

ABSTRACT

DOCTORAL THESIS

VENTILATION STRATEGIES FOR IMPROVING THE INDOOR ENVIRONMENT QUALITY IN VEHICLES

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GENERAL INTRODUCTION

Designers from the automotive industry started to be concerned on comfortable mobility only in the last decades with the lowering of production costs and with the desire of enforcement of the safety of the vehicles. Furthermore, their approach was extensively based on methods used in the research field of building systems. On the other hand, occupant's thermal comfort in vehicular cabin is gaining more importance due to the increasing distance between home and workplace [1] with direct impact on the time that people spend in vehicles [2], while the distance between the home and the workplace increased due to diversity of activities and hence job diversity. During each trip, thermal comfort must be ensured for a good psychological and physical state of the passengers. A comfortable vehicular climate, in many cases, does not only help to reduce the driver stress, but also guarantees good visibility by avoiding the fogging phenomenon and thus contributing to a safer trip for vehicles' occupants and for all traffic participants. In addition, many independent studies provided evidence of improper thermal environment and its negative influence on the human body [3, 4].

Objectives of the thesis

Starting with the previous idea of a real need of developing models for the human body for studying IEQ in vehicles and after a survey of the specialized literature we have identified several problems:

(1) There is a lack of knowledge regarding the consequences of using the existing, non-adapted, comfort models for vehicular cabins.

(2) There are few studies regarding the influence of the ventilation strategies on thermal comfort and on the passengers' behavior are available.

(3) Studies focused on improving HVAC system strategies of control are rarely connected with thermal comfort studies.

In this context, we have decided to orient the researches in this thesis around the complex problematics of cabin thermal environment and its effect on driver's and passenger's level of comfort.

Indeed, thermal comfort has been widely studied in built environments, while thermal comfort in vehicles is a relatively new subject, with relatively few dedicated studies and a non-systematic approach. In this context, the general objectives of the doctoral research project could be summarized as following:

(1) The first general objective of the doctoral research was **to deepen the knowledge and to understand thermal phenomena that occur in cabin thermal environment.**

(2) The second general objective was **to develop an advanced thermal manikin able to evaluate cabin thermal comfort** knowing that thermal manikins are the most proper measurement tool in the case of non-uniform and transient environments.

(3) The third general objective was **to develop and validate a complex numerical model in order to get insight into the complex phenomena previously evoked.**

These three general objectives were intended to sustain the main goal of the doctoral research that is: **improvement of thermal sensation of vehicle occupants, by implementation of innovative air diffusers.** To this end we oriented our research towards diffusers with a special geometry. The manipulation of the geometry is known in the literature as a passive method of flow control resulting in the improvement of mixing between the air supplied by the ventilation system and the ambient air from the cabin.

During the complex quest represented by the doctoral project we could have the opportunity to become familiar to the intricate thermal phenomena governing the thermal comfort in general, to analyze the real role played by transient environment parameters (such as radiant temperature of surfaces, air velocity pulsation, local air turbulence for instance) air flow turbulence in perceiving thermal comfort and in its estimation. During all this pursuit we tried to

stay on a line that would ultimately allow to respond to a set of fundamental questions, namely: *To what extent this kind of parameters can affect the perceiving of comfort, and also the consequences of an "incomplete" assessment proposed by the existing evaluation models? How is affected the ventilation and air conditioning design in this context due to the use of current models for pre-evaluating a good functioning of the HVAC systems – in particular for vehicles - and an acceptable environment for their users?*

CHAPTER 1 – STATE OF THE ART

A. *General theory of thermal comfort– history, problems*

Human perception induced by thermal stimulation includes two concepts: *thermal sensation* and *thermal comfort* [5]. While thermal sensation could be described as a subjective response associated with the temperature information of external objects or the environment which is explored by warm and cold receptors in the skin, thermal comfort is usually considered as a combination of the subjective sensation and the objective interaction with the environment [6]. This distinction is common in neurophysiology but not so usual in the field of indoor environment quality, where usually the thermal sensation is a measure of the state of thermal comfort.

B. *Vehicles – particular aspects*

Unlike buildings' indoor environment, the vehicular ambient climate is dominated by thermal transient conditions: the strongly non-uniform thermal environment associated with the high localized air velocities that might fluctuate if we are in the presence of an automatically controlled air conditioning system, the higher levels of relative humidity, the solar heat flux, and the radiative heat flux from the interior surfaces, the solar intensity and its scattering over the different material types and surface niches in the cabin, the angles of incidence of the solar radiation etc. [7]. The psychological component (sex, age, etc.) represents in this case even a greater supplementary challenge knowing that drivers' concentration could be associated with different thermal sensations between different subjects or compared to other passengers [8].

