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Experimental and numerical study of the air distribution inside a car cabin

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Abstract. The main declared goal of all car manufacturers is to ensure high comfort inside the cabin and to reduce the fossil fuel. It is well-known that the time spent by the people indoor has raised in the last decade. The distance between the home and the workplace increased due to diversity of activities and hence job diversity. The thermal comfort during the travel must to be ensured to reduce the occupant's thermal stress. The present study is investigating a comparison between the measured data and the numerical simulation results in the case when the ventilation system is functioning. It was evaluated the effect of the boundary conditions air flow and air velocity distribution in a passenger compartment in two cases: first is the general used constant inlet flow and the second is a new approach of importing the measured data obtained during the experimental measurement session as a boundary condition. CFD simulations were made taking as input the measured data obtained during experimental session. We have observed differences between initial simulation results and the measured data, therefore, for more accurate results, a new approach is needed, to impose as boundary conditions the measured data.

1 Introduction

Thermal comfort is a subjective concept depending which is difficult to define and to quantify. All thermal comfort definition underlines the user's personal perceptions. For example ASHRAE [1] define it as the state of mind that expresses physical and psychological satisfaction with the thermal environment. One of the first studies was made in the first half of the 19th century, for the buildings environment by Haldane [2], after that several studies were performed and in the 1970 professor Fanger developed a thermal comfort assessment model Fanger [3]. The model was developed using data collected from human subjects evaluated in controlled laboratory conditions. Fanger's PMV and PPD indexes were adopted by international standardization organization such as ISO [4] and ASHRAE [5]. Fanger's indexes were used as a start in the thermal comfort assessment and overtime several optimization and adjustments were added by researchers [6-8]. Researchers focused their attention in direction of thermal comfort of car passengers in last decades due to increasing of personal and public number of cars. One of the main reasons was an attempt to maintain the comfort state and in the same time to reduce the overall fuel consumption [9] and as a result to reduce the greenhouse gasses and other pollutants emissions with direct impact on the urban air quality.

Occupant's thermal comfort in vehicular cabin is gaining more importance due to the increasing of the

distance between home and workplace [10] with direct impact on the growing time that people spend in vehicles [11]. It was demonstrated in several independent studies that inadequate thermal environment is having negative influence on the human body [12, 13]. Vehicle environment is very different from buildings environment, mainly because the factor that influence the internal parameters such as solar radiation, air velocity, temperature differences [14] are having a high variability in very short period of time. The internal environment is fast transient and non-uniform and cannot be assimilated with indoor build environment. We can observe that the main comfort evaluation indexes are not taking into consideration all these factors therefore we can observe that we should not take into consideration classical models to evaluate thermal comfort in cabin environment.

The CFD simulation is a very powerful tool that increases in popularity in the last decade. The reason is mainly due to the high-performance calculation engines and the availability of computational power due to advances in the ICT technology. The simulation of flow patterns is still a challenge for nowadays researchers. First of all, the internal surfaces of the cabin are having a complex geometry. The ventilation system integration in this complex geometry is having a significant impact on light reflection [15], spatial management and noise propagation [16, 17]. Additionally, the air flow distributions are influenced by the surrounding surfaces temperatures [18] by the convective heat. The grilles

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design and fan characteristics are not taken into consideration by the manufacturers when designing the air conditioning system being a source of noise [19] with impact on passenger's state of mind. This article is a part of a larger study, intended to deepen the knowledge on thermal comfort inside vehicles and its numerical methods of prediction.

2 Material and method

2.1. Experimental setup

In the previous studies [21, 22], the distribution of the velocity profile from the inlet grilles was considered to be uniform. A shortcoming of this work hypothesis is that the same velocity on the entire inlet surface is not a realistic case. In this paper are compared the effects of this uniform velocity profile with a real flow velocity distribution measured by Laser Doppler Velocimetry.

The airflow directivity within a vehicle cabin is mainly influenced by the air duct orientation, number of air vents, shape and positions. Considering a uniform air velocity as boundary condition is changing the airflow distribution from the vehicle cabin and in turn the thermal sensation of passengers may differ. 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. Considering those mentioned above, for the Case 2 the inlet velocity airflow velocity distribution was measured using a LDV 3D system.

