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An overview of current methods for thermal comfort assessment in vehicle cabin

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Abstract

Thermal comfort has been studied for a long time, resulting in several indices to assess the thermal comfort today. Contrary to the case of building, assessing thermal comfort in vehicles has several particularities. The effect of solar radiation, poor interior insulation, the non-uniformity of the average radiant temperature, a very short time to ensure the comfort parameters are some of the characteristics of an automotive environment. Indoor Environmental Quality in buildings has gained importance in the last decade and now is developing a new direction of research, the environmental quality in vehicles. The ambience quality is an important criterion in marketing this type of products. It influences not only the thermal comfort inside the car, but it also reduces the risk of accidents by reducing the driver's stress and ensuring a good visibility, which leads to a safer trip. In this study, we reviewed the most popular methods for assessing thermal comfort.

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Keywords: Passenger compartment; thermal comfort; PMV, PPD indices; thermal sensation vote

1. Introduction

The thermal comfort of occupants in vehicles has become more important due to their increasing mobility, leading to more time spent by people inside the cars. Current methods of assessing thermal comfort are not optimized following two crucial and interrelated aspects: achieving thermal comfort with the lowest possible level of energy consumption. Actually, energy consumption and thermal comfort are major concerns for research

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engineers in heating, ventilation and air conditioning systems, who are studying solutions, which are more or less feasible to implement.

The influence of external factors and the subjective responses regarding the expressed thermal state make the prediction of optimal values of comfort parameters in vehicles difficult, as a number of additional parameters compared to buildings influences this particular environment. One such parameter is the space in the cabin, which is tight, passengers being constrained to spend relatively long periods seated in a confined space.

Thermal comfort is defined by ASHRAE 55 standard [1] as *a subjective concept characterized by a sum of sensations, which produce a person's physical and mental wellbeing, condition for which a person would not prefer a different environment.* The state of thermal comfort felt by a person is in close connection with their physical and mental condition. Different thermal comfort indices have been proposed over the years , the first two being the PMV (Predicted Mean Vote) [2] and the associated PPD (Predicted Percentage of Dissatisfied), that Fanger introduced over 30 years ago.

Nomenclature

M	metabolic heat rate [W/m^2];
W	activity level [W/m^2];
t_{cl}	temperature at clothes level [°C];
p_a	water vapour pressure [Pa];
t_a	air temperature [°C];
I_{cl}	thermal insulation of clothes [Clo];
f_{cl}	clothing factor [-];
t_{mr}	mean radiant temperature [°C];
h_c	convective heat transfer [W/m²°C]

2. Current standards

The current standards which propose methods for evaluating thermal comfort in the interior car environment are EN ISO 14505 [3-5] divided into three parts and the American ASHRAE - 55 [1]. The European EN ISO 7730 [6] is used for assessing thermal comfort in buildings and is based on the well-known theory of Fanger [2] and on the equivalent temperature model [7, 8].

EN ISO 7730 presents the PMV and PPD indices proposed by Fanger [9]. Over 30 years ago, Fanger conducted a study in which subjects that had "standard" clothes performing a „standard" activity. During the assessment, the persons were exposed to various thermal conditions. According to the felt sensation, the subjects assessed the condition using ASHRAE scale with seven values (-3: cold, -2: cool, -1: slightly cool, 0 neutral, 1: slightly warm, 2: warm, 3: hot)[1]. In other studies, subjects were asked to adjust their clothing, ambient temperature, etc. to obtain neutral thermal condition. After analyzing the thermoregulation and heat transfer system of the human body, Fanger proposed the PMV index- Predicted Mean Vote [9] (or Predicted Mean Option[1]), in accordance with the ASHRAE scale. By introducing the external physical quantities that influence the phenomena of heat transfer (air temperature, radiant mean temperature, partial pressure of water vapor and relative air velocity) and individual variables (thermal resistance of clothing, the level of activity and average skin temperature) in the thermal equilibrium relationship of the human body, we obtain the relationship between the produced and released body heat flux. When the heat balance equation proposed by Fanger is satisfied, the heat generated by the human body is dissipated without having an increase in the activity of body thermoregulatory system [9]. The PMV index values are between -3 and 3 on the ASHRAE scale. He quantified the average opinion of a group of subjects on the state of comfort. The PPD index (Predicted Percentage of Dissatisfied) is associated with this parameter, indicating the percentage of occupants under thermal discomfort. A value of 10% of the PPD index corresponds to the interval between -0.5 and +0.5 for PMV on Fanger's scale. Even for the PMV=0, about 5% of occupants are in discomfort.