C. *How is evaluated thermal comfort in vehicles cabins today?*

This paragraph presents the main standardized methods for prediction or assessment of thermal comfort in vehicles ISO 14505 [9-11] being related to a *first category of models* and were discussed in detail in the manuscript of the thesis. The second direction is related to the *psychological component* integration into thermal comfort evaluation, usually relying on behavioral and neuro-cognitive experimental methods related to drivers' safety mainly, by acquiring physiological signals using medical techniques like the electroencephalogram and the electrocardiogram [8]. The third direction, is represented by all studies dedicated to the use of the *nodal physiological models*

D. *Fanger's indexes and other heat balance models*

In this paragraph, the most important parameters that could play a role into the thermal comfort state were analyzed. We present the well-known comfort equation representing the thermal balance of the human body (taking in consideration all heat transferred with the environment through conduction convection and radiation, perspiration and respiration). The PMV (Predicted Mean Vote) index [12] associated to the thermal sensation scale with seven points indicated in the ASHRAE standard [13] and its associated PPD (Predicted Percentage of Dissatisfied) are explained in detail. Other models from the first category are presented such as: the *Draft Rate* (DR); the *Effective Temperature* (ET); the *Effective Temperature* (ET*) and the

Effective Temperature Scale (SET). As in the case of the PMV, these models are the equivalent characteristics of certain fictive environments, with fixed factors taken into consideration as derived from empirical models.*

E. Current standards for thermal comfort assessment in vehicles

The main standards used by the automotive industry for assessing thermal comfort are EN ISO 14505 standard 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 [9-11].

F. Nodal physiological models

The thermo-physiological model consists typically of a virtual representation of the human body as a combination of multi-layered cylinders and spheres with properties corresponding to tissues (so-called *passive system*) and a set of algorithms simulating human thermo-physiological responses such as shivering, sweating and vaso-constriction or vaso-dilatation (so-called *active system*). The main models presented are KSU-two-node model; Gagge model; Stolwijk's 25-node model; IESD – Fiala; the Berkeley Model

G. Psychological component integration

All of the rational models make the inherent assumption that there is some predictable comfort response for a given physiological state of the body. The state of comfort is inherently a psychological response, not only a physiological response and we should expect many nonphysical factors to affect the perceptions of comfort which has to be also very much dependent on expectations. Generally the integration of the psychological component into the thermal comfort evaluation in the case of vehicles is performed through other ways that it was done in the past for buildings, usually relying on behavioral and neuro-cognitive experimental methods related to drivers' safety mainly, by acquiring physiological signals using medical techniques like the electroencephalogram and the electrocardiogram [6, 8, 14]. Several approaches found in the literature are the usage of MRI or of the Electroencephalograph (EEG)

H. Synthesis of experimental evaluation of the vehicle environment in the current literature

Physical parameters observation - The standards are either difficult to interpret, either impossible to apply, either use expensive approaches. There are many papers dealing with the observation of the environmental conditions inside the vehicle that might affect the human thermal comfort and those concerning the human's response and perception of its interaction with the environment. Part of them stops only on the study of the effect of a certain parameter (the air temperature and the mean radiant, the relative humidity, the solar radiation including the effect of the glass transmittance, the outdoor temperature, etc.) on the thermal environment of the vehicle without considering any thermal comfort assessment using comfort models. Others are addressing the combined effect of several parameters from those mentioned above, and sometimes correlations with the air quality are also addressed via the recordings of the CO₂ concentration. The following parameters were evaluated in the studies from the literature and taken into consideration: the ambient temperature, air the air velocity (speed), solar radiation and relative humidity.

Experimental studies using standardized methods - Experimental evaluation of using the standardized methods include the following standards EN ISO 14505/2; Predicted Mean Vote PMV, Predicted Percentage Dissatisfied PPD indexes and an adaptive model. Secondly, manikin

measurements;

Experimental studies based on the physiological and psychological components quantification - As it is difficult to really separate the physiological and psychological components in the literature a series of studies are combining the collection of all sorts of biometric signals with the recorded thermal sensation expressed by human subjects.)Even though much research work on the bio-signals generated by human body have been actively conducted in the world, most of these studies are associated with bioelectrical signal changes under only comfortable temperature ranges. There are no studies on bioelectrical signal changes in the human body when there is a change from a temperature that causes discomfort to a comfortable temperature range. The variations in comfort and concentration with changes in cabin temperature during driving for a long time are not found in open literature. In the recent study of [14], the brain wave and pulse wave signals of subjects were measured and analyzed when the temperature is changed from a level that causes discomfort to a comfortable temperature range, with full load in the cooling and heating modes in a car cabin.

I. Numerical models for prediction and evaluation of comfort in vehicles

Several methods of prediction and evaluation of comfort in vehicles are presented in this paragraph.