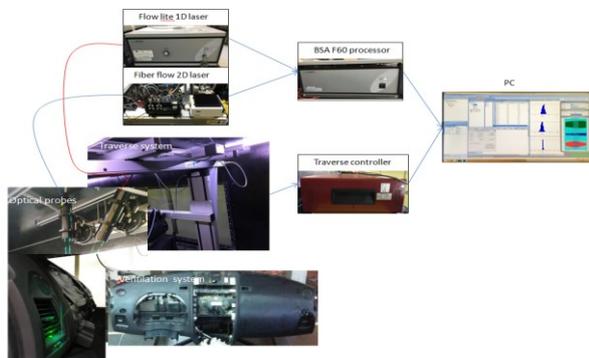


Fig. 1. Schematic presentation of 3D LDV setup.

We used a separate dashboard of the same model of car with the entire ventilation system and the original fan. The dashboard was installed in the laboratory.

A 5 mm step was imposed between the measurement points. The nearest measurement grid was at $X = 14$ mm from the diffuser grilles.

The oval shape of the board did not allow getting closer. The LDV 3D – measurement equipment used, is manufactured by Dantec and is composed from a 2D FiberFlow laser with wavelengths of 527nm and 5651nm 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.

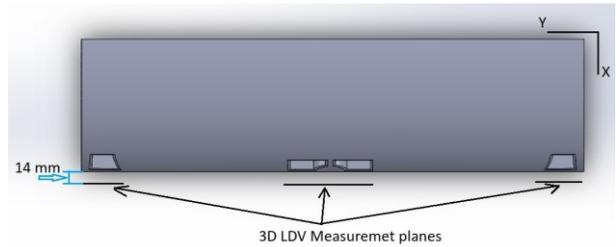


Fig. 2. Detail of measurement points at the side left grill.

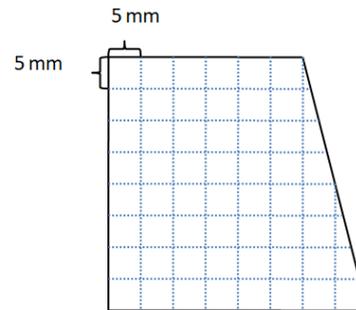


Fig. 3. Detail of measurement points at the side left grill.

2.2. Numerical setup

In previous papers [21, 22], we presented the setup of the model of a Renault Megane cabin car and we showed that we can reproduce the in-cabin environment, finding values of indoor thermal variables from the CFD model that were similar to those of experimental measurements.

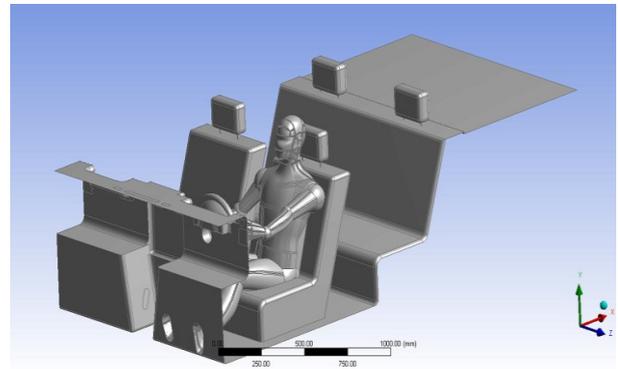


Fig. 4. Isometric view of the studied geometrical model.

The cabin was designed in Catia and then imported in Design Modeler from Ansys 18. Several meshes with tetrahedral elements where tested to check the independence of the solution. The numerical grid was realized in Ansys Workbench.

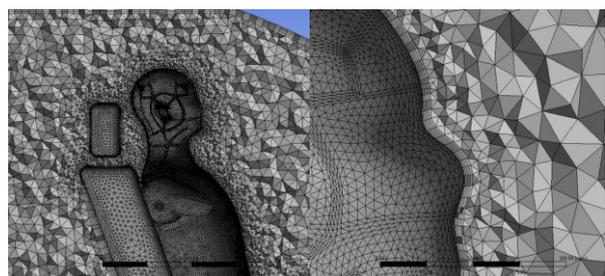


Fig. 5. Tetrahedral mesh used for numerical simulation.

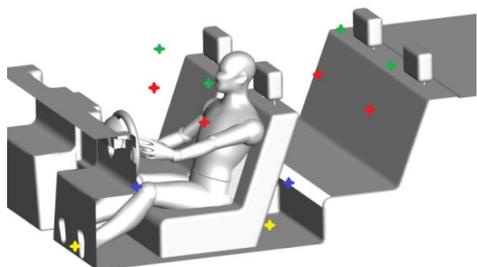


Fig. 6. Considered measurement points at different levels: green – head; red – chest; blue – knee; yellow – foot.