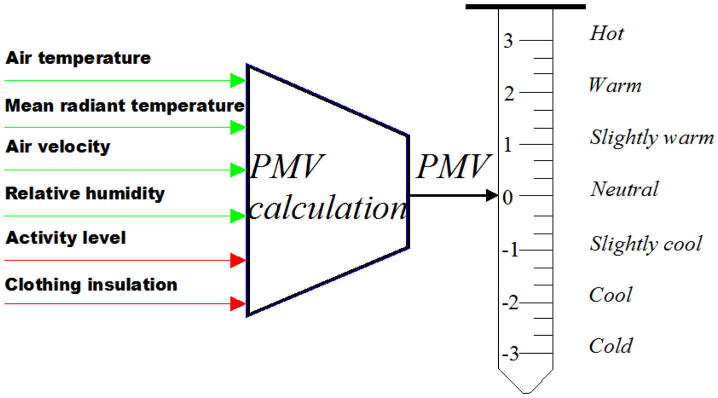

Fig. 1. Calculation factors and value scale of PMV

In *(1)* the relation used to evaluate the PMV index is presented [9]:

$$PMV = (0.303e^{0.303} + 0.028)\{(M - W) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) - 58.15] \\ - 0.0173M(5.87 - p_a) - 0,0014M(34 - t_a) - 3,96 \cdot 10^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_{mr} + 273)^4] - f_{cl} h_c (t_{cl} - t_a)\} \quad (1)$$

Where:

$$t_{cl} = 35.7 - 0.0275(M - W) - I_{cl}\{(M - W) - 3.05[5.73 - 0.007(M - W) - p_a] \\ - 0.42[(M - W) - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a)\} \quad (2)$$

The PPD index [9] is expressed by equation *(3)*:

$$PPD = 100 - 95\exp[-(0.03353PMV^4 + 0.2179PMV^2)] \quad (3)$$

Both ASHRAE 55 standard [1] and EN ISO 7730 standard [6] specify methods for the evaluation of the thermal environment of buildings in order to obtain a certain degree of global comfort for the occupants, at a certain level of activity and clothing. ASHRAE 55 [1] either uses the PMV-PPD method or the Standard Effective Temperature (SET) comfort zones for conditioned spaces. It also present an adaptive approach for the determination of acceptable thermal conditions in naturally ventilated spaces [1], while EN ISO 7730 proposes the PMV-PPD approach.

The EN ISO 14505 standard “Evaluation of thermal environments in vehicles” is structured into three parts: 1. Principles and methods for assessment of thermal stress; 2. Determination of equivalent temperature; 3. Evaluation of thermal comfort using human subjects. In the first part of the standard reference is made to EN ISO 7730, proposing the use of PMV and PPD. Unfortunately these two indices are generated particularly for homogeneous environments inside buildings. The second part of the standard proposed the T_{eq} Index – the equivalent temperature index. This is a local and global index proposed by Nilsson following his PhD thesis [7, 8, 10, 11]. The equivalent temperature uses the same method of calculation as the operative temperature for ambient air velocities under 0.1m/s. This represents the average of the air temperature and the mean radiant temperature weighted respectively by the convection heat transfer coefficient and the radiation heat transfer coefficient for the occupant. For values of the ambient air velocities greater than 0.1m/s, the equivalent temperature is expressed as a function of the air temperature, the mean radiant temperature, the air speed and the thermal resistance of clothing [12]. Several equivalent temperatures can be distinguished here: the directional equivalent temperature – referring to the heat exchange within the half-space in front of the infinitesimal plane and described as a normal vector to the measuring plane in every point, defined by magnitude and direction; the omnidirectional equivalent temperature which is all around a body part or the whole body, measured generally with an ellipsoid sensor; the whole body equivalent temperature, which is related to the whole body of a human being and which is the standardized quantity, and the local equivalent temperature related to one or several body parts. All these equivalent temperatures might be determined using one or several hot-film or ellipsoid sensors or using a thermal manikin as described in the EN ISO 14505/2[4]. The equivalent temperature method using directional sensors or a thermal manikin to evaluate the thermal sensations in vehicles has, in our opinion, as main drawback the fact that thermal sensation, primarily due to local sensitive heat variations, is evaluated by using the clothing-independent thermal comfort diagrams.

