationships of the three thermal adaptation processes. In detail, this study will explore:
(1) The theoretical justification of the thermal adaptation processes using general system theory;
(2) The objective quantitative weighting model of thermal adaptation using information entropy;
(3) Dynamic thermal adaptation in free-running buildings.

2. Theoretical justification of thermal adaptation

In order to address the "black box" of thermal adaptation, the underlying premises and logic need a rethinking and a firmer theoretical foundation [7,21].

2.1. Thermal adaptation analysis using general system theory.

In a building environment, the personal adaptive behavior depends on context, which are typically coupled human and environment systems [53]. In biology, the nature of the open system is the basis of fundamental life phenomena [54]. Occupants maintain their thermal adaptations by an exchange of materials and energy with thermal environments using different approaches, and continuous building up and breaking down of their heat balance. According to the general system theory, thermal adaptation is a typical outcome of occupants' open system [23].

Unlike closed systems, open systems maintain themselves far from equilibrium in such "steady state" characteristics by continual flows and changes. Different individuals have different comfort needs and may adopt different thermal adaptation approaches to address environmental changes and their needs [20,21]. As a result, the variability of thermal adaptation approaches between different people results in the emergence of complexity at the collective level of inhabitants. For the conventional approach in thermal adaptation studies, the complexity of a group of occupants is usually ignored by adopting an averaging method [11]. However, the complexity is an essential question if the open system is to be understood [53,55]. Knowledge of the complexity of thermal adaptation at the collective level has, to date, had little effect on comfort research [21]. As a result, the first challenge to understanding thermal adaptation in open systems is to quantify the complexity.

2.2. Thermal adaptation complexity using information entropy.

Information entropy [34] has been widely applied in quantifying complexity of behavior and physiological responses for both humans [56,57] and animals [58–60] . Information entropy (H) takes account of the occurrence probability of each behavior as shown in Eq. (1) [58–60]. In the thermal environment range, H should be continuous. That is, if all the p_j is equal, $p_j = 1/n$, then H should be a monotonic increasing function of n. Thus, H varies from 0 to maximum from the environment range, as shown in Fig.1.

Furthermore, the theoretical calculation of information entropy shown in Fig.1 tends to zero when the frequency of thermal adaptation variables in a narrow range become higher as the environment temperature increases or decreases. However, according to the second law of thermodynamics, there is only a trend in phenomena toward ever-increasing entropy. In this case, the second law of thermodynamic seems to be contradicted. Because classical thermodynamics is applicable only to states of equilibrium or close to equilibrium in closed systems [54,61]. According to Prigogine [61], in an open system, the change of entropy is the sum of the change of entropy imported from environment and change of entropy production in the system. Therefore, the total change of entropy in an open system can be negative as well as positive. The second law is not violated, or more precisely, though it holds for the system plus its environment, it does not hold for the open system itself [54]. Occupants' thermal adaptation is an open system, the change of overall entropy of thermal is in accordance with the second law.

As mentioned in section 1, information entropy takes into account the occurrence probability in a different category of each thermal adaptation . According to early studies, the clothing insulation was classified into four levels by 0.5 clo, 1.0 clo and 1.5 clo, which refer to light clothing, medium clothing and heavy clothing[8]. According to the previous studies [41,42] and SCV results in Fig. 5 in this study, the SCV were classified in 5m/s intervals between 20 m/s and 60 m/s. As the seven-point thermal sensation scale was used in this study, the TSV were clustered by the thermal sensation scale.