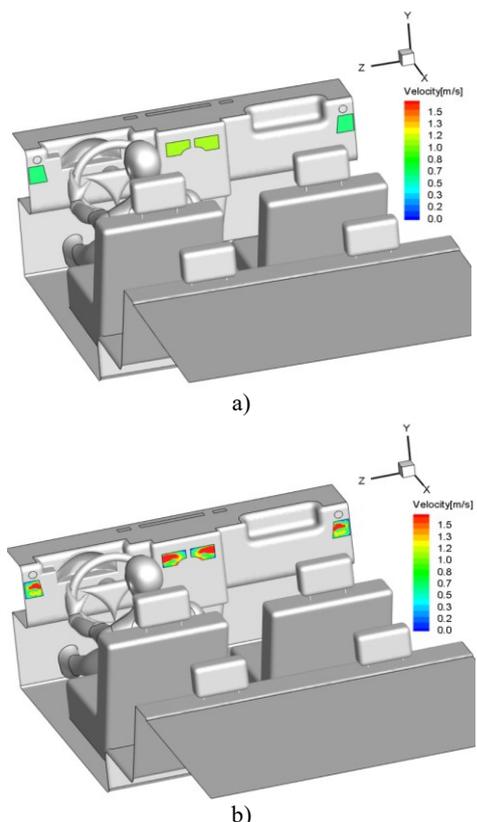


Fig. 7. Distribution of the axial velocity component at the outlets: a) Case 1; b) Case 2.

A fine mesh consisting of 6.5 tetrahedral million elements was created based on the experience from the previous studies where we performed the grid dependence test [23] (Figure 5). The boundary layer consists in five layers, with the first cell height of 0.75mm and a growth factor of 1.2. The virtual manikin has a standard height of 1.70 m and its surface area is 1.81m² being suitable for a standing posture and had a total surface area (1.20 m²) for a sitting posture. The rest of the total surface was contact with the solid surfaces of the automobile cabin.

In this study we considered the isothermal situation, therefore the value of 25°C was imposed for the inlet air temperature, internal and external ambient temperature and on the cabin and manikin surfaces temperature. For the both cases 1 we imposed as boundary conditions for the ventilation flow a mass flow rate of 0,0057 on the central air vents and a mass flow rate of 0,0043 kg/s on the side air vents. These values are corresponding to the measured values for the first position on the manual

control of the ventilation fan speed in the real car [21, 22].

3 Results and discussions

To evaluate the effects of these different boundary conditions, 16 comparison points were considered (Figure 6), these points being positioned in at the head, chest, knee and foot levels in the place of the passengers.

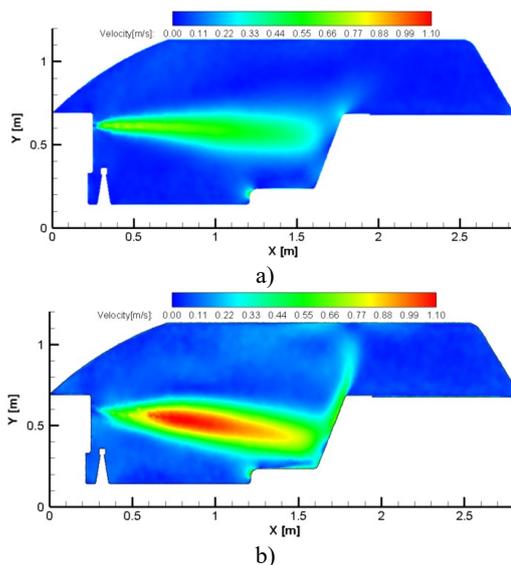
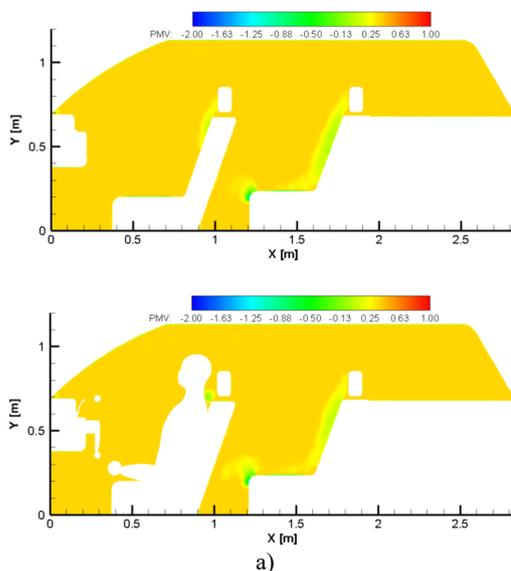


Fig. 8. Distribution of the velocity magnitude and in the middle of the car: a) Case 1; b) Case 2.