Modeling vehicular air flows and thermal environment - The first category of numerical studies includes those dealing with the qualification of passenger compartment environment without using thermal comfort assessment models. In the corresponding articles are analyzed the effect of different changes imposed over the vehicle thermal environment, relative to a reference case. The most considered parameters in these studies are: ventilation strategies [15-18], external physical factors [19-23] and the number of passengers in the vehicle [24, 25].

Predicting thermal comfort through numerical studies - Numerical studies from a second category are aiming to include also a method to evaluate the human thermal comfort. Several models were used by the researchers such as PMV/PPD index in air conditioned cars [19]; studying the influence of solar radiation [26]. Other approaches includes t_{eq} index [27]; EHT (Equivalent Homogenous Temperature) index, Berkeley model [18]. The main purpose of ventilation systems is to satisfy the need for thermal comfort and air quality for the occupants along with reduced energy consumption. These three criteria must be considered in the design of a mixing ventilation system as they are fundamental to the thermal environment and energy performance. A high induction level is desired in these systems because it allows an optimal mixing of the ventilating jet with the ambient air such as the occupants would be satisfied in terms of thermal comfort and air quality.

J. Discussions and conclusions of the first chapter

Modeling the comfort response itself is the final goal when using heat balance models. We have to note that there is no consent between the models as how comfort should be related to the physiological variables or even which are the variables that have to be considered as important parameters. Nevertheless, the importance of the thermal manikins and of the concept of equivalent temperature cannot be denied. However, the afore presented standardized methods are either difficult to interpret, either impossible to apply, either use expensive approaches. There are few articles using standardized methods for evaluating thermal comfort in the literature and even less the ones that are combining air distribution strategies with thermal comfort.

Only rare set-ups to assess the thermal comfort in vehicles using the equivalent temperatures experimentally. These are either very expensive or suitable for punctual measurements only.

However, data acquisition at different locations in the interior space of a vehicle is highly desired, generating the need for cost-effective and precise measurement equipment that are intended to allow access to the local distribution of the equivalent temperatures especially for the ventilation systems where important thermal gradients are present, allowing to evaluate the heat impact of real passengers as well. This is the motivation of developing thermal manikins in our research group and thus one of the most important objectives of the thesis was consisted by the development of the thermal manikin Suzi that is presented in the following chapter.

On the other hand, no studies combining passive induction control via the conception of air diffusers were found in the literature. The proposal of some innovative designs of air vents for the present studies was based on the previous findings of the French and Romanian research teams where the doctoral project was developed. The following parts of the manuscript are dealing with the development of an innovative thermal manikin and of new concepts of air diffusers. The approach is based on both experimental and numerical approach.

CHAPTER 2 – BUILDING AND ADVANCED THERMAL MANIKIN

A. *Short history of thermal manikins*

In this section an overview of the thermal manikin history is presented. The materials and the chronological complexity of the models is presented. Overtime features like sweating and breathing were implemented to increase the overall fidelity of the thermal assessment. In this chapter are presented the advantages and disadvantages of the experimental sessions using thermal manikins in the field of thermal comfort and clothing design.

B. *Development of our thermal manikin*

The thermal manikin was designed for both seated and standing postures. The size of the manikin is defined by the standard surface of a human of 1.8m² [28, 29]. The base structure of the manikin is made of polyvinyl and uses a medical manikin with the typical weight of a female human body. The surface of the manikin has been covered with a 5mm insulation layer (Figure 1). A medical manikin made of polyvinyl is used as a support, on which surface was glued a thermal-insulation elastomeric membrane. The function of this 5mm insulation membrane is to prevent the heat transfer to the manikin interior.

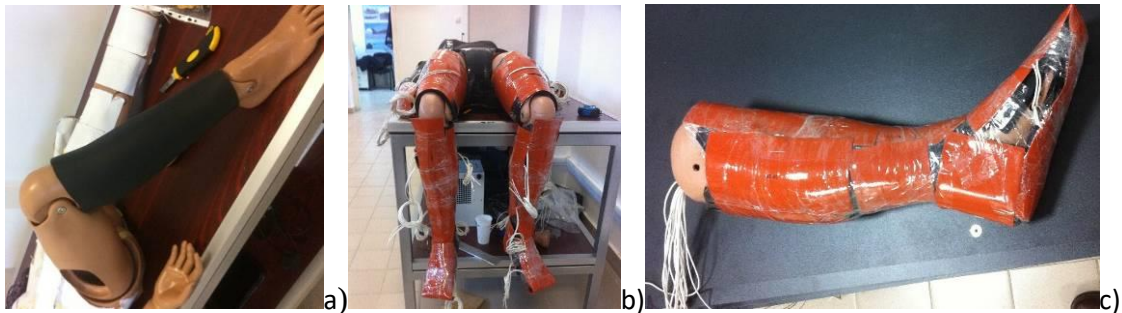


Figure 1: Different stages of making the hardware part of the thermal manikin: a) designing the heating insulation under the thermal patches, b) c) inserting the heating elements

The heating solution chosen for this prototype consist in four geometries elementary flexible patches (Figure 2), manufactured by the Keenovo Company. These are made of a thin layer of silicone (1,5 mm) that includes a heating circuit made of nickel chrome heating wire (Figure 2a.) having good electrical isolator proprieties and in the same time is a good thermal conductor.

