Isı Bilimi ve Tekniği Dergisi, 35, 1, 125-134, 2015
J. of Thermal Science and Technology

ISSN 1300-3615

INFLUENCE OF THE VENTILATION SYSTEM SETTING IN THE PASSENGER CAR ON THE LOCAL THERMAL SENSATION OF A DRIVER

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(Geliş Tarihi: 14.04.2014, Kabul Tarihi: 04.08.2014)

Abstract: This paper presents the analysis of the influence of operational parameters of the air-conditioning system have on thermal sensation in a vehicle cabin. Thermal sensation has been evaluated using equivalent temperatures for the whole body and parts of the body. The analysis has been conducted on a virtual thermal manikin with CFD software STAR-CCM+. In accordance with the standard ISO 14505-2:2008, only dry heat transfer has been observed and a driver has been modelled as a thermal manikin with the constant temperature of the surface. Variable parameters were the direction of the vents, air temperature and air velocity at the vent outlet. For those variables under different conditions, thermal sensation has been determined for the whole body and occurrence of local discomfort has been measured. The results have showed that among the selected parameters the direction of the vents has the most significant influence on the local distribution of heat fluxes over the body of the exposed person. Under the conditions presented, local discomfort has been noted even though the whole body experienced neutral thermal sensation.
Keywords: Thermal sensation, Vehicle cabin, Air-conditioning, Virtual thermal manikin, Equivalent temperature, Computational Fluid Dynamics

YOLCU OTOMOBİLİNDE HAVALANDIRMA AYARLARININ SÜRÜCÜNÜN YEREL ISIL ALGISI ÜZERİNE ETKİLERİ

Özet: Bu makalede, otomobil klima sisteminin işletme parametrelerinin kabin ısıl algısı üzerindeki etkileri analiz edilmiştir. Isıl algı, bütün vücut ve vücudun bölgeleri için, eşdeğer sıcaklık yaklaşımı kullanılarak değerlendirilmiştir. Analizler, bir sanal ısıl manken kullanılarak, HAD yazılımı STAR-CCM+ yazılımı kullanılarak gerçekleştirilmiştir. ISO14505-2:2008 standardına uygun olarak, sadece kuru ısı transferi gözlenmiştir ve sürücü, yüzey sıcaklığı sabit ısıl manken gibi modellenmiştir. Değişken parametreler hava akış doğrultusu, havalandırma deliği çıkışındaki hava sıcaklığı ve hızıdır. Bu değişkenlerin farklı değerlerinde, bütün vücut için ısıl algı belirlenmiş ve yerel konforsuzluk oluşumu ölçülmüştür. Seçilmiş olan değişkenlerden, hava akış yönünün, hava akışına maruz kalan kişinin vücudundan olan ısı akısına en çok etki eden değişken olduğu görülmüştür. İncelenmiş olan şartlarda, bütün vücut nötr ısıl algı hissettiğinde bile, yerel konforsuzluk belirlenmiştir.
Anahtar kelimeler: Isıl algı, Araç kabini, Klima, Sanal ısıl manken, Eşdeğer sıcaklık, Hesaplamalı akışkanlar dinamiği

NOMENCLATURE

A_{body}	Body area [m^2]
A_{seg}	Body segment area [m^2]
C	Convective heat flux [W/m^2]
h_{cal}	Calibration heat transfer coefficients [W/m^{2}K]
n	Number of segments [-]
q	Sensible heat flux [W/m^2]
R	Radiative heat flux [W/m^2]
R_S	Solar radiation [W/m^2]
t_a	Air temperature [°C]
t_{eq}	Equivalent temperature [°C]
TEQ_i	Relative deviation of the equivalent temperature of the i-th segment from the neutral values [-]
$\overline{TEQ}$	Mean value of TEQ_i [-]
t_{mr}	Mean radiant temperature [°C]
t_{sk}	Skin temperature [°C]
$wt_{eq\ neut}$	Reciprocal value of the neutral thermal sensation interval [1/°C]

Subscripts

air	Exposed to the air
cal	Calibration
eq	Equivalent
seg	Segmental

INTRODUCTION

Automotive air conditioning system has a task to provide comfortable conditions for a driver and passengers. Uncomfortable conditions decrease drivers' ability to control the vehicle and therefore indirectly influence safety. Due to specific design of motor vehicle cabin unfavourable thermal conditions can occur in summer as well as winter period. The need to achieve acceptable and comfortable conditions in a very short period of time after entering the cabin demands activating great amount of cooling or heating power. While engine waste heat can be used for heating the cabin, mechanically driven compressor is necessary for cooling and that is the reason why cooling has a significant influence on an economical vehicle exploitation. Therefore, relevant literature has mostly focused on an increase in energy efficiency of air-conditioning. A pre-requisite to analyse thermal conditions is to study the processes influencing human's thermal sensations, which is an integral part of such studies. Furthermore, beside laboratory and experimental field research of microclimate conditions inside a vehicle cabin, the application of Computational Fluid Dynamics (CFD) with experimental validation of a numeric model and combined with a numeric model of a human thermal regulation provides wide possibilities.

