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PMV as a thermal evaluation method for air-conditioned spaces in hot climates: a systematic review

Luiz Bueno da Silva[I], Alinny Dantas Avelino[II]

ABSTRACT

The homogeneity of the subjects that were studied to produce the PMV model developed by Fanger and the evolution of the physical environment have an impact on the usability of the model. Many studies show that the PMV model does not represent the real thermal sensations of the occupants of the analyzed building. The purpose of this review is to identify and group the studies that show some discrepancy between the PMV and the opinions of the subjects concerning modern climatized field environments in hot climates around the world. The PRISMA statement was used to recover and analyze the articles, and 23 studies were selected for this review. The majority of the articles indicated that the PMV model is not suited to evaluate this kind of environment.

Keywords: Predicted Mean Vote; Climatized Environment; Hot Climate

1 INTRODUCTION

The predicted mean vote (PMV) is a mathematical model developed by Fanger (FANGER; NGER, 1973) to evaluate moderate indoor environments regarding their thermal comfort. Since its development between 1967 and 1973, there have been many studies that indicate that the method does not agree with the reality in a variety of environments (ANDREASI; LAMBERTS; CâNDIDO, 2010; ATTIA; HENSEN, 2014; AULICIEMS; SZOKOLAY, [s.d.]; CHOI; LOFTNESS; AZIZ, 2012; CONCEIÇÃO et al., 2012; CORGNATI; ANSALDI; FILIPPI, 2009; DE DEAR et al., 2013; DHAKA et al., 2015; FANGER; TOFTUM, 2002; HUMPHREYS; NICOL, 2002; KIM; MIN; KIM, 2013; KIM et al., 2015; MAITI, 2014; MOREIRA et al., 2012; RAJA; NICOL, 1996; RICCIARDI; BURATTI, 2012, 2015; STRAUB; KUCHEN, 2017; TALEGHANI et al., 2013). The reason for this may be that the original research by Fanger was limited to American college-age students. To verify the influence of national geographic location he considered a further set of 128

[I] Pós-doutor (PPGEP/UFPE, 2009; PPGEB/UNB, 2018)); doutor em Engenharia de Produção (UFSC, 2001), mestre em Engenharia de Produção (PPGEP/UFPB, 1996). Professor Titular da UFPB. - bueno@ct.ufpb.br
[II] Mestre em Engenharia de Produção (PPGEP/UFPB, 2017) - avelino.alinny@gmail.com

college-age Danish subjects in a climate chamber. This results in a lack of heterogeneity in the subjects and environment because the summer in Denmark is colder than the winter in some tropical regions.

The low heterogeneity in the subjects' characteristics and the winter climate in Denmark cause the model to deviate from the real thermal sensations observed in field environments. This deficiency was identified by Fanger and Toftum (2002) who tried to compensate for this deficiency with an expectancy factor and a correction index for hot climates.

Over the last few years, the discrepancy has increase due to the evolution that indoor environments have been going through in hot climate countries. These environments have been climatized and received smart equipment, such as computers, that influences the room temperature and has made it unlikely that the PMV reflects the necessary conditions for thermal comfort (CHOI; LOFTNESS; AZIZ, 2012).

Therefore, this study aims to identify and group the studies that show some discrepancy between the PMV and the opinion of its subjects considering smart climatized field environments in hot climate locations around the world in order to show a consistency in these differences and identify the reasons identified by the researchers as to why this index does not reflect the reality of the analyzed environment.

2 MATERIAL AND METHODS

This review was based on the PRISMA statement method for systematic reviews and meta-analyses. To identify the studies to be filtered, two online databases were used: Scopus and Web Of Science. They were chosen because they both have similar filter options and search mechanisms, and, consequently, it was possible to reproduce the same search in both databases. The search occurred on January 8th, 2018. The terms used in the research were identified through a narrative review to obtain the maximum coverage of articles as in this phase nothing was excluded. The terms of the

search were: “Fanger” OR "thermal comfort" OR “iso7730” OR "predicted mean vote" OR “PMV” OR "thermal sensation" AND “NOT outdoor.”

