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THE IMPORTANCE OF RADIATION IN STUDIES OF HUMAN THERMAL COMFORT IN THE SEMI-ARID AND THE USE OF GLOBE THERMOMETERS TO MEASURE IT.

A IMPORTÂNCIA DA RADIAÇÃO NOS ESTUDOS DE CONFORTO TÉRMICO HUMANO NO SEMIÁRIDO E O USO DE TERMÔMETROS DE GLOBO PARA SUA MENSURAÇÃO.

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RESUMO
Este trabalho é uma revisão bibliográfica sobre a importância da variável climática radiação em estudos de conforto térmico humano a partir de seu principal modo de mensuração: o uso de termômetros de globo e da fórmula da temperatura radiante média. A partir da revisão realizada viu-se a necessidade de realização de uma exploração teórica da fórmula a fim de oferecer recomendações para o seu uso para além do encontrado na literatura.
Palavras-chave: revisão de literatura, conforto térmico humano, temperatura radiante média.

ABSTRACT
This work is a literature review on the importance of the climatic variable radiation in studies of human termal comfort, fucosing on its main measurement method: the use of globe thermometers and the formula for mean radiante temperature. Through this review, there was a recognized need for a theoretical exploration of the formula in order to provide recommendations for its usage beyond what is commonly found in the literature.
Key words: literature review, human termal comfort, mean radiante temperature.

INTRODUCTION

In the spectral composition, visible range radiation accounts for about 45% of this composition, while infrared radiation represents 46%. The remaining 9% consists of ultraviolet radiation. Solar radiation incident at the top of the atmosphere varies and depends on three factors: the time of year, time of day, and latitude. Infrared or thermal radiation is emitted by all bodies heated by solar radiation. The emissivity of these bodies (radiation absorbed and transformed into heat) is released in long waves.

The atmosphere and the Earth's surface also absorb some of the shortwave radiation and emit thermal radiation (ALVES, 2011). Air temperature, relative humidity, wind speed, and radiation are some of the factors, according to Epstein and Moran (2006), that cause thermal stress. In outdoor environments, the average skin temperature is highly correlated with air temperature and solar radiation together, explaining about 68% of its variation (BLAZEJCZYK; NILSSON; HOLMÉR, 1993).

Radiation is considered the primary form of heat loss or gain (60%), which is why the mean radiant temperature is regarded by several authors as the meteorological parameter that most affects human thermal equilibrium during sunny conditions (GIVONI, 1976; OLGYAY, 1992; BLAZEJCZYK; NILSSON; HOLMÉR, 1993; ROSSI, 2012). This premise makes this parameter extremely important for assessing human thermal comfort in environments with high levels of insolation, such as the semiarid regions.

Hodder and Parsons (2007) found that an increase of 200W/m² in direct solar radiation intensity leads to an increase of over 2°C in average skin temperature and one unit in the thermal sensation scale. These changes occur within the first few minutes of exposure, stabilizing after 10 to 12 minutes.

Petalas (2015) summarized the influence of the main climatic factors related to thermal comfort and their physiological responses in the human body in a hot environment. In this summary, it is clarified that high mean radiant temperature, when associated with high wind speed, results in a sensation of greater heat, and when associated with low air humidity, results in a sensation of dry skin. In this condition, the pulse (heart rate) is little affected by the increase in temperature within a low thermal stress threshold, although it can be greatly affected when the thermal balance reaches its limit.

The term mean radiant temperature (MRT) is commonly used to refer to the radiation component of climate. It can be defined as the ambient temperature of a surrounding area, considered uniformly black to eliminate the reflection effect, with which the body (commonly a black globe) exchanges as much energy as that of the current environment considered (Bond & Kelly, 1955; cited in Campos, 1986). THORSSON et al. (2007), based on ASHRAE (2004), define it as the uniform surface temperature of an imaginary black or gray enclosure in which an occupant would exchange the same amount of radiant heat, as in the real non-uniform space, and summarizes the exposure of the human body to all shortwave and longwave radiation fluxes (direct, diffuse, reflected, and emitted) in a given environment. They also add that mean radiant temperature (MRT) is one of the most important variables in assessing thermal comfort, especially during hot and sunny weather conditions.