The relation between energy aspects of vehicle air-conditioning (AC) and improvement of thermal conditions was presented in detail in The Vehicle Ancillary Loads Reduction Project, 1996 – 2008 (Rugh and Farrington, 2008). The project dealt with the analysis of possible reduction of energy consumption for the air-conditioning of the cabin interior. It was concluded that there is a great potential to reduce AC fuel consumption because AC systems have been designed to maximize capacity, not efficiency. The results showed that the passengers vehicle's cooling power could be reduced by 30% while maintaining a cooldown performance of 30 minutes. Simulations showed that reducing the cooling power by 30% decreases air-conditioner fuel consumption by 26%. Detailed research of design characteristics of air-conditioning vents was presented by Currle and Maue (2000). The authors used CFD to study the influence of vent characteristics on thermal sensations of passengers. It was concluded that the area of vents and airflow significantly influence the passengers' thermal sensations, more favourable case being the one with larger vents. The research was conducted with only one direction of the vents, which means that there are no data about the significance of the size of the vent in relation to its direction. Using the Theseus-Fe software, Ivanescu et al. (2010) carried out the analysis of time needed to achieve comfortable conditions in the cool down regime of the vehicle cabin with various operational modes of air-conditioning system. The effects of different settings of the air vents on thermal sensation in the passenger car were investigated by Kilic and Sevilgen (2012). Three different settings with the same cooling power were analysed under transient conditions. CFD software Fluent was applied on the virtual thermal manikin with the constant temperature. The best results in terms of heat dissipation from the driver's body were achieved using the air vents on the dashboard. The similar experimental research regarding the heating period in a vehicle cabin was carried out by Kilic and Korukcu (2012). The research on the influence of localised cooling and heating of vehicle occupants was carried out by applying the CFD method by a group of authors from Delphi Automotive Systems, Delphi Thermal Systems and General Motors Company (Ghosh et al, 2012). It was concluded that four vents could achieve savings in the cooling power of 30 to 50%, as compared to conventional air-conditioning systems where there are only two vents directed at driver.

This paper analyzes the influence of the operating parameters of air-conditioning systems on the thermal sensation in the cabin of a passenger car. The objective of virtual experiments is to analyse the dependence of the local and overall human thermal sensations in the vehicle cabin as related to temperature and air velocity at the outlet of the vents and their direction.

THE METHOD

The research described in this paper was carried out by virtual experiments using the CFD software STAR CCM+. The model consisted of cabin interior and the driver. The driver was modelled as a thermal manikin, in accordance with ISO 14505-2:2008. For evaluation of thermal conditions, the equivalent temperature was used, based on the sensible (dry) heat transfer from the body (Nilsson, 2004).

Model of the vehicle cabin interior

In order to create a simplified geometric CAD model of the vehicle cabin interior the dimensions of the cabin interior were chosen according to middle-size passenger cars (Figure 1). The cabin interior volume was approximately 2.6 m^3. Cabin space was defined by the inner surfaces only meant to provide appropriate boundary conditions and not to have any physical interpretation in the form of mass and thermal properties. The vents are 60 mm in diameter. The boundary conditions at the vents were air mass flow and temperature. Direction of the vents can be adjusted independently.

