COMPARATIVE EVALUATION OF THERMAL COMFORT INDICES:
CASE STUDY IN THE CITY OF SANTOS, BRAZIL

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Abstract

This paper presents a case study for Santos, a Brazilian coast city. The goal was to verify the applicability of outdoor thermal comfort indices for assessment of urban external spaces, according to data collected by weather station and empirical measures at different spots. For the definition of measurements spots, wind tunnel simulations were taken into consideration. The compared indices were the Heat Load (HL) by Blazejczyk (1996), the Physiological Equivalent Temperature (PET) by Hoppe (1999) and the New Wind Chill Temperature (NWCT) by Bluestein and Osczevski (2002). As a result, we have the verification of applicability for each one of these four indices on the case study, observing the limits and peculiarities of each one of these models and the situations in which each one of them is better applied.

Key words: thermal comfort indices, urban external spaces, wind tunnel simulation

1. INTRODUCTION

The study area was the Pompeia neighborhood (between canals 1 and 2), in Santos, a coastal city in São Paulo, Brazil. It is located at latitude of 23º 57’ 35” South and at a longitude of 46º 19’ 56” West. This city was chosen because there have been changes on the building height limit with brought by a new legislation and there was a need to determine the consequences of this change. The goal was to characterize the climatic conditions for analysis of thermal comfort and/or stress, using site measurements with a meteorological station and other equipment (anemometer, thermo-hygrometer). The measurements were taken at on the beach (open field), inside an dense urban canyon (vertically built area- 15 store high with few trees), at the center of the study area (open area with medium - 6 store high - buildings, far apart with trees around them) and on an open area (low buildings – 2 to 3 store high – far apart with few trees) (PRATA, 2005) The measurements point were determined considering wind tunnel simulations, carried out at the Laboratório Nacional de Engenharia Civil (LNEC), in Lisbon, Portugal.

Figure 1: City of Santos and study area

2. METHODS

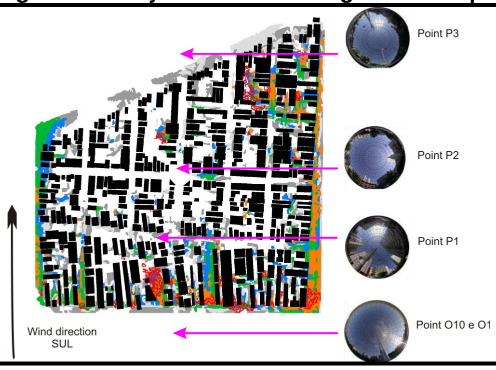
2.1 Wind tunnel tests and measurement points

Wind tunnel tests were carried out at the LNEC. The selected interest points were chosen on the central area of the model. The erosion figure technique was used for the visualization of the wind field at pedestrian level (JANEIRO BORGES et al, 1979). Figure 2 shows the wind field caused by the current urban configuration exposed to south winds. There is little ventilation on the central area of the model (2nd block), because of the blocking from the tall buildings (a “coastal wall”) at the shore. Three internal points were selected for site measurements: P1 – behind the coastal wall (buildings); P2 – at the center of the study area at an open space (central square) and P3 – at the opposite side of the model from the beach (avenues). All points were measured at 1,5 m from the ground. The beach measurements – points O10 and O1 – were taken at 10 m and 1,5 m.

2.2. Climatic data

While working with comfort in the built environment, a commonly found problem is the (un)availability of climatic data. Wind was chosen as the climatic variable for this study, since natural ventilation is the main strategy to attain comfort in tropical coastal areas. Climatic data was taken from the Airforce Base of Santos and analyzed for the study area by using the software WASP - Wind Atlas Analysis and Application Program (MORTENSEN et al., 1993). Statistical analysis of the data allowed for the identification of prevailing wind directions, which were used to determine a physical scaled model exposure to winds. Most of the wind was coming from the southern and eastern quadrants, with higher speeds from south. Thus, the model was tested in the wind tunnel exposed to south winds.

Figure 2: Study area – erosion figure technique



2.3 Site measurements

A 10 meter pole was installed on the beach (point O10), over which a meteorological station was placed. By its base, a shaded equipment set was place containing four windmill anemometers, one thermo-hygrometer and one mercury thermometer (point O1). The measurements were taken for three days (April 12th, 13th and 14th, 2006) at three times, for approximately one hour each. Wind data was collected in 5 second intervals for one minute for each one of the 4 anemometers (only the highest value for each direction – N-S and L-W – was noted). The final result was a vectorial average for the measured data points. Monteiro and Alucci (2005) present a procedure for measurement of environmental variables for thermal-physiological analysis in open spaces.

