Corrigendum: The influence of different air flows introduced on the thermal comfort of car passengers during the cooling period – Numerical Study (2021, IOP Conf. Ser.: Earth Environ. Sci. 664 012112)

P A Danca\textsuperscript{1,2}, I Nastase\textsuperscript{1}, and F Bode\textsuperscript{1,3}

\textsuperscript{1} CAMBI Research Center, Technical University of Civil Engineering Bucharest, 021414 Bucharest, Romania
\textsuperscript{2} National Institute for R&D in Electric Engineering ICPE-CA, Department of Renewable Energy Sources and Energy Efficiency, 313 Splaiul Unirii, 030138 Bucharest, Romania
\textsuperscript{3} Technical University of Cluj Napoca, Department of Mechanical Engineering 400020 Cluj - Napoca, Romania

After peer review, the authors of the paper mistakenly included templated text within the conclusion of the article. This is a result of copying text from a template provided by the conference organisers to the authors that helps ensure their work is formatted in the correct way. The authors apologise for this mistake.
The influence of different air flows introduced on the thermal comfort of car passengers during the cooling period – Numerical Study

P A Danca¹,², I Nastase¹ and F Bode¹,³

¹CAMBI Research Center, Technical University of Civil Engineering Bucharest, 021414 Bucharest, Romania
²National Institute for R&D in Electric Engineering ICPE-CA, Department of Renewable Energy Sources and Energy Efficiency, 313 Splaiul Unirii, 030138 Bucharest, Romania
³Technical University of Cluj Napoca, Department of Mechanical Engineering 400020 Cluj Napoca, Romania

Correspondence: ilinca.nastase@gmail.com, florinbode@gmail.com

Abstract. In this article the effects of different airflow rates introduced by the ventilation system are investigated by numerical simulation over the thermal comfort of the driver in a regular vehicle. The 3D LDV (Laser Doppler Velocimetry) measurement for the diffusers velocity field was imposed as boundary condition at the inlets of the investigated domain. Also, the flow rate discharged by each diffuser was measured for the first three positions of the air conditioning system. In the numerical model which was previously validated we imposed the boundary conditions from the experimental sessions. Thermal comfort was assessed by calculation of the equivalent temperature on the surface of a virtual manikin on the driver place and by the determination of the maps of Predicted Mean Vote (PMV) and the Draft rate indices. A first conclusion is that the results of the three flowrates may assure the comfort of the front passengers and a draft sensations and uncomfortable state for the rear passengers.

1. Introduction

One of the main requirements in choosing an item/system nowadays is the comfort. If this requirement is satisfied, the wellbeing state of that person which is using that item/system is improved. Further, this wellbeing state can improve the health condition, concentration, productivity and the performances of a person. The same is with the environments in which we live [1-3]

Achieving thermal comfort for occupants of the environments from buildings has been and still is the preoccupation of the Heating Ventilation and Air Conditioning (HVAC) engineers and of the developers of building services for more than five decades. On the other hand, the thermal comfort of occupants from the vehicles and generally the Indoor Environment Quality (IEQ) acquire more importance mostly because the time that people spend in vehicles has grown substantially. Also, the researchers focused their concentration in direction of thermal comfort of vehicle passengers in the last decades due to increasing of both public and private numbers of cars.

A thermal environment that is uncomfortable may affect both the physical and the psychological conditions of the passengers and may be essentially unhealthy. More than this, in the case of the driver a comfortable thermal environment may ease a sensation of fatigue and could improve their mood thus
contributing to the safety of driving. This was remarked in the study of Tsutsumi et al. [4], which shows that in the cabin environment which is not comfortable the driver’s level of tiredness is affected. In another study made by Danen et al. [5] it has been found that in extreme thermal conditions (both hot and cold) of the vehicular space, the driver performance has been affected. This way it can be noticed, that a temperate thermal environment in the vehicles cabin is significant not only for the comfort state of the driver and of the passengers but also for their safety. In the same time, the present preoccupation towards the environment impose us preserving energy resources [6]. This way it is a challenge to obtain high performance systems and in the same time a better quality of the parameters in the controlled environment.

