Elaboration of a Methodology for Estimating the Effect of Thermal Radiation on the Evaluation of Perceived Comfort in Indoor Spaces

***Tosin Omoya*[1,2], *Denis Bruneau*[1,2], *Thomas Recht*[1], *Aline Barlet*[1,2]**

[1]*Université de Bordeaux, I2M, UMR 5295, 33400 Talence, France*
[2]*École Nationale Supérieure d'Architecture et de Paysage de Bordeaux, I2M, UMR 5295, 33405 Talence, France*
Mél. : tosin.omoya@u-bordeaux.fr

RÉSUMÉ : L'objectif de cet article est de proposer une méthodologie pour aborder la relation entre les rayonnements thermiques de l'environnement et l'évaluation du confort thermique perçu par les occupants et leur comportement psychologique correspondant lorsqu'ils expérimentent ces conditions de confort physique. Dans ce but, un bilan thermique de l'individu est considéré simultanément avec le modèle de vote prédictif moyen adaptatif (aPMV) de Yao et al. afin de prendre en compte l'adaptation humaine concernant son évaluation du confort thermique. Une approche expérimentale, où les sujets sont soumis à différents stimuli thermiques de l'environnement, est alors proposée afin d'identifier les facteurs psychologiques qui gouvernent cette adaptation au confort perçu, de manière à caractériser, voire améliorer, la description de l'adaptation de Yao et al.

MOTS CLÉS : rayonnement thermique, confort thermique perçu, facteurs psychologiques

ABSTRACT: The aim of the present paper is to propose a methodology to address the relationship between environmental thermal radiations and the perceived thermal comfort evaluation of occupants and their corresponding psychological comportment when they experience this physical comfort conditions. For this purpose, an individual heat balance is considered simultaneously with the adaptive predictive mean vote (aPMV) model of Yao et al., in order to take into account human adaptation regarding to his thermal comfort evaluation. An experimental approach, where subjects are experiencing various environmental thermal stimuli, is then suggested to identify the psychological factors that govern this adaptation regarding to the perceived comfort, so as to characterize or even enhance the Yao et al. adaptation description ("black box" model).

KEYWORDS: thermal radiation, perceived thermal comfort, psychological factors

1. INTRODUCTION

Thermal comfort is defined by ASHRAE Standard 55-92 as *"the condition of mind that expresses satisfaction with the thermal environment"*. This definition depicts that thermal comfort is the satisfaction validated by the mind due to the perceptions of the human body when he experiences the impact of his physical environment. Brager et al. (2003) argued that comfort is not just an outcome of the physical environment but a complex perception built out of the intersection between objective stimuli with cognitive and emotional processes. Also Nikolopolou et al (2003) explained that people perceive the environment in different ways, and the human response to a physical stimulus is not in direct relationship to its magnitude, but depends on the 'information' that people have for a particular situation. It is therefore a complex relationship between the *psychological* information and interpretation of perception in the human mind, the *physiological* reactions and sensation of the human body, and the *physical* factors affecting the individual in his environment.

Thus, to be able to define and evaluate thermal comfort in a precise sense, all the factors influencing thermal comfort should be considered, and the complex relationship between the physical and cognitive factors must be accurately modeled. These factors includes (i) the *physical* factors such as air temperature and relative humidity, radiant temperature, air velocity, clothing insulation and metabolic activity level of the occupant, (ii) the *physiological* factors such as the convectional, evaporative and respiratory heat exchange and the heat produced based on the thermoregulatory system of the human body mechanism, and (iii) the *psychological* factors includes the experience, expectation, perceived control, emotion, attitude, habituation, cognition, personal behavior and representation of the occupant and the socio-cultural factors (culture, standard of living and technological advancement of an occupant regarding his living region location and believe). Thus, endeavoring to weigh and quantify the influence and impact of these factors on the human thermal comfort perception and evaluation is an important topic for researchers, because it may improve comfort standards. In the present paper, a methodology that evaluates each of these aspects influencing thermal comfort is proposed, with the objective of delineating the relationship between thermal radiation and the occupant's perceived comfort.

