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Parameters and Models of the Vehicle Thermal Comfort

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Abstract: Nowadays, efforts are being made to estimate the thermal comfort in vehicles by measuring each environmental parameter - air temperature, air humidity, mean radiant temperature, air velocity, human activity and clothing insulation. An optimum level of comfort in the vehicle is obtained only by using an automatic air conditioning and climate control system. The paper focuses on the analysis of the vehicle thermal comfort parameters in order to improve the measurement methods and to establish the optimum thermal comfort inside a vehicle. The paper also describes two thermal comfort models used to estimate thermal comfort inside the vehicles.

Keywords: Thermal comfort, measurement, parameters, air conditioning, vehicle.

1. Introduction

Over the last years, with the trends of reducing costs and carrying weight, the interest in ensuring an optimal efficiency for vehicles has increased in a large sense (comfort, dynamicity, performances and energy efficiency).

Construction of vehicles developed from simplistic to modern, integrating the state-of-the-art technologies, organized on functional and aesthetic criteria, which ensure the passengers' comfort, ergonomics and safety.

Thermal comfort in vehicles represents a subjective sensation of heat balance that occurs in the human body when environmental parameters - *air temperature, air humidity, radiant temperature, air velocity, human level activity and clothing insulation* - are in a range of well-defined values [1].

ASHRAE Standard 55 defines thermal comfort as "that state of mind which expresses satisfaction with the thermal environment" [2].

As Parson observed in his studies [3], thermal comfort is influenced by a combination of physical, physiological and psychological factors. Some factors include solar radiation and glazing, inside and outside colours, the size of the vehicle, the clothing type of the passengers and passenger capacity of the vehicle cabin [4]. In a vehicle environment each passenger, regardless of their size, can affect the thermal environment inside a vehicle [5-9].

Thermal comfort is achieved (i) by ensuring temperatures of 20°C ÷ 22°C, as a result of air temperature, delimitation areas, humidity and air velocity in accordance with the activity level and clothing insulation of the occupants, (ii) by avoiding situations such as the occupants coming into contact with very cold or very hot surfaces, (iii) by avoiding air currents. These requirements must be met throughout the entire year, both summer and wintertime.

The research of thermal comfort has been in progress for many years. The study of thermal comfort in vehicles was developed from basic thermal comfort research and applied work related to factories and buildings [10]. The first research in vehicles dealt mainly with agricultural vehicles and public transport systems such as subways, trains and buses [11]. Achieving a thermally comfortable vehicle environment has become an issue of main importance.

The paper presents an analysis of the vehicle thermal comfort parameters and describes two thermal comfort models (Fanger's model and thermal manikin model) used to estimate the thermal comfort inside vehicles.

2. Environmental parameters of the vehicle

Very few articles have explicitly defined the differences between vehicle and building environment. However, there are researchers who dealt with the vehicle environmental parameters and their measurement methods [5-9], [11].

ISO 7726 standard describes some methods for measuring physical qualities related to thermal comfort parameters [12]. Whereas the tendency in measuring thermal comfort has been towards using individual instruments (e.g. thermocouples, globe thermometers, net radiometers, hotwire anemometers, hygrometers etc.) to measure single parameters in buildings, the automotive research has adopted a different approach, mainly due to the small available working space and the dynamic driving tests that are required when making thermal measurements. Installing large amounts of equipment in vehicle cabins is time-consuming and presents difficulties when all parameters have to be measured in the same position. Using a transducer that measures the combined effect of all environmental parameters will make the evaluation very efficient.

In his studies, Temming observed that the thermal environment in a vehicle cabin is very complex and thus difficult to evaluate. These difficulties are due to the influence of convective, radiative and conductive heat exchange created by external thermal loads, the internal heating and by air conditioning and ventilation system [13].

The usual method to evaluate the thermal comfort parameters in vehicles is to use sensors to measure the air temperature at the level of the head and feet. The main purpose of such measurements is to determine how quickly the temperature will increase or decrease in a cold or warm vehicle cabin, to study the difference between the temperature at the feet and head level and to establish when the temperature reaches the thermal comfort level. However, using this method, only one of the needed parameters that concern the thermal comfort sensation is measured. By measuring only the air temperature, any influence of the air velocity and radiation (cold or hot) are neglected and the measurements might lead to false conclusions. This fact appears more often in vehicles than buildings, because the air conditioning system can create high local air velocities [14].

Nowadays, efforts are being made to estimate the thermal comfort in vehicle environments by measuring each environment parameter - air temperature, air humidity, mean radiant temperature, air velocity, human activity and clothing insulation. There is a great inter-correlation among these parameters. That is why the values recommended in standards are in well defined ranges. The thermal comfort can be obtained by correlating all these parameters.

