Thermal comfort evaluation in outdoor space of tropical humid climate

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ABSTRACT: The thermal comfort in outdoor spaces is important for evaluation studies and to guide urban and architecture projects. In the cities of tropical humid climate, these spaces are used during the year, and they must provide proper levels of thermal comfort. The climate, surround buildings, shading, vegetation and ventilation influence site environmental conditions.
This paper presents an evaluation of thermal comfort at the square of the condominium Downtown, in the west zone of Rio de Janeiro. It was used the Fanger's model [7]. Four square locations were considered to analyze the users PMV and PPD votes. The calculated values were corrected according to Fanger-Toftum [1]. It was also evaluated Actual Sensation Votes ASV [3]. The calculations followed De Dear [5]. The air temperatures were measured: globe, dry and humid bulb. Also, speed of the wind and relative humidity were recorded. The calculated PMV and PPD results were compared with the users' votes, and they are in accordance. Thus this show the applicability of the Fanger`s model in evaluation studies of the thermal comfort in outdoor spaces. Also, from the considered environment conditions it was possible to establish this influence on the thermal comfort for the locations selected in the square.

Keywords: thermal comfort; outdoor space

1. INTRODUCTION

The study of thermal conditions of external environment in large cities is essential to the evaluation and recommendations in urban and architectonic projects, especially in towns of humid tropical climate, where these spaces are used year round, with stronger interference of high temperature and humidity. The quality of these spaces may contribute to people's life quality or, on other hand, generate isolation and social abandon.

An extremely important aspect is the understanding of the activities that will take place in a given space, so that the planning really promotes the user's comfort.

The parameters that interfere with thermal comfort in urban space are similar to those of inside spaces, but they are more extended and variable. Due to that complexity, in terms of variability, temporality and spatiality, as well as the large possibilities of different activities of the users, the understanding of comfort conditions in these spaces has been the object of many former studies [3].

The microclimatic analysis of an urban space must consider conditions such as solar incidence and radiation exchanges, local characteristics of winds, topography, vegetation and the presence of water. Beyond these factors, the urban design, the morphology of the buildings, the characteristics of the surfaces and the behavior of the individuals are also factors that influence the thermal conditions of these spaces. The morphology and the choice of materials determine the radiative and convective exchanges, which are fundamental aspects to establish the comfort condition of an individual in an open space. The convective exchanges are due to two different factors: the action of the winds; and the differences of temperature and pressure, that are linked to the presence of different materials in the same urban space. [6]

2. METHODS OF PREDICTING THERMAL COMFORT

Among the various evaluation methods of thermal comfort in inner spaces, the studies of Fanger [2] are currently the most suitable for this work, being the base for the International Norm on thermal comfort [7] and to the ASHRAE Handbook – Fundamentals [8].

Both the ISO Standards 7730 and the ASHRAE Handbook Fundamentals describe methods to evaluate the combined influence of personal parameters (activity and clothing's thermal protection) and environmental parameters (air temperature, radiant temperature, air speed, air humidity)[9].

Based on subjective criteria to determine the influence of environmental and individual parameters (thermal balance between man and environment), and considering the analytical sensation of thermal comfort suggested by the consulted individuals - "Predicted Mean Vote" (PMV) - and the "Predicted Percentage of Dissatisfied" (PPD), this model suggests a seven point scale , from very cold to very hot, combining individual parameters (metabolism and clothing resistance) and environmental parameters (air temperature, air humidity, air temperature and radiant temperature). In this study, for thermal acceptability of an environment, the percentage of dissatisfied people must less than 10% [7].