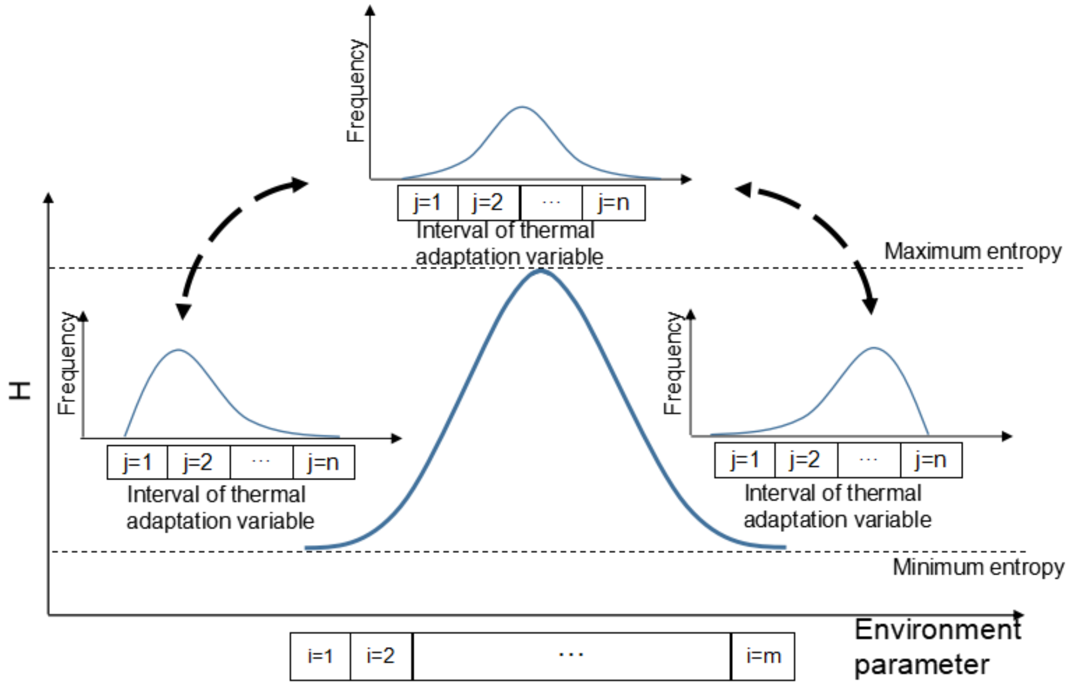

Fig. 1. Scheme of distribution of thermal adaptation variables and information entropy

3. Field studies and laboratory experimental methods

In order to verify the methods presented above, field studies and laboratory experiments were conducted in free-running residential buildings and laboratories to obtain first-hand data.

3.1. Field survey

Field surveys were carried out in three Chinese cities, namely Chongqing, Chengdu, and Wuhan, located in the hot summer and cold winter climate zone (HSCW zone) during every month from October 2008 to September 2009. In total, 6,154 samples were obtained, the proportions of samples from Chongqing, Chengdu, and Wuhan were 34%, 36%, and 30% respectively. In addition, 53% of these samples were from males and 47% from females in more than 5,900 residential buildings.

A questionnaire was employed in the on-site surveys, along with monitoring and investigation of the physical environments. Three environmental parameters were measured in the survey: the indoor and outdoor air temperature, humidity and air velocity. For the indoor environment measurement, the sensors were positioned at different points in the room and at three different heights from the floor, 0.1 m, 0.6 m and 1.1 m. The accuracy of the instruments was calibrated to conform to the requirements of the ASHRAE Standard 55 [62] and ISO 7726 [63] . The ASHRAE seven-point scale [62] was used in the surveys to investigate occupants' thermal sensation. The seven points are defined as cold (-3), cool (-2), slightly cool (-1), just right (neutral) (0), slightly warm (1), warm (2) and hot (3).

3.2. Laboratory experiments

The physiological experiments of SCV were carried out in a naturally ventilated laboratory in Chongqing University. The experiments were carried out during 2010 – 2011. SCV was measured by Neuropack Myoelectricity Evoked Potential Equipment (MEB-9104). The local hospital collaborated by providing the technical support.

The human subjects for this research were respectfully treated according to the Helsinki Declaration [64] . More than 360 university student volunteers were recruited for the experiment (Table 1). They were all in good health, from different provinces of China, and, on average, had been in Chongqing for more than 4 years.

Table 1

Summary of the subjects participating in the laboratory experiments

Gender	Total	Age(yr)*	Height (m) *	Weight(kg) *
Female	182	23.2 ± 1.5	1.59 ± 0.13	48.7± 6.4
Male	187	23.5 ± 2.1	1.73 ± 0.14	63.1 ± 9.2

* mean ± SD

During the experiments, the subjects were sedentary and the metabolic rates were 1.0 met. They wore comfortable clothing according to the seasons. The experimental time ranged from 60 to 120 minutes and SCV was measured every 10 minutes. At the same time, the environmental parameters were recorded and the subjects were asked to fill in the questionnaire.

4. Results

4.1. Behavioral information entropy based on the field surveys

4.1.1. Physical Measurements

The average indoor air temperature varied from 9 ^{o}C to 31.9 ^{o}C. The mean humidity varied from 41% to 81%. The measured thermal environments reflected the typical hot summer and cold winter climatic characteristics in HSCW zone.

4.1.2. Clothing insulation

The clothing regulation used by occupants could be influenced by seasons [20,50,51]. For this reason, the seasons were divided into winter (December, January, February), two transient seasons (spring: March, April, May and autumn: September, October, November), and summer (June, July, August). Indoor air temperatures were grouped into half-degree bins and the Clo values were averaged in each temperature bin (0.5 ^{o}C). Fig. 2 shows the relationship between mean clothing insulation and indoor air temperature. When the temperature was between 13.5 ^{o}C and 17 ^{o}C, the clothing insulation in winter was significantly higher than that in the transient seasons (p<0.01). Meanwhile, when the indoor air temperature was between 24.5 ^{o}C and 27 ^{o}C, the clothing insulation in transient seasons was significantly higher than that in summer

(p<0.01).

