State and Prospects of Natural/Cross Ventilation Research in TPU

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ABSTRACT: This paper reports results of physiological and psychological research on human subjects in a cross-ventilated environment at Tokyo Polytechnic University. The physiological concept of alliesthesia relating to cutaneous thermoreceptors has become an increasingly important issue recently. The cross-ventilated environment showed very different characteristics to a stagnant environment. In a recent human subject study using a climate controllable wind tunnel, it was found that the spectral peak frequency of skin surface temperature and sweat rate corresponded closely with the spectral peak frequency of sinusoidal wind flow in the range between 0.02Hz and 0.2Hz. The physiological thermoregulation models of a 2-node model and a 65-node model were modified taking into consideration the evaporative heat loss by diffusion in the cross-ventilated environment. The skin surface temperature could be predicted with high accuracy in the cross-ventilated environment. An experimental regression formula on pleasant sensation was proposed and could accurately predict the tendency of time history of pleasant sensation.

KEYWORDS: Cross-ventilation, Physiological characteristics, Human body, Thermoregulation model, Pleasantness, Climate controllable wind tunnel

1. INTRODUCTION

Confronting the problem of energy shortage currently being experienced around the world, together with the ever-increasing threat of extreme weather events, for instance long periods of abnormally high temperatures, there exist various impacts on community cohesiveness, long-term economic values, biodiversity, and especially human physiological comfort, health and well-being. Every year, the occurrence of heatwave events, prolonged periods of excessively hot weather, has resulted in increased loss of life in Japan. Since the Fukushima accidents in 2011, the nation has been facing a severe electricity shortfall in the summer as seasonal demand rises. The heatwave incident in July 2012 resulted in the loss of life of 39 at home, and over 21,000 people were taken to hospitals due to heat stroke. Increasing temperatures are likely to increase deaths from heat-related illnesses such as heat cramps, heat exhaustion and heat stroke. Higher temperatures also increase perspiration and evaporation. Older people's thirst responses decrease with age and involuntary dehydration increases. Thus, the elderly are most at risk and often account for a large number of fatalities from heat stroke.

Making good use of the natural resource of wind to induce ventilation can be an attractive way to combat the problems of energy shortage and hot weather (Lun, Ohba 2012[1]). Increasing the availability of adequate natural ventilation not only minimizes energy use and cost in buildings, but also allows occupants to enjoy better indoor environmental quality and maintain or maximize a healthy, comfortable, and productive indoor climate. This paper reports results of research conducted by the Environmental Group of the Wind Engineering Research Center at the Tokyo Polytechnic University on human physiological and psychological responses in a cross-ventilated environment. It includes a concise introduction to the physiological characteristics of the human body in a cross-ventilated environment, a brief review of various experimental and numerical studies on human thermoregulation, and finally focuses on results obtained from human subject tests and numerical simulations.

2. CLIMATE CONTROLLABLE WIND TUNNEL FOR HUMAN RESPONSE STUDY

The human body is a very complex system and its responses to extreme events such as hot or cold are still fraught with uncertainties. Research investigation directly using human subjects in real environments is still lacking, especially in non-uniform and transient indoor environments, and thus reliable data from human subject tests are necessary. More efforts are needed to strengthen the understanding of the relationship between naturally ventilated environments and human thermal responses, and to gain important knowledge of how the human thermoregulation system responds to different environmental conditions.

A climate controllable wind tunnel was constructed in 2009 in order to systematically investigate the relationship between natural wind fluctuations and human physiological/psychological responses. Figure 1 shows its layout. The complete controllable wind tunnel houses a test room 3.7m (wide) × 8m (long) × 2.7m (high), a pre-function room and a fan room, as shown in Figure 2. The airflow generator installed in the fan room comprises 48 plug fans driven by 400W AC motors to increase the capability of sudden acceleration/deceleration. One air-conditioning machine, which can supply airflow at 14000m^3/h and provide cooling load and heating load of 35 kW and 20 kW, respectively, was used to prevent temperature drift of supply air occurring when several air-conditioning machines were used. In addition, an electric steam humidifier was used. The air-conditioning system can control air temperature from 20 to 35^{0}C ±0.5^{0}C, humidity from 40 to 70% ±2% and wind velocity from 0.1 to 2.0 m/s (Mizutani et al 2010[2]). The maximum velocity was determined from field subject experiments in a detached house, which showed that the comfortable maximum speed for subjects was 2m/s in early summer.