The understanding of the airflow distribution is still a challenge for the researchers due to the interior intricate geometry and also because of the complexity of ventilation/climatization systems (flow rates, vents geometry and location) [4]. More than this, the non-uniformity temperatures of the interior surfaces affect directly the air flow movement through convective effects. The manufacturers do not consider the effect flow patterns on thermal sensation, given that the air flow trajectory introduced in the vehicle environment might be substantially dissimilar from the direction given by the guiding vanes of the air diffusers. This difference is bound to the previously mentioned factors but is another factor related to the intrinsic specific feature of the air diffuser itself. Indeed, Lezovic et al [7] has elaborated a study of the flow patterns produced by different angles of the vertical and horizontal guiding vanes of an usual air diffuser. In their study, to measure air velocity the authors used hot wire probe and smoke visualizations. The results are showing that the performance of the air diffuser regarding the direction of the injected airflow is globally affected by the individual diffusers geometry and by the position of the guiding vanes inside the vent and by the geometry of the duct system. The effects produced by different positions of the air diffusers on thermal sensation inside of the passenger car was numerically studied by Kilic [8]. Considering the same cooling power for each case, three cases with different positions of the diffusers were analyzed under transient conditions. The most relevant results in terms of heat dispersal from the driver's body were accomplish in the case with the air vents placed on the dashboard. The effect produced by an innovative dynamic air vent system across the heated surfaces of thermal manikins was studied by Limaye [9]. The results showed that the innovative active control method of the guiding vanes might ensure more uniform heat dissipation from the driver's body. The previously cited papers reveal that the global dispersion of the air flows introduced by the ventilation system inside the vehicular environment plays a significant role on passengers thermal sensation, outright via the possibility of heat dissipation from the human body to the vehicular ambient, and indirectly through the homogeneity of air temperature and velocity distributions.

2. Material and method

In this chapter is presented the experimental setup and the measurement equipment used to obtain the flow rates for the three ventilation running speeds and the flow distribution at the inlet for each of the two types of dashboard diffusers.

For this study was used a Renault Megane vehicle (see Figure 1) from 2003. It is equipped with a 1.4-liter petrol engine, and it has 5 places for the passengers and 5 doors. The in-cabin environment is cooled with a manual ventilation(conditioning system with four fan running speeds. During the experimental sessions the car was kept in a hall to avoid quick modifications of the parameters of the vehicle outside environment.
2.1. Flowrate measurement

Previous to the numerical simulation of thermal environments, the inlets flow rate was carefully measured for the first three running speeds of the fan - V1, V2 and V3 corresponding to positions (stages) I, II and II of the air flow controller. In the technical manual of the vehicle were available data regarding the air flow rates, but we wanted to have the real distribution of the flow rates to each discharge diffusers, since that the ducting system is not symmetric. For the fourth step of the fan we did not perform this type of measurements given the very high values of the in-cabin velocities. In order to achieve the same volumetric flow rate, for each considered diffuser and each of the three velocity steps of the fan, the integration of the radial air speed profiles was performed. The air velocity was measured with the omnidirectional probe of the Comfort Sense system. Our choice to employ the omnidirectional probe rather a directional hot film anemometer was related to the fact that this method is more accurate at very low velocities and also is recommended when the flow direction has strong three-dimensional characteristics.

Two types of TSI AIRFLOW air cone hoods were stacked to the dashboard as displayed in Figure 2 and carefully placed in front of the diffuser. Air speed values were recorded using a Dantec omnidirectional 54T33 probe in 88 points as is drown on the measurement grid from Figure 3. The velocity range of the used omnidirectional is 0,05-10 m/s and the accuracy are: ±2% for velocities values between 0,05-1 m/s, ±5% for velocities values between 1-5 m/s and ±10% for velocities values between 5-10 m/s. The free ends of the air cones have both the diameter of 10 cm. The sampling time of the air speed in every considered point was 10 seconds. Air flows values result from the integration of the measured values on the free end known surface of the air cones (see f).
The 7th Conference of the Sustainable Solutions for Energy and Environment

The airflow values obtained from these measurements (see table 1) for the three fan controller positions were imposed as boundary conditions in the numerical model.