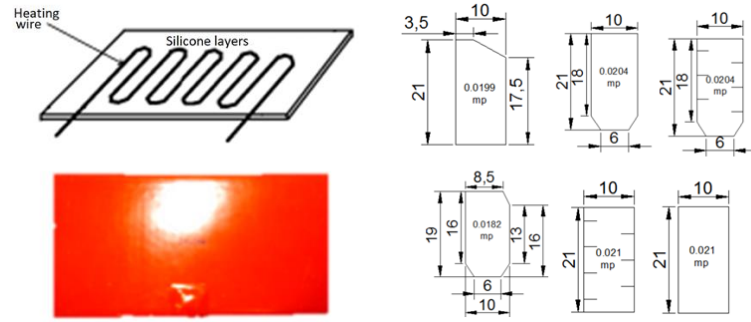


Figure 2: a) Heating element embedded in silicon b).Different geometries of the heating elements

The heating elements are flexible following the anatomic shape of the body of the manikin. The heating patch cover as much as possible the entire dummy surface, without overlapping. The electrical wires were embedded inside the manikin. Five digital temperature sensors (TSic T501) are glued on each heating element to control the temperature.



Figure 3: Photographs of TSic T501 temperature sensors as disposed on the patches

Given the constructive form of the heating elements a risk of wrong temperature measurement could appear if the temperature sensor is not in a proper place. Therefore, each sensor position has been made using a thermal vision camera Flir E40. The mean temperature value of the five sensors and of the patch is the same. The thermographs of heating elements and some sensors positions are shown on the images below. Every sensor was tested. The calibration process has been conducted using a thermostatic water bath with immersion thermostat Lauda Eco Silver. The entire manikin surface was covered with adhesive aluminum foil to ensure a better temperature uniformity trough conduction heat transfer. The entire manikin surface was covered with a transparent adhesive film to facilitate further investigations with a thermal (IR) camera. During a first test, without any control of the circuits, the temperature of each zone has been stabilized at 45°C while the room temperature was stable at 24°C. This is a rather encouraging result offering a wide range to control the temperature of each zone and the possibility to simulate different cases of body heat release.

c. Architecture of thermal manikin

The thermostatic manikin system consists of 16 regions divided in 79 circuits. Each region is covered by several heating elements (each has 24 Ohms constant resistance). Each heating element is provided, with 5 analog temperature sensors (TSic 501Figure 3) to monitor it.

The architecture of the system hardware was designed by the Mechatronics Department of the National Institute of Aerospace Research and developed with the team from UTCB. The solution proposed is having two systems provided by NI based on the FPGA. In comparison to the microcontroller solution, this solution represents an evolution in terms of high data collection capacity (up to 400chanells, etc.), being able to generate appropriate signals for all 80 channels represented in software implementation. Two development NI boards were used and was implemented a real-time software, the acquisition device also processes the data to obtain reliable mean temperature of every patch using a fault detection and isolation algorithm, while the heating control devices, using the data processed by the acquisition board, generate robust

and adequate signal using the neuro-fuzzy controller. The real-time hardware and software can run independently from the computer user interface, with the limitation of maintaining the last requested set point of temperature.

D. Innovative control model based on a neuro-fuzzy control law

The approach of using artificial intelligence for control problems concerns in principle an input-output behavioral philosophy of solution. The neuro-fuzzy control strategy adopted for the temperature control of the system was proposed by dr. Ioan Ursu from INCAS

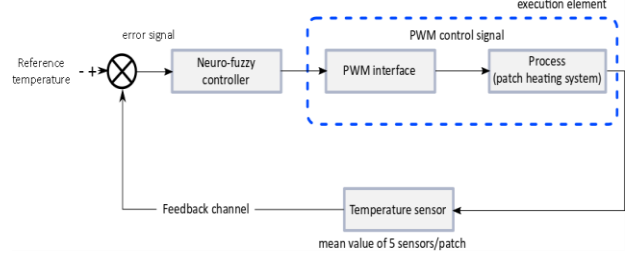


Figure 4: Control system diagram for perceptron [30]

E. The user interface

The LabVIEW platform was used to develop the programs that allow to communicate with the controller and the interface of the neuro-fuzzy system. The direct measurement of heat loss/power consumption and mean temperature of surface region eliminates the need for determining the other components. By normalization to a reference calibration environment according the definition of equivalent temperature, the heat loss can be converted to an equivalent temperature.