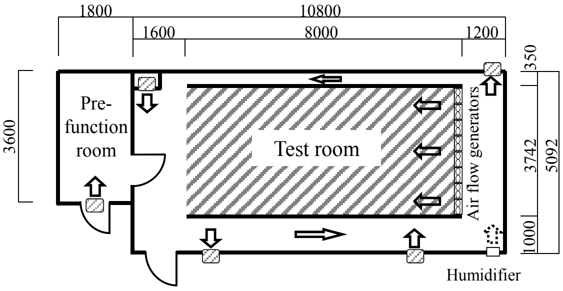

Figure 1. Overview of climate-controllable wind tunnel

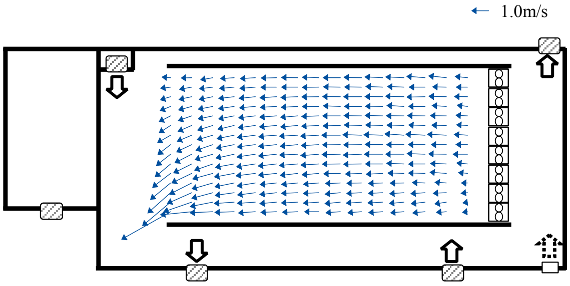

Figure 2. Horizontal plane distribution of the wind velocity of test room

3. PHYSIOLOGICAL CHARACTERISTICS OF HUMAN BODY IN CROSS-VENTILATED ENVIRONMENT

3.1 *Physiological Characteristics on Human Body*

For many decades, human biometeorology has been an important topic in assessing the effects of the thermal environment on thermal comfort and on the thermal state of the body generally. The human body is an extremely complicated fluid/thermal system. It is physically complex, involving skin, tissues, blood flow, etc. Skin is the outer covering of the body and it is the physical separator between the body's interior structure and the exterior environment. It is reported that skin temperature studies have been the major topic among a consortium of medical institutions in America since 2000 (Harvard Catalyst 2012[3]). The key role of skin is to protect the body against pathogens and to minimize unnecessary water loss as well as to maintain homeostasis. In hot conditions, it aids the body in regulating its own temperature through radiation, convection, conduction and evaporation. In addition, the sweat glands excrete sweat and the evaporation of sweat from the skin surface acts as a cooling agent to regulate body temperature and prevent heat-related illnesses such as heat stroke.

The skin is the largest organ of the human body and one of its most important. It contains thermal sensors that participate in thermoregulatory control. The thermal sensors affect the person's thermal sensation and comfort, from hot to cold, and vice versa, and all the minute variations in between. Thus, skin temperature monitoring is an essential component when estimating thermoregulatory responses due to heat exchange at the skin surface.

3.2 *Characteristics of Sweating and Skin Temperature in Cross-Ventilated Environment*

To clarify the influence of frequency of fluctuating airflow on mean skin temperature and sweat rate, which indicate the body's physiological response, human subject experiments were conducted in the climate controllable wind tunnel. Sinusoidal and uniform wind flows were produced inside the test room by adjusting the frequency of the sinusoid wave while keeping air temperature at 32ºC, humidity at 70% and air velocity at 0.4 m/s (Morikami, Ohba 2011[4]).

Figure 3 shows the power spectrum of sweat rates on the forehead/chest and wind velocity. The sampling frequency of sweat rate was 1Hz so that Nyquist frequency was 0.5Hz. It was found that the spectra of sweat rates comprised several sweating waves. In particular, the spectral peak frequency of sweat rate showed a high power component at the sinusoidal frequency of the produced wind velocity. Figure 4 shows the power spectrum of skin temperature on the chest and wind velocity. The spectral peak frequency of skin temperature corresponded closely with the spectral peak frequency of the sinusoidal wave flow.

From the results of the subject experiments, the spectral peak frequency of skin surface temperature and sweat rate corresponded closely with the spectral peak frequency of the sinusoidal wind flow in the range between 0.02Hz and 0.2Hz. The sweat evaporation rate was higher in the low-frequency range than in the high-frequency range, showing that the cross-ventilated airflow had physiological influences on the human body.

