THERMAL COMFORT INDEX FOR THE ASSESSMENT OF OUTDOOR URBAN SPACES IN SUBTROPICAL CLIMATES

Leonardo Marques Monteiro, Marcia Peinado Alucci
Department of Technology, Faculty of Architecture and Urbanism, University of Sao Paulo, Sao Paulo, Brazil

Abstract

This paper proposes an outdoor thermal comfort index, allowing the verification of urban spaces in subtropical climates. The method adopted is experimental inductive (field research of micro-climatic variables and subjective answers) and deductive (simulations of predictive models). The field research consists of 72 different micro-climatic scenarios and 2150 applied questionnaires. The simulations consider 22 different predictive models. Calibrated interpretative scales are proposed based on the results found. The empirical data is treated through multiple linear regression analysis, providing a simple and easy-to-use empirical equation to be used as predictive model. The results from this equation are compared with those from the calibrated predictive models, showing that they present better correlations with data gathered. Concluding, the methods used provided a reliable thermal comfort index to assess outdoor thermal comfort in subtropical climates.

Key words: outdoor thermal comfort, predictive model, subtropical climate

1. INTRODUCTION

This paper presents a research that proposes a thermal comfort index, allowing the verification of the thermal adequacy of subtropical climates. The method adopted is experimental inductive, with field research of micro-climatic variables and subjective answers, and deductive, with regression analysis of the data gathered. Last, the experimental comparative study of different outdoor thermal comfort predictive models allows the verification of the results. The originality of this paper is to provide a thermal comfort index which can be properly used for predicting thermal comfort in outdoor spaces on the subtropics.

2. BACKGROUND

This study considered twenty-two predictive models and their indexes. They will be here briefly presented in order to perform later correlation of their results with the results of the empirical research.

Houghten et al. (1923), of ASHVE laboratories, propose, the Effective Temperature (ET), as determined by dry and wet bulb temperature and wind speed. Vernon & Warner (1932) propose the Corrected Effective Temperature (CET) substituting dry bulb temperature with globe temperature. Siple & Passel (1945) develop the Wind Chill Temperature (WCT) from the data obtained with experiences in Antarctica. Belding & Hatch (1965) propose the Heat Stress Index (HSI), relying on a thermal balance model with empirical equations for each exchange. Yaglou & Minard (1957), propose the Wet Bulb Globe Temperature (WBGT). ISO 7243 (1989) gives an alternate equation for situations under solar radiation. Gagge (1967) presents the New Standard Effective Temperature (SET*), defining it as the air temperature in which, in a given reference environment, the person has the same skin temperature (tsk) and wetness (w) as in the real environment. Givoni (1969) proposes the Index of Thermal Stress (ITS), which considers the heat exchanges, metabolism and clothes. Originally, it did not consider the radiation exchanges. Masterton & Richardson (1979) propose the Humidex, an index calculated based on air temperature and humidity. It is used by the Environment Canada Meteorological Service to alert people of the heat stress danger. Jendrizky et al. (1979) developed the Klima Michel Model (KMM). It is an adaptation of Fanger's model (1970), with a short wave radiation model, computed in the mean radiant temperature. Vogt (1981) proposes the evaluation of thermal stress through the required sweat rate (Swreq). This index was adopted by ISO 7933 (1989). Dominguez et al. (1992) present the research results of the Termotecnia Group of Seville University, also based on Vogt (1981). The authors accept low sweat rates according to the conditioning required. Brown & Gillespie (1995) propose an outdoor Comfort Formula based on thermal budget (S) with some particularities. Aroztegui (1995) proposes the Outdoor Neutral Temperature (Tne), based on Humphreys (1975) and considering the solar radiation and air speed. Blazejczyk (1996) proposes the Man-Environment Heat Exchange model (Menex), based on thermal balance. The author proposes three criteria, which are supposed to be considered as a whole: Heat Load (HL), Intensity of Radiation Stimuli (R') and Physiological Strain (PhS). He also proposes the Subjective Temperature Index (STI) and the Sensible Perspiration Index (SP). DeFreitas (1997) presents the Potential Storage Index (PSI) and the Skin Temperature Equilibrating Thermal Balance (STE), both using the Menex Model. Höppe (1999) defines the Physiological Equivalent Temperature (PET) of a given environment as the equivalent temperature to air temperature in which, in a reference environment, the thermal balance and the skin and core temperatures are the same of that found in the given environment. Givoni & Noguchi (2000) describe an experimental research in a park in Yokohama, Japan, and propose the Thermal Sensation Index (TS). Bluestein & Osczevski (2002) propose the New Wind Chill Temperature (NWCT), through a