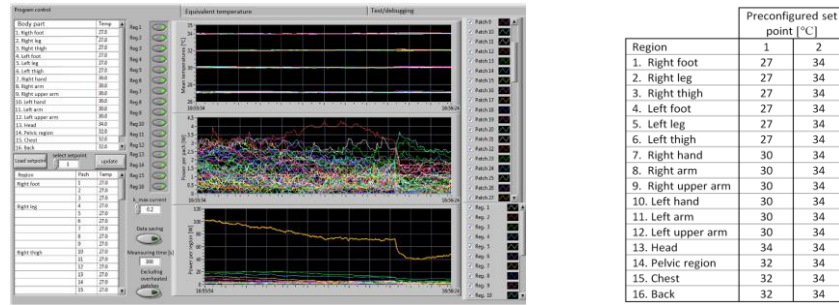


Figure 5: User interface to monitor temperature of manikin surface and control output energy consumption

F. Testing the thermal manikin

The response of the manikin was tested in a variety of conditions: in quasi-stationary and transitory environments. We also tested system's response in terms of temperature variation from 30 °C to 40°C and vice versa using a step of 1°C. An example of a simple sensitivity test was done by opening a door and allowing external air to come inside the room. The fast response of the regulation system and its high sensitivity are demonstrated after the preliminary tests on the single patch. These results show that the control algorithm might be implemented a manikin used to evaluate fast transient thermal environments as in vehicle case. There is also a great dependency between the perturbation intensity and the response of the regulation system.



Figure 6: Experimental setup and temperature distribution for upper part of the manikin

The control model was also implemented separated on different parts of the manikin in order to verify the correct functionality of each zone and to check the response of multiples heating elements that compose these zones. Satisfactory results were obtained as it was demonstrated later:

G. Calibration of the thermal manikin

The thermal manikin was calibrated in a climatic chamber in order to find the relationship between the surrounding temperature and heat lose. The values of the heat transfer coefficients obtained for this thermal manikin are quite close to results from the literature. The calibration was performed at the air temperature identical with mean radiant temperature and equal to 24°C. A first calibration was performed with the nude manikin surface at a uniform temperature of 34°C. The second calibration was performed for the anatomic distribution of temperature with no vertical temperature difference in the chamber. The relative humidity was monitored, and we found a variation of its values around 50% RH. Mean air velocity was measured as 0.1 m/s using an omnidirectional air velocity sensor. The heat losses and skin temperatures of the 16 parts of the body were measured.

CHAPTER 3 – EXPERIMENTAL SET-UP

In this chapter of the thesis are presented the measuring principles of all used measuring instruments and in a second time the three main experimental set-ups used during the entire study. We will not put in this abstract the description of the measurement principles nor of the instruments.

A. Measurement principles and employed instruments

a) Air speed and velocity measurements

- **Hot film anemometers**
- **Laser Doppler Anemometry**

b) Temperature measurements

- **Thermocouples**
- **Thermistors**

c) Relative humidity

- **Capacitive humidity sensors**

d) Comfort measurements

- **Comfort Sense**
- **Thermal manikin measurements**

The thermal manikin that was used in this study represents the object of the entire Chapter 2. In the case of our manikin, the equivalent temperature represents an indication of thermal comfort obtained by evaluating the power consumption of a region of the manikin. Interpretation of the equivalent temperature in terms of perception of thermal sensation and thermal comfort are assessed using the tables proposed by Nilsson [31, 32]. Depending on t_{eq} obtained with the manikin, thermal sensations at different levels can be classified. The asymmetric thermal conditions such as in the vehicle compartment make the determination and evaluation of local t_{eq} particularly useful.

B. Experimental set-ups and measurement protocols

The three main experimental set-ups used during the study were conceived in order to respond to the logical steps that we employed during the conception of our numerical models that are presented in Chapter 4. In a first time a simple car-cabin numerical model was designed and in our quest of methods of calibration of the correct boundary conditions, we used temperature and air flow measurements in a real car-cabin. In a second time, more complex tests, including the presence of the thermal manikin and of two types of air diffusers were performed both numerically and experimentally. An intermediary experimental campaign considered the characterization of the three-dimensional isothermal air jets discharged from the diffusers from the dash board of the cabin. Considering the sake of coherence in the development of the present chapter, we will first present the real vehicle that represented the basis of all the experimental set-ups, then we will present the two configurations that were used to inject the numerical models with real boundary conditions and to perform experimental thermal comfort evaluations, and we will end the chapter with the description of the particular experimental set-up used for the elementary air jet flows.