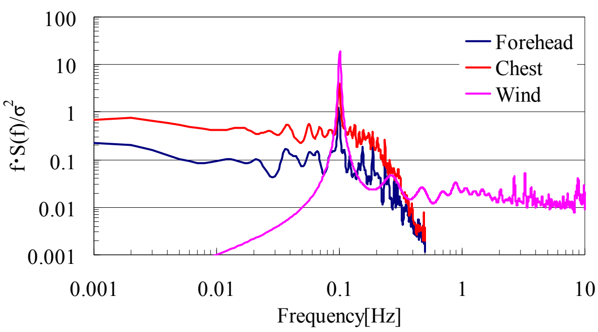

Figure 3. Power spectra of sweat rate on chest/forehead and wind velocity

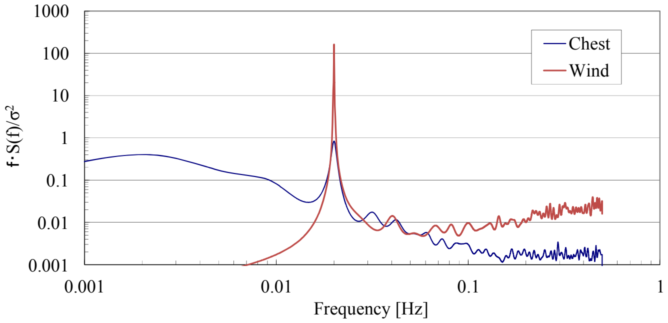

Figure 4. Power spectra of skin temperature on chest and wind velocity

3.3 *Coefficients of Convective Heat Transfer on Human Body*

Coefficients of convective heat transfer on the human body are important for predicting/evaluating the effects of airflow on thermal comfort. It is known that they take different values depending on the airflow around a heat dissipator, its shape and size, and other factors. They are also key indicators for evaluating/predicting thermal comfort.

Convective heat transfer coefficients were measured for sitting postures of human subjects and a thermal manikin under sinusoidal wave flow conditions (Morikami, Ohba 2012[5]). Figure 5 and 6 show that they slightly decreased when the sinusoidal wind flow frequency decreased. The physical cause will be investigated by CFD analysis in future, because it is thought that the length scale of airflow may influence the development of the boundary layer at the skin surface.

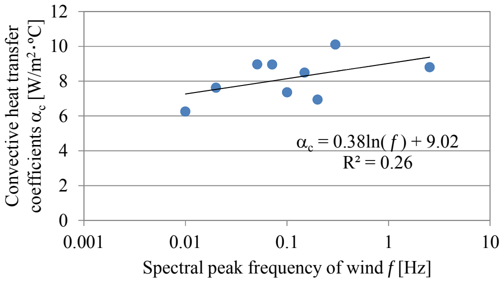

Figure 5. Relationship between convective heat transfer coefficients and peak frequency of sinusoid wave flow in human subject

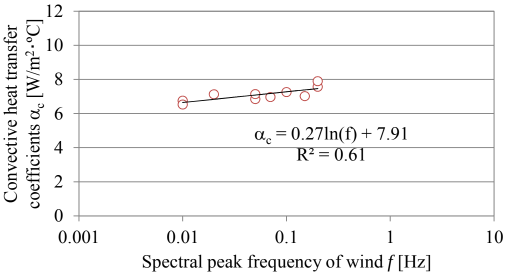

Figure 6. Relationship between convective heat transfer coefficients and peak frequency of sinusoid wave flow in thermal manikin

4. PHYSIOLOGICAL THERMOREGULATION MODEL

4.1 *Human Physiological Thermoregulation Model*

(1) Review on Physiological Thermoregulation Model

The European Renaissance in the 14th century brought an increase in experimental investigation, mostly in the field of dissection and body examination, thus advancing our knowledge of human medicine and ergonomics. Brotton (2006[6]) stated that the important development of the Renaissance was not any specific discovery, but rather the further development of the process for discovery, the scientific method that focused on empirical evidence and the importance of mathematics. The new scientific method led to great advances in fields such as biology, anatomy and medicine. Besides, the invention of the thermocouple by Thomas Johann Seebeck in 1821 paved the way to the study of body temperature. The invention of short clinical thermometers in 1866 by the British physician Sir Thomas Clifford Allbutt led to the scientific, quantitative study of thermoregulation. For instance, Lefevre (1911[7]) used thermocouples to measure the thermal topography of the body and described whole animal and human calorimetry for determining metabolic rates.