The exclusion criteria in both databases were set to include only articles or reviews written in English in the engineering or environmental science area and to exclude studies from before 1963. Articles from journals are usually peer reviewed and more reliable; therefore, all other types of documents were excluded. The English language is universal and will allow the information in this article to be reviewed by peers, which is something other languages cannot provide. The combination of words used tends to return results from biology and HRVAC fields that fall under the scope of this research; therefore, these results had to be excluded by limiting the study area. The year of 1963 is before the discussion about PMV began since the 7-point scale of opinion was only developed in 1967.

The eligibility criteria were that the study was conducted in an air-conditioned space in an indoor environment in a hot climate location. For the studies that did not use the term hot climate, the minimal temperature to be included was considered 25°C. Studies found in the narrative review were also considered after removing duplicates.

A quality assessment of the remaining articles was conducted to keep the papers that contained a methodological comparison between subjects’ opinions on thermal comfort and a measured, acquired PMV. It was also considered if sufficient information on the locations and subjects of the study was given in the methodological section of the paper.

The extraction form was elaborated based on the Data Extraction Template for Included Studies from the Cochrane Consumers & Communication Review Group because it consolidates information about publication quality, the article, subjects of the research and the minimum information required to answer this review’s research question. The extraction form was tested and refined using 15 randomly chosen studies.

The information on the extraction sheet was divided into four groups: (1) Characteristics and general information (including year, journal, author, title and

impact factor), (2) Paper basic information (including objectives, methodology, existence of a new model, comparison of the new model and outdoor climate), (3) participant characteristics (including number of subjects, occupation, geographical location, activity, age and gender) and (4) minimal information (i.e., if the PMV reflects the temperature sensation vote (TSV) and the reasons given by the authors as to why it did not when applicable).

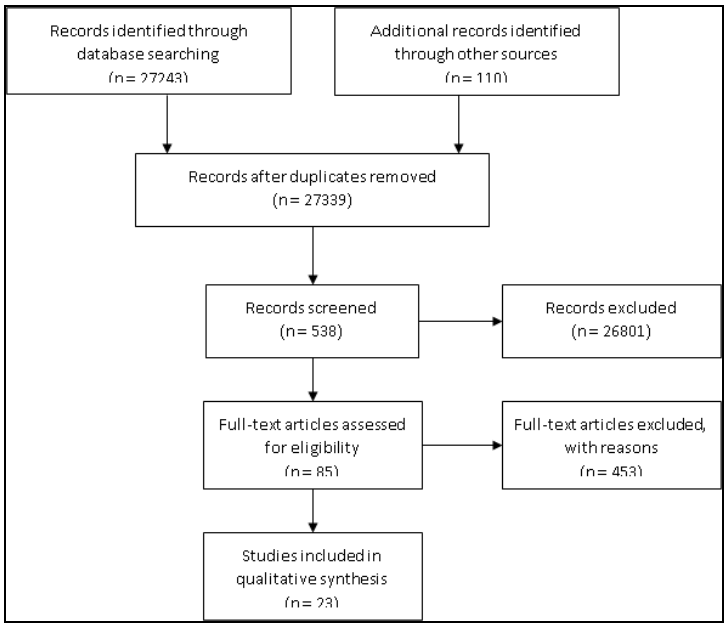
An individual bias analysis was also made in each study to identify bias, either appointed by the author of the study or noticed by the reviewers. All information or lack thereof that could change or better explain the results of the study was considered bias. Additionally, the number of subjects and conditions of the experiment were considered as they radically change the research and make it difficult to generalize.

Data were analyzed qualitatively through reading and extraction of information from each article to identify key aspects of frequency in them. All the information was organized in the extraction form and later summarized in a sheet.

3 RESULTS

A total of 27,243 papers were identified through the database search, and 110 papers were added from the narrative search. Of these, 28,801 studies were excluded because they were in a language other than English and did not explore the research question from an engineering or environmental science point of view. Of the remaining articles, 453 studies did not meet the inclusion criteria as described. After carefully reading the remaining articles, only 23 of them were used in this review as they answered the proposed question and provided quality information about the research that led to its publication. The corresponding flow diagram is in Figure 1.

Figure 1: PRISMA 2009 Flow Diagram



Source: authors

For each study, the characteristics of the participants evaluated were the number of subjects, occupation, location of the research (place, country, and continent), activity at the time of the research, age and gender. Not all the studies showed all the characteristics, but they were all included when present in Table 1.

