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THERMAL COMFORT ANALYSIS: A SYSTEMATIC LITERATURE REVIEW

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Abstract. Research related to thermal comfort is motivated by the improvement of quality of life, ergonomics, safety, energy efficiency and also as a competitive differential in the industry. In recent years, numerous researchers have sought the development of science and technology through studies of thermal comfort models, such as Fanger's PMV-PPD indices and the use of thermal mannequins through equivalent temperatures, also by modeling the body's thermoregulatory systems and in the assessment of different thermal environments. Currently, computational fluid dynamics (CFD) is employed as a powerful tool to provide numerical simulations of flow and heat transfer, thus allowing a better understanding of the various phenomena in comfort. The coupling between numerical simulations, experimental analyzes and thermal comfort models allows greater precision in the results related to the thermal environment. This work aims to carry out a systematic review of the available literature on the analysis of thermal comfort. Based on the Scopus database, this review presents important research on the topic, disseminating the way the world is addressing this issue and promoting research gaps and trends in future work to seek the advancement of science and technology.

Keywords: CFD, equivalent temperature, experimental, Fanger, thermal comfort, PMV-PPD.

1. INTRODUCTION

Global warming has been causing constant climate changes in recent years, and we can see that the temperature of the planet is increasing (NASA, 2020). With this overheating, the search for human beings for comfortable thermal environments that provide a better quality of life becomes increasingly greater.

Thermal comfort is defined as a condition of the human being's mind that demonstrates satisfaction according to the thermal conditions of the environment, where being thermally comfortable depends on several environmental and personal factors, and vary from individual to individual (ASHRAE 55, 2017).

Thermal comfort has become a source of much research in recent years. From studies of Fanger (1972), considered a pioneer in the subject, numerous researchers sought the development of science and technology in favor of better methods and ways of evaluating thermal comfort.

Having a thermally comfortable environment is of fundamental importance, as it promotes improvement in quality of life, reduction of thermal stress, promoting safety in jobs that require attention, aiming to improve issues such as energy efficiency, and also to be a competitive differential for the industry.

In recent years, research related to thermal comfort has basically been divided into three main areas: in the development of models that seek to understand the various variables that influence comfort, in the study of the human body's thermoregulation system and its modeling, and in the evaluation of different types of environments and conditions, whether homogeneous or not, stationary or transient.

The development of technology and the dynamics of computational fluids has enabled researchers to better understand how the various variables influence thermal comfort, where together with other methodologies such as Survey surveys and experimental measurements, they can provide more reliable results.

Seeking to understand this broad field of research, mapping the literature can help to identify research gaps and future trends, allowing to guide studies in search of the development of science and technology.

With this precept, this work aims to conduct a systematic review of the literature, identifying the most relevant research in the area and the trends for studies related to thermal comfort.

2. METHODS

In order to identify the most relevant research for the topic in question and improve the quality of the literature review, a bibliometric review step was inserted, where it was possible to quantify and map the most relevant works in the area. The research process for the systematic literature review was based on the integrated method (Dresch et al, 2015).

With these data it was possible to determine the important work and then carry out the analysis and discussion of the results. The first stage of the work consisted of determining the search protocol to be followed during the research, as shown in Tab. 1.

Table 1. Search protocol for systematic review.

Conceptual framework	We sought to determine the state of the art in the literature regarding the study of human thermal comfort.
Context	Broad context focused on the concern of how the topic of thermal comfort is being addressed and identification of research gaps and trends in future work.
Horizon	Works related to methods of assessing human thermal comfort and its evolution in recent years, mainly in the study related to comfort in public passenger transport.
Theoretical current	All works of a subjective, experimental or numerical character.
Languages	English.
Review question	What is the state of the art in relation to the study of thermal comfort for human beings and how is this subject being treated?
Review strategy	Aggregative, to answer the review questions.
Search criteria	Includes: Complete articles only; Just English; Only in the final version; Contains the keyword "Thermal Comfort" Exclusion: articles that do not contain the inclusion requirements; that are not articles in the final version;
Search sources	Scopus / Elsevier.
Search terms	"thermal comfort" AND simulation "thermal comfort" AND experimental "thermal comfort" AND CFD "thermal comfort" AND cabin "thermal comfort" AND vehicles "thermal comfort" AND bus "thermal comfort" AND aircraft "thermal comfort" AND train "thermal comfort" AND subway "thermal comfort" AND "solar radiation" "thermal comfort" AND dummy "Solar radiation" AND CFD AND vehicles "ISO 7730" "ISO 14505" "ASHRAE 55" "ISO 7796"

With the definition of the protocol, a search was carried out in the selected database (Scopus) and the number of articles related to the theme was identified from the defined keywords.

For bibliometric analysis, the data sets obtained in the search were exported to the VOSviewer software where it was possible to determine the most relevant authors and the best articles related to the topic. These selected articles were evaluated for further analysis and discussion of the results in order to achieve the research objectives.

3. RESULTS

Through the proposed method, a systematic analysis of the literature was carried out, where the works were initially quantified by means of bibliometric analysis and later analyzed the most relevant works in the area.

3.1 Bibliometric analysis of the literature

The search in the database showed several published research related to the topic. Table 2 shows these data based on the search terms used.

For the study, searches that obtained the keywords in the title or abstract were identified using the search tool of the Base Scopus. With the combination of the selected keywords, the sets of articles were exported to the VOSviewer Software to perform bibliometric analyzes and create maps of the most cited authors.

Table 2. Quantities of work in the Scopus base.

