THERMAL COMFORT STUDIES IN JAPAN

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More than fifty papers on thermal comfort are presented in various meetings and symposia every year in Japan. Topics covered by these papers include comfort zone, the effect of fluctuating air movement and asymmetric thermal radiation on human responses, dynamic analysis of human responses, psychological and behavioral aspects of thermal comfort, and development of environmental indices etc. This paper briefly reviews these investigations.

INTRODUCTION

Since 1920, architects in Japan have conducted studies to measure thermal comfort in houses under hot-humid conditions, while industrial hygienists have studied the effects of temperature and humidity on the performance of factory workers. After 1960 subjective experiments and field surveys were carried out to determine the thermal comfort zone for Japanese. Thermal comfort can be influenced by many variables, as illustrated in Fig. 1. Current issues are the effects of non-uniformity and fluctuation of environmental variables, and psychological aspects. More than fifty papers a year are presented at the annual meeting of the Architectural Institute of Japan and other associations; most of these papers are written in Japanese. This paper briefly summarises some of this work.

HEAT BALANCE EQUATION

Convective Heat Transfer Coefficient

There are many studies of convective heat transfer coefficients for forced convection on the human body, but there are few studies of natural convection. Mochida (1,2) developed a formula for convective heat transfer coefficients that involves transient regions from natural convection to forced convection, using Hilpert's equation and the method of Oosthuizen & Madan. Uematsu et al (3) carried out experiments to measure dry heat dissipation from the surface of the skin using heat flow meters, and calculated the heat transfer coefficient for natural and forced convections. The results for the forced convection were similar to Winslow's (4). Lee et al (5) carried out experiments using a thermal manikin and a human model. They examined the effect of air turbulence on natural and forced convection coefficient. These studies introduced the convective heat transfer coefficients for each segment of the body using direct calorimetry, whereas previous studies used predicted values.

Human Factors for Thermal Radiation

Both radiation area factors and the angle factors between the body and its surround must be known to calculate radiative heat exchange. Horikoshi et al (6) and Tsuchikawa et al (7) developed a new method to measure both factors. Fanger et al treated the human body as an infinite small point inside a space. Horikoshi et al used measurements of life-sized bodies. Since they used life-sized bodies, the angle factor between the surface of the body and the floor were larger than Fanger's (8) by about 40 %.

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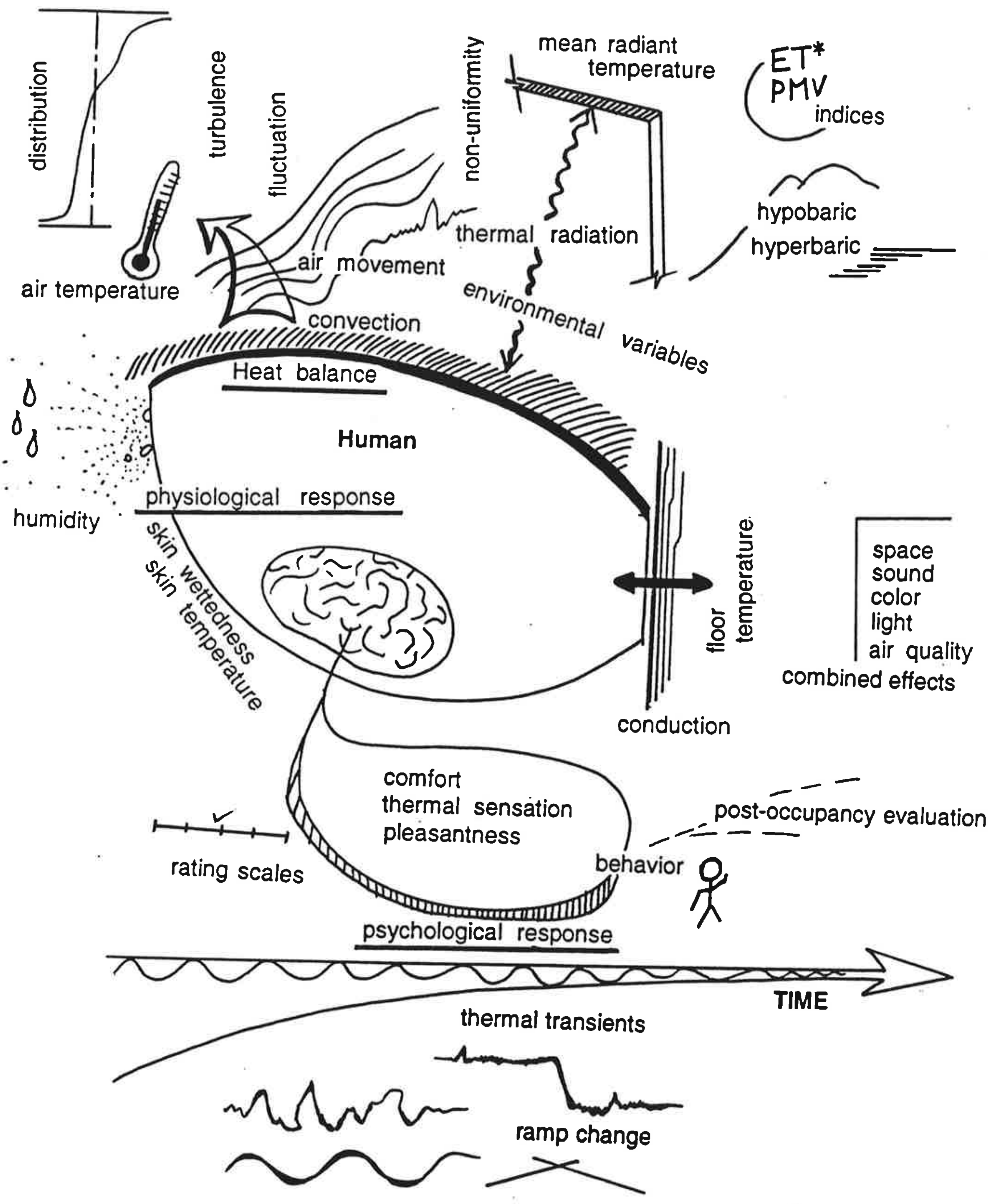