physical modelling of a face exposed to wind. Nikolopoulou (2004) presents the works developed by the project Rediscovering the Urban Realm and Open Spaces (RUROS), proposing the actual sensation vote (ASV).

3. METHODS

3.1. Empirical research

The procedures were done following guidelines and data from ISO 10551 (1995), ISO 7726 (1998), ISO 8996 (1990), ISO 9920 (1995), and ASHRAE (2005). For the measurements and application of questionnaires, three bases were set: the first one under open sky, the second one shaded by trees, and the third one under a tensioned membrane structure. In each one of the three bases, micro-climatic variables (mean radiant temperature, air temperature, air humidity and wind speed) were measured and a hundred and fifty people answered a questionnaire, in six different hours of the day. These people came from different regions of Brazil. Further studies will consider not only the results from acclimatized ones, but also comparatively the results from those who were not acclimatized. The questionnaire considered questions of personal characteristics (sex, age, weight, height), acclimatization (places of living and duration) and subjective responses (thermal sensation, preference, comfort and tolerance). Pictures were taken of everyone who would answer the questionnaire, in order to identify clothing and activity. A forth base, at 10m high, was set for measuring meteorological parameters (global radiation and wind speed). The equipment used in each base was the following. Under open sky: meteorological station ELE model EMS, data logger ELE model MM900 EE 475-016. Shaded by trees: meteorological station Huger Eletronics model GmbH WM918 and personal computer for data logging. Under tensioned membrane structure: station Innova 7301, with modules of thermal comfort and stress, and data logger Innova model 1221. At 10m high: meteorological station Huger Eletronics model GmbH WM921 and a piranometer Eppley. In each base, globe temperature was also measured through 15cm grey globes and semiconductor sensors, storing the data in Hobo data loggers. The measurements were done in intervals of one second, and the storage was done in intervals of one minute, considering the average of measurements.

On the field researches, 72 different micro-climatic scenarios were considered and 1750 questionnaires were applied during summer and winter in the city of Sao Paulo, Brazil. The limits in which the empirical data were gathered are: air temperature (ta) = 15°C~33°C; mean radiant temperature (mrt) = 15°C~66°C; relative humidity (rh) = 30%~95%; wind speed (va) = 0,1m/s~3,6m/s. One may mentioned that, although it is not a limiting factor for normal situations, the maximum and minimum clothing thermal insulation values found were 0,3 and 1,2 clo, with mean values between 0,4 and 0,9 clo. Considering the Typical Reference Year (TRY) for Sao Paulo (Goulart et al., 1988), the ranges presented represent over 90% of the general climatic situations during day time. On the other hand, if it is necessary to make an extrapolation, it must be done carefully and would better be object of further researches.

3.2. Modelling

The multiple linear regression to be presented was obtained considering the data from the seventy-two microclimatic situations, regarding the application of one thousand and seven hundred and fifty questionnaires.

$$tsp = -3{,}557 + 0{,}0632 \cdot ta + 0{,}0677 \cdot mrt + 0{,}0105 \cdot ur - 0{,}304 \cdot va \qquad \text{[Equation 1]}$$

with: r=0,936; r^2=0,875; r^2aj=0,868; se=0,315; P<0,001; *where*: tsp=thermal sensation perception, ta=air temperature [^{o}C], mrt=mean radiant temperature [^{o}C], rh=relative humidity [%], v=air velocity [m/s]

Considering the thermal sensation perception (tsp), following the categories of the applied questionnaires, result from -0,5 to 0,5 means neutrality; from 0,5 to 1,5 means warm; from 1,5 to 2,5 means hot; above 2,5 means very hot; from -0,5 to -1,5 means cool; from -1,5 to -2,5 means cold; and below -2,5 means very cold. Table 1 presents a statistic resume of the constant and dependent variables and Table 2 the analysis of variance.