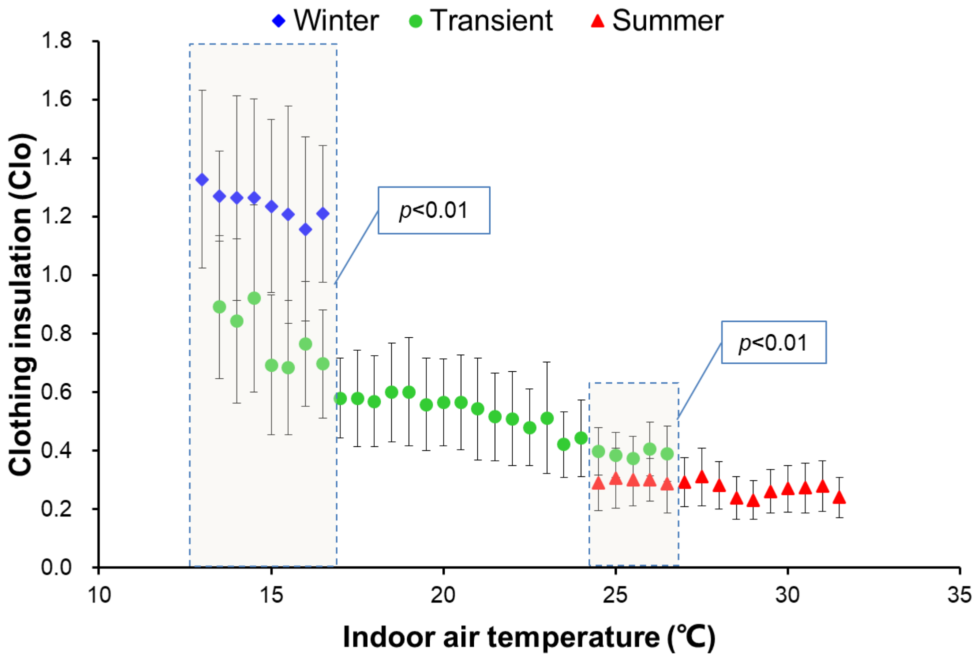

Fig. 2. Relationship between clothing insulation (mean ± SD) and indoor air temperature

4.1.3 Clothing insulation entropy

Employing the binned clothing insulation from the annual field survey, the clothing insulation entropy could be calculated in Equation (2). The relationship of clothing insulation entropy and the indoor air temperature is illustrated in Fig. 3.

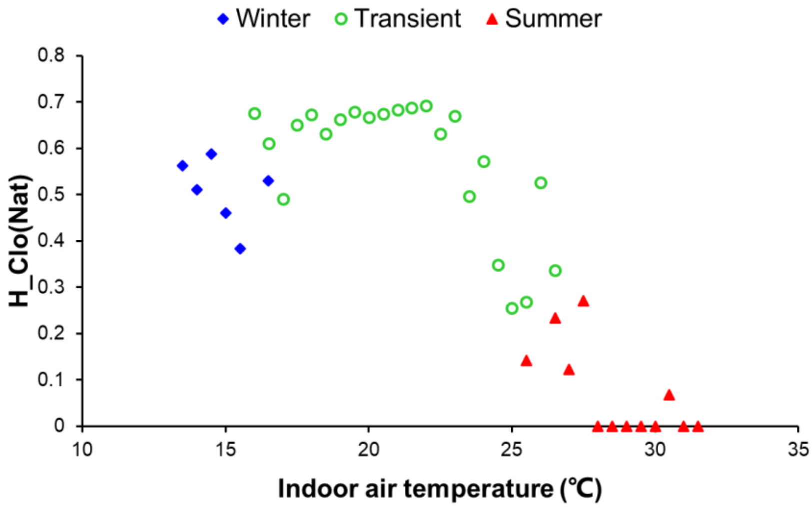

Fig. 3. Plot of clothing insulation entropy versus indoor air temperature

As shown in Fig. 3, the clothing insulation entropy decreased with the increasing air temperature but dropped to zero Nat when the air temperature was higher than 28 °C, indicating that the most of the occupants would wear light clothes in such cases. Conversely, the clothing insulation entropy increased with the air temperature decreasing and reached the peak of 0.7 Nat in the transient seasons. This indicated that the clothing adjustment adopted by inhabitants to adapt to the indoor temperature fell in transient seasons and the complexity increased. When the indoor air temperature continued to decrease in winter, the entropy fell again. This suggested that most of the occupants preferred to dress in heavy clothes, leading to a decrease in the complexity of clothing insulation.

4.1.4 Information entropy of TSV

The clustered TSV from occupants could be substituted into Equation (2) to calculate the TSV entropy. Fig.4 indicates that the TSV entropy reached the lowest value of 0.4 Nat when the temperature was close to 25 °C. When the temperature decreased or increased from 25 °C, the TSV entropy increased. However, the slope on the warm sides was bigger than that on the cold sides.

These phenomena seem to be explained by the clothing insulation entropy. With the increase of indoor air temperature in summer, the clothing regulation of inhabitants is limited so that occupants have to seek alternative thermal adjustment approaches, according to their physiological acclimatization and social and economic conditions [21]. Conversely, with the indoor air temperature decreasing, the complexity of clothing insulation makes the TSV entropy increase slowly.