a) Description of the real vehicle

In this study we used a Renault Megane hatchback car. It is equipped with a 1.4liter engine, have 5 seats and 5 doors. The in-cabin environment is heated or cooled with a manual ventilation/conditioning system. The same control panel allows modifying the air flow rate entering the cabin on a step by step commutator allowing 4 running position.

b) Preliminary characterization of the air distribution system of the vehicle

Prior to the campaigns of thermal comfort evaluation, the air flow rates on each was carefully measured for three running positions of the fan - V1, V2 and V3 corresponding to running positions (stages) I, II and II of the air flow controller.

c) First in-cabin experimental set-up

This experimental set-up and the related measurement protocol were designed for calibrating and validating our first numerical modeling approach of the vehicular cabin as it will be show in the next chapter. In this case, we modeled only the cabin, without passengers, the objective being to obtain a reasonable model of this complex geometry enclosure, and to have experimental data for both imposing boundary conditions and for verifying the numerical results. During this first experimental campaign we considered only the air distribution in the car through the original set of diffusers of Renault Megane, taking care that their ailerons should be oriented in horizontal position. Measuring sessions were conducted when outdoor temperatures were temperatures relatively similar, so both outside in the hall and in cabin temperature has constant values between 21-24.5 °C.

d) Second in-cabin experimental set-up

A second experimental set-up and measurement protocol were designed, in a more complex way for the calibration and the validation of our final numerical models. The objective of the experimental campaign was multiple:

- to record in different conditions, like previously, the evolutions of the temperatures on the surfaces inside the cabin and in different points in the air;
- to test the effect on different flow rates and cold air temperatures on the air distribution inside the cabin;
- to « measure » thermal comfort indices using the Comfort Sense system and the thermal manikin previously developed for different flow rates and two geometries of air diffusers in cooling conditions, and thus to provide data for validation purposes of the numerical models developed in Chapter 4;

- to perform subjective thermal comfort evaluations for the same flow rates and the two geometries of air diffusers in cooling conditions allowing a direct comparison between the subjective response and the dedicated measurement systems;
- to provide data recording air speed values and temperatures in different points inside the car cabin for validation purposes of the numerical models developed in Chapter 4.

Measurements were performed made during two days with similar external conditions. Inside the hall where our experimental car was placed, the air temperature variation was between 28 and 31°C. A typical example of a of temperatures evolutions inside and outside the cabin. Before each measurement session, the vehicle was turned on for 30 minutes as required by ISO 14505 standard. In this case, inside the cabin we installed 41 thermocouples. Three thermocouples were placed at the inlets level, one in the center, one on the left side air diffuser and another in the right-side air diffuser. Another nine thermocouple were placed on the interior surfaces: dashboard, windshield, sides windows, ceiling, floor, top cover of the trunk and rear window. Another fifteen thermocouples were placed in the zones corresponding to sensible parts of the passengers as head, chest, abdomen, knee and ankles. The rest of fourteen thermocouples was placed on a horizontal line passing from the middle of the height of the central air diffusers in a median plane between the two the front seats and on a vertical line from the floor to the ceiling in the center of the car, also in the median plane. PMV, PPD, DR, TSV determination was performed for different running positions of the fan controller.

e) Third experimental campaign – elementary air jets characterization

In this campaign we perform a detailed characterization of the velocity fields at the exit plane of the diffusers and at other axial distances of the jet flows through Laser Doppler Velocimetry. During this session were evaluated the classical original air diffuser of the Megane compare with innovative lobed grilles. The lobed grilles were manufactured using 3D printing technology at UTCB.