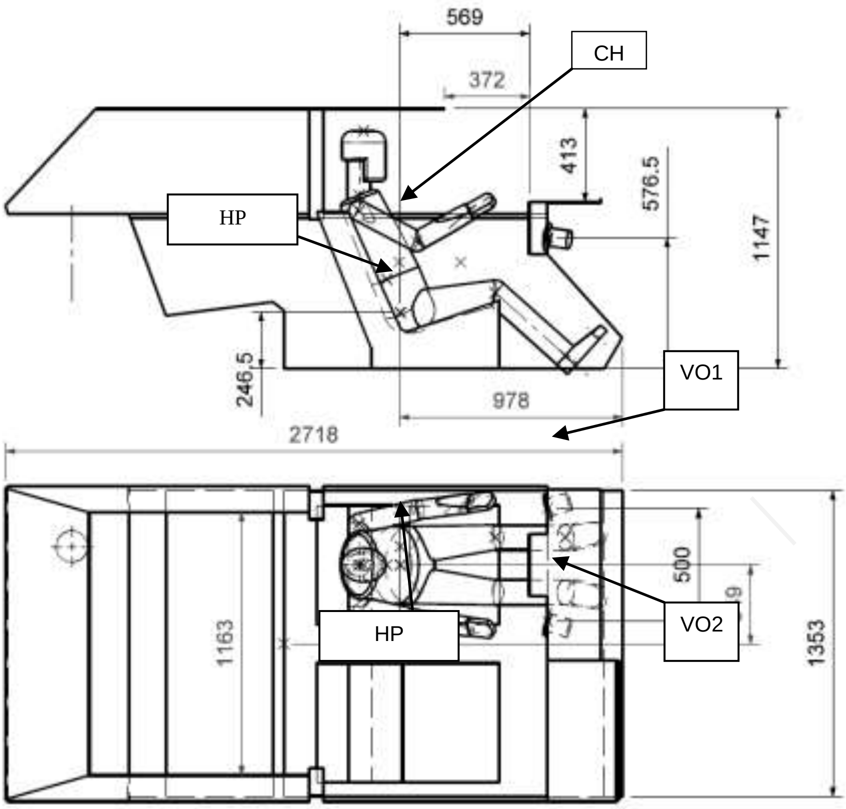

Figure 1. Geometry of cabin model with virtual thermal manikin. HP - H-point, CH – Chest, VO1 and VO2 – vents.

Virtual Thermal Manikin

Virtual thermal manikin (VTM) was shaped in a form of a simplified human body in a sitting position, Figure 2. Dimensions of the body were retrieved from the database of CAD program CATIA, for 50-percentile male. Body height of the manikin in a standing position would be 1.74 m and the total body area in a sitting position is 1.796 m^2. The position of the manikin inside the cabin was determined using the H-point. VTM's surface temperature was at constant 34°C and it was divided into 18 segments.

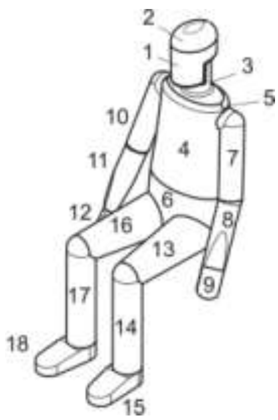

Figure 2. Virtual thermal manikin with numbered segments

Numerical model

Size and type of finite volumes for generating a mesh in this model was initially taken from the work of Ružić and Bikić (2013). Due to more complex configuration of the inside of a cabin than the one of the chamber used for VTM validation by comparison with the results of benchmark tests (Nilsson et al, 2007), finer mesh was chosen, especially in the vents area. Basic characteristics of the finite volume mesh of the cabin interior with the VTM are presented in Table 1. The entire virtual model was discretized in about 170,000 polyhedral finite volumes with several layers of prismatic finite volumes at the surface of solids.

Table 1. Basic parameters of the finite volume mesh

Domain boundaries	Target/minimum surface element size, mm
walls in the front part of the cabin	24/12
walls in the rear part of the cabin	54/30
vent (domain inlet)	15/7.5
duct	18/9
constant pressure outlet	60/30
virtual thermal manikin surface	24/12

Reference sources indicate that turbulence models used in simulations of such and similar problems are RNG k-ε (Kilic and Sevilgen, 2012; Mazej and Butala, 2012), RANS Realizable k-ε (Chen et al. 2012) or RANS SST k-ω (Martinho et al. 2008; Voelker and Kornadt, 2011). Preliminary simulations of this research proved that RANS Standard k-ε and RANS SST k-ω turbulence models had larger instability of the residuals so that further research used Two-layer RANS Realizable k-ε turbulence model (Ružić and Bikić, 2013).

For model validation and verification of its results it was necessary to have adequate experimental results. The experiments were carried out in the passenger car and the reduced size cabin model. Physical quantities used for comparison were the air temperature and air velocity at multiple points inside the cabin. Velocity distribution and the temperature in the cabin space obtained by simulations proved satisfactory for the validation of the chosen model. Given the complexity of the flow due to the complex internal geometry of the cabin, the comparison value of the results was limited to the magnitude and the nature of the change of the selected flow parameters. It was unrealistic to expect the overall agreement with the experimental data, relevant to the values and the spatial distribution, since a large number of parameters affected the results in such complex problems, both in physical systems and in the numerical model.