Table 1 – Characteristics of the subjects

Occupation	**Number of subjects**	**Continent**	**Country**	**Place**	**Activity**	**Age (years)**	**Gender**
Bankers	NI	South America	Brazil	Bank	Sedentary	NI	NI
Welders	9	South America	Brazil	metal-mechanic industry	Welding	NI	NI
Diverse	110	Asia	Malaysia	facility department	Sedentary/office/catering	20-30	24.5% male and 75.5% female
Non-patient diverse work	188	Asia	Malaysia	Malaysia's teaching hospitals	Sedentary/office/catering	NI	28.2% male and 71.8% female
NI	836	Australia	Australia	12 office buildings	Sedentary/office	Average: 33.5	41.5% male and 58.5% female

NI	235	Asia	Singapore	13 office buildings	Sedentary/office	17 - 60 Mostly between 21-40	38.7% male and 61.3% female
Students	100	Asia	Malaysia	lecture halls, labs and at work stations	Sedentary	18 - 28 Average: 23	NI
Students	2	North America	USA	Office/home	Sedentary	22 and 35	100% male
Prayers	NI	Asia	Malaysia	Mosque	Near sedentary	NI	100% male
Office workers	60	Asia	North Korea	Office	Sedentary/office	NI	NI
NI	18	Asia	South Korea	NI	Sedentary	25.44 ± 2.91	NI
Office workers	238	Europe	Greece	Office	Sedentary		40% male and 60% female
Students and staff	75	Asia	India	Electronics Laboratory	NI	21.3% under 20; 76% 20-40; 2.7% over 40	96% male and 4% female
Office workers	33	South America	Brazil	Office laboratory	Sedentary	20 - 40	51.5% male and 48.5% female
Customers and staff	1100	Europe	Sweeden	Supermarket	Shopping	Average: 45	46% male and 53% female
Office workers	NI	NI	Iran	Commercial and office building	Sedentary/Office work	37% under 30; 52% 31-50; 11% over 50	63% male and 37% female
Office workers	NI	Europe	Italy	Office space	Sedentary/Office work	average: 35	NI
Patient, visitors and medical staff	928		Thailand	Hospital	NI	Patients: 47; visitors: 42 Staff: 31	35% male and 65% female

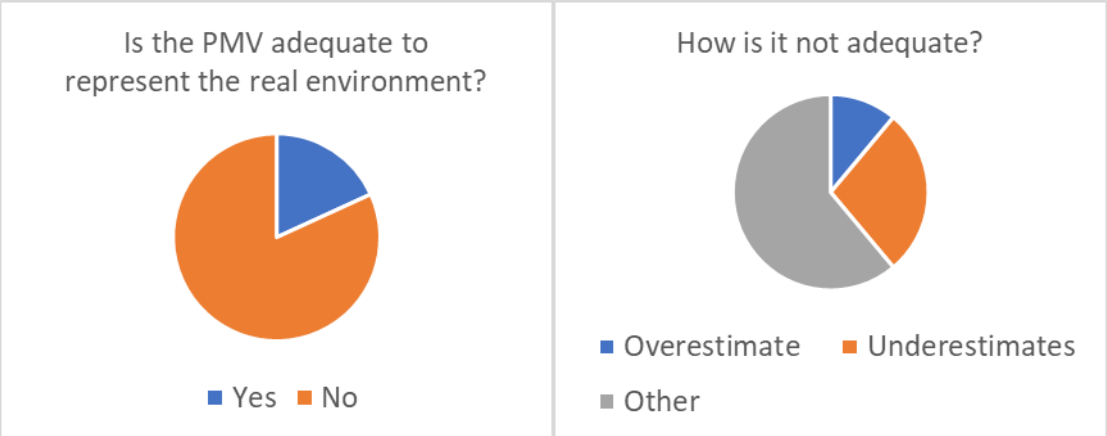
Textile workers	823	Asia	China	Textile company	NI	NI	37.7% male and 62.3% female
Textile workers and students	192	Asia	China	Textile company	Spinning Workshop	workers average: 44 students average: 23.5	47.4% male and 52.6% female
Diverse hospital occupation	114	Asia	Malaysia	Hospital	Diverse hospital activities	NI	12.3% male and 87.7% female
NI	28	Asia	Malaysia	National Museum	NI	20-28	71.4% male and 28.6% female

Source: authors
NI – Not Identified in the study

All the environments depicted in the studies are mechanically ventilated through air conditioning. Also, they are all located in a hot climate considering the minimal external temperature to be included was considered 25°C.