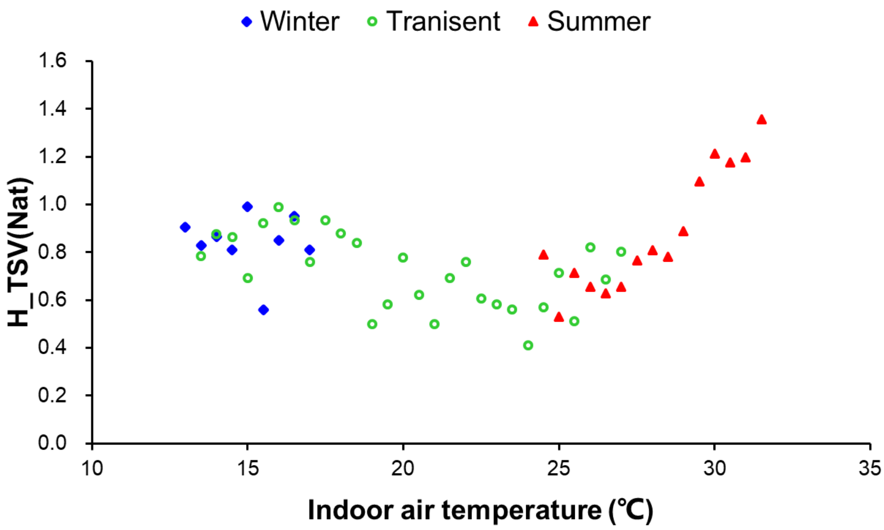

Fig. 4. Relationship between entropy of TSV and indoor air temperature

4.2 Laboratory experimental results

4.2.1. The Impact of Indoor Operative Temperature on SCV

Fig. 5 illustrates an S-curve relation between the average of SCV in each temperature bin (1 °C) and the indoor air temperature. When the temperature increased from 10 °C to 30 °C, a remarkable increase in SCV would be considered as a response to the thermal stimulus. The change trends in SCV were basically consistent with the changes in the indoor operative temperature, which was in accordance with some previous studies [41,42] .

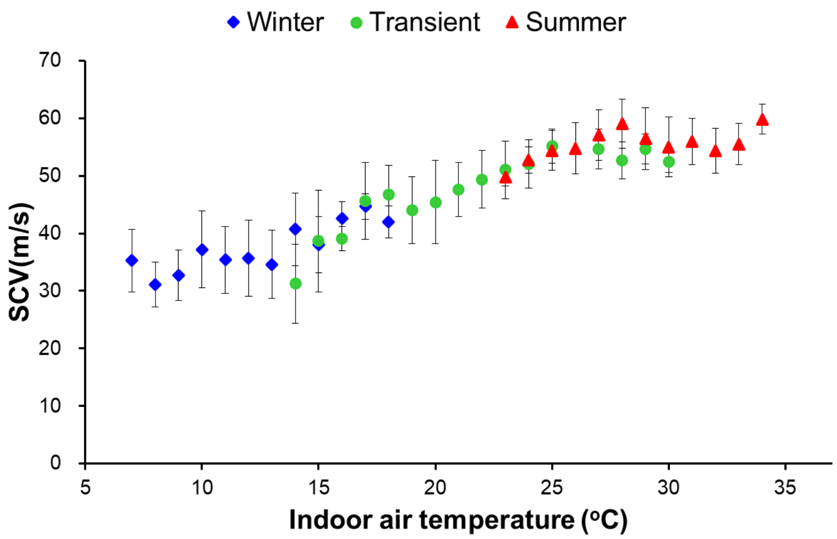

Fig. 5. The relationship between SCV (mean ± SD) and indoor air temperature

4.2.2. The impact of indoor air temperature on the SCV entropy

The SCV entropy is determined by Equation (2) and the relationship between the information entropy of SCV and the indoor air temperature is shown in Fig. 6. There was a significant negative linear relationship between the SCV entropy and indoor air temperature in the transient seasons (p<0.01). In the winter and summer, there was no significant influence of the indoor air temperature on SCV entropy.

Furthermore, the entropy in summer was lower than that in other seasons, due to fewer adaptive methods used without other effective passive cooling methods. In winter, people to a great degree regulated their clothing to reduce the environmental cold effects, which may be one reason that the SCV entropy reached the highest level in winter.