In other words, Mean Radiant Temperature (MRT) is a methodologically defined way to measure radiation in an environment. MRT is commonly measured through two methods: using a globe thermometer and through computational models, such as RayMan (MATZARAKIS et al., 2007), SOLWEIG (LINDBERG et al., 2008), and ENVI-met (BRUSE, 2011). The use of these models is more common in studies of human thermal comfort in urban environments because they require not only meteorological and geographical input data (such as latitude) but also urban morphology data. In Petalas's work (2015), photographs using the fisheye lens technique were taken to assist in measuring MRT using Rayman software.

Measuring the intensity of radiation by measuring temperature variations within a globe and subsequently using a mathematical formula to correlate globe temperature with mean radiant temperature is the most common method of utilizing this climatic component in studies of human thermal comfort. The mentioned formula will be described and explored in the following sections of this work.

The ASHRAE Handbook of Fundamentals norm (ASHRAE, 2001) is a fundamental reference for determining mean radiant temperature from globe thermometers, indicating even the types of instruments to be used for measurements. The measurement of globe temperature is commonly carried out in the field in experiments like those shown in the following figures.

Figures 1 and 2: Equipment measuring the temperature of the globe in an external environment, in the first image from a meteorological station and the second from a stick thermometer attached to a globe.

Sources: fig.1 - Gobo and Galvani (2016) and fig.2 – Authors' Collection.

In a methodological article, Gobo and Galvani provided some guidelines regarding how to measure the temperature of the globe to calculate the TRM, such as the recommendation of a medium gray[1] globe when the sensor is exposed to direct solar radiation to better agree with the outer surface of clothed people (ISO 7726, 1998; ASHRAE, 2001), and the guidance that to be able to record sudden variations in MRT with a globe thermometer, the sensor needs to have a sufficiently short response time to achieve this objective and the globe, therefore, must be small in size and have a low heat capacity. (NIKOLOPOULOU et al., 1999).

[1] In several studies measuring Mean Radiant Temperature (MRT) using globe thermometers, the color commonly used for the globe is black, with the term "black globe" being quite common in this field. However, various studies conducted in outdoor environments have concluded that the black globe would overestimate MRT, and a globe painted in medium gray would be closer to the average albedo color of a clothed person. Therefore, while studies in indoor areas (often related to architecture) still use the black globe, in outdoor studies, it should be painted gray

Em muitos trabalhos são utilizados globos metálicos, sendo esta opção de material, inclusive, a mais usada em estações meteorológicas portáteis como a da figura 1. Contudo, mais importante que o material do qual é feito o globo é a sua espessura, que deve ser bastante fina, sendo o ideal menos de 0,4mm, segundo trabalho de avaliação de materiais alternativos para confecção de termômetro de globo de SOUZA *et al.* (2002). O globo acoplado ao termômetro de espeto mostrado na figura 2, por exemplo, é de material plástico e espessura fina. Muitos trabalhos (Nikolopoulou, 1999; Thorsson et al., 2007; Yalia e Johanson, 2013; Johansson et al., 2014) tem utilizado materiais semelhantes, tendo, em especial, ganhado notoriedade a adaptação de bolas de ping pong para esta finalidade.

Como já explanado, os valores mensurados de temperatura de globo serão utilizados para calcular a temperatura radiante média através de uma fórmula. Nesta fórmula outras variáveis são necessárias, sendo uma delas a emissividade do material do globo. Neste caso, essa variável poderia ser alterada ao se utilizar um globo com material diferente do metálico, contudo, diversos trabalhos (Hirashima e Assis, 2011;Silva e Alvarez, 2015; Fernandes e Masiero, 2018) mesmo usando globos plásticos, mantém o mesmo valor de emissividade de globos metálicos, a saber, 0,9 para globos pintados na cor cinza e 0,95 para globos pintados na cor preta (indicados para estudos em áreas internas ou com a radiação incidindo de forma indireta, comumente vinculados à Arquitetura).

Sobre o uso da radiação como um componente de análise em trabalhos de conforto térmico humano a mesma vem sendo considerada como uma variável importante para as análises desde meados do século XX.

Missenard (1948), por exemplo, desenvolveu o índice de conforto Temperatura Resultante (RT), quando incluiu os efeitos da umidade e movimento do ar em pesquisas com indivíduos com e sem vestimenta. De acordo com Araújo (1996), a primeira definição prática deste índice foi a de que a temperatura de globo reproduzia o comportamento de um corpo humano.