Evaluation of thermal sensations

The equivalent temperature is defined as the uniform temperature of an imaginary closed space with the air velocity equal to zero, in which a person would have the same sensible heat transfer as in a real environment. By equating the heat exchange with the surroundings by convection and radiation in a real environment with an imaginary homogeneous environment in which the air temperature is equal to the mean radiant temperature, i.e. to the equivalent temperature, the equivalent temperature is obtained in the general form of:

$$t_{eq} = t_{sk} - \frac{q}{h_{cal}}, \text{°C} \tag{1}$$

where

$$q = C + R\ (+\ R_S) = C_{eq} + R_{eq} \tag{2}$$

The coefficients of segmental dry heat transfer, required for the calculation of the equivalent temperature, were determined by calibration. Virtual calibration was performed in a chamber the size of 2 × 2 × 2 m, with homogeneous microclimate conditions ($t_a = t_{mr} = t_{eq} =$ 24°C) without forced air flow. Based on segmental heat loss under these conditions, the calibration coefficients of heat transfer were calculated using Eq. (3).

$$h_{cal,seg} = \frac{q_{cal,seg}}{t_{sk} - t_{eq}} \tag{3}$$

The results of the calibration are shown in Table 2.

Table 2. Calibration coefficients

Segment	h_{cal}, W/m^{2}K
Head	11.5
Scalp	10.3
Neck	8.3
Chest	8.8
Back	9.6
Pelvis	8.7
Upper arm	9.4
Lower arm	10.3
Hand	11.0
Upper leg	8.9
Lower leg	9.3
Foot	10.2
Body	9.6

Back, pelvis and upper legs are in contact with the seat. The virtual thermal manikin has a constant surface temperature and presuming that the seat is adiabatic and that upon establishing thermal balance would not warm-up or cool down, there would also be no heat flow through the surface in contact. Therefore, the equivalent temperature in that zone was equal to the surface temperature, i.e. $t_{eq\ seat} = t_{sk}$ = 34°C. If the heat flux at the surface of the manikin exposed to the air is determined, taking into account that the flux at the surface in contact with the seat equalled zero, for the segment of the body in contact with the seat the corrected equivalent temperature is given in Eq. 4.

$$t_{eq\ \ seg}^{air} = t_{sk} - \frac{q_{seg}}{h_{cal\,seg}} \frac{A_{air\,seg}}{A_{seg}} \tag{4}$$

The ratio of VTM body surface exposed to the air and the surface of the whole body was 0.872, while the values for certain body segments are given in Table 3. Symbol t_{eq} hereinafter refers to the corrected values i.e. the *air* index is omitted for better overview.

Table 3. The ratio of segments exposed to the air and in contact with the seat to the entire area of those segments

	$A_{air\ seg}/A_{seg}$
Back	0.494
Pelvis	0.755
Upper leg	0.684

Thermal conditions are considered favourable if the equivalent temperature deviates less from the neutral value (Figure 3). Due to local discomfort thermal conditions can be considered uncomfortable even when the equivalent temperature of the entire body is at the neutral value. For this reason, the deviations in the segmental equivalent temperatures from their neutral values, taking into account the thermal sensitivity and size of the individual segments, were evaluated in this study. This allows comparison of the two microclimatic conditions even when their $t_{eq\ body}$ are equal. Similar approach was used in the research that was carried out by Bohm et al. (2002). Conditions with less standard deviation of the relative difference of the segmental equivalent temperature from the neutral values were considered to be more comfortable. The standard deviation was calculated by:

$$SD_{teq\,rel} = \sqrt{\frac{\sum\left(TEQ_i - \overline{TEQ}\right)^2}{n}} \qquad (5)$$

where the following were:

n = 18 segments,

$$TEQ_i = wt_{eq\,neut,seg}\left|t_{eq\,seg} - t_{eq\,neut,seg}\right|\frac{A_{seg}}{A_{body}} \qquad (6)$$

$$wt_{eq\,neut\,seg} = \frac{1}{t_{eq\,neut,seg\,max} - t_{eq\,neut,seg\,min}} \qquad (7)$$