Figures 8 and 9 are presenting the distributions of the velocity magnitude and of the in-plane vectors for the median plane of the driver for both cases. One could observe that the global pattern of the flow inside the cabin is changing with the change of the boundary conditions. The distribution of the flow is dramatically changing. Even if the mean velocity at the air grilles is the same, the local velocity profiles on the surface of the grilles have a different aspect as shown in Figure 7. The black line is corresponding to the horizontal planes from Figure 9.



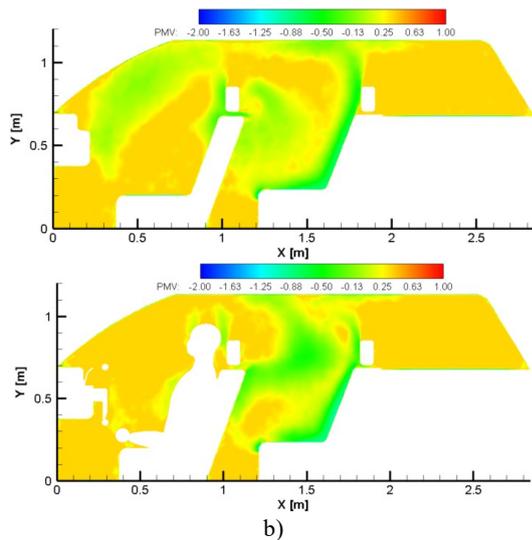


Fig. 9. Distribution of PMV index in the median plane of the passenger and driver for: a) Case 1; b) Case 2.

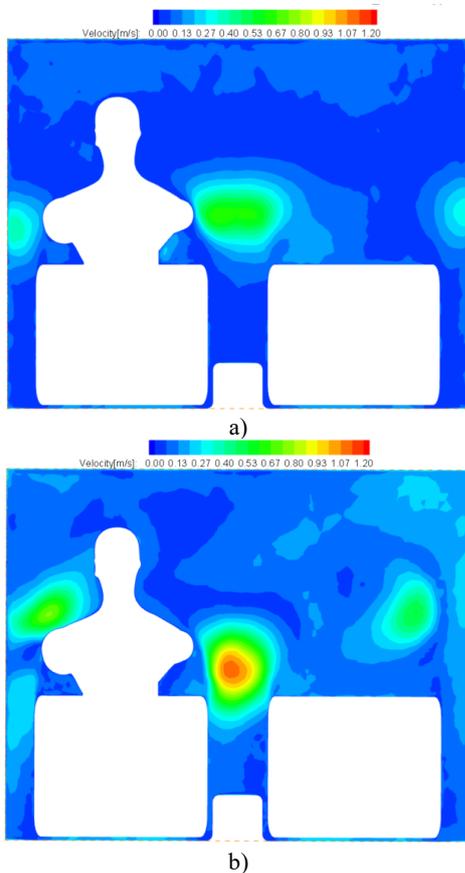


Fig. 10. Distribution of velocity in vertical plane for front part of the car for: a) Case 1; b) Case 2

Knowing the air velocity magnitude values from the numerical model and considering the metabolic rate value of 1 met and clothing insulation of 0.7 clo, the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indexes were calculated. Tables 1 and 2 presents values for the PMV and PPD indexes obtained at the right of each passenger place in the cabin for respectively the head, the chest, the knees and the feet. We observe that even the mean velocity in the inlet is the same, the case when measurement data imposed as boundary conditions leads

to a different airflow distribution inside the cabin. The jets have different jet throws, influencing the overall comfort, the percentage of dissatisfied increasing in the second case.

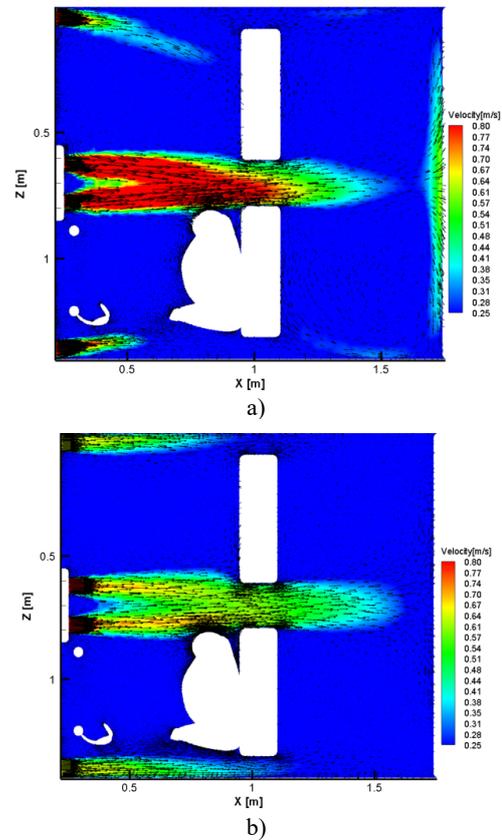


Fig. 11. Distribution of the velocity magnitude and of the in plane vectors for the median plane of the passenger: a) Case 1; b) Case 2.