3. THERMAL COMFORT AND HEAT STRESS INDEXES

In order to counteract the specificity of each index, this research used the calibration proposed by Monteiro and Alucci (2007), which was developed for a population acclimated to conditions similar to those of the study area.

3.1 Heat Load (HL)

Blazejczyk (1996; cited by Blazejczyk, 2002) proposed the MENEX (Man-ENvironment heat EXchange) model. This model calculates the human body thermal balance, considering metabolic heat production according to ISO 8996 (1990) and heat exchanges with the surroundings. The peculiarities of the model are: the skin evaporative loss calculation, which considers a weighting coefficient for sex (1,0 for men and 0,8 for women); the skin long wave loss radiative calculation, which considers weighting for cloud cover and the solar radiation calculation, which uses specific models. Thermal load is determined as function of the accumulated heat (S), of the absorbed solar radiation (RC) and of the skin evaporative losses (Esk). Thermal stress is classified according to Table 1, proposed by Blazejczyk (2002), and according to the thermal sensation calibrated by Monteiro & Alucci (2007).

Table 1: Heat Load (HL), by Blazejczyk (2002) and calibrated by Monteiro & Alucci (2007).

HL	Classification	Calibration	Sensation
		≥ 1,65	Very hot
≥1,600	Extreme stress (heat)	1,23 - 1,65	Hot
1,186 - 1,600	Moderate stress (heat)	1,08 - 1,23	Warm
0,931 - 1,185	Thermal neutrality	0,88 - 1,08	Neutral
0,811 - 0,930	Moderate stress (cold)	0,72 - 0,88	Cool
≤ 0,810	Extreme stress (cold)	0,65- 0,72	Cold
		≤ 0,65	Very cold

3.2 Physiological Equivalent Temperature (PET)

Höppe (1999) proposes the Munich Model (MEMI), based on the human body thermal balance equation and on parameters from the two node model by Gagge (1986). Höppe's model differs from Gagge's model in the way of calculating regulatory sweat rate (as a function of tsk – skin surface temperature and tcl – clothed body external surface temperature) and the heat fluxes, for it considers clothed and unclothed body parts separately. In order to calculate the PET, one should proceed accordingly to the following steps: (1) calculate the body's thermal conditions (tsk and tc - core temperature), using the equation system from the MEMI model for the given combination of meteorological and individual parameter combination; (2) insert tsk and tc in the MEMI model, solving the system for air temperature (ta), considering mrt = ta, w =0,1 m/s (proposed by the original model and recalculated for this paper, using wind speeds previously presented), pv = 12hPa, M = 114 W and Iclo= 0,9 clo; (3) the resultant air temperature is the PET. The PET index originally did not present reference ranges for interpretation, since it was developed to provide comparison with a reference environment. Table 2 presents the calibration proposed by Monteiro & Alucci (2007) have proposed a calibration for the thermal sensation according to the following PET index.

3.3 New Wind Chilled Temperature Index (NWCTI)

Siple & Passel (1945, cited by Williamson, 2002) have developed the wind chilled temperature from data of experiments carried out in Antarctica. Bluestein & Osczevski (2002) present empirical work for the reformulation of equations leading to a new wind chilled temperature (NWCTI). The index calculation is based on a reference relative wind speed of 4,8 km/h, representing a situation where one would have equivalent heat loss rate and skin temperature as in a real situation, given temperature and wind speeds. Table 3 presents the interpretation ranges according to Bluestein & Osczevski (2002) and according to the calibration proposed by Monteiro & Alucci (2007).

Table 2: Calibração proposta por Monteiro & Alucci (2007) para o índice PET.

PET	Sensação
> 43	Very hot
31 - 43	Hot
26 - 31	Warm
18 - 26	Neutral
12 - 18	Cool
4 - 12	Cold
< 4	Very cold

Table 3: NWCTI, de Bluestein & Osczevski (2002) e calibração proposta por Monteiro & Alucci (2007).