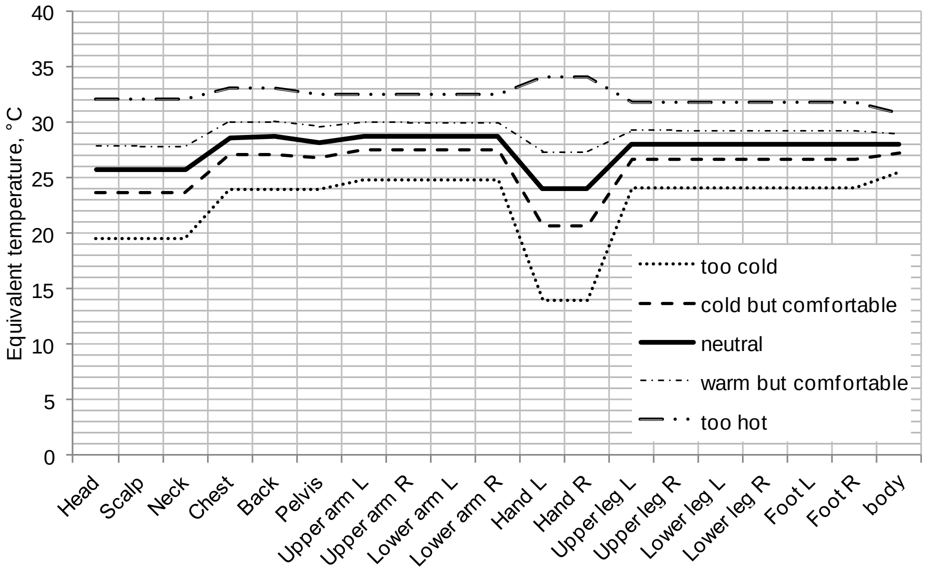

Figure 3. The equivalent temperatures limits: values from the standard ISO 14505-2: 2008, adjusted to the defined body division

BOUNDARY CONDITIONS

As the focus of this study was the influence of air-conditioning on human thermal sensation, where convection is the main mode of heat transfer, the latent heat exchange was not included and the heat transfer by radiation was kept constant. The guidelines for defining boundary conditions in virtual experiments were, in addition to the conditions given in standard ISO 14505-2: 2008 for steady-state conditions, the results of experiments carried out by Ružić (2006) and the results of the available relevant literature (Ghosh et al, 2012; Kilic and Sevilgen, 2009; Kilic and Sevilgen, 2012; Ružić and Stepanov, 2013; Sandiki, 2012):

- the initial air temperature in the cabin 35°C;
- constant temperature of the interior surfaces 35°C;
- emissivity of the interior surface ε = 0.95,
- virtual thermal manikin with constant and uniform surface temperature of t_{sk} = 34°C, emissivity ε_{sk} = 0.95, solar absorptivity α_S = 0.62;
- solar transmissivity of glass τ_S = 0.5;
- solar radiation 800 W/m^2, solar altitude θ_S = 60°, azimuth Φ = 0°.

The following factors were varied in virtual experiments:

- air mass flow through the vent ($\dot{m}_{aVO}$),
- air temperature at the outlet of the vent (t_{aVO}),
- the direction of the chosen vent.

RESULTS AND DISCUSSION

The starting point for the research presented in this paper was the existence of quantitative relations as well as the rules established in the previous studies and available literature sources:

- if a vent is directed at a certain body segment (target point), a greater heat loss can be expected in that segment;
- if the velocity is increased and/or the air temperature from the vent lowered, the heat dissipation from the zone at the point where the vent is directed will increase;
- direction of the vent is a factor of greater importance for the thermal sensation compared to its position in the cabin (Ružić and Časnji; 2011, Ružić, 2012);
- with more vents and/or their larger areas directed towards the body cooled air is better utilised (Ghosh et al, 2012).

The initial virtual experiment, labelled VE1, was carried out under conditions that correspond to cooling of the cabin with all four vents on the dashboard directed horizontally, Figure 4. Through each of the four vents the air mass flow rate was 0.0167 kg/s, at a temperature of 10°C, which are values corresponding to the values of the conventional automotive air-conditioning systems.

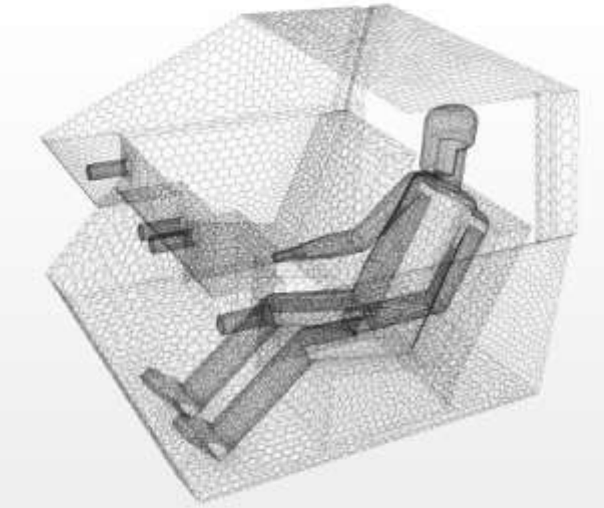

Figure 4. The finite volume mesh of the vehicle cabin with the virtual thermal manikin

The resulting equivalent temperatures of individual body segments and the whole body are shown in Figure 5. The equivalent temperature of the whole body was 4.7° higher than the neutral value, which classifies these conditions under the ones with the sense of warmth outside the comfort zone. The standard deviation of the relative difference for the segmental equivalent temperature from the neutral value was 0.096.