Table 1: Psycho-physiological scale of thermal sensation values from ISO 10551-95

PMV	Thermal sensation
+3	hot
+2	warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	cool
-3	cold

Taking into account the thermal sensation votes, established by means of statistical regression analysis , the expression of PMV [7]:

$$PMV = [\ 0,303.\exp(-0,036.M) + 0,028]\ L$$

Where:

PMV = Predicted Mean Vote, or thermal comfort analytical sensation (adimensional)

M= Metabolic heat production tax (W/m²)

L= Thermal load actuating over the body (W/m²)

According to the predicted votes, are unsatisfied those people that voted +3,+2,-3,-2 in the sensation scale. The +1 and -1 votes did not characterize people dissatisfied with the environment.

The quality of the thermal environment may also be expressed as the predicted percentage of dissatisfied, *PPD index,* which is related to the *PMV value.* For the analysis of the internal environment, another equation is proposed considering the relationship between the PMV of people and the dissatisfied percentage:

$$PPD=100–95.\exp[-(0.03353.PMV^4+0,2179.PMV^2)]$$

In this expression, we observe that for a full comfort situation, or PMV=0, there will be a minimum percentage of dissatisfied of 5%. For the maximum percentage of 10% (PPD<10%) of dissatisfied people, recommended as acceptable in *ISO Standards 7730,* the PMV may have values between +0.5 and – 0.5 (-0.5<PMV<0.5).

The calculation of the PMV and the PPD is nowadays facilitated by the disponibility of computer programs like the one presented by De Dear [4].

Due to climatic diversity, other proposals were developed that aimed to adapt Fanger´s algorithms to internal environments without climatization.[1].

In the case of external environments, many studies are applying and comparing Fanger´s models, trying to adapt them to the diversity of these environments, considering their dynamic conditions and other influencing factors, such as direct solar radiation, and distinct human activities profiles [3] [6] [13]. Among the studies that have been made for external environments, we emphasize the work developed by the RUROS project [3], based on the Actual Sensation Vote – ASV, that develops comfort prevision algorithms for many European cities.

This work intends to apply Fanger´s model [7] to a public square, with the correction proposed by himself and Toftum [1], and the model of RUROS project [3], establishing a comparison between the results obtained through the votes of this external space users.

3. METHODOLOGY

The case study will consist of three stages:

1- Analysis of the thermal comfort conditions of the studied place, to obtain the Actual Sensation Vote – ASV [3].

2- Prediction of comfort through the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD), adapted to external environment, using the computer program developed by De Dar [5].

3- Comparison of the results of the Actual Sensation Vote of the users and the calculated PMV and PPD.

In the first stage, the analysis of the thermal comfort conditions in urban space must combine the measurement of environmental variables and the collection of subjective data from the users, by means of questionnaires and observation, simultaneously performed.

The measuring equipments must always be close to the interviewed individuals, allowing the monitoring of the local environment physical conditions. The environmental parameters such as air temperature and radiant medium, relative humidity and wind speed must be registered following ISO/DIS 7726 [10].

The information on personal and subjective data, collected in the interviews, must be recorded in questionnaires that show the perceived thermal sensations (ISO10551 [12]), the kind of clothing (ISO 7730 [7]), age and sex.

The results compilation will furnish the dissatisfied percentage by the Actual Sensation Vote of the users.

In the second stage, the comfort prediction of the referred external space must consider the data obtained by the measurements made in the site, and the typical profiles of the users, clothing and activities, applied to the program developed by De Dear [5].

In the last stage, the comparison between the results of the Actual Sensation Vote of the users and the calculated PMV and PPD, obtained in the two preceding stages, will allow the verification of the efficacy of the comfort prediction algorithm, for use in calculations and estimatives in external environments, subsidizing urban and architectonic projects.

It is important to emphasize that in this case study the data used in the calculations, both microclimatic and from the users, correspond to really observed situations, what does not occur in the case of a real project, when the place is still to be built and the users haven't occupied it yet. In the case of a project, these variables may be simulated with the aid of a computer program or calculated based on determined assumed premises.

4 –CASE STUDY– Downtown Condominium

The studied area is located in Rio de Janeiro, Brazil, a city of humid tropical climate, latitude 22°54'10"S and longitude 43º12'27"W. The studied public square is inside the Downtown condominium, at 500, Americas Avenue, Barra da Tijuca, a coastal neighborhood with constant winds, mainly southeast.