Air temperature

The optimal value for the inside temperature is a function of the season time. During wintertime the optimal inside temperature adopted is $\theta_i = +22^oC$; during summertime different values for inside temperature are indicated in the literature.

Temming underlines that air temperature zones inside a vehicle are not homogenous. Whereas the air temperature in buildings generally increases with height from the floor to ceiling, this fact is not acceptable in vehicles. In vehicles, the air temperature at the ankle level is expected to be higher than at head level.

ASHRAE Standard 55 prescribes 3ºC for the vertical air temperature difference between head and ankle level [2]. Other studies set this limit up to 6ºC [15].

Moreover, the air temperature depends upon the “class” of the vehicle. A larger vehicle with leather upholstery during warm-up conditions may have an entirely different air temperature than a small economy-class vehicle during the same driving conditions.

The inside temperature is measured using temperature sensors. The recorded temperature values are between the values of the air temperature and the values of the mean radiant temperature. In order to reduce the error introduced by the solar radiations, the temperature sensor must be as small as possible. The purpose of using appropriate temperature sensors is to see how quickly the temperature will increase or decrease in a cold or warm vehicle cabin and to measure the difference between the temperature at the level of head and feet.

Air velocity

Air velocity inside the vehicle usually has reduced values, ranging between 0.1 and 0.4 m/s. The maximum air velocity allowed inside a vehicle is considered a function of the air temperature determined by the convection heat exchange between the human body and environment. Due to air velocity fluctuations, the measurements must be carried out over a period of 3 ÷ 5 minutes to obtain a reasonable average value. When a model is developed, the air velocity value is neglected because it has a reduced value.

Air flow sensation is subjective and varies according to the person's sensitivity (some parts of the body are more sensitive, e.g. nape). The appearance of air currents is mostly due to the untight environment and to the air flow of the air conditioning system. The air flow coming through an open window increases the air velocities and the thermal discomfort as well.

Inside the vehicle, the air flow can only be directed to smaller sections because of a reduced volume (as opposed to buildings). The heated air should be directed toward the bottom half of the occupant's body and the cool air should be directed toward the upper half [16].

The studies of many researchers show that in a warm environment, higher air flow could provide a thermal comfort [17-19].

Figure 1 shows the correlation between the air velocity limit and the inside air temperature. As it can be seen in this figure the limits of air velocity values increase at high air temperature values.

The air flow sensation appears above the air velocity curve. The air flow sensation is subjective and affects mostly the back of the passengers' neck. Moreover, air flow sensation depends on the body's thermal state [20].

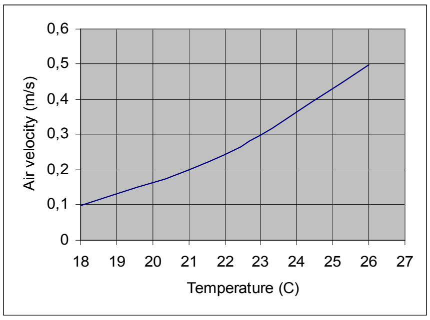

Figure 1: The air flow sensation curve [20].

Mean radiant temperature

The mean radiant temperature (MRT) is the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space [2]. MRT represents the mean temperature of all the objects surrounding the body. MRT will be positive when surrounding objects are warmer than the average skin temperature and negative when they are colder. MRT governs human energy balance and human body heat losses, especially on hot sunny days [21].

Mean radiant temperature, θ_m, is obtained if surface S_i and temperature θ_i are known for every construction element (e.g. door panels, dashboard) delimitating the passenger's area.

Mean radiant temperature is calculated by using the following formula:

$$\theta_m = \frac{\sum_1^n S_i \cdot \theta_i}{\sum_1^n S_i} \quad (1)$$

The mean radiant temperature can be determined if temperature and position of every construction element (e.g. door panels, dashboard) around the passenger inside the vehicle are known.

Relative humidity

ASHRAE Standard 55 defines relative humidity as the ratio of the partial pressure of water vapour in a gaseous mixture of air and water vapour to the saturated vapour pressure of water at a prescribed temperature [2].

Relative humidity is measured in only one place inside the vehicle because the pressure of the water vapour is uniform in the entire vehicle. The human body is sensitive to air humidity changes. The thermal comfort sensation is optimal when the relative humidity value is about 50%.

Temming observes in his studies that humidity plays a minor role. However, relative air humidity is correlated with inside temperature. These two parameters influence the thermal comfort of the passengers and they are the main parameters of the air conditioning system [21].

Figure 2 shows the correlation between temperature variation and the relative air humidity. As it can be seen in this figure, the relative air humidity increases when temperature decreases. A high relative humidity (over 70%) causes a sultry weather sensation increasing the discomfort level and can lead to problems of condensation, such as misting of windshields and shorting of electrical components. A low relative humidity (under 30%) causes a dry sensation, which can irritate the passenger’s bronchial ways.