In the following virtual experiment, labelled VE2, the verification of the hypothesis that the direction of the vents has greater importance on the human body heat loss than cooling of the entire cabin was carried out. Two air vents in front of the passenger were turned off while keeping the same boundary conditions. The difference between the equivalent temperature of the whole body and the neutral value was slightly higher (5.5° difference), while the standard deviation of the relative differences was the same as in VE1, 0.096 (Figure 5, Table 4). Under these conditions, the cooling power was reduced to one-half compared to the previous case. In both cases, the intense local cooling of the upper arm can be noted with the low equivalent temperatures outside the thermal comfort.

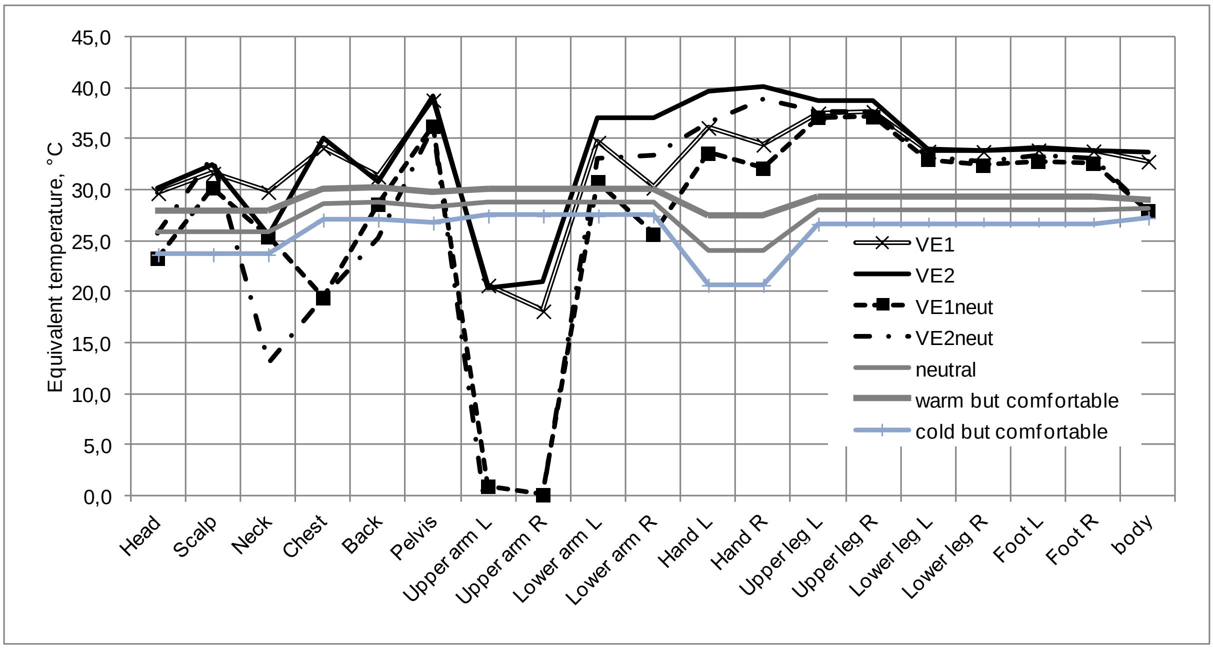

Figure 5. The equivalent temperatures in VE1 and VE2; 'neut' index marks the virtual experiments where the neutral equivalent temperature of the whole body was achieved

In order to achieve the neutral equivalent temperature of the body under the chosen boundary conditions, it was necessary to increase the cooling power by changing the operating parameters of the system, i.e. by lowering the temperature and/or increasing the air flow. In the case when all four air vents were active ($VE1_{neut}$), that was t_{aVO} = 6°C and $\dot{m}_{aVO} = 0.031$ kg/s, which meant the increase of cooling power to 210% compared to VE1. With only two air vents active ($VE2_{neut}$) the parameters were t_{aVO} = 6°C and $\dot{m}_{aVO} = 0.040$ kg/s and then the cooling power was 135% of the cooling power in VE1. However, although the deviations from the $t_{eq\ neut\ body}$ were minimal in both cases, the extreme values of the local segmental equivalent temperatures were so low that the conditions could not be considered comfortable: on the upper arms, which were directly exposed to the cold air of high velocity, the feeling was the same as exposure to the air temperature near zero! Figure 5. These adverse conditions were quantitatively described by other criteria, since the deviation of the relative difference in the segmental equivalent temperatures in the first case was 0.202 and in the second 0.208. Settings and results of all four initial virtual experiments are summarised in Table 4.