Table 1: Statistic summary of dependent variables

	c	se	t	p	VIF
ct	-3,557	0,249	-11,17	<0,001	
ta	0,0632	0,0143	3,796	<0,001	2,101
mrt	0,0677	0,011	-2,803	<0,001	1,135
rh	0,0105	0,00305	2,220	<0,001	2,089
va	-0,304	0,0053	12,861	<0,001	1,915

Table 2: Analysis of variance

	DF	SS	MS	F	p
Regression	4	46,667	11,667	117,44	<0,001
Residual	67	6,656	0,0993		
Total	71	53,323	0,751		

where: ct= constant, c = coefficient, se= standard error, t= statistical test t, p= significance, VIF= variance inflation factor, DF= degrees of freedom, SS= sum of squares, MS= mean square, F= statistical test F, p= significance.

Monteiro & Alucci (2005), reviewing the state of the art of outdoor thermal comfort modelling researches, observe that there is a tendency to use equivalent temperatures instead of interpretative ranges, since an equivalent

temperature itself, without an interpretative range, would give a notion of the thermal sensation, taking into account a reference environment. In this research, in order to propose an equivalent temperature model, the following assumptions to the reference environment where done: mrt = ta; rh=50% and va=0 m/s. Considering these assumptions, the relationship between the air temperature of the reference environment and the thermal sensation perception is the following:

$$ta,re = 23,395 + 7,639 \cdot tsp \qquad \text{[Equation 2]}$$

where: ta,re = air temperature of the reference environment [^{o}C], tsp = thermal sensation perception [dimensionless]. Following equations 1 and 2, equation 3 is proposed, with TEP in ^{o}C.

$$TEP = -3,777 + 0,4828 \cdot ta + 0,5172 \cdot mrt + 0,0802 \cdot rh - 2,322 \cdot va \qquad \text{[Equation 3]}$$

The Temperature of Equivalent Perception (TEP) of a given environment is defined as a thermal sensation scale which presents values numerically equivalent to those of the air temperature of a reference environment (mrt=ta, rh=50%, va=0) in which the thermal sensation perception is the same to the one verified in the given environment.

Following equation 2, one may observe that the air temperature of neutrality, in the case of a reference environment, is approximately equal to 23,4°C. Yet the advantage of equivalent temperatures is the intuitive interpretation of their values, it is also interesting to provide a interpretative range, since the intuitive interpretation is only possible after the exposition to several environments and their respective equivalent temperatures. In the *Discussion* topic of this paper, interpretative ranges for the Temperature of Equivalent Perception (TEP) will be proposed. Considering the applicability of the proposed equation, the limits in which the Temperature of Equivalent Perception (TEP) is valid are the ones verified for the empirical research. The limits of the microclimatic variables, in which TEP is based, are: ta=15,1~33,1^{o}C; mrt=15,5~65,5^{o}C; rh=30,9~94,7%; va=0,1~3,6m/s; TEP=13,7~45,3^{o}C. Further studies to be developed, with more comprehensive empirical data, would test the validity of the results beyond those limits.

3.3. Criteria and calibration

Three criteria were established for comparing the simulation results with the field research results aiming to verify the significance of the results provided by the new proposed predictive model.