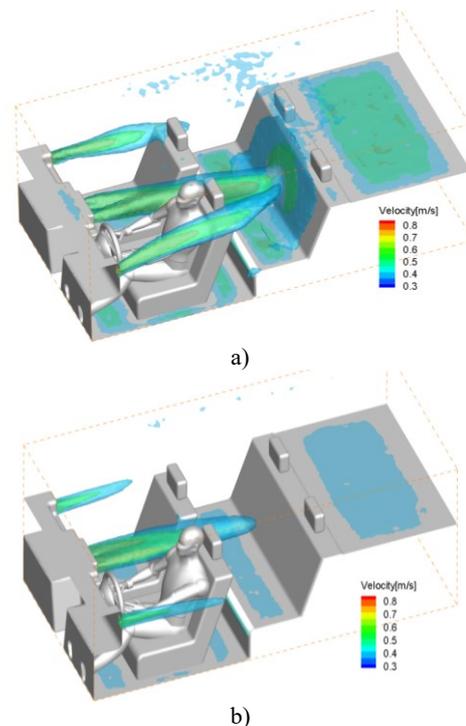


Fig. 12. Velocity isocontours real inlet velocity distribution; b) uniform velocity distribution; Legend: blue – 0.3 m/s; green – 0.55 m/s; red – 0.75 m/s.

Table 1. Comparison of local air velocities and temperatures for both cases.

Point/parameter	CV	RV	CV	RV
	v		θ	
	[m/s]		[°C]	
Driver Head	0,05	0,08	23,0	23,0
Passenger Head	0,04	0,04	23,0	23,0
Rear right pass head	0,07	0,12	23,0	23,0
Rear left pass head	0,07	0,21	23,0	23,0
Driver Chest	0,02	0,12	23,0	23,0
Passenger Chest	0,02	0,06	23,0	23,0
Rear right pass chest	0,05	0,13	23,0	23,0
Rear left pass chest	0,06	0,08	23,0	23,0
Driver Knee	0,01	0,13	23,0	23,0
Passenger Knee	0,03	0,07	23,0	23,0
Rear right pass knee	0,10	0,10	23,0	23,0
Rear left pass knee	0,11	0,15	23,0	23,0
Driver Foot	0,03	0,05	23,0	23,0
Passenger Foot	0,02	0,03	23,0	23,0
Rear right pass foot	0,05	0,05	23,0	23,0
Rear left pass foot	0,05	0,06	23,0	23,0

Table 2. Comparison of cabin comfort indexes.

Point/parameter	CV	RV	CV	RV
	PMV		PPD	
	-		[%]	
Driver Head	-0,5	-0,5	11,2	11,2
Passenger Head	-0,5	-0,5	11,2	11,2
Rear right pass head	-0,5	-0,6	11,2	13,7
Rear left pass head	-0,5	-0,9	11,2	21,9
Driver Chest	-0,5	-0,7	11,2	14,1
Passenger Chest	-0,5	-0,5	11,2	11,2
Rear right pass chest	-0,5	-0,7	11,2	14,6
Rear left pass chest	-0,5	-0,5	11,2	11,2
Driver Knee	-0,5	-0,7	11,2	14,9
Passenger Knee	-0,5	-0,5	11,2	11,2
Rear right pass knee	-0,6	-0,6	11,9	12,5
Rear left pass knee	-0,6	-0,8	12,5	17,1
Driver Foot	-0,5	-0,5	11,2	11,2
Passenger Foot	-0,5	-0,5	11,2	11,2
Rear right pass foot	-0,5	-0,5	11,2	11,2
Rear left pass foot	-0,5	-0,5	11,2	11,2

4 Conclusions

The study considered the effect of the boundary conditions on air distribution and air velocity inside a passenger compartment for two cases: using a constant inlet mean velocity and importing the measured data obtained during the experimental measurement session as a boundary condition. CFD simulations were made imposing as input the measured data obtained from the

LDV measurements at inlet. The results indicate that imposing measurement data for the boundary conditions, for the same mean velocity, will lead to different airflow inside the cabin.

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