Date of search	Search terms	Number of works
August 21, 2020	"thermal comfort" AND simulation	2,891
	"thermal comfort" AND experimental	2,399
	"thermal comfort" AND CFD	848
	"thermal comfort" AND cabin	272
	"thermal comfort" AND vehicles	339
	"thermal comfort" AND bus	79
	"thermal comfort" AND aircraft	156
	"thermal comfort" AND train	80
	"thermal comfort" AND subway	41
	"thermal comfort" AND "solar radiation"	584
	"thermal comfort" AND dummy	8
	"Solar radiation" AND CFD AND vehicles	20
	"ISO 7730"	539
	"ISO 14505"	12
	"ASHRAE 55"	186
	"ISO 7796"	0

With the combination of the terms "thermal comfort" AND simulation, the most relevant groups of authors were identified and researched on the topic. To illustrate and identify these groups, maps were created with the VOSviewer Software. Figure 1 shows an analysis map of the most cited and relevant authors.
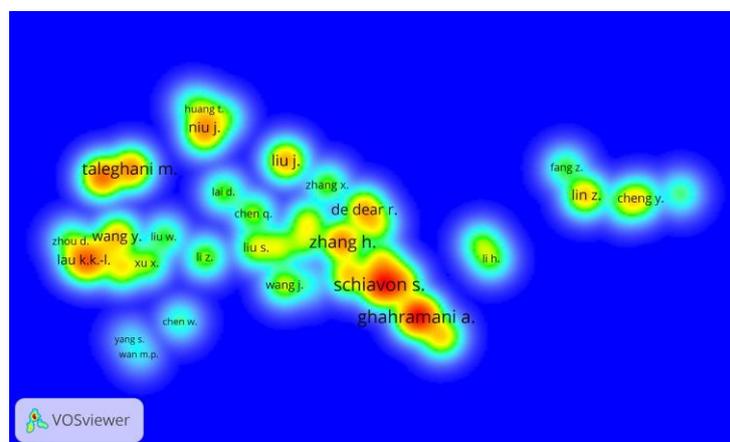

Figure 1. Map of relevant authors for chosen combination

With this procedure, it was possible to identify the relevant works in the area and select them to carry out the analysis and discussion of the results. For each combination of defined keywords, the most relevant articles were selected based on bibliometric analysis.

We selected 40 articles published in the last 20 years, giving greater relevance to the most recent works. Figure 2 shows the number of articles selected per year, showing the largest number of studies selected for review in recent years.
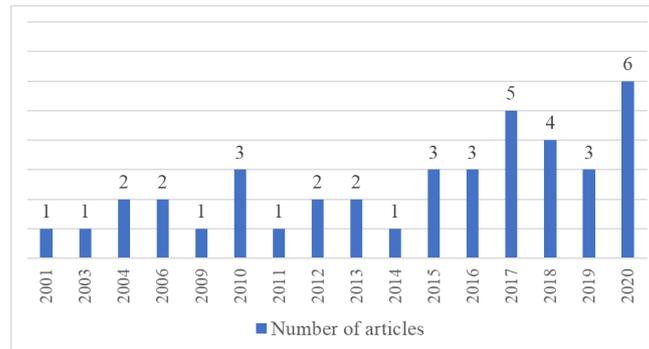

Figure 2. Number of selected articles per year

For the 40 selected articles, 3 major research areas were identified: studies aiming to promote improvements and developments related to thermal comfort models, research with the main focus on the environment in which the human being is inserted and works that seek to model and evaluate the human body and its thermoregulation system. Figure 3 shows the percentage of articles selected in this work for each major area, which demonstrates that most of the selected works show the interest in evaluating the environments in which the human being is inserted and ways of evaluating thermal comfort. Among the selected works, the types of diverse environments referred to in the studies were also evaluated, where Fig. 4 presents the percentage based on the evaluated environments.
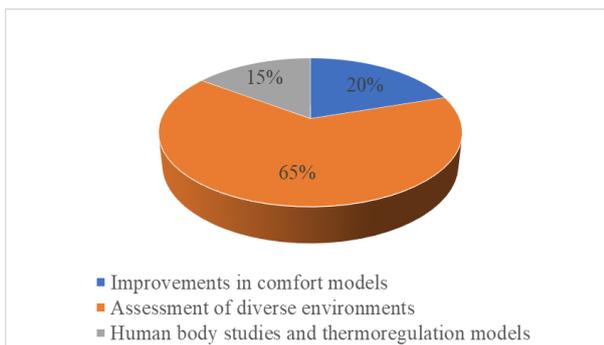

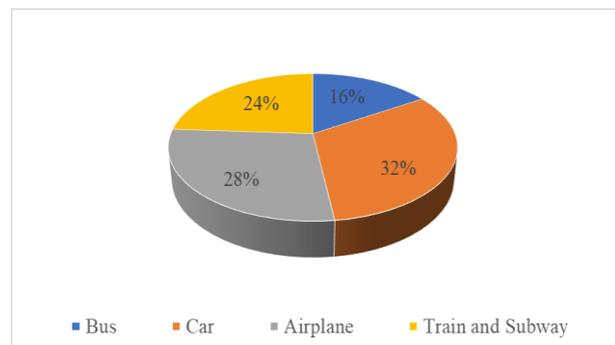Figure 3. Percentage of works based on the main objective of the study

Figure 4. Percentage of works based on the study environment

Through the bibliometric analysis carried out, the discussion and analysis of the selected works was conducted. For the evaluation, the articles were separated based on the main objective of the research: studies aiming to promote improvements and developments related to thermal comfort models, research with the main focus on the environment in which the human being is inserted and works that seek to model and evaluate the body and its thermoregulation system.

3.2 Development and improvement of thermal comfort models

According ASHRAE 55 (2017) thermal comfort is defined as a condition of the human being's mind that demonstrates satisfaction according to the thermal conditions of the environment. There are six primary factors that influence the thermal comfort of the human being, namely: the metabolic rate, the clothing used, air temperature, radiant temperature, air speed and relative humidity. In addition to these, other factors also influence comfort, such as age, physical inactivity, health conditions, among others.