In the third part of the standard EN ISO 14505 a direct method for assessing thermal comfort in automobiles is presented, the main index being the Thermal Sensation Vote (TSV) of human subjects that are surveyed. This subjective method quantifies and records the response of people about their thermal sensation in an environment, on the same scale of values as for the PMV. The TSV only takes into account the psychological and physiological factors. A study using this method involves standardized questionnaires for a controlled and representative sample of population. By centralizing the obtained results, one could then have an idea about the particular investigated situation.

In general, the ISO 14505 standard [4] seems more sensitive to the warm environment parameters and less sensitive to cold environment parameters, compared with other approaches for non-isothermal environments such as the Berkeley model [13]. This may signify that the ISO 14505 [3] standard is suitable for thermal neutral situations only, where the latent heat of evaporation constitutes a very small part of the total heat transfer of human body. Moreover, if we are talking about the thermal comfort in the vehicles' cockpit, other design parameters may influence the occupants' sensation in an unpredictable manner. One such parameter is the thermal sensation offered by the car seats, in terms of seat cover conduction coefficient, for example [14-16].

3. Literature Review

Achieving thermal comfort for occupants in buildings with high user expectations irrespective of the outside environmental conditions has been the main focus of the Heating Ventilation and Air Conditioning (HVAC) design engineers and systems developers for more than fifty years. On the other hand, in the last decade, with manufacturers having in mind to cut production costs and at the same time to increase the security of vehicles, there is a certain amount of pressure on the designers in the automotive industry who focus on comfortable mobility. Comfortable interior climate control helps not only to reduce the driver stress in many cases, but also guarantees good visibility by defogging the windscreen faster, thus contributing to driving in safer conditions. Contrary to the case of buildings, the ambient of the cabin is mainly influenced by the transient thermal conditions. Differences between psychological and physiological features of the passengers further accentuate these delicate issues. Thus, the environment inside the cabin is affected by a number of parameters that include: various structures of the surfaces and their temperatures, the local variation of air temperature, the speed distribution of air in an interior over complex geometry, relative humidity, solar radiation intensity and its reflection, the angle of incidence, type of clothing, etc. Moreover, some of these parameters are connected by relations that are still unknown [2]. All these factors complicate both modelling and experimental approach attempts.

Croitoru et al. [17] reviewed the most popular thermal comfort models and methods of assessing thermal comfort in buildings and car interior spaces. They showed that most of these methods and models are limited to specific steady states, thermally homogenous environments and only a few of them address human responses to both non-uniform and transient conditions such as the car interior environment. They also emphasized the fact that the standardized models were defined two or three decades ago and have remained unchanged ever since.

Moreover, as explained by Alahmer [14] assessing and predicting the state of thermal comfort in the vehicle interior is influenced by characteristics of this environment according to strong transient parameters both in time and space. Indeed, the average temperature of a passenger car is subjected to significant and rapid change and is strongly influenced by outdoor conditions. For instance, indoor temperature inside the car can reach 72°C in summer for an outdoor temperature of 34°C and for values of solar radiation of around 800W/m^2 according to Grundstein [18]. In most cases, air distribution grilles that allow the control of the heating or cooling loads in the cockpit are installed only in the front part of the vehicle, the state of thermal comfort for passengers in the back being obtained with more difficulty.

Many studies have been conducted in order to find an answer in terms of thermal comfort in vehicles following the three ways of approach from the EN ISO 14505 [3-5] standards. Some of these studies take into account the subjective methods based on results collected from questionnaire surveys, while others evaluate environmental quality based on experimental assessment of comfort parameters through instrumentation. In most cases, both in practice and in standards, air temperature is the most observed and discussed of these parameters. A comfort value of the temperature is usually fixed inside the cockpit as global set point according to the outdoor air temperature. One method currently used to evaluate the thermal comfort as a function of air temperature is the use of sensors to measure local air temperature values at head and ankles level. The main purpose of this approach is to determine how quickly the temperature will increase or decrease in a cold or warm vehicle cabin, to study the non-homogeneity between the temperature at feet and head level and to establish if the global temperature level is situated within the limits of the accepted intervals. In any case, by using this method, only one of the needed parameters that concern the thermal comfort sensation is measured and any influence of air velocity and radiation (cold or hot) are neglected leading to false conclusions. This fact is a particularity of the thermal environment in vehicles where the air conditioning system leads to high local air velocities.