This condominium is composed of buildings of no more than 4 floors, with inner patios and open air circulation areas that form pedestrian "streets", with gardens with covering and shading vegetation, in a site of flat topography in all its extension and surroundings.

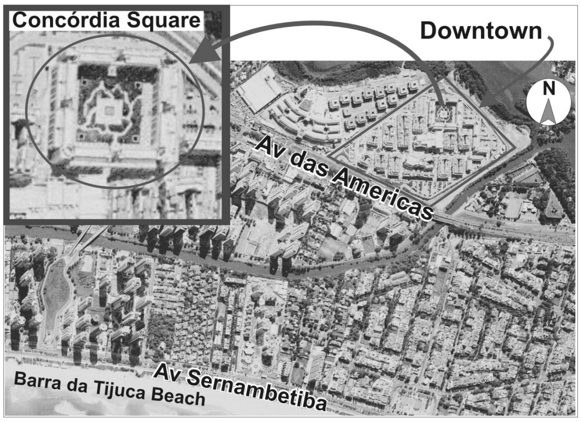

Figure 1: Downtown Condominium location and Concordia Plaza detail

The Concordia Plaza was chosen as research area because it is highly frequented by the condominium users, who are basically local company employees, students, shop and cinema users, all day long, but especially between noon and 2 pm, lunch time in which it is used for leisure, reading, etc.

The Plaza is square and has a surface of approximately 4000 m², having a lot of benches, in shaded places or not, that allow the permanence of people in the Plaza for long periods and in different thermal conditions. Besides the shade provided by the buildings, specially in the surrounding circulation area, variable in time, there is in the plaza a large arborized area, as well as a water feature, that may interfere in a significant scale in the thermal comfort conditions.

Figure 2: General view of the Plaza.

4.1 Field analysis

The evaluation of the thermal conditions was achieved by means of measurements, questionnaires and photographic registers, following the previously established parameters, all data being registered in files or completed by the users.

For the field measurements were used the following equipments:

- Globe thermometers, wet and dry bulbs (INSTRUHERM – TGD 100)
- Hot wire anemometer (LUTRON – AM-4204)
- Digital thermo hygrometer (TFA)
- Surface temperature measuring device (RAYTEK–MT4)
- Luximeter (GOSSEN – PANLUX ELETRONIC 2)

The measurements were made in May, 16, 2005, a clear sky, cloudless day, during two hours, between 11AM and 1 PM. The interviews took place at the same time, in a total of 40 votes.

The points chosen in the Plaza for the measurements and interviews include shaded, sunny and half-shade areas, promoting different possibilities of thermal conditions. The four chosen points, the areas shaded by the vegetation and the results of the measurements may be verified in the following tables and figures.

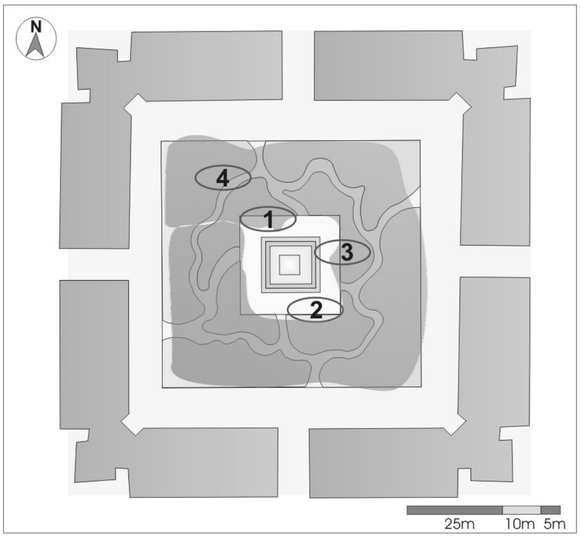

Figure 3: Measurement and interviews points and areas shaded by the vegetation indication

Figure 4: View of the chosen points

4.2 Questionnaire application

40 questionnaires were applied, in 4 points (figures 3 and 4).