Each of the factors that involve the thermal comfort of human beings has been a source of research, such as the thermal insulation of clothes, observed in the work of Schiavon and Lee (2012), where they developed a research in order to identify the insulation of clothes normally used by office occupants aiming at the application in thermal comfort calculations. Based on the data available in the ASHRAE database, the influence of 20 variables on the insulation of clothing was analyzed statistically. The results showed that the average insulation of the clothes is 0.59 clo in the summer and 0.69 clo in the winter. This suggested average value is significantly lower than the indicated value and international standards (1.0 clo) for the winter. The data obtained allows the dimensioning of air conditioning systems and more accurate thermal comfort calculations.

Based on studies of Fanger (1972), considered as the pioneer in thermal comfort studies, where we sought to relate the various variables that influence comfort through indices, based on subjective responses and experimental measurements, which originated the PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) attributed by the standard ISO 7730 (2005).

Since then, numerous researches have been carried out aiming to evaluate the applicability of these indexes in different environments and also the development of new indexes and researches to improve the thermal comfort models as also addressed by Hoof et al. (2010) in its literature review with studies since the 1990s, mainly addressing the PMV-PPD indices, as illustrated in Fig. 5.

Due to the fact that thermal comfort is something complex, where providing comfort conditions acceptable to all human beings is difficult due to the physical characteristics of each individual, several studies seek to evaluate new methods and models of thermal comfort to improve the accuracy of the thermal sensation.

Thus, in addition to global comfort indices that involve several variables, there are local indices that influence comfort such as asymmetric radiation, the vertical difference in temperatures, drafts, hot or cold floor temperatures. As can be seen in the study, Liu et al. (2020) evaluated the vertical difference in temperatures based on subjective and environmental data. The objectives of the study sought to develop a statistical model to estimate the percentage of dissatisfaction for this vertical difference. The results suggest that the vertical temperature gradient between the feet and the head can be increased to 5 ° C, noting that the standards (ISO and ASHRAE) suggest 3 ° C / m as the limit.

Many authors also tend to separate comfort assessments in homogeneous and non-homogeneous environments, bringing different approaches for each type of environment, however further studies are still needed to validate each method adopted in each type of environment. The following works demonstrated these differences found.

Cheng et al. (2012) carried out a review of several thermal comfort models that address thermal sensations mainly in non-homogeneous environments, highlighting their advantages and limitations. After that, two typical comfort models, the ISO 14505-2 standard and the UC Berkeley comprehensive comfort model (UCB model), were coupled to the computational fluid dynamics (CFD) numerical simulation with different processes for assessing the thermal environment of a small office. The results indicated that the ISO standard model can be applied as a convenient method to evaluate comfort in non-uniform and thermally neutral environments in general. Comfort in non-uniform and often transient thermal environments has been a source of recent studies for researchers.

Similarly, Schellen et al. (2013) discussed a physiological model for a non-homogeneous environment built to evaluate a thermal sensation through computational numerical simulation (CFD). The results were compared with studies in the literature to validate the method in three available models: predicted average vote index (PMV), UC Berkeley thermal heating model and the ISO 14505 standard (as shown in Fig. 6). The use of each model is used to link physiological responses to the thermal sensation. The results obtained show that PMV is not able to predict comfort when local effects are more influential. In addition, they indicate that thermological physiological models combined with UC Berkeley or ISO standard models seem promising for predicting thermal heating in non-uniform environments in general. However, more research is needed to substantiate such claims.
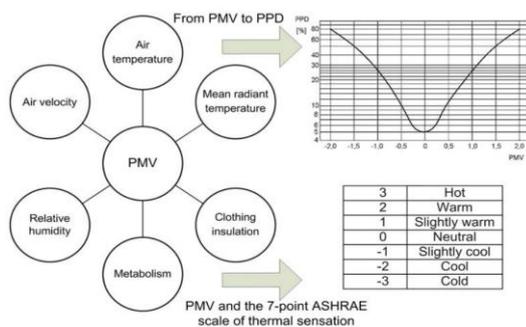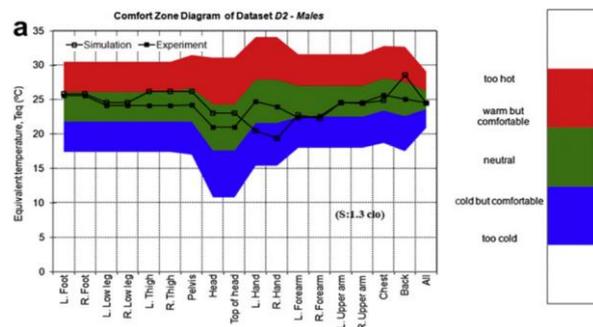

Figure 5. PMV-PPD indices

Figure 6. Equivalent temperature

The standard ASHRAE 55 (2017) brings an advanced model to predict thermal comfort in environments, named SET (standard effective temperature). Researchers seek to improve methods more and more, bringing greater precision to models such as the SET provided for in the standard. An example can be seen in the research of Zhang and Lin (2020), who proposed two SET-based models to assess thermal comfort, namely: Extended predicted thermal sensation (PTS) and Predicted adaptive thermal sensation (aPTS). To validate the proposed models, case studies were carried out using data from building fields with natural ventilation and air conditioning. As a result, it was identified that both models improve the prediction of the thermal sensation, surpassing the conventional models.

Similarly, Zhang et al. (2010) studied and developed models to predict thermal sensation and comfort throughout the body. The developed models apply to sedentary activities in different environments: uniform and non-uniform, stable and transitory. The research was carried out based on data collected in experimental research for the environments already mentioned. And concluded that, in order to keep the whole body comfortable, one should eliminate as much as

possible uncomfortable local conditions that present the highest values, and there may also be benefits providing personal control of environmental conditions.