Since the beginning of medical research, scientists have been most concerned about physiological systems and their applications. They have tried to find the most accurate model of the human temperature regulation system for simulating reactions to different environmental conditions. Table 1 shows the process of human thermal system modeling over the years. It should be noted that the list of references in this table can by no means be considered complete, but it gives an indication of cutting-edge research in human thermophysiological modeling.

(2) Modification of Two-Node Model for Cross-Ventilated Environment

The first two-node model was proposed by Gagge et al (1971[8]). The model subdivided the human body into two layers: skin and core, where energy balance equations of these compartments were derived to evaluate thermal sensation of the body. The two-node thermal sensation transient model is employed in thermal comfort standards of ASHRAE and ISO7730.

In the thermal stagnant environment, by using the climate controllable wind tunnel, it was confirmed that mean skin temperature in thermal-transient conditions of a stagnant environment could be predicted by modifying the human thermoregulation coefficients of sweat rate and evaporative heat loss of diffusion of the 2-node model.

In a cross-ventilated environment produced by step-wise changing of wind velocity, the accuracy of skin temperature prediction by the 2-node model deteriorated, as shown in Figure 7. Figure 8 shows the relationship between maximum evaporative potential and evaporative loss by diffusion through the skin from subject experiments. Regardless of wind velocity, evaporative heat loss by diffusion was kept constant. However, the two-node model showed that the evaporative heat loss by diffusion was 6% of the maximum evaporative heat loss, which is a function of wind velocity. We modified the sweat rate and evaporative heat loss by diffusion of the 2-node model. As shown in Figure 7, the time history of mean skin temperature in thermal-transient conditions in a cross ventilated situation could be predicted with high accuracy.

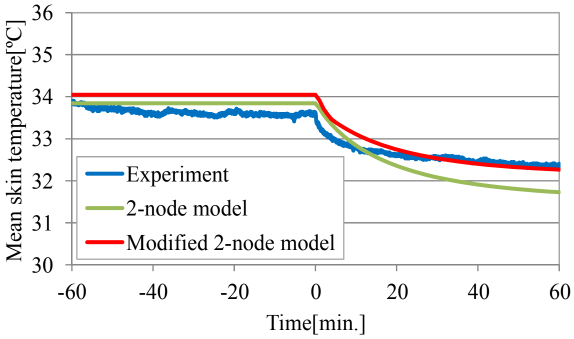

Figure 7. Comparison of measured and predicted skin temperatures in cross-ventilated environment

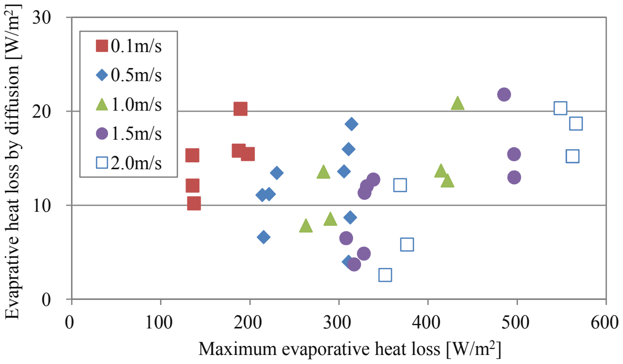

Figure 8. Relationship between maximum evaporative potential and evaporative loss by diffusion through skin from subject experiments

4.2 *CFD Physiological Thermoregulation Model*

(1) Review on CFD Physiological Thermoregulation Model

It can be seen that scientists, for decades, have used different types of models to represent and explain physiological functions in order to improve our understanding of the body's response to various conditions. Human temperature regulation system models have taken many forms: verbal, pictorial, mechanical, neuronal, and mathematical. Mathematical models became popular in the 1930s when the first programmable computer was invented. Mathematical models of the human thermal system have developed from easy to more complex ones by using a variety of linear and nonlinear equations, differential equations, integrals, trigonometric functions, and combinations of these functions. However, due to the natural complexity of human thermoregulation, it has been difficult to determine the accuracy of these models. In addition, quantitative comparisons among models are also difficult due to the individual characteristics of each model under particular environmental conditions (Haslam and Parsons, 1989[9]; Crandall et al, 1994[10]). Thus, it is unclear which of the models would be best suited to a particular environment and application. In recent years, human thermophysiological studies with computational models in virtual environments have been seen as a new way of evaluating and simulating the influence on human beings, as shown briefly in Table 2.

