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Energy and Buildings 36 (2004) 1281–1286

ENERGY and BUILDINGS

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Conditioning strategies of indoor thermal environment in warm climates

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Received 27 March 2003; accepted 12 July 2003

Abstract

Commenting on some negative effects of traditional conditioning strategies of indoor thermal environment in warm climates, the authors present a fundamental concept of thermal comfort and acceptability, new air-conditioning strategies by using fluctuating air movement based on the findings of human responses to transient thermal environment, and a prediction of energy saving caused by elevated indoor temperature settings. In addition, how to meet the requirement of providing human-beings a healthy, comfortable and affordable indoor air temperature, and to achieve a goal of sustainable development are also discussed in this paper.

Keywords: Indoor thermal environment; Conditioning strategy; Thermal sensation and comfort; Transient air movement

1. Introduction

In general, there will be over 80% of human being's lifetime indoors. Concerning this fact, to provide a healthy, comfortable and affordable indoor environment is not only related to the living standard, but also connected to the energy consumption and environment pollution. In the last century, air conditioning technology and manufacturing technique were rapidly developed, so that not only public and commercial buildings, but most residential buildings and houses were also equipped with air conditioning installations in developed countries.

Certainly air conditioning facilities have enabled human beings to extricate themselves from the dependence to the natural environment; therefore the living standard of occupants has greatly improved. Standards for designing indoor environmental conditions have been set up after long-term studies and practical use. But it is obvious that most of the studies on indoor thermal environment were conducted at steady-state conditions, therefore, the existing air conditioning strategy has been based on the concept of maintaining environmental parameters constant and the assessment of subjective acceptability is perceived by thermal sensation and thermal comfort. According to the heat balance of human body at certain activity and clothing levels, to achieve neutral thermal sensation (neither warm, nor cool), combined with the limitation of moderate air humidity (in general, RH = 50%) and low air velocity (less than 0.2 m/s) has been referred as thermal comfort conditions and the main target of thermal environment control strategy [1,2].

In practice, this strategy has led to some negative effects, such as so-called "non-adaptability of air conditioning", possible causes of "sick building syndrome" and high energy consumption. Facing such reality, "Can some negative effects be avoided?" and "Is it possible to challenge the traditional conditioning strategy?" are frequently questioned. In order to find out the answers, a series of experimental studies on human responses to transient thermal environment were carried out in the test chamber of HVAC laboratory of Tsinghua University [3–8].

As a result, human responses to transient thermal environment, including sudden, ramp and swing air temperature changes, and different air movement modes, represent more or less benefits of human acceptability to the thermal environment. Particularly, using different air movement mode, for example, is an easy way to improve indoor thermal environment.

2. Concept of air-conditioning strategies

First of all, it is necessary to discuss the conceptual argument, which is related to the air-conditioning strategy and the controlled environmental quality. In philosophical point of

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0378-7788/$ – see front matter © 2004 Published by Elsevier B.V.
doi:10.1016/j.enbuild.2003.07.002

view, indoor environmental conditioning could be achieved by two ways: one is to "search for excellence", that is to say, every indoor thermal parameter should have no stimulative effect, be kept at constant, and the thermal perception of human body in the indoor environment should be of indifference or in neutrality; the other is to create an environment, in which one or some of thermal parameters could be fluctuated within limited ranges and the subjective perception of human beings is not constant. In other words, the fluctuated parameter (e.g. fluctuating air movement) seems to be a slight stimulus. Now the question is: which way should be taken?

As mentioned above, traditional conditioning strategy will cause "non-adaptability of air conditioning" because of lower air temperature (in general, less than 26 °C). Occupants exposed to relatively low air temperature for long time will result in impeded blood-flow, shrunk or closed sweat glands and sebaceous glands, and disordered nervous system. In addition, there will be a hot shock as one enters or exits between indoor and outdoor environments. Symptoms caused by "non-adaptability of air conditioning" could be heatstroke, headache, sleepiness, fatigue, pain of joints etc. Although the evidence of negative effects of traditional conditioning strategy is not abundant, a few examples of symptoms have been obtained [9,10]. Since some of the symptoms have recessive character, it is difficult to figure out a quantitative analysis through a questionnaire or field study.