Aiming to provide researchers, professionals and students with tools for assessing thermal comfort based on standards, Tartarini et al. (2020) developed an online tool for the calculation and visualization of various thermal comfort assessment methodologies based on international standards (ISO, ASHRAE and EN 16798–1). The program incorporates the latest thermal comfort models based on these standards, such as: the average expected vote (PMV), the standard effective temperature (SET), adaptive models, and local discomfort. It also has solar chart information and insulation for clothing. It is possible to dynamically observe the thermal comfort zones according to the variables by means of graphs. This tool allows users to perform complex thermal comfort analyzes based on international standards and free of charge.

This field of research that seeks the development of new methodologies to evaluate the thermal comfort of human beings is of paramount importance, since working together with advances in technology, it can provide several benefits such as energy efficiency, health and quality of life to Society.

3.3 Evaluations of thermal mannequins and human body thermoregulation system

Another area of great importance that is also a source of research in recent years are studies that seek to model the thermoregulatory system of the human body. These mathematical models developed allow us to better understand how the thermal distribution of the body is, to evaluate issues such as breathing, perspiration, and also, if used in conjunction with the numerical simulations of environments and models to predict thermal comfort, it can provide great advances in science and technology.

Several studies seek to represent the phenomena of conduction, convection and radiation applied to humans and their thermoregulation system. As can be seen in the work of Huizenga et al. (2001), that present a model of human regulation that simulates the layers of the body and also of the clothes, according to associations shown in Fig. 7. Physiological factors such as vasodilation, vasoconstriction, sweating and metabolic heat production are also considered. The model is also able to predict the physiological response to transient and non-uniform thermal environments. These environments present the greatest difficulties of current models for predicting comfort.
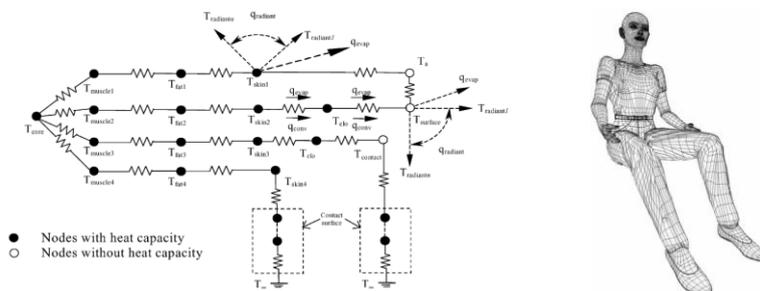

Figure 7. Resistance associations for the human body thermoregulation model

With this mathematical development of the human cup thermoregulatory system, several studies also propose the coupling of these models with computational simulation tools and models of thermal comfort. As an example, the work of Gao et al. (2006), where they investigated through a numerical solution the personalized ventilation aiming to evaluate the air quality and the thermal comfort in the place. A thermoregulation model of the human body was attached to the CFD and then the customized ventilation systems were evaluated. Personalized ventilation has great potential to improve air quality and local thermal comfort. The air velocity calculated by the CFD close to the body surface and inserted in a thermoregulation model (Berkeley) so that local thermal comfort in a non-uniform environment can be investigated.

Another similar work was carried out by Treeck et al. (2009), who developed and tested a parametric model of multisegmented thermal mannequin of human thermoregulation models using computational codes to study the effects of transient and local thermal perception and sensation. The developed interface allows the interaction with the computer simulation (CFD). Clothing conditions and activity level can be modified on a real-time scale. The visualization on the skin of the mannequin includes the surface temperatures, the votes of the local thermal sensation (LTSV), the predicted average vote (PMV) and the dynamic thermal sensation (DTS). The model was validated based on experimental data.

Several studies have developed studies of these effects on humans, such as Gao et al. (2019) who investigated the effects of ambient temperature, air speed and wind direction on the body's thermal conditions. The results showed that higher ambient temperatures led to a decrease in the heat transfer coefficient and an increase in the radiation coefficient. And also Tian et al. (2011) who evaluated the influence of the average local air temperature in an office using a numerical method. The results showed that when the air supply increases from 19 ° C to 21 ° C, the average

temperature of the occupied area increases from 24.5 ° C to 26.5 ° C. The air quality is improved when the supplied air increases from 19 ° C to 21 ° C. In addition, the PMV-PPD comfort indices meet the requirements of ISO 7730: 2005.

In addition to simulation and mathematical formulations, the validation of thermal mannequins through experimental evaluations is essential. As observed in studies such as Cheng and Lin (2016), who experimentally investigated the effect of a human body on the pattern of a global air flow and correlation with subjective research allowed us to better assess the human being's thermal sensation in the face of air flows, and also to validate the models developed.

Similar to the previous work, Fojtlín et al. (2019) examined typical approaches to obtain local thermal properties of clothing and subjective perception in heterogeneous environments. Standing and sitting conditions were also assessed. The impact on the thermal sensation is demonstrated based on the simulated thermo physiological responses. The results showed noticeable differences in the thermal properties of the clothes between the sitting and standing positions on the lower limbs and torso.

The development of studies related to thermal mannequins and modeling of the human body's thermoregulatory system is essential for a more in-depth assessment of comfort, especially in transient and non-homogeneous environments, where each part of the body may be providing comfort conditions different from global levels, as well as variation over time, in naturally ventilated environments for example.

3.4 Thermal comfort studies in different environments

Another great area very widespread among thermal comfort researchers is to identify, based on the environment in which the human being is inserted, ways to predict whether the thermal environment is comfortable and how to carry out the evaluation. For this research, the environments of interest were collective passenger transport, as conducted through the keywords selected for searching the database.

In this way, it was basically divided into four collective passenger transport: airplane, car, bus, train and subway. Where the methods and results obtained were evaluated for each environment.