Fig.1. Thermal comfort study system

Partitional Calorimetry

Partitional calorimetry of the human body has been established by Winslow et al (4). Obtaining more exact parameters and examination of that calculation in detail is, however, essential to validate thermoregulation models and to establish the environmental indices for thermal comfort. A few investigators carried out examinations for partitional calorimetry in Japan: Horikoshi et al (9) examined the two node model, and Fukai et al (10) conducted experiments to verify the new effective temperature ET* for application to Japan.

THERMAL ENVIRONMENTAL INDICES

While the new effective temperature (ET*) and predicted mean vote (PMV) were introduced, some Japanese researchers were developing other indices based on the human heat balance equation. Examples of these indices are: Thermal Sensation Chart (11), Equi-calorimeteric Temperature(12) and Model Skin Temperature(13). Mochida (14) pointed out that ET* is defined as: air temperature at 50 % relative humidity; still air (0.15m/s or 0.1m/s); mean radiant temperature equal to air temperature, and constant skin temperature and wettedness. However, wettedness is not always constant for equal skin temperatures. Moreover, equal skin temperature loci are not straight on the psychrometric chart in hot conditions, if equal skin temperature indicates equal thermal sensation. Mochida described a thermal sensation chart in which the equal skin temperature loci are curved rather than straight lines (15).

Tanabe et al(16) proposed Modified Temperature defined as: the air temperature at 50 % relative humidity, 0.1 m/s mean air velocity; 0.6 clo clothing insulation value; 1 met metabolic rate and mean radiant temperature equal to air temperature. These conditions provide the same thermal sensation as under the actual thermal conditions was used for data analysis based on Fanger's comfort equation (17). Tanabe et al conducted experiments using Japanese students as subjects and compared their results to U.S. and Danish experiments using the modified temperature as described above. Linear regression analysis showed that the regression line for Japanese subjects was similar to the one for U.S. subjects. The effects of sweating or humidity at high temperatures and relative humidity are considered by this index, whereas Fanger's equation (17) only accounts for sweating under comfortable conditions.

Horikoshi et al (18) attempted to indicate the separate effect of the four variables based on the human heat balance equation. The temperature index, HOTV, is expressed as the sum of the air temperature, plus the effective temperature difference (with respect to the air temperature) caused by the thermal velocity field(TVF), effective radiant field(ERF), and the reduced-effective humid field(RHF), that is the quantities that correspond to air velocity, thermal radiation, and humidity, respectively. By using these indices, we can learn both the combined and individual effects of the four thermal environmental variables - air temperature, velocity, thermal radiation, and humidity - on the human body.