On the other hand, to maintain relatively low air temperature will consume more energy, e.g. shifting the air temperature setting from 24 to 28 °C, the estimated energy saving will be over 36%, comparing with the energy consumption at 24 °C [11]. Furthermore, the environmental pollution caused by the refrigerant leakage and exhausted heat from outdoor unit of air conditioner cannot be ignored.

Initially the main aim of traditional conditioning strategy, in principle, is to provide a comfortable indoor climate. In reality, the aim is not achieved, but just neutral thermal sensation is maintained, because the so called thermal comfort could not be perceived in steady-state environment. Thermal comfort can only emerge in transient conditions [12]. And "a given stimulus will arouse either pleasure or displeasure according to the internal state of the stimulated subject" [13].

Considering the negative effects of traditional conditioning strategy, a "dynamic" conditioning strategy is presented based on the research of transient thermal environment. The main feature of this strategy is to make one or some thermal parameters indoors variable within certain ranges. Accordingly this conditioning strategy is not aimed at providing constant thermal neutrality, but thermal acceptability. It means that the long-term mean of perceived thermal sensation will be around neutral, but possibly deviate from neutral at a certain time. In the process of returning to neutrality, the subjective response could be comfortable, or adversely uncomfortable when deviating from neutrality. So the dynamic conditioning strategy does not concentrate on minimizing the stimuli caused by fluctuated thermal parameters, and from the point of view of hygiene, in fact, a number of authors have expressed disquiet at absolute thermal neutrality, and the flexibility of the heat regulating mechanism and the adaptation speed of the body may become atrophied [9]. In addition, thermal neutrality can be regarded as one of minor physiological adjustment, within which the organism has no need to struggle against heat or cold, and thermal stimuli of low intensity are subjectively interpreted as varying degrees of comfort or pleasantness [14]. So it is evident that reasonable stimuli could motivate body metabolism and strengthen its ability of adaptation.

3. Human responses to transient thermal environment

Human responses to transient thermal environment were conducted under the conditions of fluctuating air temperature and/or air movement. All the experimental investigations were carried out by subjective votes in the test chamber (3.4 m × 4.0 m × 3.0 m). Subjects (equal number of males and females in most cases) are college students, aged from 18 to 23 and dressed with 0.5–0.7 clothing values at sedentary activity level.

The most interesting responses happened at the stages of sudden temperature changes from 25 to 35 °C or higher than 35 °C, and reverse from 35 °C or higher than 35 to 25 °C, correspondent from neutral to warm or hot thermal sensation and reverse. In neutral to warm/hot, thermal sensation was gradually increased, but in warm/hot to neutral process, thermal sensation vote (TSV) was immediately decreased and presented an over-sense (Fig. 1).

It is obvious that human body is more sensitive to cold stimulus. This phenomenon may be explained as the difference of depth and distribution density between warm and cold sensors. Existing research results show that cold sensors are located at the depth of 0.2 mm from the skin surface, and warm sensors at the depth of 0.5 mm from the skin surface. In addition, the distribution density of cold sensors is of 6–10 times that of warm sensors [15].

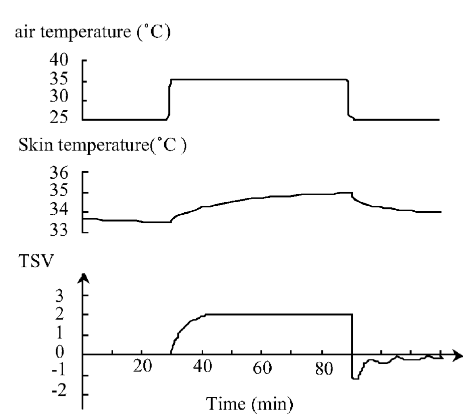

Fig. 1. Human responses to sudden air temperature changes.

In fact, changing the air temperature indoors with a certain mode (e.g. fluctuating as a sine curve) will meet some difficulty because of the thermal performance of building materials. Concerning this point, to use fluctuating air movement could be the easy way to improve indoor thermal environment.

Air movement, as a useful means, can be used to offset air temperature, especially as it could enhance the heat and mass transfer from human body to the surroundings. In previous studies, a number of researchers were focusing on the effect of steady-state air movement on human sensation and comfort and attempted to establish the relationship between the mean air velocity and temperature [16]. For reasons of maintaining human neutrality, to elevate steady-state air movement may not be necessary and expected, so that low air velocity was recommended, otherwise, cold air draft will be caused [17]. On the other hand, in hot and humid conditions, as an offset measure, higher air velocity can be accepted [18].