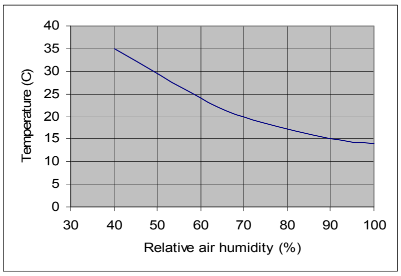

Figure 2: Correlation between temperature and relative air humidity [21].

The recommended values for inside temperature and air humidity in correlation with the outside temperature are given in *Table 1*.

Table 1: Inside temperature and air humidity as a function of outside temperature [22].

Outside temperature [˚C]			Winter	Summer			
			till +20	+20	+25	+30	+32
Inside temperature [˚C]			22	22	23	25	26
Relative humidity	%	Min	35	-	-	-	-
		Max	70	70	65	60	55

Human activity level and clothing insulation

The equivalent temperature, θ_{eq}, is calculated with formula [22]:

$$\theta_{eq} = A \cdot \theta_i + (1 - A) \cdot \theta_m \quad (2)$$

where: θ_i – inside temperature;
θ_m – mean radiant temperature;
A – weight factor (*Table 2*).

Table 2: Weight factor values at different air velocities values [22].

Inside air velocity, v [m/s]	< 0,2	0,2……0,6	0,7……1
Weight factor, *A*	0,5	0,6	0,7

Figure 3 shows the equivalent temperature curves of thermal comfort as a function of the human activity level, q_o, (1 met=58.2 W/m^2) and clothing insulation (1 clo=0.155 m^2·K/W). The diagram was created for relative air humidity of 50% and for inside air velocity of v_a = 0 m/s, if human activities $q_0 \leq 1$ met; for relative air humidity of 50% and for inside air velocity of $v_a = 0.3 \cdot (q_0 - 1)$ if human activities $q_0 > 1$ met.

The surface temperature of the human body is an average temperature, as people have different skin temperatures for different parts of the body. Clothing insulation increases together with the temperature increase due to the lower difference between the air temperature and the human body's surface temperature. *Figure 4* shows the skin temperature corresponding to different parts of the human body versus the inside air temperature. As it can be seen in this figure, the temperature at the feet level is lower than the temperature at the head level. These temperature differences influence the thermal comfort of the passenger.

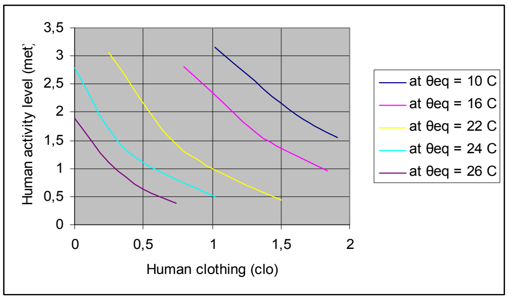

Figure 3: Thermal comfort limits for equivalent temperature as a function of human activity level and human clothing [23-25].

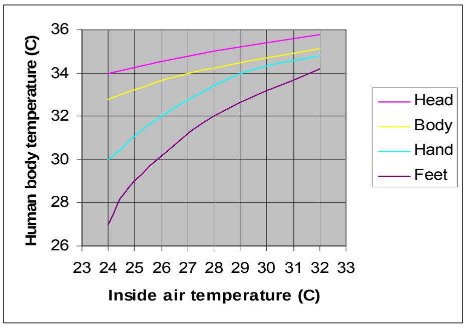

Figure 4: Skin temperature of different human body parts versus inside air temperature [23-25].

Several supporting standards for clothing insulation (ISO 9920) and metabolic rate (ISO 8996) are available [26-27].

When all these parameters are measured, their combined effect on the occupants of the vehicle can be determined.

In order to obtain an increased thermal comfort of the passengers, the parameters analyzed above are used to design the air conditioning system.

3. Thermal comfort models

Vehicle thermal comfort has been modelled using a combination of mathematical and statistical relationships.

Different models of thermal comfort have been also developed that can be used to predict subjective comfort assessment. The models are usually based on six parameters - air temperature, air humidity, mean radiant temperature, air velocity, human activity and clothing insulation [28]. Some models have been validated as a result of research on human subjects.

There are two significant models that can be used to predict thermal comfort and to estimate the environmental parameters of the vehicles (a mathematical model - Fanger's model and a physical model using thermal manikins). These models are the basis for designing and improving the air conditioning system.

Fanger's model

The most notable researcher on the thermal comfort analysis was P.O. Fanger [29]. Fanger's model suggests that thermal comfort can be predicted if the values of all six environment parameters are known. According to Fanger, the thermal comfort is analyzed by PMV (*Predicted Mean Vote*), and thermal discomfort can be analyzed by PPD (*Predicted Percentage Dissatisfied*).