(2) Modification of 65-Node Model for Cross-Ventilated Environment

CFD simulation was done by the 65-node model, which was developed by Tanabe (2002[11]). This model, based on the Stolwijk (1971[12]) multi-node model, is a physical model based on heat balance equations for individual body parts. Its inputs include age, sex, basal metabolic rate, and fat rate. It considers thermal conductance between tissues, the detailed vascular system, and the thermoregulatory system consisting of perspiration, vasomotion, shivering heat production, arterio-venous anatomies, etc.

The Launder-Kato-modified linear low-Reynolds-number k-ε turbulence model was used in this study. The QUICK scheme was applied to deal with the convection term of the equations and the SIMPLEC algorithm was used to control the pressure-velocity coupling. The first cell was 0.2 mm from the surface and the y^+ value was equal to 1. In this fine grid region, five layers were set with a change of thickness ratio of 1.1.

In order to verify the skin temperature and skin wettedness predicted by the modified 65-node model, the subject experiment was carried out 10 times in the climate controllable wind tunnel. The subjects were in a standing posture and they wore trunks with 0.03 clo. In these 10 tests, only young male persons were investigated. The air temperatures of the room were set at 32°C. The wind speed was kept at 1.0 m/s and blew from the front of the subjects.

Figure 9 shows the results of CFD analysis. The 65-node model predicted that the surface temperatures at chest and back were around 2.5 to 3°C lower than the subject experimental results. This is because the evaporative heat loss by diffusion was over-predicted in the cross-ventilated environment. We modified the evaporative heat loss by diffusion using the regression equation obtained from the subject experiment. The modified 65-node model increased the prediction accuracy of skin temperature.

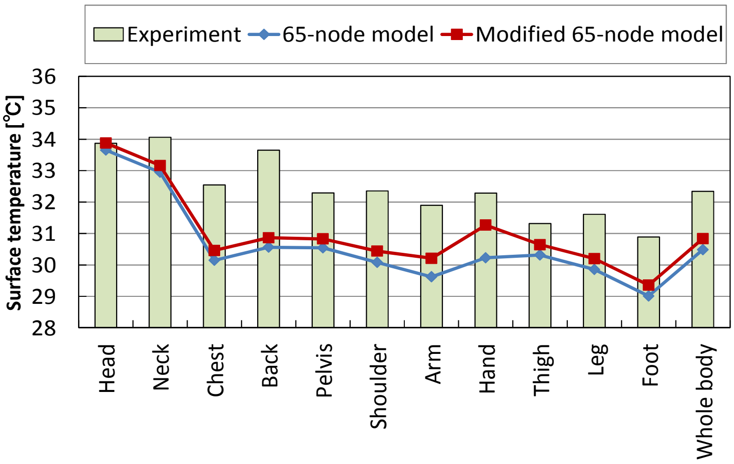

Figure 9. Prediction accuracy of body skin temperatures at 32°C in early summer environment by modified 65-node model

5. EXPERIMENTAL PREDICTION OF PLEASANT SENSATION IN CROSS-VENTILATED ENVIRONMENT

(1) Review on Thermal Comfort and Pleasant Sensation

Thermal comfort indexes were proposed by Fanger and Gagge et al. in 1984 and 1986, respectively. The PMV index of Fanger was adopted by the ISO7730 (1984[13]). It was derived from subject experiments in a stagnant environment, and succeeded in directly combining the heat balance of the human body with the thermal comfort vote. This index is being used worldwide because of its easy measurement and innovative idea. However, the comfort equation can only be established in a stagnant environment and not in a cross-ventilated environment (Fountain et al. 1994[14]).

Richard de Dear et al (1998[15]) suggested the Adaptive Model, which takes into consideration the effect of natural ventilation on human comfort. The Adaptive Model indicates that the indoor thermal comfort zone changes according to outside air temperature, if behavioral thermoregulation such as clothing adjustment or window opening by residents can be allowed to improve the indoor thermal environment. However, the influences of cross-ventilation on thermal comfort have not been quantitatively analyzed. Therefore, it is thought to be difficult to derive a universal thermal environment index that includes the evaluation of transient thermal comfort on cross-ventilated environments.