3.4.1 Airplane

The study of thermal comfort in aeronautics is of great interest to several researchers, and of great importance to society, as it is the main means of international transport. As addressed by Fan and Zhou (2018) in your review of the literature on thermal comfort in airplanes, there are several factors that influence comfort such as low relative humidity, radiant temperature, and human metabolism. According to the authors, comfort models can be divided according to the environment, being stationary or transient, and uniform or non-uniform. In this environment, many authors have studied ways to improve air quality without reducing comfort conditions, proposing new models of ventilation systems.

As can be seen in the research of Maier et al. (2017) who studied three different versions of ventilation systems (100% by variable displacement; 70:30% hybrid system combining variable displacement and mixed ventilation; 50:50% hybrid system combining variable displacement and mixed ventilation) in a simulated aircraft cabin. For the assessment, they conducted surveys based on objective and subjective data with 40 participants in each system. Air speed and temperature data were also collected and thermal dummies were used in the aircraft's unoccupied seats. The results were compared with a previous study with mixed ventilation only. The data obtained revealed that the vertical temperature difference in systems 100% by variable displacement and mixed ventilation is relatively smaller. Air speed was lower with a variable displacement system and increased with a greater amount of mixed ventilation provided.

Another interesting job was done by You et al. (2018) where they carried out experimental and numerical studies to improve the ventilation system of the airplane cabin, as can be seen in Fig. 8. A new system was proposed designed to reduce contaminants and maintain thermal comfort. With the research, it was verified the best configuration of diffusers and exhaust fans that the cabin must have to transport contaminants and maintain thermal comfort.
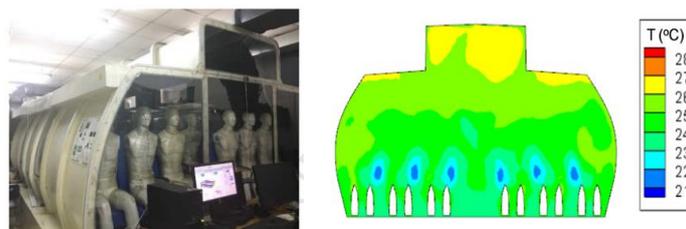

Figure 8. Numerical and experimental study of the airplane

You et al. (2016) they also evaluated, through experimental and numerical measurements, the distribution of air in an airplane cabin model. The study demonstrated the best practices for carrying out the experimental measurements and for the numerical simulations, corroborating with the previous study referring to improvements in the aircraft's ventilation systems.

Other ways of seeking to improve the ventilation systems of aircraft cabin is the use of optimization methods. According to research Wei et al. (2019), where they studied optimization methods to improve the ventilation system of an aircraft cabin. The results indicated that the integration of several methods made it possible to obtain the best solutions and reduce computational time. The results made it possible to achieve optimal design values to ensure better conditions of thermal comfort for passengers and improve the ventilation system.

In addition to these simulation fields with a focus on the cabin ventilation system, experimental studies and subjective research are essential to validate the methods and models of comfort in this environment. Thus, we can observe two studies that carried out studies like this.

Cui et al. (2014) who explored the field of thermal comfort in an aircraft cabin including the spatial distribution of the environment with parameters such as air temperature, relative humidity, black globe temperature and air speed, in addition to a survey questionnaire for passengers. In the aircraft, the position of the seats can influence comfort, if it is close to the window it can be influenced by hot or cold radiation and passengers in areas of high human density can be influenced by the higher temperature. The results indicated that the spatial distribution in the cabin was not uniform, but the difference did not significantly influence the assessment of comfort, probably due to the possibility of self-adjustment of passengers. Based on the local analysis, it was observed that the upper body was the most comfortable. The study also showed that by improving local comfort in some parts of the body, it is possible to achieve better conditions of global thermal comfort.

Another interesting study was conducted by Giaconia et al. (2015) who investigated thermal comfort in short-haul domestic flights by means of experimental measurements, comfort indexes and subjective research. Air temperature, radiant temperature and relative humidity data were collected during the flights. The air temperature varied between 22.2 ° C and 26.0 ° C, the humidity between 8.7% and 59.2%. The calculated PMV values ranged from -0.16 to 0.90 and were confirmed based on the responses of the passengers. The equivalent temperature was also calculated based on ISO 14505-2, correlating with the other determined indices. The results indicated that the equivalent temperature can also be used to assess comfort in this environment, in addition to the PMV index.

Each environment has its particularity that influences thermal comfort, as well as several methodologies for evaluation, either experimental or subjective, or through numerical models. The combination of these methods is fundamental for the assertiveness of comfort predictions. The study of the various variables that influence thermal comfort in humans is quite complex, where in aircraft, the study of ventilation systems where better air quality and thermal comfort conditions is very important, since they are long trips in which the human being will be exposed.

3.4.2 Car

Similar to airplanes, automobiles are widely used by human beings, and also a source of various research. However, the environment of the car and the conditions that influence comfort are quite different, as an example, the length of stay of the human being is much shorter than long international trips, also due to the conditions imposed by the external environment such as direct solar radiation, large glass area, air renewal, among other factors.

In automobiles, solar radiation is one of the most studied factors today. Several studies have developed numerical simulation models with experimental validation to represent this solar condition. In parallel, the use of thermal comfort models standardized in ISO 14505-2 for automobiles, where it uses the method of segmenting the human body and determining equivalent temperatures for each area of the body is widely used together with the PMV-PPD indices for comparison methods.