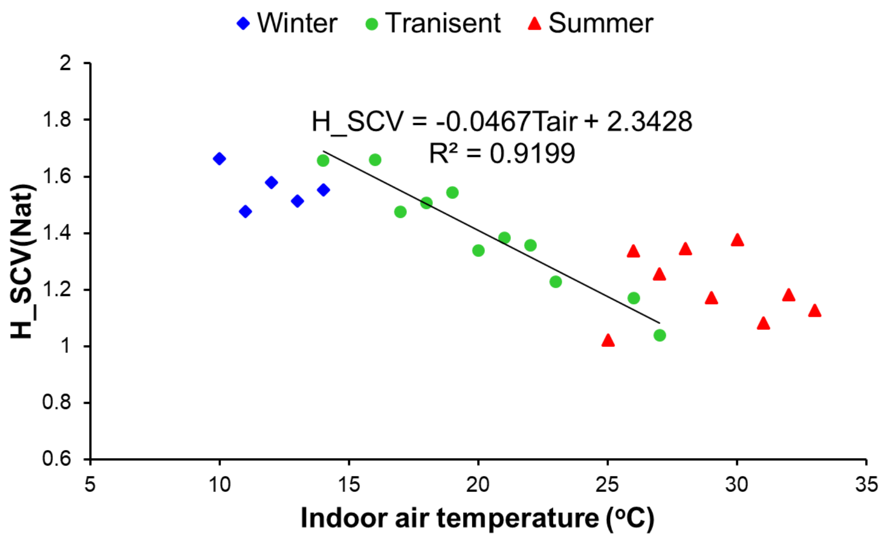

Fig. 6. SCV entropy in relation to indoor air temperature

4.3 Information entropy models of thermal adaptations

The regression models of the information entropy of Clo, TSV, SCV, total entropy and indoor air temperature were developed using Matlab software (version 8.6), and the results are shown in Fig. 7 and Table 2.

Fig.7 shows that the individual differences of clothing behavior were less compared to that of TSV and SCV. By contrast, the physiological differences of occupants were the biggest when the temperature was below about 31 °C. The opposite trend is observed for the curves of TSV and SCV. The overall mirroring of the two curves suggest that the psychological adaptation and behavioral adaptation may be modulated by a mutual process described in previous conceptual frameworks [1,22,65].Interestingly, the total entropy model exhibits a periodic change of temperature and appears an anti-S curve (Fig.7). As demonstrated in Fig.7, the minimum and maximum total entropy are 3 Nat and 2 Nat respectively, and the corresponding indoor air temperatures fluctuate from 16 °C to 27 °C.

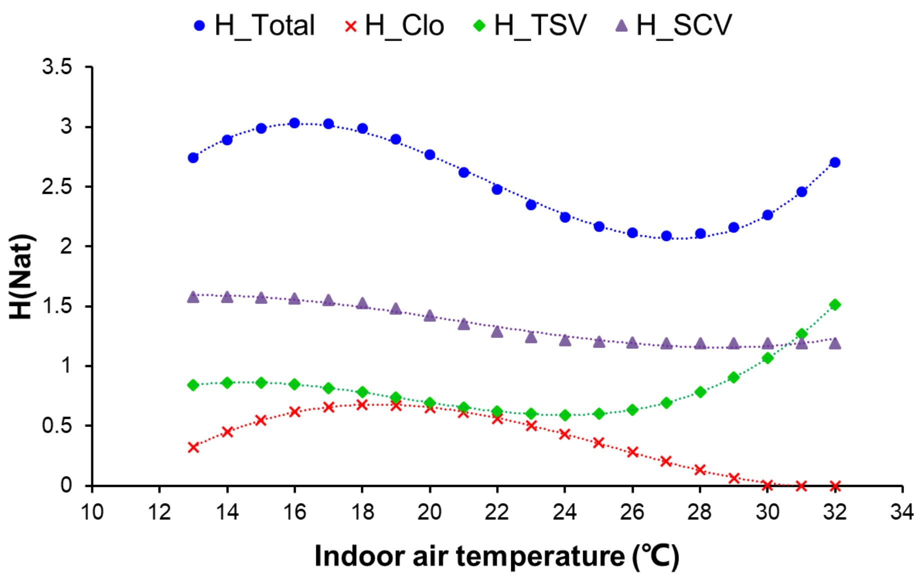

Fig. 7. The regression models of the information entropy of Clo, TSV, SCV and Total

Table 2

Regression models of information entropy of Clo, TSV, SCV and Total

Regression model	R^2
$H_{\_Clo}$=0.0004471×T_{air}^3−0.03474×T_{air}^2+0.8228×T_{air} −5.485	0.82 (p<0.05)
$H_{\_TSV}$=0.000646×T_{air}^3−0.037284×T_{air}^2+0.6739×T_{air} −3.0365	0.77 (p<0.05)
$H_{\_SCV}$=0.39/(1+2.43×exp(5.19×(T_{air} -21.76)/7.09))+1.19	0.74 (p<0.05)
$H_{\_Total}$ = 0.0014 ×T_{air}^3 - 0.0909×T_{air}^2 + 1.8453×T_{air} - 8.9413	0.996 (p<0.05)

T_{air}, indoor air temperature

4.4. Weighting three types of thermal adaptation approach

To understand the adaptive properties of the human-environment system, there is a need to quantify the physiological, behavioral, and psychological effects in the adaptation process. Liu [19] used the analytic hierarchy process (AHP) to determine the weights of three categories of adaptation based on the data from a subjective survey of experts and academics conducted in the UK and China. In this study, we used entropy of Clo, TSV, and SCV as indices of the behavioral, psychological, and physiological adaptations respectively. Then the weight factors of the three adaptive categories could be defined based on Equation (4):

$$\mathrm{Weights_i} = \frac{\mathrm{mean\_H_i}}{\mathrm{mean\_H_{total}}} \tag{4}$$

Where, $Weights_i$ represents the weights of three categories of thermal adaptation; mean_H_i represents the mean entropy of three categories of adaptation; and mean_H_{total} represents the mean total entropy.