In order to investigate the effects of airflow turbulence intensity and frequency on human thermal sensation and comfort, a series of experimental studies have been done [19]. It is clear that airflow turbulence intensity has significant effect on reducing preferred mean air velocity (see Fig. 2) and that the more effective frequency of airflow is 0.3–0.5 Hz, the same frequency range as found in local cold air draught.

Air movement with a constant air velocity, even it can be accepted for a short time, is not desirable for long time exposure. In hot or warm conditions, a few subjects exposed to constant airflow will also have draft and annoying feelings. For a long-term exposure, it is necessary to investigate the effective use of air movement. By comparing different air movement modes, it is found that the preferable air movement is so-called artificial natural wind, which is simulated according to features of real natural wind [20]. Fig. 3 shows the results of acceptability of airflow modes, gained from the experimental votes.

In principle, a natural wind has its own characteristics and can be mainly featured as turbulence intensity, probability distribution and power spectrum. Fig. 4 shows the characteristic differences between artificial air movement and natural wind. It can be seen that the turbulence intensity of natural wind is higher than that of artificial air movement, that the probability distribution of artificial air velocity is quite different from natural and that the spectrum density of natural wind in low frequency range is much higher than that of artificial airflow. Based on these characteristics of natural wind, how to simulate it by artificial means is highly concerned.

The preferred mean air velocities voted for the simulated natural wind are listed in Table 1. Compared the values in

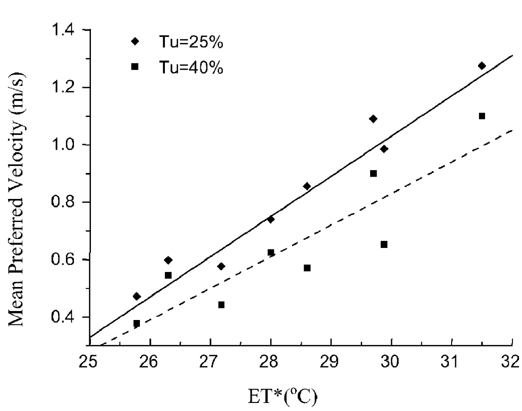

Fig. 2. Preferred air velocity at different turbulence intensity.

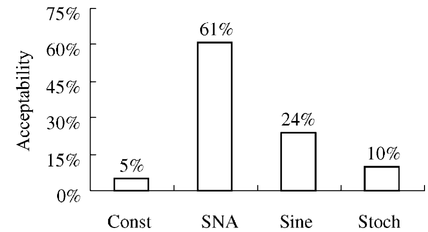

Fig. 3. Acceptability of different air movement modes.

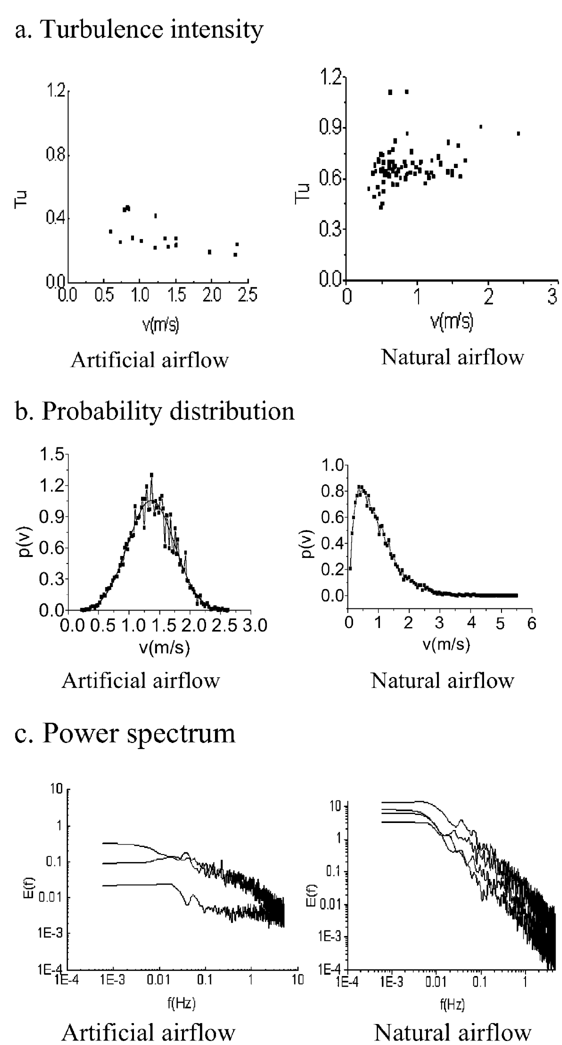

Fig. 4. Characteristics of natural and artificial air movement.