Table 4. Values of the factors and results of the initial virtual experiments VE1, VE2, VE1$_{neut}$ and VE2$_{neut}$

	Factors			Results	
	Active vents	$\dot{m}_{aVO}$, kg/s (u_{VO}, m/s)	t_{aVO}, °C	Δt_{eq}, °	$SD_{teq\ rel}$
VE1	All four	0.0167 (4.9)	10	4.7	0.096
VE2	Two, in front of driver	0.0167 (4.9)	10	5.5	0.096
VE1$_{neut}$	All four	0.031 (6.1)	6	–0.2	0.202
VE2$_{neut}$	Two, in front of driver	0.040 (11.8)	6	–0.3	0.208

The results indicate the need to change the vents' direction. Since there is no exact data regarding the influence of vent direction on thermal sensation, the direction towards VTM's body segments was selected according to which, in the initial virtual experiments, heat loss was the smallest. Chest (CH) and pelvis (HP – H-point) were selected as the target points, as the segments that have a large impact on thermal sensation (Bohm et al, 2000; Ghosh et al, 2012). The left vent was directed at the H-point and the right one at the chest. The values of air mass flow and the air temperature in virtual experiments VE3 – VE6 are given in Table 5. The segmental equivalent temperatures in this group of virtual experiments are presented graphically in Figure 6.

Table 5. Values of the factors and results of virtual experiments VE3 – VE6

	Factors		Results	
	t_{aVO}, °C	$\dot{m}_{aVO}$, kg/s (u_{VO}, m/s)	Δt_{eq}, °	$SD_{teq\ rel}$
VE3	10	0.0167 (4.9)	1.6	0.066
VE4	6	0.0167 (4.9)	0.2	0.096
VE5	10	0.0261 (7.7)	–2.5	0.163
VE6	6	0.0261 (7.7)	–4.4	0.220

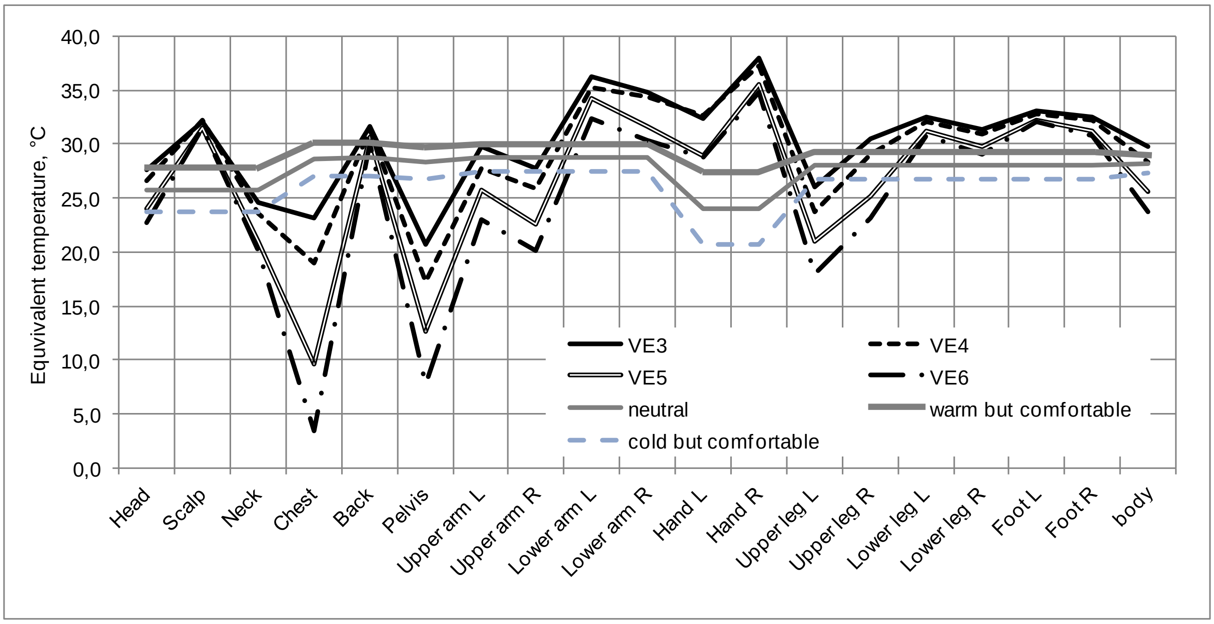

Figure 6. The equivalent temperatures in VE3 – VE6

From the point of deviation from the neutral value of the whole body equivalent temperature, in the second group of virtual experiments (VE3 – VE6) the most favourable case is VE4. Using the linear approximation on the observed range of factors certain dependence of Δt_{eq} from $\dot{m}_{aVO}$ and t_{aVO} was obtained, as shown in Table 6. From the condition Δt_{eq} = 0 a combination of values $\dot{m}_{aVO}$ and t_{aVO} were analytically determined as shown in Figure 7 and Table 6. The results of virtual experiments with these factors confirmed the dependence presented in Table 6. The results show that even though neutral value of the equivalent temperature has been achieved for the whole body the amounts of segmental equivalent temperature dissipation indicate the occurrence of local discomfort. Thus, in order to improve distribution of heat fluxes over an exposed body the number of target points should be increased and that would mean changes in the design of the observed (conventional) ventilation system.