Cabanac (1981[16]) defined “pleasant sensation” as a positive comfort against comfort that is regarded as a lack of discomfort in steady state proposed by Gagge et al. A pleasant sensation index for the thermal environment has not been established yet. Pleasantness occurs when there is a sudden change from a discomfort environment to a neutral environment. Kuno (1987[17]) has investigated a pleasantness of a thermal comfort environment by subject experiments. However, a predictive method for determining pleasantness is not yet established. Nagano et al (2005[18]) investigated the unsteady-state thermal environment by using the movement of human subjects outside and inside rooms, and reported that the transient thermal sensation in unsteady-state could be well predicted by using an experimental regression formula based on mean skin temperature. Pleasantness achieved by cross-ventilation can improve the comfort sensation of a residential environment.

(2) Experimental Regression Formula for Pleasant Sensation in Cross-ventilated Environment

Air temperature was kept constant at 28°C during the experiment, while wind velocity was changed step-wise from 0.1 m/s to 1.0 m/s. Figure10 shows the time history of the psychological response of a subject. Cold-hot sensation showed variation between “slightly hot” and "neutral" in Phase 1 and "neutral" in Phase 2 for wind velocities of 0.1 m/s and 1.0 m/s, respectively. The thermal comfort sensation showed “neutral” in Phase 1, and it was kept approximately constant at “slightly comfort” in Phase 2. However, the time history of pleasant sensation showed a different transient tendency with the cold-hot and thermal comfort sensation. Pleasant sensation showed “pleasant” for a short time in Phase 2 after the wind velocity was changed step-wise, but it to "neutral" with time. While pleasantness was occurring, comfort sensation moved to a more comfortable level.

The phenomenon that pleasantness decreases with time was approximated by an exponential function. Mean skin temperature and a differential mean skin temperature as explanatory parameters were selected to correlate the psychological response with the physiological response in this subject experiment.

Figure 11 compares the time histories of pleasant sensation of prediction and experiment. The pleasant sensation values were averaged by three subjects. The predicted pleasantness was slightly lower than the experimental pleasantness from the time just after the step-wise change of wind velocity. The tendency of time history of pleasant sensation could be predicted with an accuracy within a standard deviation of 0.08 (Morikami,Ohba 2013[19]).

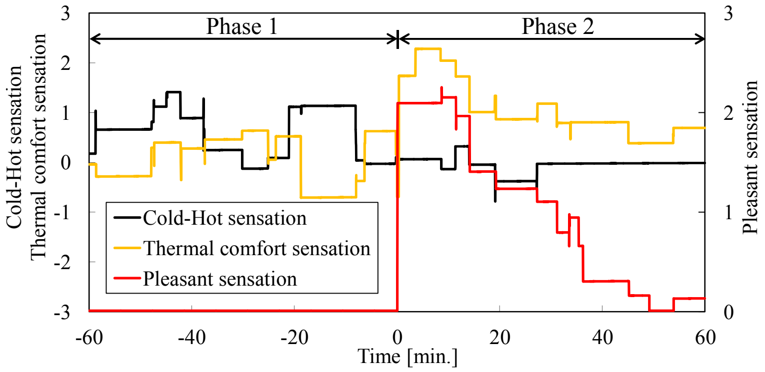

Figure 10. Time history of the psychological responses of a subject in cool-biz environment

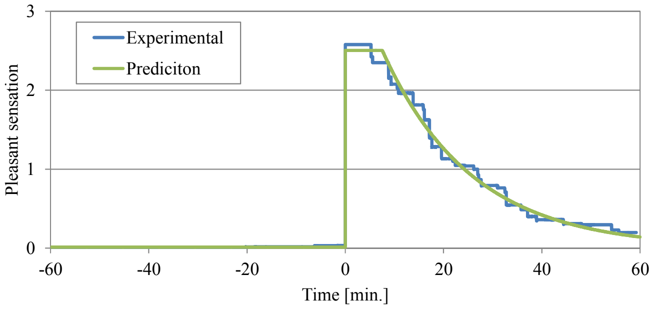

Figure 11. Comparison of time history of pleasant sensation of prediction and subject experiment

6. FUTURE PROSPECTS IN NATURAL/CROSS VENTILATION

Today, environmental concerns have increased and sustainable design has become more desirable. Hence, natural ventilation has become the preferred system for meeting occupants' requirements. The energy used by natural ventilation is minimal. It thus enables considerable cost savings through reduced construction costs as well as maintenance and running costs. It can also help alleviate the prevalence of indoor air quality (IAQ) problems in buildings, such as sick building syndrome (SBS) and concentration rates. Decreasing cooling demand improves comfort conditions and reduces indoor pollution levels, and these are problems that have direct impacts on human beings. It is necessary to take immediate action to seek a solution before it is too late. It is a real challenge for building designers, architects, engineers and researchers to present the possibilities of alternative cooling and ventilation strategies.