NWCTI	Sensação	Calibração	Sensação
> 35	Very hot	> 38	Very hot
27 - 35	Hot	31 - 38	Hot
23 - 27	Warm	24 - 31	Warm
21 - 23	Neutral	14 - 24	Neutral
17 - 21	Cool	7 - 14	Cool
9 - 17	Cold	0 - 7	Cold
< 9	Very cold	< 0	Very cold

4. RESULTS AND FINAL CONSIDERATION

These models were used to calculate thermal comfort and heat stress of users in shaded and under the sun conditions, using data from site measurements. Mean radiant temperature was estimated from averaged solar radiation data for the periods where Δta= ±1. Solar radiation was calculated using a model from Kuwabara et al (2005), sky temperature by using the Bliss model (Duffie & Beckman, 1980), surface temperatures, according to IRC (2000) and surrounding temperatures from EDSL (2004). Adopted values were: clothing insulation, Icl = 0,5 clo; metabolic rate, M=135 W/m²; individual speed, vi = 1,1 m/s. Air temperature, relative humidity and wind speed were taken from site measurements and mean radiant temperature was estimated for under the sun and shaded conditions. The results of computational calculations for each index, according to calibration by Monteiro and Alucci (2007) are presented in Table 4.

Table 4: Results of computational calculations for each index

point	d	h	HL	HL sun	PET	PET sun	NWCT	point	d	h	HL	HL sun	PET	PET sun	NWCT
O10	1	9	C	C	PC	PC	C	P1	1	9	MC	MC	PC	C	C
O10	1	12	PC	C	PC	C	C	P1	1	12	C	C	PC	C	C
O10	1	15	N	C	PC	PC	C	P1	1	15	PC	C	PC	C	C
O10	2	9	N	PC	N	PC	PC	P1	2	9	N	PC	PC	PC	C
O10	2	12	N	C	N	PC	PC	P1	2	12	N	C	PC	C	C
O10	2	15	N	C	N	PC	PC	P1	2	15	N	C	PC	PC	C
O10	3	9	PC	C	N	PC	C	P1	3	9	C	MC	PC	C	C
O10	3	12	C	MC	N	PC	C	P1	3	12	C	MC	PC	C	C
O10	3	15	PC	C	N	PC	PC	P1	3	15	PC	C	PC	PC	C
O1	1	9	C	MC	PC	C	C	P2	1	9	MC	MC	PC	C	C
O1	1	12	PC	C	PC	C	C	P2	1	12	C	MC	PC	C	C
O1	1	15	PC	C	PC	C	C	P2	1	15	PC	C	PC	C	C
O1	2	9	N	PC	N	PC	PC	P2	2	9	PC	C	PC	PC	C
O1	2	12	PC	C	PC	C	C	P2	2	12	PC	C	PC	C	C
O1	2	15	N	C	N	PC	C	P2	2	15	N	C	PC	PC	C
O1	3	9	C	C	N	PC	C	P2	3	9	C	MC	PC	C	C
O1	3	12	C	MC	N	PC	C	P2	3	12	C	MC	PC	C	C
O1	3	15	C	MC	N	PC	C	P2	3	15	PC	C	PC	PC	C
								P3	1	9	MC	MC	PC	C	MC
								P3	1	12	C	MC	PC	C	C
								P3	1	15	C	MC	PC	C	C
								P3	2	9	PC	C	PC	C	C
								P3	2	12	C	MC	PC	C	C
								P3	2	15	C	C	PC	C	C
								P3	3	9	C	C	PC	PC	C
								P3	3	12	MC	MC	PC	C	C
								P3	3	15	C	MC	PC	PC	C

Legend: **MF**: very cold; **F**: cold; **PF**: cool; **N**: neutral; **PC**: warm; **C**: hot; **MC**: very hot.

The HL results show that, under exposure conditions of the beach (points O10 and O1), the best conditions would be obtained by using solar protection (shading). Users on this area are privileged, since they can also minimize heat stress by cooling skin with sea water. If the results for the same index in the center of the area are observed, one can note that heat conditions are also reduced by shading. The urban configuration may improve user conditions, by creating sunny and shaded areas according to the seasons (winter and summer). The analysis of the PET index resulted in milder thermal conditions. While the HL indicates a MC (very hot) scenario, PET calculations indicate values between N (neutrality) and C (hot). It is hard to single out the best index; the choice usually hangs on availability of data and on the evaluation scenarios. For instance, results for an index like the NWCTI do not depend on average radiant temperature, since they are a function only of air temperature and wind speed. It should also be pointed out that the index application was not followed by questioning thermal sensation of users. Therefore, in order to validate the results and improve evaluation of urban design solutions, it would be important to conduct an empirical study about thermal sensation of users (inhabitants and pedestrians) of nearby areas.

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