Outra importante contribuição de Missenard deu-se ainda antes, em 1935, quando demonstrou que os coeficientes de transmissão por radiação e convecção do corpo humano são os mesmos para o diâmetro de 90mm do termômetro de globo (para o ar parado). Posteriormente que tamanho menores de globo favoreciam a observação mais rápida de variações da radiação, o que se revelou importante para estudos de variação de conforto térmico humano e correlação de índices de conforto com respostas subjetivas de indivíduos a diferentes situações meteorológicas.

Tais premissas chegaram ao Brasil. O índice de bulbo úmido e termômetro de globo (Yaglou e Minard, 1957), também chamado IBUTG - que inclui os efeitos da radiação, temperatura do ar, umidade e velocidade do vento, foi adotado pela NR15 do Ministério do Trabalho no Brasil, para avaliação de ambientes de trabalho.

Vários trabalhos foram realizados no Brasil enfatizando a importância da componente radiação no conforto térmico humano. Funari (1995), por exemplo, estudou os efeitos da ocorrência do eclipse total do Sol (novembro de 1994), no conforto térmico; o estudo demonstrou que houve significativa variação do índice de conforto se comparado ao dia anterior ao eclipse – sendo considerados os mesmos horários e tipo predominante de tempo - ; tal fato é associado à queda da radiação solar direta, com o correspondente declínio da temperatura do ar e aumento da umidade relativa. Observe-se que tal influência foi identificada mesmo em médias latitudes, visto que o estudo se deu em Chapecó (SC).

Despite this, there is a clear tendency to use, in Brazil, comfort indices that use only the most basic components for human thermal comfort: temperature and relative humidity, especially because they are easier to apply, considering these data are widely captured and made available at meteorological stations[2].

A trend noted by Epstein and Moran (2006) when analyzing various indices divides them into three groups: 1 - rational, 2 - empirical (incorporating environmental and physiological variables, hence more complex), and 3 - simple, calculated using basic climate variables such as temperature and relative humidity. After their study, they suggest adopting the Discomfort Index (DI), developed by Thom (1959) for heat stress studies. Indeed, this comfort index, also known as the Thom Discomfort Index (TDI) or simply DI (Discomfort Index), is one of the most commonly used in the country.

This trend of using simpler indices significantly reduces the number of studies analyzing the radiation component in human thermal comfort, at least in outdoor analyses linked to Geography. Studies in indoor environments, commonly associated with Architecture, more often include this variable in their analyses. This fact is intriguing because radiation obviously has a greater influence on outdoor thermal comfort, given the occurrence of direct solar radiation. Nevertheless, such architectural studies help reinforce the importance of analyzing this component in outdoor comfort studies.

Regarding studies of thermal comfort in semi-arid regions that consider the radiation variable (or MRT) in their analyses, there is a low prevalence compared to studies that do not analyze this component.

In a literature review on the main indices of human thermal comfort used in the semi-arid region, Gomes and Zanella (2023) identified that less than twenty percent of the studies include indices that use radiation (MRT or other forms of measurement) as one of the calculation variables. This is problematic, according to the authors, considering the region's natural characteristics of intense solar radiation. In their words, "based on the semi-arid region's climatic characteristics, we highlight the importance of using indices that take radiation into account (such as WBGT, UTCI, and other analytical indices) in studies in the region."

The regional characteristics of the semi-arid region, with high insolation rates and high temperatures, are a consequence of its latitudinal position since the region is subjected to strong solar radiation throughout the year. Thus, most of the Northeast region has annual average temperatures ranging from 26 to 28ºC. Only areas situated at higher altitudes have averages below 26ºC (Zanella, 2014).

Such average values can be reached because, as Santos (2009, p. 15) states, in some places in the semi-arid region, on days with the highest insolation, temperatures can exceed 45°C. Additionally, the region exhibits a low annual thermal amplitude ranging from 5°C

[2] Weather stations typically provide comprehensive data on radiation, often measured in watts per square meter (W/m²), rather than in degrees like Mean Radiant Temperature, which is an input variable for thermal comfort indices. While it's possible to establish a correlation between these pieces of information, it's not commonly found in academic literature.

to less than 2°C, from southern Bahia to the northern coast (NIMER, 1989). However, it is known that the daily thermal amplitude is considerable, easily exceeding 10°C.