Finally, Tanabe (19) proposed that thermal environment should be evaluated using thermal manikin, so the actual effect of non-uniform environments could be described.

EFFECT OF EACH THERMAL ENVIRONMENTAL VARIABLE

Effect of Air Movement

A number of studies investigating the effects of non-uniformity, fluctuation and air turbulence on psychological and physiological responses have been carried out. Isoda et al (20) exposed clothed subjects to six kinds of fluctuating air with equal mean velocity. They found unique comfort envelopes for different combinations of air fluctuation. Further studies are expected to obtain a predictive index for the cooling power of fluctuating air.

Another group (21) have investigated the effects of sine and triangle wave shaped air fluctuations, with equal mean velocity. Subjects reported cooler sensations for air movements that had high turbulent intensity, than air movements having low turbulent intensity. Mean skin temperature rose in summer experiments whenever turbulent intensity was high. They suggested that frequency analysis of air movements should be used in addition to mean air velocity and turbulent intensity.

Some investigators have examined the influences of local and non-uniform air movements as a stimulus to thermal and dynamic subjective effects (22,23).

In the summer most Japanese use cross ventilation to control the climate indoors. Ishii et al(24) investigated the cooling effect of cross ventilation in a suite of high-rise apartment houses. They reported that indoor PMV can be convertly derived from the ambient conditions.

Air Temperature Distribution

Spatial air temperature distribution can affect thermal comfort. Ito et al (25) recommended that air temperature distribution be indicated by standard deviation from the design temperature, rather than the actual mean temperature in an occupied zone.

Imagawa et al (26) obtained comfortable conditions when the upper and lower parts of the body were separately exposed to different temperatures. The most comfortable condition was 20/26 °C upper/lower air temperature for males, and 23/26 °C for females. The acceptable temperature differences between the upper and lower parts of the body are 4 °C for higher upper temperature and 6 °C for higher lower temperature. These results have implications for the design of personal air-conditioning systems.

Effect of Thermal Radiation

Non-uniform and asymmetric thermal radiation fields can induce discomfort. Nakamura (27) discussed direction and quantity of thermal radiation using vector radiant flux, and developed a measuring instrument consisting of 6 pairs of black and silver heat flow meters on each surface of a cube. This instrument measures directional mean temperartures and directional radiant heat flux on every surface of the cube. Horikoshi et al (28) described the effects of asymmetric thermal radiation fields using partial mean radiant temperature based on angle factors for a rectangular solid as a model of the human body, and verified this in experiments. Horikoshi et al found that subjects sometimes reported cool sensations and sometimes warm sensations when exposed to an asymmetric radiation field with thermal-neutral operative temperature.

Another important issue is the influence of floor heating systems, because Japanese often sit on the floor. Most experiments aim to specify the optimal combination of floor and air temperatures(29). Oyama et al (30) exposed subjects to floor heating for four hours in a Japanese-style house. The optimal condition was 25.5/20 °C floor/air temperature: subjects reported "hot" at 29/22.5 °C floor/air temperature. Choi et al (31) focused on heat conduction between the human body and the floor. The operative temperature and mean skin temperature were modified and applied to take into account the effect of conduction heat exchange. These indices correlated with each other. Tsuchikawa et al (32) investigated the effect of the thermal environment on the naked standing people. All previous studies of naked subjects used sedentary positions. They found that skin temperatures on the anterior thigh were lower when standing than when sitting, for identical ambient conditions.

PSYCHOLOGICAL ASPECT

Many researchers have used ASHRAE or Bedford's seven point scale to measure subjective responses. However, the scales "cool" and "warm" cannot be exactly translated into Japanese: the corresponding Japanese words "suzushii" and "atatakai" mean cool and warm with pleasantness; in Japanese. "comfort" and "pleasantness" are sometimes confused, even though these are different words for each (comfort-Kaiteki, pleasantness-Kaikan). Horikoshi(33) reviewed the definition of "thermal comfort" and pointed out that standardized definitions are essential for research progress. Kuno et al (34) described a model that explains the relations between each sensation including "suzusii (slightly cool with pleasantness)" and "atatakai (slightly warm with pleasantness)" in Japanese, and have conducted experiments to verify the model. Matsubara (35) raised similar questions about the definition of "pleasantness" and "comfort", two concepts which are ubiquitous in the comfort research.