2.2. Airflow distribution measurement

In some of the previous studies [10-13], we considered the distribution of the velocity profile at the inlets uniform as in the majority of the articles from the actual literature. A drawback of this work hypothesis is that imposing the same velocity on all the inlet surface is not a realistic case. In this paper are compared the effects of three different flowrates introduced by diffusers with real flow velocity distribution measured by Laser Doppler Velocimetry. Normally, the airflow directivity is mainly influenced by the air duct orientation, number of air diffusers, their shape and positions. Imposing a uniform air velocity at the inlets as boundary condition is modifying the airflow pattern distribution and the thermal sensation of passengers may be modified [13]. The competition for space in new vehicles is intense, so the HVAC ducts are often squeezed between different components and the ducts geometry is very complex.

For the LDV – 3D measurements we used a separate dashboard identical to the one on board of the real car with the entire ventilation/conditioning system and the original fan.

![Figure 3. Measurement points grid](image)

![Figure 4. Detail of measurement points at the side left diffusers](image)
The air velocity was measured with a step of 5 mm in the front of the diffused as in Figure 4. The measurement grid was established at X = 14 mm from the diffusers due to the circular shape of the dashboard which does not allow to measure closer. The LDV 3D – measurement equipment used, is manufactured by Dantec and is composed from a 2D FiberFlow laser with wavelengths of 527nm and 565nm and 2D FlowLite with wavelengths of 532 nm. These are connected to a Burst Spectrum Analyzer BSA Processor F/P 60 is connected to a computer, used to setup the measurements planes. The two measurement probes were fitted on a traverse system.

In Figure 5 is represented the distribution of velocity magnitude in front of a central diffuser. With the black thin lines are represented the diffuser shape.

![Figure 5 Velocity magnitude in the front of a central vent](image)

In order to impose the measurement results as boundary conditions many operations were made due to the differences of the coordinate axes between LDV measurements and numerical model.

3. Numerical model

In previous papers [10-16], were detailed the construction, the setup and the validation of the numerical model of a Renault Megane cabin. We showed that we can reproduce the in-cabin thermal environment, we can find values of indoor thermal factors from the CFD model that were similar to those found in experimental measurement sessions. The cabin geometry was designed in Catia software and then imported to Design Modeler in Ansys. To check the independence of the solution, six different numerical grids with tetrahedral elements where tested. The numerical grid was realized in Ansys Workbench software. The numerical simulation was carried out in Fluent software.
Figure 6  a) Geometrical model presented in isometric view b) Detail of the mesh in the zone of the manikin

After the mesh independency test, we choose a numerical grid composed of 6.5 million elements with tetrahedral geometry Figure 6. The boundary layer consists of five layers, with the first cell height of 0.75mm and a growth factor of 1.2. For the pressure-velocity coupling we utilized the COULPED algorithm. A second order upwind scheme was used to calculate the convective terms in the equations, integrated with the finite volume method. For the near-wall modelling, the standard wall function was used. The chosen turbulence model used for the numerical simulation was RNG $k$-$\varepsilon$, because the overall performance of this model is one of the best for the indoor environment modelling [17, 18]. The geometry of the virtual manikin is a freeware version of the manikin found on the internet. It was modified and introduced inside the cabin geometry. The manikin has a height of 1.70 m and its total surface area is 1.81m².