Relative humidity, which is directly connected to the air temperature, is, another factor with great influence on thermal comfort [14, 19]. Humidity inside the vehicle will influence the evaporation of sweat from the skin. Therefore, it is really important to keep relative humidity in a proper range because in a hot environment it will limit body heat loss. A relative humidity between 30% ~ 70% does not have an influence on thermal comfort at neutral temperatures, but when the RH is over 70% and the interior temperature is over the neutral temperature range, it will prevent the sweat evaporation and it will then cause a suffocating weather sensation that will lead to occupants' discomfort. When the RH is lower than 30%, it will a cause dry sensation, which has a bad effect on mucous membranes. The relative humidity can be evaluated by measuring any point with a dedicated probe. Relative air humidity is correlated with the global air temperature but less subjected to non-homogeneities.

At the same time, taking into account the previously discussed transient character of the vehicular environment, the thermal parameters of the vehicle change dramatically during the first few minutes of occupancy. Moreover, as shown by Zhang et al [20], in the case of mono-zonal air conditioning systems a quasi-steady state of thermal equilibrium is attained in the front part of the cockpit in around 5 minutes and in the rear part of the cockpit in around 10 minutes. Taking into account that the period of use of the vehicles is sometimes very short and insufficient to obtain a uniform thermal environment and knowing that 85% of automobile travelling involves a travel distance of less than 18 km, with a duration between 15 and 30 minute, it could be difficult to achieve a real state of thermal comfort [11] in this period., Zhang et al [20], tried to assess the transient temperature distribution in a vehicular cockpit in real operating conditions during the cold season. The air temperature was measured in a number of positions in a full size vehicle cabin under natural winter environment in South China by using a discrete thermocouples network. The authors monitored the occupant's the skin temperature on different body parts simultaneously. The human body was divided into nine segments; the occupant's local thermal sensation was continuously recorded at head, body, upper limb and lower limb level. The skin temperature was evaluated by using a discrete thermocouples network, and the local thermal sensation was evaluated by using a seven-point thermal comfort scale. The results showed, as expected, that the air temperature is highly non-uniform inside the vehicle. It was also shown that the positions of the occupants had a major influence on thermal responses, on skin temperature and on thermal sensation votes. The authors found a correlation between the various parts of the body skin temperature and the local thermal sensation. They showed that there were substantial differences between the skin temperature and the local body parts sensation given by the non-uniformity of thermal environment and by the subjective thermal feeling responses of the occupants. They suggested that monitoring skin temperature might represent a good approach to evaluate the thermal sensation of occupants in this transient environment.

Solar radiation, connected to the strong transient thermal regime, is one of the principal factors of thermal discomfort both directly and indirectly. Kilic et al. [21] recorded temperature values by 2°C higher in the case of sensors exposed to sunlight compared to those placed in the shaded zones, while a percentage between 18% - 31% of the cooling system capacity is used to reduce the load caused by the direct contribution of the solar radiation. In this case, the window color is very important as it can significantly reduce energy consumption for cooling by controlling the amount of fresh air introduced in the vehicle [22].

Srisilpsophon et al. [23, 24] proposed a correlation between the TSV obtained from the questionnaire survey related to direct solar radiation. The experiments were carried out under the climate of Bangkok, Thailand, when all the windows except the windscreen were coated with 40% cut-off anti-solar protection film. A set of empirical models to evaluate the surface temperatures of the windows and the cabin walls was proposed by the authors based on the experimental data. It was noticed that the mean radiant temperature inside the cabin was closer to the global air temperature in case of using the protection film than without the film. For films with 40, 60 and 80% solar radiation cut-off, when the outside air temperature was lower than 25°C, the 40% cut-off anti-solar film obtained performances similar to the darker film. When the outside temperature was higher than 25°C, the 80% radiation cut-off film showed an advantage in reducing the mean radiant temperature values. As a result, they observed a reduction of solar heat of 14%, 18 % and 20% respectively and a reduction in fuel consumption of 11.7%, 14.4% and 18% respectively compared to the case when windows were without protection film. Moreover, the surveyed subjects felt more comfortable in the situation with protection film.