The average annual precipitation in the Brazilian semi-arid region is around 750 mm (MARENGO et al., 2011). In some areas, the average precipitation does not exceed 400 mm annually. The average potential evapotranspiration can reach 2,500 mm per year, leading to high water deficits (MONTENGRO and MONTENEGRO, 2012). This fact is due to high insolation rates, high temperatures, low annual thermal amplitudes, low and highly variable rainfall totals over time and space (ZANELLA, 2014).

Regarding the region's rainfall and the semi-arid nomenclature, Gomes and Zanella (2023), in a bibliographic article on the region, clarify that the term semi-arid is found in various climatic classifications, and the region delimited as semi-arid in Brazil does not necessarily correspond to a semi-arid type in any climatic classification. Depending on the methodology adopted by the climatic classification, the region recognized by state agencies as semi-arid may present conditions ranging from sub-humid to arid cores, as has been reported in the national press in recent months.

In the semi-arid region, especially during the dry season (in the northern part of the region between the months of August to December), a common meteorological situation is: high average radiant temperature, high air temperature, low relative humidity, and high wind speed.

The objective of this work was to conduct a bibliographic analysis of the use of the solar radiation climatic variable within the perspective of human thermal comfort studies in Brazil and the semi-arid region and to raise methodological guidelines for its main measurement method: globe thermometers and Mean Radiant Temperature formula. To this end, a theoretical exploration of the MRT formula was also carried out to investigate additional methodological guidelines for the use of this radiation measurement methodology

MATERIAL AND METHOD

The methodology used in this work has two bases of analysis, the first is an exploratory and free bibliographical survey on the topic; the second is a theoretical exploration of possible results found for the average radiant temperature using the equation below and therefore dependent on the globe thermometer temperature.

In the second approach, exploratory and theoretical, the Matlab R2022a software was used to carry out the calculations and export graphics. In this approach, we sought to analyze the dependence of the TRM values calculated by the formula below in relation to wind speed, keeping the other variables constant..

$$Trm = \left[\left(T_g + 273 \right)^4 + \frac{1{,}1 \cdot 10^8 \cdot V^{0,6}}{\varepsilon_g \cdot D^{0,4}} \left(T_g - T_a \right) \right]^{\frac{1}{4}} - 273$$

On what:

Trm: Average radiant temperature (°C);

T_g: Globe temperature (°C);

T_a: Air temperature (°C);

V: Wind speed (m/s);

ε_g: Emissivity of the globe;

D: Diameter of the globe (m).

RESULTS AND DISCUSSION

The bibliographic bias of this analysis resulted in two main conclusions. The first is that despite radiation being a climatic component whose influence on human thermal comfort is well documented within the evolution of comfort studies in the twentieth century, it is not included in the majority of human thermal comfort studies in Brazil, including those in the semi-arid region.

In comfort indices that include the radiation component among their variables, the most common way is through the Average Radiant Temperature, we have examples in UTCI[3], PET[4] and SET[5]; There is also the WBTG that directly uses the global temperature.

The second conclusion drawn from the bibliographic bias of this analysis is that the most common method of measuring radiation in comfort indices is via Mean Radiant Temperature (MRT), calculated from globe thermometers. However, for this measurement to be effective, it requires some methodological considerations that are not always systematized and exposed in the studies that employ it.

Thus, we proceeded to order the following methodological guidelines for measuring TRM using globe thermometers: 1 – time required of at least 20 minutes to adjust the globe thermometer before the first reading (HIRASHIMA E ASSIS, 2011); 2 - diameter of the globe, the smaller the more sensitive it is to radiation variations (HIRASHIMA E ASSIS, 2011), 3 - color of the globe, which must be medium gray for studies in external