3.1. Boundary conditions

Air flow values (Table 1) its distribution obtained for each type of diffusers from the previous experimental measurement sessions for the three fan controller positions were imposed as boundary conditions in front of the diffusers in the numerical model. It can be seen that the airflow values are very different even if the shape of the diffuser is the same (for the case of left and right diffusers). One of the causes may because of the different shapes and lengths of the ventilation ducts. It may be also the explanation for the differences of temperature measured (Table 2)

Table 1 Airflow imposed at the diffusers

| Diffuser position | V1 [m³/s] | V2 [m³/s] | V3 [m³/s] |
|-------------------|-----------|-----------|-----------|
| Central diffuser  | 0.0131    | 0.0258    | 0.0380    |
| Right diffuser    | 0.0068    | 0.0124    | 0.0197    |
| Left diffuser     | 0.0047    | 0.0093    | 0.0158    |

The other boundary conditions are presented in the Table 2 and Table 3. These were obtained from experimental measurement sessions presented in some previous studies [15, 16]. There is presented the experimental set-up measurement and protocols and measurement tools.

Table 2 Temperatures imposed to the introduced airflow

| Diffuser position | V1 [°C] | V2 [°C] | V3 [°C] |
|-------------------|---------|---------|---------|
| Central diffusers | 2.96    | 5.79    | 11.14   |
| Right diffuser    | 6.99    | 8.02    | 12.57   |
| Left diffuser     | 9.85    | 9.83    | 12.07   |

Temperatures on the surface of the manikin body represent the skin temperature
### Table 3 Temperatures imposed on different surfaces

| Vehicle interior surface | Temperature [°C] |
|--------------------------|------------------|
| Windshield               | 28.83            |
| Ceiling                  | 26.63            |
| Right side               | 25.16            |
| Left side                | 25.16            |
| Rear window              | 28.41            |
| Floor                    | 21.08            |
| Driver seat              | 29.00            |
| Passenger seat           | 29.00            |
| Back seat                | 29.00            |
| Trunk                    | 27.44            |
| Dashboard                | 25.23            |
| Manikin                  | 34.00            |

4. Results and discussions

The pathline representation of the air flow rates for the three studied cases coloured by the velocity are presented in figure 7. For the first case the maximum air velocity is 1 m/s at the inlets. And the inlets do not affect the

![Figure 7](image)

For the second flowrate imposed, the maximum velocity found have the value of 2 m/s at the inlets. Inside the cabin environment the central diffusers are impinging in the rear seats with a velocity of 0.8 m/s.
The higher air flowrate imposed produced a higher value of air velocity inside the car, its values varying between 1.2 m/s and 1.7 m/s in the places of the passenger. The highest velocity value is at the inlet 3 m/s.

The air velocity is one of the most important factors of thermal comfort. The high velocities values seen in the previous images are corresponding to the cold and cool regions from the PMV distributions maps (Figure 9). This may be the main reason of the thermal discomfort in the rear part of the vehicle. The PMV values in the proximity of the driver remain in the comfortable limits for V1, while for V2 and V3 the injected cold air returns creating uncomfortable sensation at the head and chest level.

As a first conclusion which can be drawn from figure 7 and figure 8 is that at the lower flowrates (V1 and V2) injected by the ventilation system are producing a larger zone with increased level of comfort at the driver’s side, while for the rear part cold sensation and uncomfortable draft sensation are found. On the other hand, the third flowrate step can lead to a very uncomfortable thermal state for the rear passengers.

In figure 9 are presented the Draft Rate values in the same plane as the PMV values.
The virtual thermal manikin convective heat transfer affects the equivalent temperature $t_{eq}$ of the body parts which is in our opinion the most adapted evaluation index for non-uniform environments. It considers the combined effect of the local air temperature with the local thermal radiation and with the local air velocity based on the local heat transfer rate at the skin surface.

In figure 10 are represented with different colours the values of equivalent temperature for each of the 16 standardized body parts for the three studied cases.

![Figure 10: Equivalent temperatures on the surface of the virtual thermal manikin](image)

Because human body parts perceive different a thermal environment, the ranges of equivalent temperature are different. Consequently in Fig. 11 spaces between the dashed lines are numbered from 1-5 each represent by standardized thermal sensation. As example zone 1 (bordered with blue dashed line) the uncomfortable cold sensation. Zone 3 is corresponding to the neutral sensation, while zone 5 which is outside of the red dashed line hot thermal sensation is perceive.