The studies were also read to determine whether the PMV matched the TSV and for the cases when they did not match, why they did not match. This information is summarized in Figure 2.

Figure 2: Does the PMV represent the TSV and why not?



Source: authors

The other items in the extraction table were to organize and assess the quality of each research. The summary of these data is available in Table 2.

Biases were identified for each study individually through reading. The authors of the studies pointed some out, and some were identified as bias by the reviewers. They were: clothing (Andreasi, Lamberts and Cândido, 2010), date of data collection (Andreasi, Lamberts and Cândido, 2010), definition and differentiation of groups (GILANI; KHAN; ALI, 2016; SATTAYAKORN; ICHINOSE; SASAKI, 2017), number of subjects (HASAN; ALSALEEM; RAFAIE, 2016), lack of characterization of the subjects (HUMPHREYS; NICOL, 2002; HUSSIN et al., 2015), measure points (HUSSIN et al., 2015), unorganized display of results(KOSMOPOULOS et al., 2012) and existing noise on the equipment(KUMAR; SINGH; SUD, 2010).

These results were grouped into two kinds of bias: technical and communication. The technical biases were clothing, date of data collection, number of subjects, measure points and existing noise on the equipment. They represent research choices that may have influenced the results of the studies. The other biases were considered communication biases that happen when the authors of the article do not display some of the information necessary to characterize the article in this review.

Table 2 – Summary of the research data

Year	**Journal**	**JCR**	**Number**	**Title**	**Is there a new model**	**Outdoor climate**	**Is the new model more adjusted than the PMV?**
2010	Building and Environment	4.053	(Andreasi, Lamberts and Cândido, 2010)	Thermal acceptability assessment in buildings located in hot and humid regions in Brazil	No	Hot	Does not apply
2014	International Journal of Industrial Ergonomi	1.415	(BRODAY; XAVIER; DE OLIVEIRA, 2014)	Comparative analysis of methods for determining the metabolic rate in order to provide a balance	Yes	Hot	Yes

	cs			between man and the environment			
2013	Indoor and Built Environment	1.181	(AZIZPOUR et al., 2013a)	A Thermal Comfort Investigation of a Facility Department of a Hospital in Hot-Humid Climate: Correlation between Objective and Subjective Measurements	No	Hot	Does not apply
2013	Energy and Buildings	4.067	(AZIZPOUR et al., 2013b)	Thermal comfort assessment of large-scale hospitals in tropical climates: A case study of University Kebangsaan Malaysia Medical Center (UKMMC)	No	Hot	Does not apply
	ASHRAE Transactions: Research		(DE DEAR, RICHARD J; FOUNTAIN, [s.d.])	Field experiments on occupant comfort and office thermal environments in a hot-humid climate	No	Hot	Yes
1991	International Journal Of Biometeorology	2.204	(DE DEAR, 2004)	Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore	No	Hot	Does not apply
2016	Applied Thermal Engineering	3.356	(GILANI; KHAN; ALI, 2016)	Revisiting Fanger's thermal comfort model using mean blood pressure as a bio-marker: An experimental investigation	Yes	Hot	Yes
2016	Building and Environment	4.053	(HASAN; ALSALEEM; RAFAIE, 2016)	Sensitivity study for the PMV thermal comfort model and the use of wearable devices biometric data for metabolic rate estimation	Measure through fitbit	Hot	Yes
2002	Energy and Buildings	4.067	(HUMPHREYS; NICOL, 2002)	The validity of ISO-PMV for predicting comfort votes in every-day thermal environments	No		Does not apply
2015	Architectural Science Review	-	(HUSSIN et al., 2015)	The reliability of Predicted Mean Vote model predictions in an air-conditioned mosque during daily prayer times in Malaysia	No	Hot	Does not apply
2015	Energy and	4.067	(KIM et al., 2015)	Development of the adaptive PMV model for	Yes	Hot and cold	Yes