In terms of air quality, the desired effect of an air distribution system in a cabin is to provide fresh air as well as to compensate heat or cold needs and to create a pleasant ambient. Sometimes, thermal comfort sensation is influenced by the 'lack of fresh air' sensation associated to high CO_2 levels. Kilic et al. [21] studied the effects of ventilation mode - i.e. fresh air introduction versus recirculation mode - on thermal and air quality sensation of the occupants. The authors measured air temperature, relative humidity, air velocity and CO_2 concentration during summer. They discovered that in air recirculation mode, the CO_2 level inside the cabin exceeded in the first 5 minutes the threshold limit of 1200 ppm suitable for safety driving and it could exceed the 3200 ppm value after one hour.

Sepehr et al. [25] used a fuzzy controller in their study in order to control two parameters: the air speed at the discharge grill and the percentage of recirculated air. The authors showed that by using the controller it took less time to attain the desired interior temperature (20°C), which could be reflected on the energy consumption. The use of multi-zonal air distribution systems is another method of reducing the fuel consumption of the vehicle. Statistics show that, if the vehicle has a low level of occupancy, conventional mono-zonal systems recorded an unnecessary energy consumption for cooling in the unoccupied space. Following the same idea of optimizing air distribution and the local thermal micro-environment of the occupants, as pointed by Zhang et al [20], the application of skin temperature to the designing and controlling parameters of the HVAC (heating, ventilation and air conditioning) system may represent a new way to benefit in terms of improving thermal comfort and reducing energy consumption.

On the other hand, returning to the perspective of fuel consumption, Su et al.[26] studied the effect of the air-conditioning system. In this study, the authors investigated the effects obtained by reaching more efficient cooling around the occupants. They modified the air distribution system, installed discharge grills for rear passengers the air being thus introduced through the discharge grilles from the dashboard for the front passengers, and ceiling discharge grills for the rear passengers. The PMV index was evaluated based on computational fluid dynamics simulations correlated with empirical relations. The experimental validation of the simulations consisted in evaluating the performance of the air-conditioning system at various airflow rates and air temperatures. The energy consumed by the localized air-conditioning system was decreased by 20.8% and 30.2%, respectively, compared to a conventional situation.

Another innovative air distribution system was studied by Lee et al. [27]. They concluded that in order to achieve the comfort parameters in the shortest time, the best place to install additional ventilation diffusers is behind the rear seat passengers. During the warm season, the authors found PMV index values between (-0.3 and 0.2), totally different from the values of (-0.1 and 1) obtained for situation without discharge grille behind the rear seat passengers. Moreover, the authors noticed a non-uniformity between temperature measured at chest level between the front and rear parts of the vehicles which exceeded 2°C.

4. Conclusion

At the moment there are no international standards which allow to easily assess thermal comfort specific to the vehicular environment space. The current state of the art has been inconsistent in methodology; there are often crucial differences in the theoretical approaches of existing studies and important differences in the experimental methods which assesses thermal comfort. Researchers who have studied thermal comfort in vehicles have adopted many concepts and methodological procedures from the only previously existing thermal comfort literature which was mainly intended for buildings. We note the importance of local discomfort assessment methods; many of which are adapted to the actual conditions of buildings. It is necessary to insist in this field by using numerical and experimental approaches to study thermal comfort by using for instance virtual and experimental thermal manikins. It is also important to develop new thermal comfort indices for occupied spaces that are able to take into account these local effects of thermal discomfort inside the car.

We can notice that in the case of actual thermal comfort indices solar radiation is not taken into consideration, a parameter with an influence in assessing thermal comfort. This parameter does not only raise the indoor air temperature but is also a local discomfort parameter.

Implementing an anti-solar foil is a proven solution to reduce the solar radiation influence, but during the night, it has a negative influence on the driving safety. Another solution is to implement local ventilation grille to reduce the energy consumption and to ensure a better uniformity for the indoor parameters of the cabin.

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