2. STATE OF THE ART

Two kinds of approach exist in contemporary thermal comfort evaluation: heat balance models based on laboratory studies and the adaptive models based on field studies. The heat balance models mainly considered the thermal equilibrium and heat exchange between the occupant body and his surrounding while the adaptive thermal comfort models considered the adaptive behavior of building occupants as a significant component of the thermal comfort evaluation.

2.1. HEAT BALANCE MODELS

In the human body, the internal energy stored in the food is converted into mechanical work and thermal energy through the chemical process of digestion. The relevant quantity that indicates the generation of energy is the metabolic rate φ. When the human body losses heat L to surrounding environment at a rate that is not equal to the metabolic heat φ generated, some involuntary actions are taken by the body to re-establish a stable heat balance with the surroundings. These involuntary actions are known as body thermoregulation. During this thermoregulation process, the individual experiences and perceives some level of discomfort based on the magnitude of the difference between the rate of internal heat generated φ and the heat loss L through the body surface and respiratory ducts to its surrounding environment, involving convection, radiation, evaporative and conductive heat transfer processes. According to the heat balance model, this discomfort continues until thermal equilibrium is reached:

$$\varphi = L \tag{1}$$

where $L = W + \varphi^{conv} + \varphi^{rad} + \varphi^{evap} + \varphi^{cond}$ in which φ^{conv}, φ^{rad}, φ^{evap} , φ^{cond} are the heat losses achieved by convective, radiative, evaporative and conductive exchanges and W is the work done by the activity of the body.

Based on this concept, several heat balance models were developed, such as the Fanger's Predicted Mean Vote (PMV) model that gained popularity and more acceptances since 1970 due to its ability to describe the physiological heat exchange processes of the body into a mathematical representation that is correlated to human thermal sensation votes (TSV) obtained from laboratory physical and sensitive relevant experiments. Fanger carried out this experimental study on human comfort perception, involving a large number of young subjects, with the same activity level and clothing insulation, in air-conditioned chamber in Denmark in the 1970s. He was able to generate a set of equations that establish relationships between the human body sensitive perception and the physical (thermal) factors of his HVAC environment, in the form of a thermal sensational vote on a seven-point scale from "cold" (−3) to "hot" (+3), namely PMV. He also contributed, through a predicted percentage dissatisfied (PPD) index (percentage of people who feel too cool or too warm -people thermally dissatisfied-) to Standard ISO 7730.

However, the Fanger’s results from field studies in warmer climates in buildings without air-conditioning revealed that the PMV model predicts a warmer thermal sensation than the occupants actually feel (Brager & de Dear, 1998). Thus, the ISO 7730, which is based on the heat balance model, was claimed to overestimates the occupant responses on the ASHRAE scale at high temperatures and underestimates them at low temperatures. This is not surprising: field studies in thermal comfort domain often point out that respondents from different climate regions and of different socio-cultural and socio-economic backgrounds have different perceptions of comfort that straddle a large temperature spectrum. This implies that the adaptive quality of the human body is not a passive recipient of thermal stimuli as portrayed by heat balance model, but an active recipient interacting between the person and the environment system via multiple feedback loops. Thus, Fanger PMV model is actually not universal, because of these fundamental discrepancies; therefore a family of “adaptive thermal” comfort model have been developed (see hereunder).

2.2. Adaptive Thermal Comfort Models

The term ‘*adaptation*’ can be broadly defined as the gradual decrease of the organism’s response to repeated exposure to a stimulus, involving all the actions that make this organism better suited to survive in such environment. In the context of thermal comfort, this may involve all the processes that people go through to improve the fit between the environment and their requirements (Nikolopolou et al., 1999). This signifies that people are always interacting and reacting to the condition and state of their environment, both voluntarily and involuntarily, to tend towards achieving comfort for themselves. There are two families of adaptive responses or behaviors developed by humans because of their environment conditions: physical family and psychological family.