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Table 1 Physiological thermoregulation models

Models	Authors	Description	Remarks
Verbal:	Ott (1887)	Studied the heat center in the brain from the concept of thermotaxiccentre which composed thermogenic, thermoinhibitory, and thermolytic centers involved in temperature regulation.	The brain was identified as important in temperature regulation on warm-blooded animals
	Rubner (1902)	Showed the difference made by a protecting layer of adipose tissue on animals when thin has a much higher metabolism at various temperatures than when fat.	First to relate the first law of thermodynamics to animal metabolism.
	Barbour (1921)	Implanted fine silver tubes into the hypothalamus of laboratory animals to test the effect of heat and cold applied directly to this temperature-responsive region of the brain.	Demonstrated for the first time that the hypothalamus actually functioned as a thermostat.
	Bazett (1949)	Studied two sets of antagonistic functions with separate but integrated centers designated as warm (thermogenic) and cold (thermolytic).	Explained human temperature regulation and used widely in medical schools
Pictorial:	DuBois (1948)	Depicted the neurophysiological components of the temperature regulatory system and its connection to the control elements, sweat glands, blood vessels, and skeletal muscles	The model contained the basic knowledge of what is known today of the neurophysiology of temperature regulation.
	Chatonnet and Cabanac (1965)	Proposed a model which assumed that the motivation for behavioral temperature regulation originated in feelings of discomfort related to central and peripheral thermal stimulation and physiological responses.	This simple model stimulated considerable research in behavioral temperature regulation.
Mechanical: Physical	MacDonald and Wyndham (1950)	A physical analog used an electrical circuit to model temperature regulation that the temperature was represented by electrical potential, and heat flow was defined by the electrical current.	One of the first predecessors to the later analog computer simulations of temperature regulation.
Electrical	Crosbie et al (1963)	An electrical analog constructed to simulate the physiological responses to heat and cold in a nude man by using the basic equations for heat balance and taking into account heat losses by radiation, convection and evaporation.	This model closely predicted steady-state conditions in rectal temperature, skin temperature, metabolic rate, vasomotor state, and evaporative heat loss at rest and during exercise.
Neuronal:	Nakayama et al (1961)	Studied the temperature-responsive neurons in the anterior hypothalamus and preoptic area	Details of inter-neuronal connections of temperature-sensitive units in the preoptic area of the hypothalamus were first outlined.
	Hammel (1965)	Proposed a neuronal model to explain set-point thermoregulation based on a synaptic network encompassing four different types of hypothalamic neurons: i.e., warm-sensitive and temperature-insensitive neurons and heat loss and heat production effector neurons.	This model offered some unique concepts that were not present in other feedback control systems and understanding of the neural counterparts of error comparators, reference signals, and set points.
	Mekjavic and Morrison (1985)	Used stimulus response expressions to predict thermogenesis based on static peripheral, core, and central temperatures and incorporated the characteristics of thermosensitive neural structures of the body.	The model was successful in describing the body's temperature response to environmental changes
Mathematical:	Burton (1934)	Investigated the skin temperature/blood flow relationship using mathematical modeling.	Early mathematical model opened the door to new developments in temperature regulatory research.
	Machle and Hatch (1947)	Applied the physical laws of heat transfer to the analysis of thermal responses of a human body to his environment.	First nonsteady-state model of the core and shell concept using measurements of rectal and mean skin temperatures, respectively.
	Pennes (1948)	Modeled the single element of a human body based on quantitative analysis of the relationship between arterial blood temperature and tissue temperature.	One of the earliest workers to analyze heat transfer in human arm, with the cylindrical concept was introduced.
	Wyndham and Atkins (1960)	Developed a model to predict the transient responses of the human body by approximating the human body by a cylinder which consists of a number of thin concentric shells.	First to introduce a transient model in predicting transient response of human body.
	Wissler (1961, 1964)	Extended Pennes' model of the forearm to obtain the temperature distribution of the entire body.	First multi-element steady-state model of the entire human body, and it widely used for prediction of temperature elevation during hyperthermia.
	Crosbie et al (1963)	Studied a simple proportional regulator which gave effector actions proportional to deviations in the core temperature from a set point and to deviations from the skin temperature from a set point.	First successful computer simulation of human temperature regulation.
	Stolwijk and Hardy	Contributed a simpler 8-node mathematical model based on a simplified config-	These models have become the standard anatomical approach to