The first criterion is the correlation between the results of the model parameter and the results of the thermal sensation responses obtained in the field study. The second criterion is the correlation between the results of the index and the results of the thermal sensation responses obtained in the field study. The last one is the percentage of correct predictions. Concerning the indexes based on equivalent temperatures, the criterion for interpretation of the indexes used was the one by De Freitas (1997). Yet the author proposes this one only for effective temperatures, it was used for other equivalent temperatures because no other references were found; except for STI, for which was used Blazejczyk (2002). All the criteria are based on results concerning new empirical field researches, performed during summer and winter, in three different locations, in another neighbourhood of Sao Paulo, using the same procedures established before, and considering twenty-six new micro-climatic scenarios and the mean thermal sensation responses for each one of this scenarios (eight hundred and fifty eight applied questionnaires).

Aiming better results to the specific evaluation of open spaces of Sao Paulo, a calibration was performed in order to fit the results from the simulations to the results found in the empirical researches. In order to do so, each index was linguistically compared to seven values (the same used in the field researches): three positive ones (warm, hot, very hot), three negative ones (cool, cold, very cold) and one of neutrality (negative values do not apply for models that consider only hot environments). The calibration was done through iterative method, changing the range limits of each index in order to maximize the correlation between its results and those found in the empirical researches. The calibration could be done, also iteratively, to maximize the percentage of correct predictions. However, it was assumed that is more important to assure the maximization of the correlation between the results of the index and those from empirical data, once this correlation expresses the tendency of correctly predicting other situations.

4. RESULTS

Table 3 presents the final results considering the comparison criteria presented. This table presents the correlation modules between field study results and simulation results, without and with the calibration process presented. In such table, C= Correlation with the model parameter; Co= Correlation with the original index without calibration; Po= Percentage of correct predictions without calibration; Cc= Correlation with the index with calibration; and Pc= Percentage of correct predictions with calibration.

Table 3: Correlation between field study and simulation results

Index	C	Co	Po	Cc	Pc	Index	C	Co	Po	Cc	Pc	Index	C	Co	Po	Cc	Pc
ET*	0,73	0,59	44	0,71	72	**HU**	0,74	0,70	69	0,78	81	**SP**	0,89	0,82	78	0,89	86
CET*	0,89	0,77	11	0,85	81	**PMV**	0,87	0,82	65	0,83	86	**ECI**	0,78	0,72	42	0,80	81
OT	0,72	0,69	47	0,72	75	**Sw_{req}**	0,87	-	-	0,86	83	**PSI**	0,89	0,86	78	0,88	83
EOT*	0,70	0,66	42	0,73	75	**S'**	0,89	0,65	61	0,87	83	**STE**	0,79	0,71	58	0,81	83
WCTI	0,69	0,64	31	0,74	78	**Tne**	0,88	0,70	33	0,89	86	**PET**	0,89	0,78	31	0,89	86
HSI	0,83	0,72	68	0,89	81	**HL**	0,89	0,76	62	0,88	86	**TS**	0,87	0,84	78	0,89	89
WBGT	0,86	-	-	0,86	89	**PhS**	0,81	0,71	28	0,89	86	**NWCTI**	0,62	0,60	22	0,71	72
SET*	0,89	0,84	28	0,86	86	**R'**	0,86	0,76	69	0,86	83	**ASV**	0,85	0,77	76	0,89	86
ITS	0,84	0,75	62	0,89	8	**STI**	0,87	0,79	53	0,82	78	**TEP**	0,94	-	-	0,94	96

5. CONCLUSIONS

The empirical data gathered was treated through multiple linear regression analysis, providing a simple and easy-to-use empirical equation, considered in terms of an equivalent temperature, the proposed Temperature of Equivalent Perception (TEP), to be used as a predictive model. The results from this equation, compared with those from the other predictive models, even with calibration based on the same microclimatic situations, showed that, for the specific case of subtropical conditions, they present better correlations with the data gathered. Concluding, the methods used provided a simple, easy-to-use and reliable thermal comfort index to assess outdoor thermal comfort in the subtropics.