As shown in Fig. 8, the results illustrate that physiological adaptation accounted for the highest weighting of 53%, followed by psychological adaptation (32%), and clothing behavioral adaptation (15%), which is consistent with the results shown in Fig.7. The weighting factors of the three categories derived from the objective data were consistent with the results from a subjective survey [19]. Furthermore, the weighting factor for behavioral adaptation in transient seasons (20%) was above the average (15%), indicating that clothing adjustment played an important role in transient seasons.

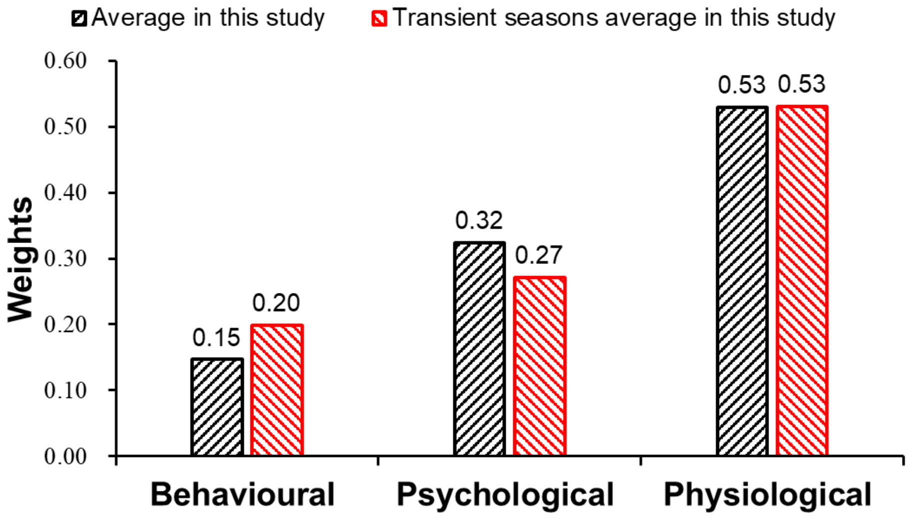

Fig. 8. Weights of three categories of adaptations

The relationship between the weights of three adaptations and indoor air temperature is illustrated in Fig.9. The results show that the weighting factors were not static. Similar to Fig. 7, the ordering of the three curves is the same. The physiological entropy weight ranked first, followed by psychological and behavioral entropy below about 31 ºC.

The two weight curves of psychological adaptation and behavioral adaptation show the opposite trend, as shown in Fig.7.Within the temperature range of 20-30 ºC, inhabitants might adapt to the changing temperature through the clothing adjustment due to the individual physiological difference. With the air temperature increasing, the psychological adaptation weight increased and ranked almost first place when the air temperature was more than 30ºC. Meantime, the weights of physiological adaptation decreased when the behavioral adaptation weight reached the limit of zero. The results indicates the three thermal adaptation approaches weights varies with the temperature and people's psychological and behavioural adaptations is essential for setting up dynamic facilities management and control strategies for building designers and facilities managers[19].

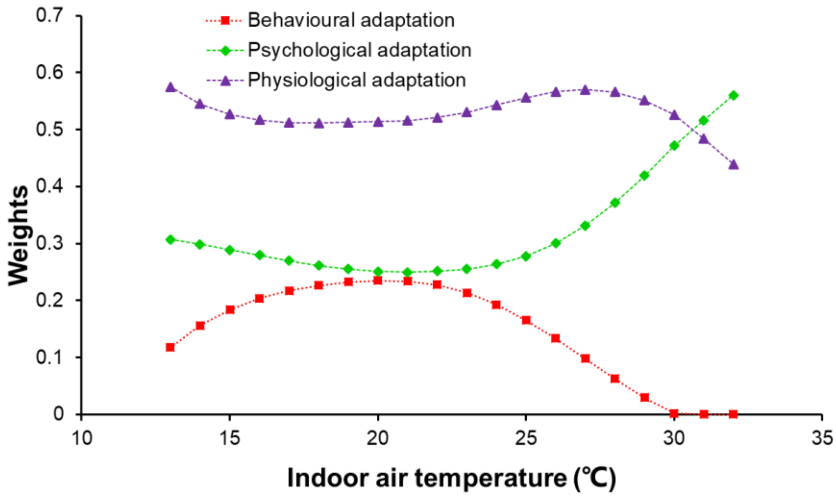

Fig. 9. The relationship between the weights of three categories of adaptation and indoor air temperature.

5. Discussion

5.1. Comparisons of thermal adaptation in free running environments of different regions

A number of studies have been conducted in different countries and regions to establish the adaptive models [4], while the perceived indoor air temperature ranges by these models were different. This indicated that there would be a difference in thermal adaptation among inhabitants in different countries/regions [21]. In order to examine the difference, the data from field studies conducted in free running buildings in the RP884 database [66] was adopted to compare the Clo and TSV entropies for different regions. Fig.10 illustrates that the Clo entropy in Pakistan is higher than that in the HSCW zone in China. As a result, the TSV entropy of Pakistan is generally higher compared to the TSV entropy in this study (Fig.11).