	Buildings			improving prediction performances			
2013	International Journal of Smart Home	-	(KIM; MIN; KIM, 2013)	Is the PMV Index an Indicator of Human Thermal Comfort Sensation?	No		Does not apply
2012	International Journal of Ventilation	0.391	(KOSMOPOULOS et al., 2012)	An Assessment of the Overall Comfort Sensation in Workplaces	Yes (non substitutive model)	Hot	Does not apply
2010	International Journal On Smart Sensing And Intelligent Systems	-	(KUMAR; SINGH; SUD, 2010)	An approach towards development of PMV based thermal comfort smart sensor	Yes	Hot	No
2006	HVAC and R Research	0.928	(LEITE; TRIBESS, 2006)	Analysis of thermal comfort in an office environment with underfloor air supply in a tropical climate	No	Hot	Does not apply
2017	International Journal of Refrigeration	2.779	(LINDBERG et al., 2017)	Thermal comfort in the supermarket environment – multiple enquiry methods and simultaneous measurements of the thermal environment	No	Hot and cold	Does not apply
2008	Indoor and Built Environment	1.181	(NASROLLAHI; KNIGHT; JONES, 2008)	Workplace satisfaction and thermal comfort in air-conditioned office buildings: Findings from a summer survey and field experiments in Iran	No	Hot	Does not apply
2012	Building and Environment	4.053	(RICCIARDI; BURATTI, 2012)	Thermal comfort in open plan offices in northern Italy: An adaptive approach	No	Hot	Does not apply
2017	Energy and Buildings	4.067	(SATTAYAKORN; ICHINOSE; SASAKI, 2017)	Clarifying thermal comfort of healthcare occupants in tropical region: A case of indoor environment in Thai hospitals	No	Hot	Does not apply
2015	Mathematical Problems in Engineeri	0.802	(YANG; LIU; ZHOU, 2015)	Predicted Thermal Sensation Index for the Hot Environment in the Spinning Workshop	Yes	Hot	Yes

	ng						
2015	Energy and Buildings	4.067	(YANG; LIU; REN, 2015)	Thermal environment in the cotton textile workshop	yes	Hot	Yes
2009	indoor air	4.383	(YAU; CHEW, 2009)	Thermal comfort study of hospital workers in Malaysia	No	Hot	Does not apply
2013	Indoor and Built Environment	1.181	(YAU; CHEW; SAIFULLAH, 2013)	A Field Study on Thermal Comfort of Occupants and Acceptable Neutral Temperature at the National Museum in Malaysia	No	Hot	Does not apply

Source: authors

4 DISCUSSION

In 18.18% of the reviewed papers, the PMV was considered adequate to predict the TSV among the subjects of each research. Predominantly, the PMV was found to be inadequate. In these cases, it more frequently overestimates the TSV for hotter votes while underestimating colder votes in the 7-point scale (HUMPHREYS; NICOL, 2002; KIM et al., 2015; KOSMOPOULOS et al., 2012; YAU; CHEW; SAIFULLAH, 2013).

Although many reviews have been made to show the discrepancies between the PMV and the TSV, this one shows that the PMV is also inaccurate to air-conditioned spaces in a hot climate, going against what's stated by Fanger and Toftum (FANGER; TOFTUM, 2002) that the PMV model agrees well in buildings with HVAC systems, situated warm climates and studied during the summer.

Studies indicate that individuals residing in hot humid regions have a higher tolerance to high temperatures than those residing in temperate climates. The comparison of the thermal sensation indicates that those subjects have significantly higher or wider ranges of thermal comfort for tropical climates than those obtained in Central and Western Europe. (HIRASHIMA; ASSIS; NIKOLOPOULOU, 2016)

Research in air-conditioned buildings started in 1991 (DEDEAR; LEOW; FOO, 1991), mostly in university environments and offices and focusing on sedentary work. In university and industrial environments, the subjects are mostly male, while in

hospitals and offices the subjects are mostly female. The papers do not classify their results based on the subjects' characteristics such as gender or age.