As an example, the work of Khatoon and Kim (2017) and Khatoon and Kim (2020) where they investigated thermal comfort in a car cabin using numerical simulation, solar radiation and models of thermal comfort (Fanger, modified Fanger and equivalent temperature). Through the results it can be seen that the combination of comfort indexes can improve the precision obtained in estimating the thermal comfort of the vehicle. Comparing the thermal comfort models, it was found that the Fanger models (PMV-PPD) provided satisfactory results for the overall comfort index, despite the equivalent temperature model demonstrating the inhomogeneity of the thermal environment in the vehicle. Fig. 9 shows one of the analyzes of the simulation performed.
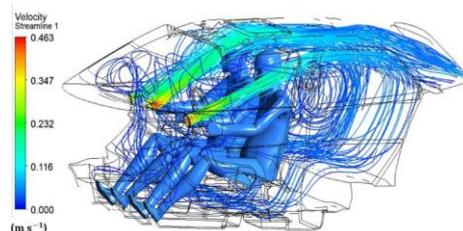

Figure 9. Analysis of the current lines of the simulation in the automobile

Similarly, Moon et al. (2016) investigated, through numerical simulation, the thermal comfort in a passenger compartment considering the spectral solar radiation. Using the ANSYS Fluent software, which has a built-in solar

charge model, the simulation was performed to accurately predict the thermal and flow fields under operational conditions of heating, ventilation and air conditioning. In this study, the Fanger model and the equivalent temperature model for comfort analysis were compared. Based on the results obtained, the temperature estimated near the driver and passengers increased by about 1 to 2 ° C when considering solar radiation. When comparing the two thermal comfort models, it can be seen that, unlike the Fanger model, which demonstrates comfort on a global level, the equivalent temperature model can predict local temperature problems in comfort levels.

Rosendahl and Olesen (2006) also evaluated the thermal environment of a vehicle using three parameters to assess thermal comfort (air temperature, operating temperature and equivalent temperature). The tests were carried out in the winter period during heating. To assess the environment, ISO 14505-2 was used as a basis using the equivalent temperature method. Six transducers were used to represent different parts of the body. The results showed that the use of air temperature or operating temperature only as a parameter for assessing thermal comfort in vehicles is not very ideal. The equivalent temperature better represents the inhomogeneity in the evaluated case.

RUŽIĆ and Stepanov (2013) evaluated through numerical simulation, the influence of the direction and intensity of solar radiation on the thermal flow of a car driver. The results indicated that the greatest heat flow caused by solar radiation can occur when the sun is in front of the vehicle as proposed in ISO 14505-2. With these conditions, the driver's chest region receives the greatest heat flow. According to the authors, designing the vehicle's air distribution system so that the diffusers provide air conditioning directly to these areas (with a higher incident heat flow) is a way to reduce localized thermal discomfort.

Mao et al. (2018) developed a numerical and experimental study to assess the distribution of air inside an electric vehicle under static and dynamic conditions, during the cooling and heating periods. Data on air temperature, vehicle surfaces and the human body were collected at different points. The numerical model showed temperature variations with differences of less than 10% in relation to the experimental data. The analysis of the distribution of temperatures and air velocities showed that the thermal storage of the seat significantly affected the thermal comfort for the transitory conditions. The movement of the vehicle increased the heat transfer by convection on the external surface of the cabin, which increased the heat transfer to the interior and consequently the time needed to promote comfort conditions.

As observed in the works related to thermoregulatory models, it is possible to couple these in numerical simulation models of the environment, providing greater precision in thermal comfort assessments. The following works show this coupling.

Ozeki et al. (2003) evaluated the effect of different radiation sources (solar and infrared lamps) on the reflective and transmissive performance of a car's glass. The performance of thermal comfort inside the vehicle was also assessed. For this, the numerical simulation method was used combining a model of thermoregulation of the human body and models of thermal and solar radiation. It was observed that the numerical model performed well to evaluate the equivalent temperature standardized in ISO 14505-2. It was also found that the transmissive and reflective performance of the glasses is quite different with the different sources of radiation. The difference in air temperature around the occupant is less than 1 ° C with different radiation sources, but there are significant differences in the equivalent temperature causing local discomfort.

Dixit and Gade (2015) investigated the use of the simplified thermoregulatory Bio-heat (STB) equation to be solved in parallel to the Navier-Stokes equation within a CFD tool referring to the cabin of a vehicle. For the numerical simulation, a domain that represents the cabin of a vehicle with a human body mannequin with 17 segments was used. The transient analysis was performed using the ANSYS Fluent software. To represent the heat transfer of the human body, the simplified Bio-Heat Equation was used as a condition of the mannequin's contour by means of a UDF (User Defined Function). For the evaluation of thermal comfort, the Fanger model was used by means of the PMV and PPD. The Fanger Equation was applied to each part of the body, which was possible due to the coupling with the simplified Bio-Heat Equation. The PMV-PPD indices were calculated at a distance of 5 cm from the human body to consider environmental variables. The results obtained showed good agreement with the compared cases.

From the observed studies, it appears that in automobiles the research on solar radiation, coupling of thermoregulatory models and also comparisons between the Fanger model (PMV-PPD) and the equivalent temperature for each part of the body are still objects of studies for researchers.

3.4.3 Bus

Buses are excellent for the collective transport of passengers, and their use provides numerous benefits to society, such as improving urban mobility and reducing pollution. Providing thermal comfort and air quality to the occupants is essential to promote the use of this vehicle and also to be a competitive differential for bus assemblers.

Thermal comfort for bus drivers is directly related to driving performance, making it a safety requirement for all occupants. As noted in the study of Ismail et al. (2015), where they investigated the correlation between thermal comfort and performance of bus drivers in Malaysia. The survey method used was the Survey, where questionnaires were applied to examine the relationship between thermal comfort and environmental factors in the performance of drivers. Approximately 260 drivers were assessed with a 95% confidence level and 0.05 accuracy. According to the statistical analysis, a correlation between performance and thermal comfort was obtained. As a result, it became evident that thermal comfort and environmental factors significantly influence the performance of drivers.