Furthermore, the deviations in the two entropies between the two countries vary with temperature. It can be inferred that a significant social and cultural diversity exists between these two different countries: a typical ensemble of the traditional Pakistani clothing for winter in the cooler areas will be a heavy weight woolen shalwar kameez, with a woolen pullover and maybe a heavy woolen waistcoat lined with cotton with socks and shoes on the feet [67] . The ensemble may be completed by a woolen cap and scarf or 'muffler' on top and a sleeved cotton undervest beneath. By contrast, in summer, a typical ensemble will be a loose lightweight cotton/polyester shalwar kameez and sandals [67]. The Clo entropy differences between Pakistan and China could be attributed to the greater flexibility of traditional Pakistani clothing than that of China.

Therefore, when establishing an adaptive model for different countries/regions there is a great need to verify what the degree of complexity of the thermal adaptation conditions in the different countries or regions would be.

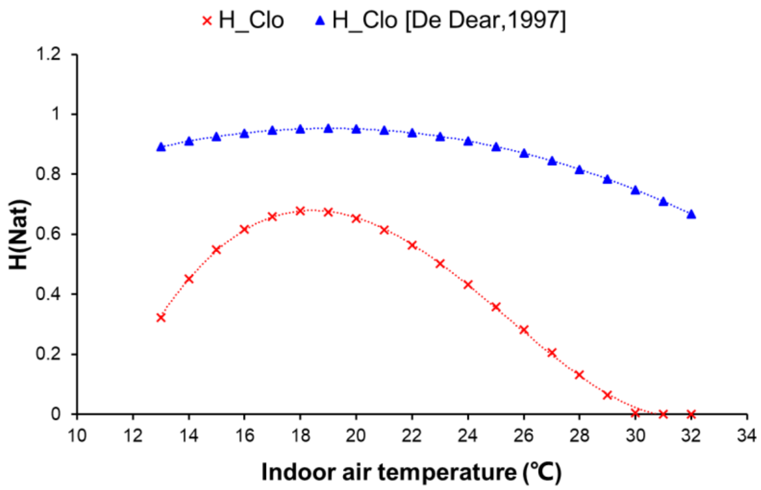

Fig. 10: Comparison between Clo entropy in China and Pakistan

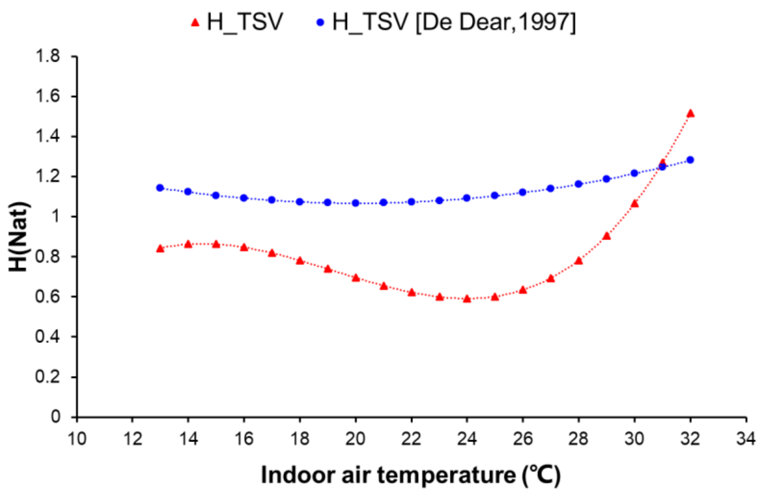

Fig. 11. Comparison between TSV entropy in China and Pakistan

5.2. Comparisons of the TSV entropy in free running environments and artificial environments

It has long been argued whether adaptive approaches or climate chamber experiments [4,7] provide more empirical evidence to address this issue. In this study, climate chamber data established by Fanger was taken as an example [8] .

To note, since subjects who participated in the experiment were asked to wear uniform clothes in Fanger's study, the Clo entropy in the climate chamber experiments could be easily calculated to be zero according to the definition of entropy and Equation (2). However, the Clo entropy in this study varies with temperatures and seasons (Fig.7 and Fig.9).

Furthermore, the TSV entropy of the climate chamber remains constant at around 1.2 Nat (Fig.12). For the comfort temperature at 26 °C, the TSV entropy of participants in a climate chamber is higher than that in free running buildings in our study. This may attribute to the subjects wearing uniform clothing that could not be changed according to their habit and physiological condition, which differs from real-life situations.This reflected that the individual thermal sensation performance could be more consistent with the "average person" in the field surveys than in climate chamber studies, which conflicts with the theoretical assumptions of the heat balance model. The average TSV of collective occupants could not represent the complexity of occupants' TSV.