A physical adaptation may be reactive and interactive adaptations while the psychological adaptation is usually referred to as an altered perception of, and reaction to, sensory information due to subjective past thermal experiences and expectations (de Dear et al., 2002). Nikolopolou explained that people perceive their environment based on the ‘information’ that they have for a particular situation. Psychological adaptation can be in the form of perceived control, habituation, attitude, personal behavior and evaluation due to psychological factors such as experience, expectations, cognition, emotion, perception and representation.

The adaptive hypothesis states that one’s satisfaction with an indoor climate is achieved by matching the actual thermal environmental conditions, prevailing at that point in time and space with one’s thermal expectations of what the indoor climate should be like (Bragger et al. 1998). Therefore the fundamental assumption of the adaptive approach is expressed by the adaptive principle: if any change occurs such as to produce discomfort, people react in ways which tend to restore their comfort (Nicol et al., 2002). So, on the premises of this fundamental principle, researchers were able to develop models, mathematic correlations and equations that fused some of the adaptive behavior of human into thermal comfort evaluation. Some of these models are based on the thermal correlation between the outdoor temperature and the indoor operative temperature especially for non HVAC building. This method is utilized by the EN15251 standards, but it still lacks the capacity to take into account some psychological adaptation that influences the perceived comfort of occupants.

However, based on the psychological adaptive factor of past experience and expectation of occupants, Fanger and Toftum (2002) proposed an extended PMV model that incorporated an expectancy factor 'e' which depends on how common air-conditioned buildings are present in a region; Thus, an adaptive PMV model (PMVe) was developed by multiplying the value of PMV with the expectancy factors e for warm climate:

$$PMVe = e \times PMV \tag{2}$$

Thus, the value of e depends on the calculations of what is few or many air-condition buildings in a particular region.

To improve on the adaptive comfort evaluation of occupant, Yao et al. 2009 considered the adaptation behavior of occupant by endeavoring to quantify the weight of the influence of some adaptive factors in relation to PMV. He was able to enumerate theoretically that Fanger's PMV was majorly a relationship between the physiological processes of the human body and the physical conditions of his environment, thereby omitting the adaptive and psychological factor influencing the thermal sensational of the occupant. To buttress this, de Dear (1998) revealed that psychologically adaptive self-regulation plays a significant role in determining human thermal sensations based on his research on occupant's thermal comfort in free-running buildings. Consequently, Yao proposed an adaptive comfort model called the adaptive predicted mean vote (aPMV); it is a "black box" model built on the adaptive principle that, if any change occurs such as to produce discomfort, people react in ways which tend to restore their comfort (Nicol et al., 2002). Yao also postulate that, similar to the steady state theory, physiological adaptation is contained within a 'Black Box', but psychological and behavioral stimuli will give an ''Adaptive (negative) Feedback'' (Yao, 1997). This implies that the physiological component (X) that exist in the "black box" (G) responds proportionately to the effect of the load from the physical input factors δ, while the adaptive component (Y) in the "black box" acts adaptively contrary to the value of the physiological perception weighed on a thermal sensational scale. Thus, Yao proposed the following mathematical expression to define this relationship:

$$aPMV = X - Y \tag{3}$$

where the physiological component has been written by Yao as follows:

$$X = G \times \delta = PMV \tag{4}$$

and the adaptive one has been written by Yao by introducing a psychological coefficient K_δ :

$$Y = G \times K_\delta \times aPMV \tag{5}$$

Yao defined the adaptive coefficient η as:

$$\eta = \frac{K_\delta}{\delta} \tag{6}$$

Then Combining equations 3-4-5-6

$$\mathrm{aPMV} = \frac{\mathrm{PMV}}{1 + \eta.\mathrm{PMV}} \tag{7}$$

The Yao's model is thus useful to distinctly evaluate the physiological component (X) and the adaptive component (Y) of this "black box". The qualities of this model validate its suitability to be used to examine the effect and significance of each of the physical factors on the adaptive behavior of occupant. Nevertheless, this model can be enhanced, in order to examine the effect of the psychological factors in the adaptive behavior of occupant, by obtaining the value and significance of the psychological coefficient K_δ.