In parallel to the driver's environment, several studies also seek to assess the environment of passengers on the bus. As an example, the work of Lin et al. (2010) where they investigated by means of experimental measurements (based on ISO 7726: 1998) and Survey research (based on questionnaires ISO 10551: 1995 and ISO 14505-3: 2006) in 2,129 respondents, the thermal comfort of short and long distance buses . The experimental results indicate that the high temperature of the air, the strong solar radiation and the low movement of the air explain the discomfort of the passengers. It has also been found that passengers over short distances generally adjust the air vents to increase thermal comfort, while passengers in long distance vehicles prefer to close the curtains to reduce discomfort due to solar radiation. This behavior demonstrates the several variables that influence comfort, where several studies are needed for each one.

Similarly, Velt and Daanen (2017) evaluated the sensation and thermal comfort of electric bus passengers on a cold day in the Netherlands. 28 men and 72 women were evaluated based on the temperatures measured by an infrared thermometer (of the hands and face) and information on age, height, weight and clothing. The sensation and thermal comfort were based on scales of the ISO 10551: 2001 standard. From the collected parameters and the use of linear regression, an equation was determined relating the variables obtained in order to determine the temperature of the bus to promote thermal comfort to passengers. As a result it was obtained that for the evaluated conditions and local climate the ideal temperature for comfort is 20.9 ° C with the ambient temperature outside the bus of 13.4 ° C.

In addition to experimental research with buses in operation, numerical studies are essential in order to better understand the parameters that influence comfort. The combination of these three main methods of comfort study, Survey research, experimental measurements and numerical methods further improves the accuracy of the results obtained. As addressed by Zhu et al. (2018) where they studied, through field measurements, questionnaires and a numerical simulation system, the comfort and air pollution in the environment of an air-conditioned bus. For subjective research, questionnaires were applied on defined routes. The experimental tests were carried out in two days where air temperature and PM_{10} concentration data were collected. For the numerical method, geometry was assessed equal to that assessed in the field. ANSYS Fluent software and the RANS model were used for turbulence. To simulate passengers, an evenly distributed heat dissipation of 58.2 W / m was considered. Figure 10 shows the results of the obtained temperature field. The results indicated low air quality and unsatisfactory thermal comfort conditions in the current system. To solve these problems, three scenarios were evaluated by evaluating the ventilatory parameters. According to the results, reducing or adding air vents would shorten the time to reach steady state conditions, weaken the air flow and decrease the temperature. Changing the inflation angle can also reduce the concentration of contaminants (PM_{10}) and improve air quality.

Based on the research carried out in the database, not many studies were found evaluating the environment of the buses, mainly numerical works for the region of the driver's cabin, bringing opportunities for researchers to fill this research gap. As well as the use of the available comfort models, such as the global models of Fanger (PMV-PPD) and even the models of segmented mannequins (through the equivalent temperature).
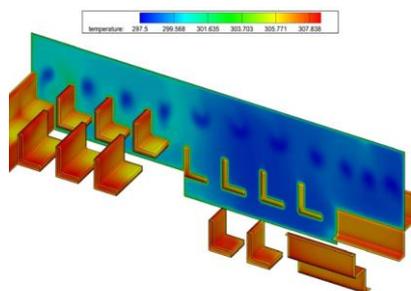

Figure 10. Bus temperature distribution through numerical simulation

3.4.4 Train and subway

Other means of passenger transport, widely used mainly in Europe, are trains and subways. Several studies have conducted research related to thermal comfort in these environments, as can be seen in the literature review of Ampofo et al. (2004) where they investigated works related to thermal comfort in underground / rail environments. In general, from the results obtained the authors concluded that there are differences in comfort between modern and old subways, generally the level of air speed is acceptable and a little higher sometimes, the air temperature is high, and there is no radiation problem, factors such as the variation in the number of passengers, the clothes used and the metabolic rate also impact comfort.

As with other public passenger transport, the study of ventilation systems and their influence on thermal comfort are also sources of research on trains and subways. Lian et al. (2004) investigated a new type of air supply for a train car in China. The thermal comfort and energy savings provided by the system were also evaluated. For the evaluations, numerical simulations were carried out, validated experimentally. To validate the model, temperature and speed measurements were made on a prototype similar to the numerical model. In general, low relative errors (average of

4.69%) were obtained between the experimental and the simulation. It was found that the proposed system has advantages of better air distribution and energy savings compared to conventional models.

Schmeling and Bosbach (2017) evaluated the influence of sensitive heat on ventilation efficiency and thermal comfort in a generic train compartment. To this end, a series of studies in humans have been conducted at various temperatures. Complementing the study, measurements were also made with thermal manikins with controllable sensitive heat release. Data on temperature, air speed, humidity and thermal images were collected. The PIV (Particle Image Velocimetry) technique was also used to capture the components of air velocity. In addition to experimental measurements, subjective data was collected from people in the train compartment. As main conclusions it can be observed that the ventilation values in the place are very good observing average temperature patterns. Another important point was that the variation in sensitive heat has a negligible impact on speeds close to the passenger dummies.

Similarly, Yang et al. (2017) used numerical simulation to study the characteristics of the internal distribution of air conditioning in a high-speed train. The distributions of temperatures, air velocities, pressures and concentration of contaminating gas were evaluated. The results showed that the distribution of temperatures, pressure and speed has an uneven gradient, and there are possibilities to improve the distribution in the environment. Figure 11 shows the results of the study for the distribution of temperatures and air velocities. Studies like this are essential to promote improvements in the design of the air conditioning system and provide comfort to passengers.
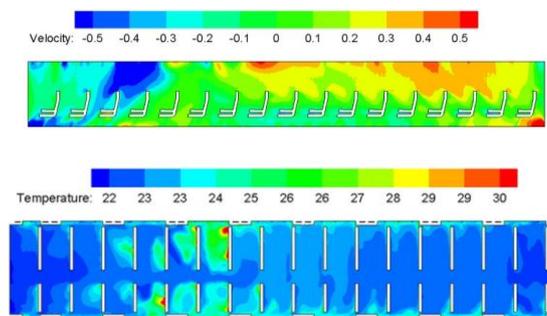