China has been given attention as an emergent country in thermal comfort research (DE DEAR et al., 2013), and though investigations conducted in China appear in the review, Malaysia is the country that has been developing the majority of the studies in the field.

The main purpose of the articles was not in most cases to simply evaluate the environment. Of the papers, 31.81% presented a new model to evaluate thermal comfort in the said environments, and some of them included a comparison between PMV and the adaptive model, which is also listed as one of the tendencies of research in this field in the last few years (DE DEAR et al., 2013; DJAMILA, 2017). Of the new models proposed, 85.71% showed better results than the PMV in the environments to which they were applied.

The reasons appointed to justify the discrepancies found in the papers from the PMV to the TSV varied between the metabolic rate, acclimation, air velocity, clothing insulation, chair insulation, lack of gender differentiation, psycho-physiological reasons, environment temperature, scale, inconsideration of personal variables and limitations from the questionnaire.

The majority of the articles presented either metabolic rate or some criteria associated with it (such as personal variables) as the reason the opinions disagree with the PMV. A 15% error in the assessment of metabolic rate can easily lead to errors in the PMV greater than 0.3 depending on other conditions (HAVENITH et al., 2002), which can explain why the metabolic rate and associated factors appear as the most frequent bias in the papers reviewed.

As identified by some of the authors (ANDREASI; LAMBERTS; CÂNDIDO, 2010; HUSSIN et al., 2015) the lack of agreement between TSV and PMV is often due to sensitivities of the input values (ANDREASI; LAMBERTS; C??NDIDO, 2010; AZIZPOUR et al., 2013b; BRODAY et al., 2014; GILANI; KHAN; ALI, 2016; HASAN; ALSALEEM; RAFAIE, 2016; HAVENITH et al., 2002; HUSSIN et al., 2015; KIM et al., 2015; KUMAR; SINGH; SUD, 2010; LINDBERG et al., 2017; YANG; LIU; ZHOU, 2015). The reasons appointed to

justify the discrepancies found in the papers from the PMV to the TSV varied between the metabolic rate, acclimation, air velocity, clothing insulation, chair insulation, lack of gender differentiation, psycho-physiological reasons, environment temperature, scale, inconsideration of personal variables and limitations from the questionnaire.

The main appointed reason for the discrepancy was the metabolic rate or activity levels (BRODAY; XAVIER; DE OLIVEIRA, 2014; GILANI; KHAN; ALI, 2016; HASAN; ALSALEEM; RAFAIE, 2016; KIM et al., 2015; KUMAR; SINGH; SUD, 2010; LINDBERG et al., 2017). Therefore, it is possible to infer that unrealistic values for the metabolic rate can be the reason of overestimation/underestimation of the experienced thermal sensation. This can result in systematic errors which have just recently begun to be highlighted in the literature.

The papers do not disclosures enough of the questionnaires used in each of the studies to evaluate their elaboration, but one(RICCIARDI; BURATTI, 2012) of the 23 identifies the questionnaire as a possible reason to the inadequacy of the PMV to the studied environment.

The main limitation of this review is that the diagnosis of the reason as to why the PMV was inadequate for the environments was given by the author of each study, and therefore, each author limits what is adequate and what is inadequate.

The models presented in the studies that show a new model cannot be generalized as they were produced in a specific environment and can only be applied to that environment.

5 CONCLUSION

The data collected and analyzed through this review show that the PMV is not generally adequate to express people's sensation considering just smart climatized field environments in hot climate locations. The studies selected included a variety of environments of the selected type showing that this issue is not concentrated to a specific kind of environment or related to a specific activity. It is obvious that the

evolution in this field is steady, and people are constantly looking for models that best suit the environment researched.

As expected, the number of articles that fitted the research eligibility and exclusion criteria was very limited due to the bottleneck imposed by the searched criteria. As already known at the beginning of Fanger research activity, PMV model cannot be generalized in all conditions and cannot be applied to this specific type of environment.

In practical terms, the use of this model may cause excessive use of energy due to miscalculations of comfortable temperatures. Theoretically, it shows a gap that needs to be filled with models that consider the reasons discussed in this article as to why the PMV is not adequate for said environments. Findings from field surveys like the ones presented in this paper are a step forward to improve the applicability of the PMV model.

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