Figure 7: Air diffusers with lobed ailerons before painting

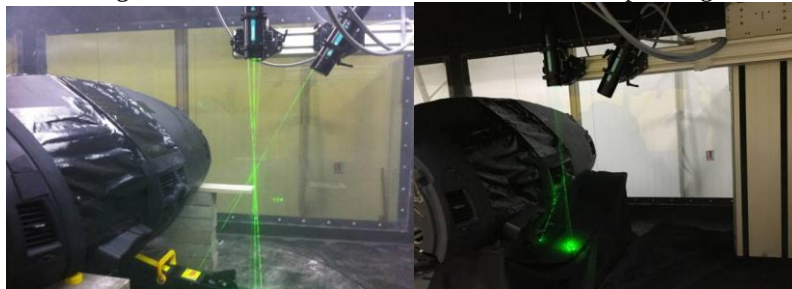


Figure 8: LDV probes in the front of the central air diffusers

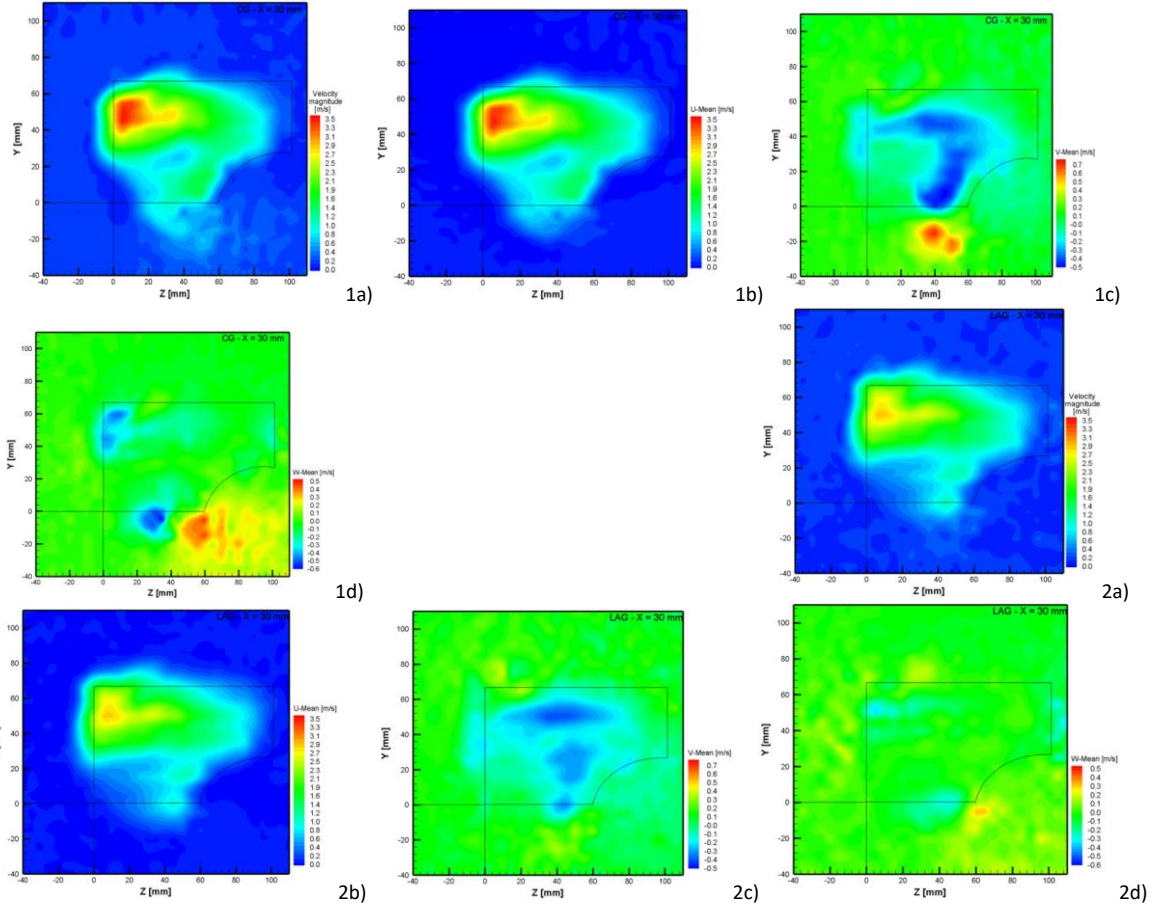


Figure 9: Velocity distributions for the center left air diffuser at the exit plane ($X=14$ mm): 1) classical air diffuser - CG, 2) lobed air diffuser- LAG : a) velocity magnitude, b) U component, c)V component, d) W component