It could be noticed in this figure that relatively large variations of the equivalent temperature for each considered body parts occur, indicating variations of the local heat fluxes on the surface of the manikin. surface of the virtual body being probably explained by subtle changes in the air flow at the solid/fluid interface between the manikin and its ambient. It allows also to qualitatively observing that thermal transfer occurs differently for each part of the body and each considered case.

5. Conclusions

This paper is focused on the comfort assessing in a transient non-uniform environment inside a vehicle. Determination of the vehicle occupants’ thermal comfort is very complicated due to the transient nature and non-uniformity of the vehicle interior. More than this, the actual standard is proposing three evaluation indexes and was developed for steady state and controlled conditions and some of the indexes are not adapted to this complex environment.

A first conclusion is that the results of the three flowrates may assure the comfort of the front passengers and a draft sensations and uncomfortable state for the rear passengers. As it is obvious that the virtual body suffers a non-uniformly distributed convective heat transfer, with high differences between the various studied cases. There are some little differences only at the level of body parts than are on the direction of the air jets from the diffusers. Equations should be centred and should be numbered with the number on the right-hand side.
Acknowledgement
This work was supported by the grant Innovative system to extend the range of electric vehicles at improved thermal comfort – XTREME, PN-III-P2-1.1-PED2019-4249 and by a grant of the Romanian National Authority for Scientific Research, CNCS, UEFISCDI, Project code: PN-III-P2-1.1-PTE-2019-0394.

References
[1] A. Bogdan and M. Chludzinska, HVAC&R Research, 2010, 16, 529-542.
[2] E. Barna and L. Bánhidi, Energy and Buildings, 2012, 51, 234-241.
[3] F. Rohles and S. Wallis, Society of Automotive Engineers, 1979, INC 790122.
[4] H. Tsutsumi, Y. Hoda, S. Tanabe and A. Arishiro, SAE International, 2007.
[5] H. A. Daanen, E. van de Vliert and X. Huang, Appl Ergon, 2003, 34, 597-602.
[6] C. G. a. F. P. O. Fang L., Ind. Air, 1998, 8, 80–90.
[7] T. Ležovič, F. Lízal, J. Jedelský and M. Jícha, EPJ Web of Conferences, 2012, 25, 01049.
[8] M. Kilic and S. M. Akyol, Heat Mass Transfer, 2012, 48, 1375-1384.
[9] V. M. Limaye, D. M. D., S. M. and V. Kumar, in SASTECH, 2012.
[10] P. Danca, F. Bode, I. Nastase and A. Meslem, Energy Procedia, 2017, 112, 656-663.
[11] P. Danca, F. Bode, I. Nastase and A. Meslem, E3S Web Conf., 2018, 32, 01018.
[12] T. Horobet, P. Danca, I. Nastase and F. Bode, E3S Web Conf., 2018, 32, 01022.
[13] P. Danca, I. Nastase, F. Bode, C. Croitoru, A. Dogeanu and A. Meslem, IOP Conference Series: Materials Science and Engineering, 2019, 595, 012027.
[14] F. Bode, I. Nastase, P. Danca, A. Meslem and P. Danca, in 2017 International Conference on ENERGY and ENVIRONMENT (CIEM), 2017, pp. 442-446.
[15] P. Danca, F. Bode, A. Dogeanu, C. Croitoru, M. Sandu, A. Meslem and I. Nastase, E3S Web Conf., 2019, 111, 01048.
[16] P. Dancă, F. Bode, I. Năstase, C. V. Croitoru and A. Meslem, E3S Web Conf., 2019, 85, 02014.
[17] Z. J. Zhai, Z. Zhang, W. Zhang and Q. Y. Chen, HVAC&R Research, 2007, 13, 853-870.
[18] Z. Zhang, W. Zhang, Z. J. Zhai and Q. Y. Chen, HVAC&R Research, 2007, 13, 871-886.