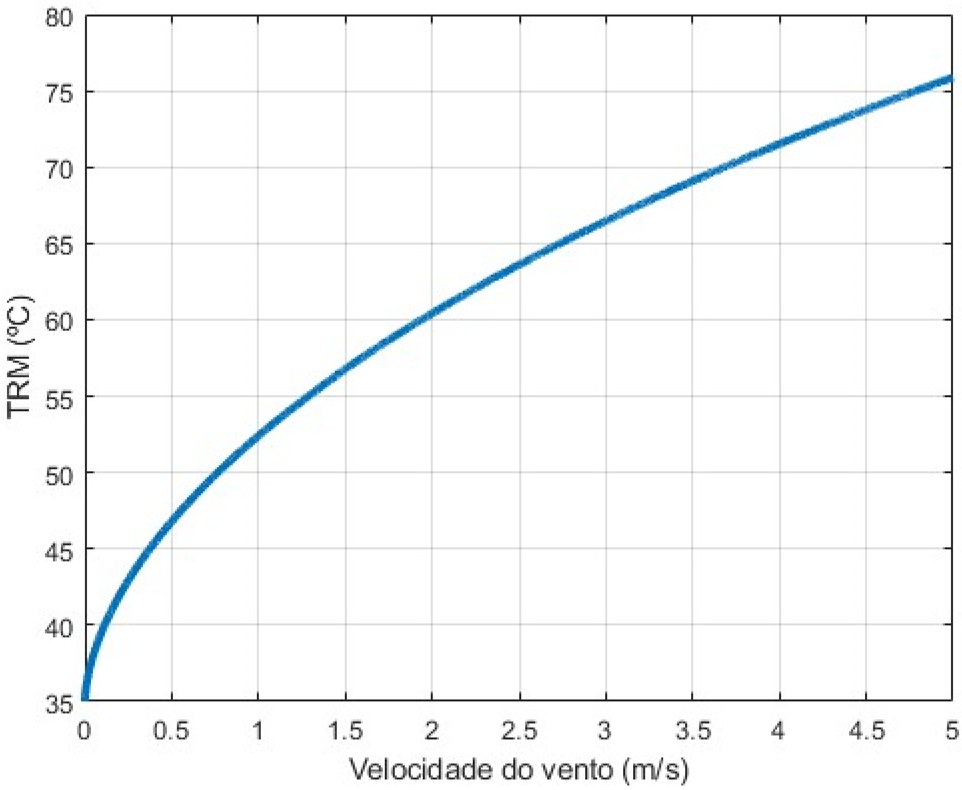
[3] Universal Thermal Climate Index. See Broede et al. (2010)
[4] Equivalent Physiological Temperature. See Höppe (1999).
[5] Standard Effective Temperature. See Gagge et al. (1986).

environments (ISO 7726, 1998) and black for studies in internal areas, 4 - globe material, metal or plastic being acceptable as long as they are thin - ideally less than 0.4mm - (SOUZA et al., 2002); 5 - emissivity of the material, a value that is required in the TRM formula and which is usually 0.95 in work with a black globe and 0.9 in work with a gray globe (ASHRAE, 1997).

It was observed, based on the bibliographic systematization performed and presented above, that there were no methodological guidelines for the use of the MRT formula for acceptable ranges of its variables. Therefore, through free and theoretical exploration of the formula, we sought to analyze the MRT result under different wind speed conditions (while keeping other formula components constant).

The exploration was conducted with wind speed varying from 0 to 5 m/s, and the results obtained were organized in the following graph.

Figure 3: Graph with TRM results for different wind speed conditions.



Source: prepared by the authors.

From the analysis of the formula and the graph of results, it was observed that in situations of complete calmness (when wind speed is zero), the behavior of the formula does not follow the pattern observed when values are different from zero. It tends to overestimate the wind cooling factor and makes the MRT tend toward the same value as the Globe

Temperature, disregarding all heat loss from the globe to the environment, which occurs even in a situation of total calmness.

CONCLUSION

Based on what was verified in the theoretical exploration of the MRT formula and outlined above, we add to the methodological guidelines previously systematized and presented in the results the conclusion that MRT should not be calculated from the globe thermometer temperature with a wind speed value of zero in situations of complete calmness. In these meteorological conditions, we recommend considering a wind speed value of 0.1 m/s. This recommendation is based on the fact that situations of complete calmness of winds are meteorologically rare, punctual, and interspersed with conditions of higher (albeit low) wind speeds. It is worth noting that depending on the methodological orientation for measuring this wind speed, the values would not tend to zero even in calm conditions, if the average wind speeds over an acceptable time interval were considered, allowing for the perception of gentle breezes (see THORSSON et al., 2007).

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