3. A PROPOSAL OF A COMBINED MODELING-EXPERIMENTATION METHODOLOGY

The adaptive coefficient η was the sole outcome of Yao's experiments and data were obtained from the subjects in the classrooms of Chongqing University. He did not go further to investigate the parameters of the psychological coefficient K_δ and physical input factor δ, which is an important aspect of adaptive behavior and perceived thermal comfort. However, in our case we will investigate and evaluate the psychological coefficient K_δ (and the physical input factor δ) which will be related to psychological behavior of the occupant.

Therefore to complete Yao's model, we chose an expression of the physical input factor or stimuli δ (°C) based on an operative temperature concept (in place of an air temperature concept, used by Yao) in order to take into account the radiative and convective thermal exchange stimuli of the human body from his environment and not only the convective exchanges, but go further to evaluate the psychological coefficient K_δ (°C^{-1}). This is initiated from equation (**7**) above:

where

$$\mathrm{PMV} = (0.303\mathrm{e}^{-0.036\,\varphi} + 0.028) \times (\varphi - \mathrm{L}) \tag{8}$$

and where we choose to detail the human body heat losses L (W/m^2)as follows:

$$L = \varphi_{sk}^{Conv} + \varphi_{net,cl}^{rad} + \varphi_{sk}^{Sw} + \varphi_{sk}^{Diff} + \varphi_{res}^{Conv} + \varphi_{res}^{evap} \tag{9}$$

Where $\varphi_{sk}^{Conv} = F_{cl}h_c(T_{cl} - T_a)$, $\varphi_{sk}^{Sw} = 0.42[(\varphi - w) - 58.15]$, $\varphi_{sk}^{Diff} = 3.05 \times 10^{-3}[5733 - 6.99(\varphi - W) - P_a]$, $\varphi_{res}^{Conv} = 0.0014\varphi(34 - T_a)$ and $\varphi_{res}^{evap} = 1.7 \times 10^{-5}\varphi(5867 - P_a)$

Where F_{cl}= clothing factor, h_c= convective heat transfer coefficient, T_{cl} = clothing temperature, T_a = air temperature, P_a= vapor pressure

Among these thermal losses terms in equation (9), the 1st modeling is a classical one, however in relation with this paper objectives a particular attention has been chosen for the 2nd one (see equation (11), (12)), the 3rd, 4th, 5th, 6th ones are coming from bibliography (Gagge et al 2011, Diana Enescu 2019, ISO 7730:2005).

Thus, in the modeling of the physical stimuli δ in equation (**6**) we chose to consider the following:

$$\delta = \mathrm{T_{op}} - T_{op}^n \tag{10}$$

where the neutral temperature T_{op}^n is the value of operative temperature $\mathrm{T_{op}}$ for which subject feels neither hot nor cold, namely: $T_{op} = T_{op}^n \Leftrightarrow aPMV = 0$

The diagram in Figure 1 describes the actions and reactions of the component of the model of which we chose to consider the *long wave thermal radiation* as a fundamental component of the physical input factor in an indoor environment.