Point 1 was located in the shade, where the interviewed people were sitting on a granite bench.

Point 2 was located in a sunny area, also having a granite bench.

Point 3 was in partial shade area, and the interviewed people were sitting on a wood bench.

All three points were located close to the central fountain of the plaza, in an area paved with "portuguese stones"[1], while point 4 was located in an area surrounded by vegetation and totally shaded, with the same pavement and wood benches.

4.2.1 Results from a global evaluation

The evaluation was performed in a group of 55% of men and 45% of women, in an age range from 20 to 55 years, mainly clothed in short sleeve shirts and long pants. Most people were seating, resting or reading.

The interviews were made in full sun areas (25%), shadow (55%), and half shadow (20%). Considering the plaza ventilation, 57% of the interviewed perceived a slight draft, 37.5% wind absence, and 5% just enough wind. Regarding comfort, 67.5% appointed a thermal comfort sensation, 10% very comfortable, 12.5% uncomfortable and 10% very uncomfortable.

4.2.2 Results analysis: global evaluation

If we analyze the questionnaires in a global way, we will arrive at 77% of satisfaction, a very high rate.

By these results, one could infer that the Plaza has no problems, which is not true. If we evaluate each point individually, we will notice that the unsatisfaction percentages that are low in general, are specially concentrated in point 2, which happens to be very uncomfortable. In this way, it is necessary to evaluate comfort in an independent way, that is to say, point by point, in order to verify the real sensations obtained in each point of the plaza.

4.2.3 – Point evaluation

In sequence will be presented the comparative results of the Comfort Sensation obtained point by point.

Table 2: Thermal Sensation

	Pt 1	Pt2	Pt3	Pt4
Very cold	-	-	-	-
cool	-	-	-	-
Slightly cool	5%	-	-	-
Neutral	76%	-	40%	100%
Slightly Warm	19%	44%	60%	-
Warm	-	33%	-	-
Very Hot	-	22%	-	-

Table 3: Comfort and Discomfort Sensation

	Pt 1	Pt2	Pt3	Pt4
Very comfortable	10%	-	-	40%
comfortable	90%	11%	80%	60%
Uncomfortable	-	44%	20%	-
Very Uncomfortable	-	44%	-	-
Unbearable	-	-	-	-

4.2.3.1 Results analysis: Point evaluation

It is observed that the interviewed people in points 1 and 4 were predominantly in the shade, while those in points 2 and 3 were mostly in the sun. It is noticeable that, in account of that fact, the comfort conditions are highly altered between the points. In points 1 and 4 a tendency to neutrality (from 76% to 100%) and to comfort (100% are in the very comfortable or comfortable band) is observed. In points 2 and 3, the presence of heat, varying from slightly hot (most of the answers in point 3) to very hot (in point 2 by 22% of the interviewed) is observed, as well as the appearance of answers of uncomfortable and very uncomfortable, amounting to 88% in point 2.

4.3 Field measurements

Table 4: Obtained results.

Measurement	Pt 1	Pt 2	Pt 3	Pt 4
Dry bulb temperature (ºC)	28	31	28,9	29,8
Wet bulb temperature (ºC)	24	24,2	23,5	23,5
Globe temperature (ºC)	29,4	46,3	29,3	30,2
Wind speed (m/s)	0,2	0,2	0,2	0,2
Relative humidity (%)	82	76	78	77
Surface temperature of materials(ºC)	Granite bench:			
	24,8	44,8	28	24,8
	Wood bench:			
	31,6	52,4	35,2	28
	"Portuguese stone" pavement:			
	23	43	28	25
	vegetation:			
	25,6	36	26	24,8
lightning (lux)	5000	95000	6000	2500

4.4 Prediction of comfort using PMV

To the prediction of comfort based on the PMV method developed by Fanger [7], we used the computer program developed by De Dear [5] applying as reference the data obtained in the measurements and the users characteristics. The following tables present the results of the simulation.