Table 1
Preferred mean air velocities by using simulated natural wind

Ambient temperature/supply air temperature (°C)	Air velocity (m/s)
28.5/22.2	0.68 ± 0.11
28.5/24.2	0.86 ± 0.11
30.0/22.7	0.71 ± 0.10
30.0/25.7	1.14 ± 0.15
30.0/30.0	1.19 ± 0.18

Table 1 with the data in Fig. 2, it is noticed that the mean air velocity in the mode of simulated natural wind is higher than that in the mode of constant airflow when the air supply is isothermal. Evidently the simulated natural wind has higher turbulence intensity than general air supply from an artificial outlet.

4. Investigated devices with simulated natural air supply

To provide a fluctuating airflow is not difficult, but to create an airflow with basic features of natural wind is not easy. The key point of designing an air supply unit, which can provide a power spectrum close to natural wind, is related to the right choice of regulating device. Theoretically to use a throttle mechanism is not suitable, since it will cause a lot of small vortexes, which will affect the power spectrum deviating from a spectrum of natural wind. Up to now, two types of air supply devices have been developed. One is simply demonstrated in Fig. 5.

When the rotating desk is driven by a step-motor, each passage area will be changed at the same time; so two airflows with different air volume will be discharged. On the other hand, specially programmed software is used to control the step-motor. The distribution probability of the natural wind velocity is abnormal [8]. In practice, one of the discharged airflow could only be the best of simulated natural wind if the other is used for conditioning the background climate indoors.

Another type of air supply device is to use a swing plate, by which the airflow in the passage can be separated into two, shown in Fig. 6. With the step motion of swing plate, two discharged air volumes are changeable one another.

As mentioned above, only one of discharged airflows can be well simulated as a natural wind. As both discharged airflows are supplied to occupied zones at the same time, then features of the airflow, especially the probability distribution of air velocities, will somewhat deviate from simulated natural wind. However the frequency span (e.g. 0.3–0.5 Hz) can be enhanced.

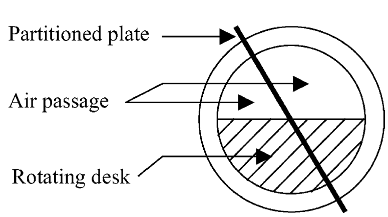

Fig. 5. Air supply device with rotating desk.

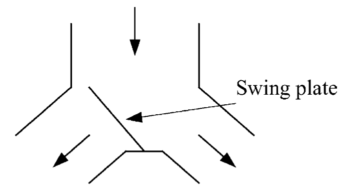

Fig. 6. Air supply device with swing plate.

Based on the thermal performance test of the air supply unit equipped with cooling coil in each passage, the cooling capacity of the unit in the operating mode of moving swing plate has a little decrease (3–5%), compared with the capacity in the mode of stopping the plate at perpendicular angle. The reason of the capacity decrease is caused by the decrease of total air volume of the unit, since the resistance of the air passage is changed as the plate swings [19].

5. Conditioning procedure suggested

By using isothermal and non-isothermal transient air movement, a conditioning procedure of indoor thermal environment is suggested. It can be seen in Fig. 7 that the procedure is intended to effectively use natural ventilation and isothermal fluctuating airflow for conditioning indoor environment. As a matter of course, non-isothermal airflow should be provided so long as the subjective thermal sensation is gong to be over slightly warm. According to the experimental results, the thermal sensation of sedentary occupants could be satisfactory only by adjusting the mean air velocity of transient isothermal airflow as the air temperature is 30 °C and relative humidity is lower than 70%.