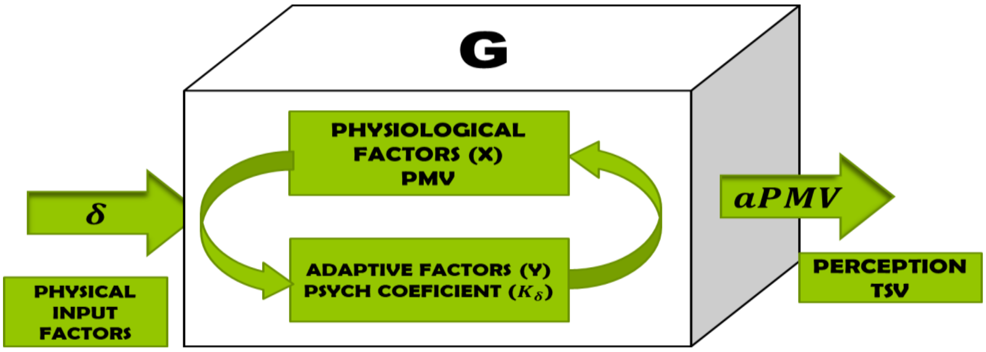

Figure 1: Model Components and reactions

3.1. THERMAL RADIATION MODEL

The long wave thermal radiation will be modeled by evaluating the radiant heat transfer between each surface of the enclosure (experimental room); then the radiant heat transfer between the subject and the surrounding enclosure is evaluated. The first stage of the model requires evaluating the radiosity of each thermal surface of the enclosure. The radiosity of a surface is the sum of the irradiated energy that is reflected by the surface and the radiation emitted by it. The radiosity B_i of each i-surface of a multi-surfaced enclosure which are opaque, gray and of uniform temperature T_i will be quantified via the equations below;

$$B_i = (1-\varepsilon_i)\sum_{j=1}^{n} F_{i-j}\, B_j + \varepsilon_i\left(\sigma T_i^4\right) \quad i=1,\dots,6 \tag{11}$$

where ε_i is the i-surface emissivity and F_{i-j} is the view factor from the i-surface to the j-surface.

We therefore assume that the human body, which surface and volume are not so predominantly relative to the experimental room, does not significantly influence the radiative transfer between the 6 surfaces of the enclosure.

Furthermore, to evaluate the net radiant density of the human body in the enclosure, we calculate the difference between the radiant heat emitted by the human body and the heat absorbed from the radiosity of the wall surfaces:

$$\varphi_{net,cl}^{rad} = \varepsilon_{cl}\left(\sigma T_{cl}^4 - \sum_{i=1}^{n} B_i F_{i-cl}\right) \tag{12}$$

where the subscript “cl” is relative to the human subject clothes.

Note that in equations (6) to (10) above there are 6 unknown variables, namely aPMV, PMV, L, η, K_δ, δ. Thus, obtaining the 6th equation for closure is necessary; this “closure equation” will be obtained by performing experiments, in an indoor environment where the convective and radiative parts of the thermal radiation loads will be adjustable. This equation formulates the relation between the psychological coefficient K_δ, the experimental conditions values and the human subject adaptation.

3.2. EXPERIMENTAL PROTOCOL SCHEME

The experimental strategy and protocol consists in the following steps:

1. setting up the experimental conditions in the experimental cell,

2. evaluation of PMV using measurements and experimental conditions according to Equations (13)&(9),
3. evaluation of the aPMV based on the analysis of the result from the questionnaires,
4. calculation of the adaptive coefficient η according to Equation (7),
5. evaluation of the physical input factor δ by determining the neutral temperature T_{op}^{n} and then evaluating the thermal distance ΔT_{op} from T_{op}^{n} according to Equation (10);
6. evaluation of the psychological coefficient K_{δ} according to Equation (6).

4. EXPERIMENTAL SETUP

The experiments will be carried out in a selected enclosed room of rectangular floor area with a 45 m² floor space and about 100 m³ air volume. In this room, a 2.55 m × 4 m experimental cell was recently built. Each wall of this experimental cell is made of a uniform and conductive surface material (metallic plate which emissivity value at ambient temperature, to be precisely measured, is greater than 0.5 (in order to be efficient in terms of wall radiative generation). The temperature of each surface will be modified by heating and cooling the enclosure externally. A surface temperature sensor is placed over each walls (and floor and ceiling) surface. A meteorology acquisition station is set near the human subject in order to record the air temperature, relative humidity air velocity, and the black globe temperature.

The heating and cooling of the walls will be done to imitate an actual office environment experiencing solar gains from two external walls. Therefore, two walls will be frankly cooled (range from 18 to 0 °C) or heated (range from 28-40 °C) externally, and these temperatures will be modified for each experiment. Concurrently, each subject is allowed in the experimental cell to complete the questionnaires.