A vehicle represents a "moderate" thermal environment described by Fanger's equation. The equations that led Fanger to develop the concept of PMV and PPD are based on the physiological processes that underlie human heat balance. The interaction between the human body and the environment is described by the heat balance equation between thermal heat developed by metabolism in the human body and the heat transferred through convection, conduction, radiation and evaporation [30].

The PMV is based on the subjective seven-step scale [31]. The value of the PMV index has a range from -3 to +3, corresponding to human sensations from cold to hot, respectively, where the null value of the PMV index means neutral. The PMV evaluation method treats the entire body as one object. It does not distinguish between different parts of the body. If one side is warm and the other cold, the PMV model would calculate a zero thermal load and therefore yield a neutral thermal sensation (PMV=0). It is noted that the optimum value for thermal comfort (PPD is 5% and PMV is 0) can be obtained only with automatic air-conditioning systems.

The model was developed based on data from uniform thermal environments. Because it only calculates the heat transfer for the entire body, it cannot predict local discomfort. Clothing is assumed to cover the entire body uniformly which results in one skin temperature across the entire body.

The PMV model is a basis for most current standards prescribing methods for evaluating thermal comfort in vehicles [2], [26], [32].

Fanger model has limitations related to: (i) thermal steady state or dynamic state, (ii) distinction between local and whole-body thermal comfort, (iii) environmental particularities of the vehicle. The PMV model depends on the context and is more accurate in vehicles with air-conditioning systems than in the ones with natural ventilation, because of the influence of outside temperature. The inadequate measurements of the thermal insulation of clothing and the metabolic rate will reduce the accuracy of the PMV index. Other limitations are related to the local effects of asymmetrical conditions or local air movement around the face of occupants.

Thermal Manikins

Measurement and assessment of thermal climate using a thermal manikin makes it possible to evaluate the best solution for thermal control. It can also be used to measure clothing and chair insulation.

The first thermal manikin was introduced in 1985 by Wyon [33] and after that other manikins have been developed [34-36].

Thermal manikins are currently available but they are used primarily for measuring the thermal insulation condition of the clothing. The problem is that the manikin does not respond to the environment in the way the human body does. Most current manikins do not possess a sweating capability and hence only sense dry heat transfer. Evaporative cooling is a critical and often used component of the thermoregulatory system of the body. A thermal manikin should possess this capability in order to accurately simulate the response of the body in all thermal environments.

A thermal manikin that possesses a high degree of sensory spatial resolution, local thermoregulatory responses including sweating, a fast time response and a feedback loop to continuously react and adjust to a thermal environment like a human has never been developed. An advanced thermal manikin with these capabilities would help industry develop more effective and energy efficient climate control systems for transportation environments, or others where transient and extremely non-uniform thermal environments exist [37].

A thermal manikin needs to have the following properties in order to accurately simulate the human body: correct body shape and size; control of heat emission; control of the distribution of heat across the skin surface; emission of the skin; control of the distribution of perspiration across the skin surface; control of pose and movement and control of core [38].

So far, no manikin meeting all these criteria has been available. Depending on certain situations, for example, when wearing cold-weather gear in cold conditions, existing thermal manikins are limited to a uniform temperature distribution across the skin surface even though the human body’s extremities experience large drops in skin temperature. This leads to an overestimation of heat loss from the extremities in the result obtained using the thermal manikin.

In order to improve the air conditioning system, measurements of local climate disturbances with a man-sized thermal manikin have to be made and have to be correlated with the thermal sensation experienced by subjects exposed to the same conditions. Criteria for acceptable climatic conditions can be defined in terms of quantities measured with the manikin.

Although there are some limitations, the thermal manikin model represents a quick, accurate and efficient model for evaluating the vehicle's thermal comfort.

3. Conclusion

The vehicle is characterized by a moderate thermal environment. This environment is defined by six thermal comfort parameters: air temperature, air humidity, mean radiant temperature, air velocity, human activity and clothing insulation. By measuring all these parameters, the combined effects on the occupants of the vehicle can be calculated. Specific models for thermal comfort are analyzed and used to estimate the thermal comfort of the passengers.

Inside air temperature zones within the occupant space of vehicles are neither homogenous, nor desired to be homogenous. The inside temperature is correlated with inside relative air humidity. These two parameters influence the thermal comfort of the passengers and they are the main parameters of the air conditioning system. *Humidity fluctuations* play a minor effect if the values are in the range of 30% to 70%. *Mean radiant temperature* depends on the "class" (size and quality) of the vehicle and influence the passenger thermal comfort. *Air velocity fluctuations* are mostly due to the untight environment and to the air flow of the air conditioning system. In order to obtain an increased thermal comfort of the passengers, new measurement methods and efficient models must be developed.

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