Figure 11. Distribution of temperatures and air velocities through numerical simulation

In addition to studies in public transport, it is essential to understand how the human being feels right before entering these environments, that is, in the subway stations, for example. Thus, Pan et al. (2020) proposed a dynamic thermal comfort research method, where participants enter a metro station, take the train and leave a metro station. The environmental characteristics and sensations of the passengers are observed in order to verify the adaptive behavior of the human being in these environments. For this purpose, objective measurements and Survey research were carried out. Based on the experimental measurements, differences of 10 °C were identified between the external environment and the subway environment. For the humidity it was observed that with the increase of the humidity of the external environment there is a decrease of the humidity of the subway. As for the air flow, it was found that in the subway the speeds are higher than in the external environment. Passengers' thermal sensations vary according to location, where in general, the station and subway environments were acceptable. The survey showed that 80% of respondents consider it comfortable at the station and the subway.

Corroborating the study mentioned earlier, Wu et al. (2020) evaluated air quality (by PM particulate index) and thermal comfort (by Relative Heat Index) during the transfer process of the Beijing subway. For experimental measurements, data on temperature, air speed, relative humidity, concentration of pollutants ($PM_{2.5}$ and PM_{10}) distributed in different points of the metro stations were monitored. With these data collected, comfort indexes were calculated based on the ASHRAE-55: 2013 standard. It was found that the level of thermal comfort is not ideal in 87% of the measured spaces and is slightly warm in general.

3.5 Discussion of results

Based on the results obtained from the systematic literature review, several trends were identified to provide the advancement of science in this extremely important area, which is the thermal comfort of human beings.

Initially, as discussed, the development of models and methods for assessing thermal comfort, using indices that encompass the various parameters that influence comfort, are extremely important to predict human satisfaction with the environment. Fanger's PMV-PPD indices, standardized in ISO 7730: 2005, are widely used in various researches, making it a benchmark for comparison with other assessment and development methods. As an example, the equivalent temperature method, standardized in ISO 14505-2: 2006, used as a reference in local comfort analysis on thermal mannequins. These were the models most cited during the research.

As discussed by several authors, the assessment of thermal comfort in environments can be divided into homogeneous and non-homogeneous, stationary and transient. Which promoted several studies to verify the

applicability of each method in each environment. Some authors suggest that the PMV-PPD indices bring excellent results to determine the overall comfort following the model's restrictions, while the equivalent temperature method performed through the segmentation of a thermal manikin provides better results to determine local comfort levels.

It was also observed that, as researched by several authors, there are several variables that influence comfort, and the study of better indexes that provide better precision in the results is in constant discussions. As well as there are several forms of comfort evaluation as observed in the works, which are: through subjective analysis, experimental measurements or numerical simulations. The coupling of these methods allows to provide better precision regarding the thermal satisfaction of the human being in the environment.

Another major area of research was the thermoregulation models of the human body. The coupling of these, with CFD models of the environment allows to predict with lower computational costs, the adaptation of the human being in the environment, making an efficient way to evaluate comfort mainly in transient environments, discussed by many as suggestions for future work.

The use of these concepts of models of thermal comfort and thermoregulation of the human body applied to different types of environments is also a great area of research. Due to the complexity of evaluating the various variables that influence thermal comfort, and also the factors of each environment, especially in public passenger transport, research becomes essential for the development of science and technology.

With this, it is expected that the advancement of computational resources, thermal comfort models and numerical simulations will provide the development of technologies in the future, optimizing products, improving issues such as energy efficiency and indoor air quality in the most diverse environments in which the human being will be inserted.

4. CONCLUSION

This work presents a literature review through a systematic methodology, identifying the state of the art related to thermal comfort analyzes.

The systematic review method used for the review allows the identification of studies relevant to the area. Furthermore, the bibliometric analysis stage included in the selection and analysis of the research is an excellent tool to quantify the published works, and to identify the most relevant research in question.

The subject of human thermal comfort is broad and complex, thus providing numerous challenges and possibilities for researchers. As noted in the results obtained from the review, there are several possible paths to be studied and better understood to provide the advancement of science and technology.

Relating the various variables that influence thermal comfort, transforming subjective thermal sensation into mathematical equations and comfort indexes is one of the major stages of studies related to the theme of comfort. Another approach, as observed in some research, is the modeling of the human body's thermoregulatory system, allowing to make thermal comfort models more accurate and more efficient. The application of these two approaches in different environments is another major area of research, as observed in the various researches found.

For the assessment of thermal comfort, mainly three methodologies can be adopted: through subjective analysis (very important for the creation of thermal comfort indexes), by experimental measurements (if used in conjunction with subjective analysis, it allows the validation of comfort models), and finally, numerical simulations (sources of study for many researchers today).

Through the discussions of the results by the observed works, numerous research gaps and trends for future works were identified, as reported below:

- The evaluation of the various types of environments that have not yet been studied, promotes the development of technology, placing more emphasis on the topic of thermal comfort and providing greater quality of life;
- The study of non-homogeneous and transient environments for the assessment of thermal comfort are trends for future work;
- The coupling between thermoregulation models of the human body with the computational fluid dynamics can provide great advances, bringing greater precision to the results obtained in the evaluation of thermal comfort;
- The use of optimization methods coupled with numerical simulations can also promote the advancement of technology in the area.

The literature review allows researchers and professionals to identify the best ways to conduct their research, observe the gaps that still need to be filled, know how the topic is being dealt with in the world and identify future trends, thus promoting the advancement of science and consequently the technology in this area is very important for human beings.

5. ACKNOWLEDGEMENTS

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