[1] Portuguese stone paving is a mosaic pavement system that uses dark basalt and white limestone, forming decorative patterns, each stone cut and set by hand.

Table 5: Entry data

Environmental Parameters		Personal Parameters	
ambient temperature (°C)	28	subject weight (kg)	70.0
radiant temperature (°C)	29.4	subject surface area (m^2)	1.8
barometric pressure (hPa)	1013	clothing insulation(clo)	0.5
vapour pressure (hPa)		metabolic rate(W m^{-2})	70
relative humidity (%)	82	work rate–external (Wm^{-2})	0
room air velocity (m s^{-1})	0.2	exposure time (min)	10

Table 6: Results of point 1 applied in the program

Effective Temperature (ET^*)	30.50	
Standard Effective Temperature (SET^*)	30.05	
Discomfort (DISC)	1.20	Slightly Uncomfortable
Thermal Sensation (TSENS)	0.60	Slightly Warm
Predicted Mean Vote (PMV)	1.11	Slightly Warm
Predicted Percentage Dissatisfied (PPD)	31.16	
Heat Stress Index (HSI)	59.37	

Body Temperatures			
Skin Temperature (T_{sk})	34.38	Core Temperature (T_{cr})	36.85
Heat Balance Summary (W m^{-2})			
Metabolic Rate (METAB)	70.00	Metabolic Shivering (SHIV)	0.00
Metabolic Work (WORK)	0.00		
Respiratory evaporative heat loss (E_{res})	3.34	Respiratory sensible heat loss (C_{res})	0.588
Dry heat loss from skin surface (DRY)	29.44	Total Evaporative heat loss at skin surface (ESK)	22.75
Heat storage in the skin (SSK)	9.834	Heat storage in the core (SCR)	5.385
Skin Blood Flow (SKBF) (L m^{-2} hr^{-1})	16.69	Amount of sweating (REGSW) (g hr^{-1} m^2)	26.96

Table 7:Synthesis of the results of the checked points

Results	PONTO 1		PONTO 2		PONTO 3		PONTO 4	
DISC	1.20	S.U	3.57	V.U.	1.28	S.U.	1.58	S.U.
TSENS	0.60	S.W.	1.71	W.	0.64	S.W.	0.75	S.W.
PMV	1.11	S.W.	4.19	V.H.	1.26	S.W.	1.56	W.
PPD	31.16		100		38.15		54.14	

V.U. - Very Uncomfortable/ **S.U.** - Slightly Uncomfortable
S.W. - Slightly Warm / **W.** – Warm/ **V.H.** - Very Hot

4.5. Comparative analysis of the results

The evaluation was performed in May, when temperatures are generally lower than those in the summer, in a day with a light breeze. Being so, almost all the Concordia Plaza could be classified as thermically agreeable. This affirmative was confirmed by the observation of the permanence time of the users, and the results of the questionnaires and measurements made in this period. All the permanence points happened to be mainly located in shaded or half-shaded areas, provided by small and medium trees with a large area of low vegetation.

However, in the simulation made for the PMV calculation, we observed dissatisfaction rates (PMV) higher than the admissible in all the points, that being, higher than 1.0, values that according to the questionnaires would be around neutrality (-1<0<+1). Still through the simulation, in all points we observed high dissatisfied percentages (PPD), varying between 31% and 100% of dissatisfied, what could not be observed in the evaluations made by real votes of the users, that led to higher satisfaction percentages than in the achieved result. In points 2 and 3, 20% to 44% of high discomfort was found, but in points 1 and 4 the comfort percentage reached 90% to 100%.