It has to be noticed that the procedure suggested above is mainly suitable for sedentary youths. For elder people

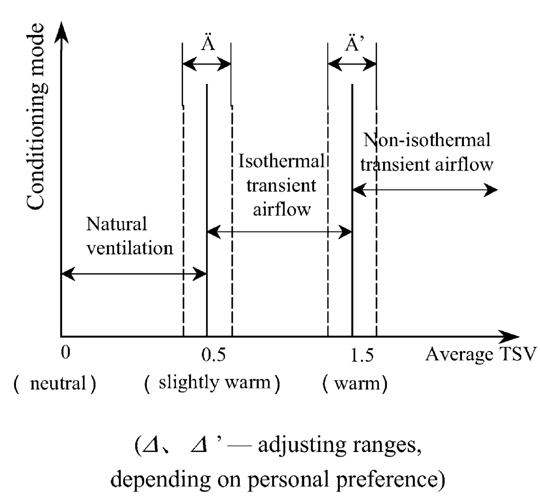

Fig. 7. The suggested conditioning procedure.

and children, and for people lived in humid regions, it must be more or less modified. With the result, the suggested procedure provides a possibility to get rid of maintaining steady-state thermal environment.

Furthermore, different from traditional air supply, transient airflow must be directly reached to occupants, so that the mixing effect could be decreased as much as possible and the perceived air quality could be improved.

Practically our aim is to provide people a healthy, comfortable and affordable indoor environment with less energy consumption and less environmental pollution. From the viewpoint of energy saving, this conditioning procedure is of great significance because of elevated air temperature. The predicted energy saving is about 40–50%, compared to the energy use when the air temperature is kept at 24 °C [20].

6. Economic analysis

An office building located in Beijing urban with five floors was taken as an example for comparing different solutions. The building gross area is about 6000 m^2, in which 4800 m^2 is air-conditioned. Fig. 8 shows the building plan.

The air-conditioning systems to be used in the building consist of fresh air intake system & fan-coil unit. The difference between dynamic and steady state operation modes is the temperature settings, i.e. 28.5 °C for dynamic, and 25 °C for steady state, respectively. The results gained from economic analysis in detail are described in Ref. [21]. The results showed that, by using dynamic strategy, the cooling load caused by the building envelope could be decreased by 14.02%, and the load caused by fresh air intake decreased by 29.66%, compared with the steady state operating mode. At the same time, the first cost for air conditioning installations can be lowered by 14.42% because of smaller size of equipment. In addition, 12.17% of the maximum cooling load can be reduced. Finally the operating cost can drop by 39% and the running hours of chillers are also shortened. It is obvious that a considerable benefit could be obtained by using the novel conditioning strategy.

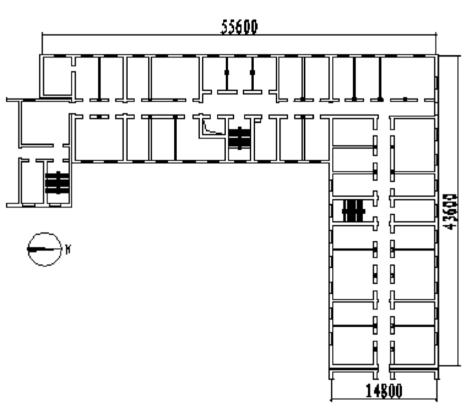

Fig. 8. First floor of the office building.

7. Summary

Air conditioning is a great progress in extricating people from extreme natural environment. It makes a substantial change in living standard, but brings a number of negative effects. In order to overcome these effects, a new conditioning concept is presented and aimed to provide a stimulating and inspiring indoor environment. Transient thermal environment can be established by changing air temperature and/or air velocity. Comparatively to make airflow changeable is easier. Fluctuating air movement can be used to offset high air temperature and to provide better perceived air quality.

New conditioning strategy focuses on the effective use of simulated natural wind, which has special features in turbulence intensity, probability distribution and power spectrum. Terminal air supply units with rotating desk and swing plate have been investigated. The cooling capacity of terminal unit shows a slight decrease because of the changeable resistance of the moving part.

Finally an air-conditioning procedure aimed to provide healthy, comfortable and affordable indoor environment is presented. A substantial energy saving can be achieved.

Acknowledgements

The successive researches have been financially supported by China National Nature Science Foundation (No.5870277, No.59276262 and No. 59836250) and supported by Hong Kong Polytechnic University and Qinghua Tongfang Artificial Environment Co. Authors would also like to express sincere thanks to Dr. Jia Qingxian, Dr. Xia Yizai and Professor Xu Weiquan for their outstanding research works.

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