The questionnaire is structured to provide information and data for operation 3 in the experimental protocol scheme. The content of the questionnaire does include the thermal sensation votes (TSV) to obtain the value of aPMV. It also includes questions that will provide quantitative values on the evaluation of the physical and psychological adaptation of the subjects: questions related to thermal sensation, preferred perception, comfort level, thermal tolerance, schema, environmental stimulation, thermal acceptability and thermal satisfaction of the subject. The objective is to relate the consistency of changes and trends of the psychological behavior of occupants to the change in the psychological coefficient of the model and consequently calibrate the behavior in parallel to the coefficient derived.

5. CONCLUSION

A methodology for estimating the effect of thermal radiations on the evaluation of perceived comfort in indoor spaces has been proposed. It is composed with an adaptive thermal comfort model that includes the Fanger experimental correlation of PMV in an HVAC environment , and the Yao adaptive approach; in this model, an attentive care about the radiative influence on the body thermal balance has been developed, in terms of radiative modeling and in terms of physical stimuli choice (the operative temperature). The closure equation of this model is researched by developing human perception experimental protocols, the main objective of it being to obtain an expression that governs the relation between the psychological coefficient of the aPMV model of Yao and the radiative exchange and as well as the stimuli experienced by the occupants. The experimental cell is under construction and first phase of the experiments will be driven in summer 2022.

Acknowledgements:

The authors thank the Petroleum Technology Development Fund (PTDF), Nigeria, for the financial support provided for this research.

6. REFERENCE

ASHRAE 55-1992. "Thermal environmental conditions for human occupancy", *American Society of Heating, Refrigerating and Air-conditioning Engineers Inc*.

Brager G. S. and de Dear R. J., 1998. "Thermal adaptation in the built environment: a literature review". *Energy and Buildings*, 27, 83–6.

Brager G. S, de Dear R. J., 2003. "*Historical and cultural influences on comfort expectations*". In Buildings, Culture and Environment: informing Local and Global Practices. Eds: R. Cole, R. Lorch, Blackwell, Oxford, UK, 177-201, 179.

de Dear R and Brager G. S., 1998. "Developing an adaptive model of thermal comfort and preference". *ASHRAE Transact*, 104(1): 1–18.

de Dear R. J., Brager G. S., 2002. "Thermal comfort in naturally ventilated buildings: revisions to ASHRAE standard 55". *Energy and Buildings*, 34(6), 549–61.

Diana Enescu, 2019. "Models and Indicators to Assess Thermal Sensation Under Steady-state and Transient Conditions", *Energies*, 12, 841; doi:10.3390/en12050841

Fanger P.O., 1970. *Thermal comfort analysis and application in environment*. McGraw, Hill New York.

Fanger P. O., Toftum J., 2002. "Extension of the PMV model to non-air-conditioned buildings in warm climates". *Energy and Buildings*, 34,533–6.

Gagge A. P. & Richard R. Gonzalez, 2011. "Mechanisms of heat exchange: biophysics and physiology", *American Physiological Society*. DOI: 10.1002/cphy.cp040104

International Organization for Standardization, 2005. "Moderate Thermal Environments—Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort". 3rd ed.; Standard ISO 7730:2005; *International Organization for Standardization*: Geneva, Switzerland.

Nicol J. F., Humphreys M. A., 2002. "Adaptive thermal comfort and sustainable thermal standards for buildings". *Energy and Buildings*, 34, 563–72.

Nikolopouloua Marialena, Steemers Koen, 2003. "Thermal comfort and psychological adaptation as a guide for designing urban spaces". *Energy and Buildings*, 35, 95–101.

Nikolopoulou M., Baker N., Steemers K., 1999. "Thermal comfort in urban spaces: different forms of adaptation". *Proceedings of the REBUILD 1999 on Shaping Our Cities for the 21st Century*, Barcelona.

Yao Runming, Baizhan Li, Jing Liu, 2009. "A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV)". *Building and Environment*, 44, 2089–2096.

Yao R., 1997. "Study on indoor climate simulation and thermal comfort". PhD thesis. Chongqing Jianzhu University, Chongqing, China.