The differences observed in the simulation, presenting higher dissatisfaction results (very hot) than those effectively voted by the users, were expected, as similar researches conducted in humid tropical climates also showed them. These differences are justified by the fact that users in this climate profile are more adapted to heat, as quoted by Fanger [1].

Associating the "*new extended PMV model*" applied by Fanger [1] to warm climates to the present work, we can verify that if we use the *expectancy factor* –e for "*regions with few air-conditioned buildings*" where expectancy is considered low – between 0.5 and 0.7- we will have a result more approximate to the real vote, compared to those obtained in the computer simulated PMV.

Another simulation hypothesis that we may use considering the evaluation of open spaces is the application of the "Models for calculation of ASV" developed by CRES [3] for many European cities, using the model:

ASV= 0.049 Tair_met + 0.001Sol_met – 0.051 V_met + 0.014 RH_met – 2.079

In the simulation of ASV [3], as well as in the computer application (De Dear), the results didn't present values close to those obtained in the questionnaires. This may have occurred in view of the use of an evaluation designed for European standards.

Considering the results obtained by direct vote, we can observe that in the area chosen for the evaluation, points 1 and 4 were preferred for permanence, obtaining most of the votes in the questionnaire on thermal conditions, being classified as comfortable or neutral. This is justified by the fact that both points are located in shaded areas. Point 2 was classified as uncomfortable or very uncomfortable and less tolerable for permanence in account of the direct insulation that makes the area very hot, verified by the measurement made with the globe thermometer that presented a temperature of 46.3°C, exceeding in 16.9°C the measurement made in the shaded area of point 1.

Another factor that confirms the dissatisfaction mentioned in the questionnaires was the result of the measurements registered of the surface temperatures of the materials located in this point, as the "portuguese stone" pavement, granite benches and brown painted wood benches, presenting differences of 20°C in relation to point 1. In point 3 short term permanence was observed, as it was a half-shaded area, and the sunny area was enlarged with the passage of time.

There is still one more factor to be considered in the classification of points 1 and 4 as the more agreeable, besides the shade provided by the existing trees. It is the proximity of areas with ground covered by vegetation, which presented lower values in the measurement of surface temperatures than those of other surfaces, especially in the sunny areas, where the variation was very inferior. In the shaded areas close to sunny paved ground ("portuguese stone"), as points 1 and 3, the results of temperature measurements were slightly higher than those taken in areas surrounded by more shade, as in point 4. This difference is due to the higher heating of artificial surfaces than of the natural ones, as observed in the temperatures obtained with dry bulb, wet bulb and globe on the registered surfaces.

5. FINAL CONSIDERATIONS

The method applied in this study is recommended for existing places, as it uses, besides the prediction of the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD), the real vote of the users, registered in questionnaires, making it possible to evaluate situations were inadequacies of the urban space are observed. In this case, the method will help in the prediction of comfort and guide projects to modify this space, even though it is necessary to develop adaptative models for external spaces and humid tropical climates, as the work elaborated by project RUROS [3], in which an algorithm for real vote (ASV – actual sensation vote) was developed for many European cities.

The project of the CONCORDIA Plaza presented in this evaluation good thermal quality of the studied spaces. Most of the areas with benches for permanence were shaded, being almost only the fountain area in the sun. Even though this research presented a negative result of satisfaction in some of the spaces, the relation between shaded and sunny areas may be classified as adequate, as these sunny areas may be an alternative to permanence in the months of lower temperatures. A dynamic space is then possible, proportional to the climatic characteristics of the region of Rio de Janeiro.

In the case of projects of new spaces, a method that simulates the conditions previewed in the project must be taken in consideration, or that permits its calculations, making it possible to predict the conditions of thermal comfort to the future users.

Even though the evaluation here presented was performed in only one day, with the objective of testing the PMV (Predicted Mean Vote) method, we can notice the importance of this research, comprehending observations, interviews and measurements, that when correlated may lead to the quality analysis of the thermal comfort conditions of the urban space.

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