The ASHRAE seven point scale is an ordinal scale, although McIntyre (36) explains that it can be seen as an interval scale. Tsuchikawa et al (37) reviewed the rating scales for thermal sensation, comfort and pleasantness; they pointed out the necessity of examining all scales and proposed a graphical line as an interval scale. Nishi (38) advocated the used of standardized thermal sensation scales. Emura (39) discussed how to transfer a nominal or ordinal scale to an interval scale, and how to map physical variables onto a psychological scale. Several models were proposed, i.e. multinomial selection model, possible distribution model, and dynamic system model. Their application to thermal comfort studies are reported. Although the multinomial selection model can be built up, it is not easy for this model to map subjective data onto continuous numerical set.

There are also a few studies investigating the influence of the thermal environment on human performance. Horie et al (40) had subjects perform single figure addition, and found that performance was lowest at 30 °C; subjective evaluation was best at 22 and 26 °C and worst at 34 °C. This means that thermal or comfort sensations are not always consistent with human performance.

FLUCTUATING ENVIRONMENT AND EFFECT OF TIME

Exposure time is another important variable which effects human response. Few dynamic analysis of thermal comfort or human responses have been attempted. Horikoshi et al (41) and Horie et al (42) estimated the impulse responses of skin temperature and thermal sensation to air temperature excitation using Fast (Discrete) Fourier transformation. Those works were carried out under the assumption that the human thermal response system is linear as the first approximation. Weighting functions relating skin temperature and thermal sensation vote to ambient temperature were calculated using Fast Fourier Transformation of step-wise increase or decrease in ambient temperature. Emura (43) carried out non-linear analysis of the same phenomena using Volterra's functional. Ohkura et al (44) and Ohno (45) studied the effects of linear increases in ambient temperature on skin temperature and thermal sensation: Ohkura et al obtained interesting data but were unable to successfully analyze it, whereas Ohno et al found seasonal differences in rate of skin temperature changes and subjective ratings "ryo-dan (cool- warm)". Kajii (46) developed a new globe thermometer with high rapid response ability to measure fluctuating environment.

FIELD SURVEY AND PRACTICAL APPLICATION

Kobayashi et al (47) and Naruse et al (48) made extensive Post Occupancy Evaluation (POE) of offices, factories and schools, and proposed thermal comfort envelopes based on the results of these studies. The comfort zone in these studies is slightly higher than ASHRAE comfort zones for both air temperature and relative humidity. Many POE surveys have begun to evaluate the working combined influences of air quality, lighting, sound, color and space (49). Sawachi et al (50) analyzed temperature regulation in residential houses using questionnaires and behavioral measures. Other researchers are collecting examples of behavioral indoor climate control to clarify the interaction between the physical environment and everyday behavior (51,52).

Numerical analysis of indoor climates have been conducted to design comfort heating/air-conditioning systems(53,54). These studies include numerical calculation of air temperature distribution, air movement and thermal radiation exchanges and the prediction of comfort.

COMBINED EFFECTS

Sakurai et al(55) studied the combined effect of temperature, illuminance and noise on subjective discomfort using a psychological non-specific scale. They expressed discomfort by the linear combination of these three environmental factors. A method to predict the combined effect of the three environmental variables was also proposed (56). Nakahara et al (57) studied the effect of color on subjective perception. When air temperature changed from cool (18 °C) to neutral(26 °C), the phenomena corresponding to the "hue-heat" hypothesis (61) were observed. Thermal comfort in hyperbaric and hypobaric environment has also been investigated: Kakitsuba et al (58,59) investigated heat transfer between the human body and its surroundings, and human psychological and physiological responses, in helium hyperbaric environment; Ohno et al (60) exposed subjects to equivalent air pressures of altitude up to 4000 m and examined the effects of air pressure and temperature on skin temperatures and thermal sensation.

CONCLUSION

Investigators have examined the effects of air movement on thermal comfort to maximize energy savings at high air temperatures. The effects of non-uniformity and fluctuation of environmental variables have also been studied, to optimize the design of personal air-conditioning systems. Studies of thermal comfort indices based on human heat balance equations have also been conducted. Future studies will reveal the combined effects of heat and other factors, e.g. light, sound or air quality.

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