	(1966)	uration of the human body but took into account the physiological thermoregulation mechanism.	modeling human temperature regulation, and many other multi-node models were based on these models with significant improvements such as body segments and layers.
	Stolwijk (1971)	Developed a 25-node model of thermoregulation to evaluate local blood flow rate, metabolic rate, evaporation rate.	
	Gagge et al (1971)	Subdivided the human body into two layers: skin and core, where energy balance equations of these compartments have been given to evaluate thermal sensation of the body.	The two-node thermal sensation transient model has been employed in thermal comfort standards of ASHRAE and ISO7730.
	Huizenga et al (2001)	Improved human comfort model from six body segments to unlimited segmentation to assess blood flow, sweating, metabolism and comfort of sedentary human subjects in complex thermal environments.	The model was found to be accurate in predicting blood flow in a wide range of applications and environments.
	Werner and Webb (1993):	Described the basics of a 6-cylinder model of human thermoregulation for use on personal computers	One of the earliest models applicable to water immersion conditions and validated with human data in cold water.
	Kohri and Mochida (2002)	Developed a dispersed two-node model to predict steady-state physiological responses of a human in a vehicle.	This model could give practical precision when considering the environment where radiative heat load was uneven.

Table 2 CFD physiological thermoregulation models

Authors	**Description**	**Features of work**
Gan (1994)	Developed a CFD code for the indoor environment in ventilated rooms. The program produces thermal sensation indices, PMV and PPD for evaluation.	Early use of numerical thermal occupants for assessment of indoor thermal comfort, steady-state airflow simulations, two-equation k-ε turbulence model.
Kato et al (1996)	The flow and temperature fields around a computational manikin and the age of the supplied air as well as the residual lifetime were analyzed by CFD.	Steady-state simulations, low Re k-ε turbulence model, three different positions of the contaminant generation analyses.
Murakami et al (1997, 1998)	Developed a computational thermal manikin on the basis of coupled simulation of CFD, radiation, moisture transport, and heat transfer inside the human body as a new resolution method with regard to thermal sensation.	Physiological model, low Re k-ε turbulence model, coupled simulations, and the dynamic effects of air flow around the body is demonstrated.
Bjorn et al (2000)	Numerical simulation of the effects of respiration measured in displacement ventilated rooms. The model geometry is well-defined geometrical primitives, easy to convert into an accurate virtual geometry for CFD simulations.	Steady-state simulations, RNG k-ε turbulence model with buoyancy effects and second order discretisation scheme, geometry of the manikins with a body fitted, unstructured grid.
Han et al (2001)	Numerical prediction of occupant thermal comfort to support automotive climate control systems by using a model of the human thermal regulatory system based on the Stolwijk 16-segment model.	Ability to predict local thermal comfort level of an occupant in a non-uniform thermal environment as a function of air temperature, surrounding surface temperatures, air velocity, humidity, direct solar flux, as well as the level of activity and clothing used.
Tanabe et al (2002)	Integrated a 65-node human thermoregulatory model with a 3D model of a nude male body in CFD which incorporated radiation heat transfer.	The physiological model uses anthropometric data of an average man; body weight and body surface area, for radiation and CFD analyses, maintaining sufficient accuracy.
Zhu et al (2002)	More complicated unsteady-state simulations taking account of inhalation and exhalation processes	CFD model with a complex shape is used to evaluate the influence of local effects of real human body by low Reynolds number k-ε model.
Nilsson (2004)	Investigated the perceived thermal climate using subject and manikin correlated model. Numerical simulation adopted zero-equation with dynamic boundaries.	Develop a general comfort zone diagram, which is applicable to different manikins and instruments, evaluating different comfort climate situations.
Croooer et al (2009)	Studied the indoor climate with CFD in combination with a detailed thermal comfort model describing the human thermoregulation	Demonstrate the application of the coupled system on heat and moisture transfer at the surface of a human body for naturally ventilated buildings and provide guidelines for modeling CFD and human-environment interactions.
van Treeck et al (2011)	Presented a co-simulation procedure for scale-adaptive indoor thermal climate simulation which comprises a middleware platform for coupling heterogeneous computational codes for distributed simulations.	Provides a framework and a documented class library for weak coupling of heterogeneous computational codes in distributed environments.