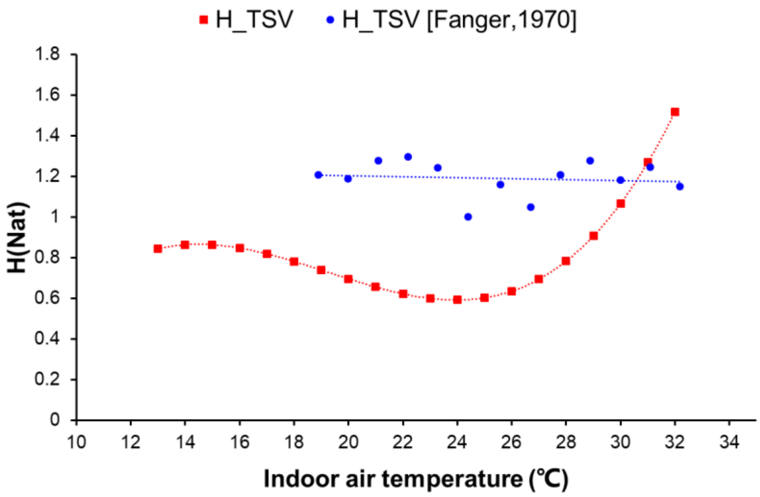

Fig. 12. Comparison of TSV entropy between China and Fanger's studies

5.3. Comfort temperature drawn by total entropy

Fanger [8] noted that optimal comfort is a condition in which a high percentage of people are thermally comfortable. In order to determine the optimal comfort temperature, extensive experiments have been performed under well-controlled laboratory conditions, to find the physiological temperature limits [8]. While the climate chamber experiments provide tight control over the relevant physical variables and provide analytical rigor for research design, they represent artificial contexts in which subjects must surely find it hard to suspend their disbelief in the authenticity of the situation [68].

These experiments are essentially a reductionist approach [11,69,70]. With the reductionist view, researchers exclude and decline to quantify the highest percentage of the group in Fanger's operative definition of comfort temperature [8]. The System theory thinking employs the mathematical approach to handle this issue. According to the definition of thermal adaptation entropy, as shown in Equation (2) and Fig.2, the highest percentage of the occupants in field studies shows a thermally comfortable state, the total entropy of the group would be smaller. That the thermal adaptation entropy attains the minimum could help to draw the optimal comfort temperature in free running buildings.

Taken together, the minimum of total entropy represented in Fig.7 is about 2 Nat when the indoor air temperature is 27 °C. At such a temperature, occupants express the highest percentage of consistency in thermal adaptation. Therefore, the temperature near 27 °C could be a comfort temperature for free running buildings, which is higher than the value of 25.5 °C obtained in chamber studies [8]. We could attribute this result to the different clothing adjustment opportunities.

5.4. Rethinking the acceptable thermal environment

The definition of an acceptable thermal environment in ASHRAE 55 is a thermal environment that a substantial majority (more than 80%) of the occupants find thermally acceptable [62]. According to the previous analysis, the total entropy would increase while the temperatures are higher or lower than the comfort temperature. However, the adaptive process for increasing and decreasing temperature is different.

When the temperature increases to above the comfort temperature, the Clo entropy decreases, and SCV entropy remains at a low level (Fig.7). Conversely, the TSV entropy increase accounts for the rise in the total entropy. At 30 °C, the Clo entropy reaches nearly zero, meaning the occupants have the same clothing regulation and a lower complexity of physiological adaptation. Based on the adaptation theory, occupants could adjust to the thermal environment[15,22] in a thermally acceptable range. Above 30 °C, the Clo and physiological adjustment reach their limits so that the temperature of 30 °C would be the upper limit.

When the temperature decreases below the comfort temperature, the Clo entropy and SCV entropy increase (Fig.7). However, the increase in the TSV entropy is slower than that of the temperature being above the comfort temperature. When the temperature is lower than 16 °C, the total entropy decreases but occupants' clothing insulation in winter is higher [2]. The adjustment of thermal adaptation shares a higher consistency. Hence, 16 °C could be the lower acceptable limit for HSCW zone in China.

6. Conclusions

This study develops a new quantitative methodology to explore the three categories of process for thermal adaptation. The major conclusions to improve the body of knowledge are as follows:

- Information entropy is employed to quantify the complexity in the thermal adaptation process, and the entropy of Clo, TSV and SCV are developed.
- The entropy of Clo, TSV and SCV are calculated and the dynamic state of the three entropies is established using the database from field studies and laboratory experiments conducted in the HSCW zone of China.
- The respective models of the clothing behavioral adjustment, physiological adjustment, and psychological adjustment are established over a wide range of temperatures using entropy.

The outcomes of this research reveal that:

- According to the entropy models and the average weights, physiological adaptation is the dominant factor. Moreover, the weights of the three thermal adaptations vary with the temperature.
- The difference of thermal adaptation between China and Pakistan is compared using the Clo and TSV entropy, indicating the significant social and cultural diversity in these two different countries.
- The TSV entropy of participants in the climate chamber remains constant and is higher than that in free running buildings, partly due to the Clo entropy of 0 in chamber experiments.
- The comfort temperature for the HSCW zone is quantified using the entropy model. Temperatures near 27 ^{o}C could be a comfort temperature for free running buildings, and the upper and lower limits of acceptable temperature are 30^{o}C and 16^{o}C respectively.

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