References

Aroztegui, J. M., 1995. Índice de Temperatura Neutra Exterior. In: ENCAC, 3, 1995. *Anais*... Gramado: ENCAC.

ASHRAE, 2005. *Handbook of fundamentals*. Atlanta: ASHRAE.

Belding, H. S.; Hatch, T. F, 1955. Index for evaluating heat stress in terms of resulting physiological strain. *Heating, Piping, Air Conditioning,* 27, p.129-42.

Blazejczyk, K. 2002. *Menex 2002*. www.igipz.pan.pl/klimat/ blaz/menex.htm. Accessed on 24/04/2004.

Bluestein, M.; Osczevski, R, 2002. Wind chill and the development of frostbite in the face. Preprints, *15th Conf. on Biometeorology and Aerobiology*, Kansas City, MO: Amer. Met. Soc., p. 168-171.

Brown, R. D.; Gillespie, T. J, 1995. *Microclimatic landscape design*. New York: John Wiley & Sons.

Dominguez et al, 1992. *Control climatico en espacios abiertos*. Sevilla: Universidad de Sevilla.

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

Gagge, A. P. *et al*, 1967. Comfort and thermal sensations and associated physiological responses. *Environ. Res.*, 1, p. 1-20.

Givoni, B. , 1969. *Man, climate and architecture*. New York: John Wiley & Sons.

Givoni, B.; Noguchi, M., 2002. Issues in outdoor comfort research. In: PLEA, 17, 2000. *Proceedings*... London: J&J, p. 562-565.

Goulart, S. et al, 1998. *Climatic data for energetic evaluation of buildings in fourteen Brazilian cities*. Florianópolis: UFSC.

Höppe, P. R., 1999. The physiological equivalent temperature. *Int. J. Biomet.*, 43, p. 71-75.

Houghten, F. C.; Yaglou, C.P, 1923. Determining lines of equal comfort. *ASHVE Transactions*, 29.

Humphreys, M. A., 1975. Field studies of thermal comfort compared and applied. *BRE Current Paper*, 75/76, London.

ISO. *ISO 10551*, 1995. Ergonomics of the thermal environment: assessment of the influence of the thermal environment using subjective judgment scales. ISO: Genève.

ISO. *ISO 7726*, 1998. Ergonomics: instruments for measuring physical quantities. ISO: Genève.

ISO. *ISO 8996*, 1990. Ergonomics: metabolic heat production. ISO: Genève.

ISO. *ISO 9920*, 1995. Ergonomics of the thermal environment: estimation of the thermal insulation and evaporative resistance of a clothing ensemble. ISO: Genève.

Jendritzky, G. et al, 1979. *Klimatologische Probleme* – ein einfaches Verfahren zur Vorhersage der Wärmebelastung, in Zeitschrift für angewandte Bäder und Klimaheilkunde. Freiburg.

Masterton, J.; Richardson, F, 1979. Humidex: a method of quantifying human discomfort. *Environment Canada*, CLI 1-79. Ontario, AES.

Monteiro, L. M.; Alucci, M., 2005. Outdoor thermal comfort: numerical modelling approaches. In: PLEA, 22, 2005. *Proceedings*.

Nikolopoulou, M. (org), 2004. *Designing Open Spaces in the Urban Environment*: a Bioclimatic Approach. Atenas: CRES.

Siple, P. A.; Passel C. F., 1945. Measurements of dry atmospheric cooling in subfreezing temperatures. *Proceedings of the American Philosophical Society*, 89 (1), p.177-199.

Vogt, J.J., 1981. Ambiances thermiques. In: Scherrer, J. et al. *Précis de physiologie du travail, notions d'ergonomie*, Masson, 2ème édition, 217-263.

Williamson, S. P., 2003. *Report on wind chill temperature and extreme heat indices*. Washington: OFCMS Supporting Research.

Yaglou, C.; Minard, D., 1957. Control of heat casualties at military training centers. *Archives of Industrial Health*, 16, p. 302-16.

Acknowledgment

The authors would like to thank the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the financial support in this research.