Table 6. Linear approximation of dependence Δt_{eq} from $\dot{m}_{aVO}$ and t_{aVO}

			Results	
		Values for $\Delta t_{eq} = 0$	Δt_{eq}	SD
$\dot{m}_{aVO} = 0.0166$ kg/s	$\Delta t_{eq} = 0.341\ t_{aVO} - 1.796$	$t_{aVO} = 5.3$°C	0.0	0.103
$\dot{m}_{aVO} = 0.0261$ kg/s	$\Delta t_{eq} = 0.477\ t_{aVO} - 7.245$	$t_{aVO} = 15.2$°C	0.2	0.095
$t_{aVO} = 6$°C	$\Delta t_{eq} = -492.2\ \dot{m}_{aVO} + 8.453$	$\dot{m}_{aVO} = 0.0172$ kg/s	0.0	0.101
$t_{aVO} = 10$°C	$\Delta t_{eq} = -434.3\ \dot{m}_{aVO} + 8.850$	$\dot{m}_{aVO} = 0.0204$ kg/s	–0.1	0.105

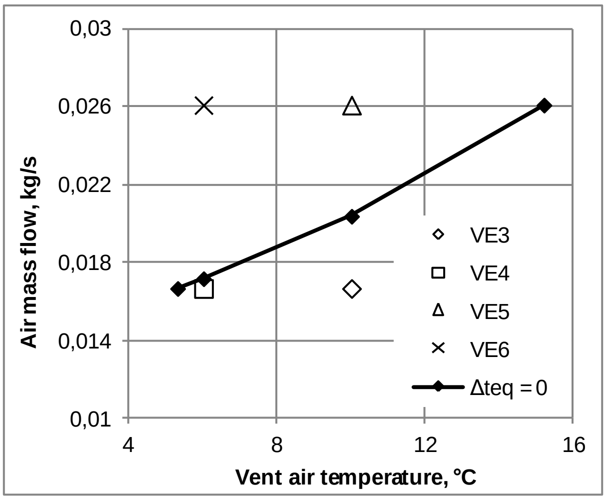

Figure 7. Values of the factors in VE3 – VE6 and dependence between $\dot{m}_{aVO}$ and t_{aVO} for $\Delta t_{eq} = 0$

CONCLUSION

The aim of the research presented in this paper was to determine the influence of the air mass flow, air temperature at the outlet of vents and their direction on human thermal sensation in the vehicle cabin. The equivalent temperature as the assessment criteria of thermal conditions, was extended by determining the deviation of the relative difference of the segmental equivalent temperatures from the neutral values. In this way it was possible to compare the conditions with the equal equivalent temperatures of the whole body and additionally quantify the occurrence of local thermal discomfort.

Virtual experiments were divided in two groups according to the vent direction. The first group had the vents positioned horizontally while in the second they were directed towards the body of the driver. The results showed that, among the selected factors, the direction of the vents is the most significant factor influencing the local distribution of heat fluxes over the body of a person seated in the vehicle cabin. A change of a vent direction changes distribution of heat fluxes entirely and with that it changes local and overall thermal sensation. For the same vent direction but with the change of air speed and temperature the equivalent temperature changes proportionally without changing overall body distribution. By directing vents towards body parts in greater need of cooling the air is used more efficiently but it can also lead to experience of local discomfort. It follows that an increase in the number of target points and by increasing the number of vents the deviation of differences in the segmental equivalent temperatures from the neutral values would be reduced.

Due to inter- and intra- individual differences among people and because of non-uniformity of boundary thermal conditions in the vehicle cabin there needs to be the possibility for precise temperature air flow and direction adjustments of each vent. Settings of the operating parameters of air-conditioning systems must be wide enough and the use of it suitable and understandable to the exposed person. From the aspect of energy efficiency, the approach to direct cooling of the body is the most justifiable in cases when there is only one person in the vehicle cabin since the required energy for cooling increases with the number of passengers.

Additionally, the research could be extended to other criteria, such as the value of microclimate parameters in the facial area or time needed to achieve the required conditions. It can be noted that optimization might lead to contradictions in the requirements and then to conflicting decisions about optimal solutions.

ACKNOWLEDGEMENTS

This research was done as a part of the project TR35041 – "Investigation of the safety of the vehicle as part of cybernetic system: Driver-Vehicle-Environment", which was supported by the Serbian Ministry of Education and Science. The author wish to thank Dr Maša Bukurov for enabling the use of the licensed CFD software.

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