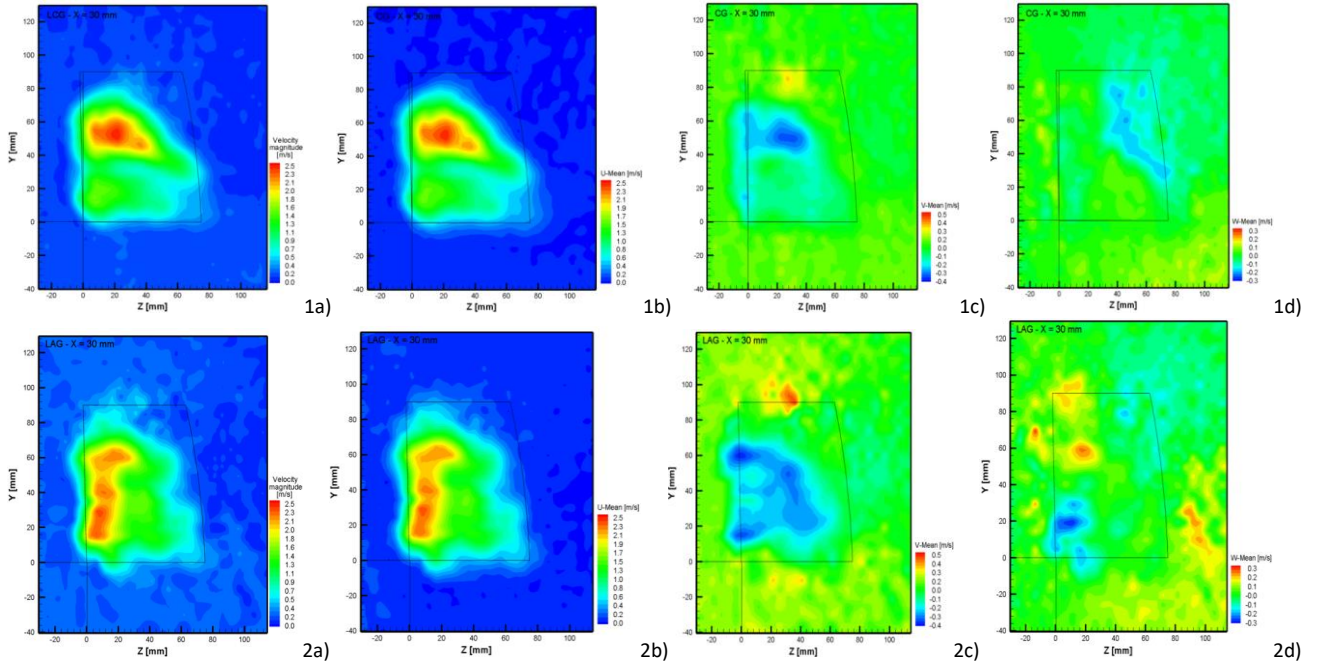


Figure 10: Velocity distributions for the left side air diffuser at the exit plane ($X=14$ mm): 1) classical air diffuser - CG, 2) lobed air diffuser- LAG : a) velocity magnitude, b) U component, c)V component, d) W component

The velocity fields distributions at the exit plane of both Classical air diffuser Grilles (CG) and Lobed Air Grilles (LAG) are presented in Figures 13 and 14. Their evolutions at other

distances are presented in the manuscript of the thesis through a comparison with results from the numerical model. As it could be observed in this figure the initial distribution of the velocity fields is different for the CG and LAG cases. The difference is more important at the lateral diffusers especially for the axial component of the velocity U and inherently for the velocity magnitude. This will have an impact on the whole field distribution as we will observe later on.

CHAPTER 4 – NUMERICAL MODEL

In the introduction of the Chapter 4 we propose to pass briefly through the current developments related to Computational Fluid Dynamics applied to air distribution and thermal comfort. In the bibliographical chapter we put in evidence all numerical studies that we found in literature relevant for our subject. Still, the great majority of these studies lacks details and explanations of modeling choices, this way we decided to rely on the knowledge gained in the much more studied field of air distribution and thermal comfort in buildings. In the following parts of the chapter are presented the steps employed in our numerical approach. In a first time a simple car-cabin numerical model was designed and in our quest of methods of calibration of the correct boundary conditions, we used temperature and air flow measurements in a real car-cabin. In a second time, a complex numerical model has been developed. This model includes a passenger with anatomic shape and takes into consideration to types of air diffusers. The validation of the chosen approach for introducing the effect of the flows generated by the two types of diffusers is also presented in this chapter.

A. *Numerical modeling: limitations for thermal comfort domain*

For numerical modeling in indoor environment quality studies, the equations of conservation of mass, motion and energy are generally used, in the structure of a system of partial differential equations. Numerical models generally use three methods: finite difference method, finite element and finite volume method. Depending on the spatial scale of the investigated area (building, room, enclosure, vehicle cabin) and the phenomena investigated we distinguish nodal models, zonal and CFD type. The latter will be referenced and discussed below because they are our choice in this study. The choice of CFD models was motivated by the possibilities of deepening the analysis of the considered cases. These models are used to replace the experimental methods when the experimental approach would raise special problems or when parametric studies would require a long time. CFD models are based on numerical solving of Navier-Stokes equations for all mesh points of the studied domain. Solving the equations of conservation of mass, momentum and energy allows knowledge at any point of the distribution of a various state variables. The particularity of a fine or very fine mesh (million elements) allows a very detailed simulation of airflow, in our case in enclosures with complex shapes and different thermal states. This is the main reason why we turned to this type of numerical approach since the intention is to study the influence of parameters correlated with fluid dynamics and fine and very fine resolution of the airflow.

- a) Equations and mathematical models
- b) Turbulence modeling
- c) CFD models in thermal comfort domain

A state of the art related to the CFD models used in the literature is presented in this chapter starting with the first CFD study performed by Nielsen [33] in 1973 until nowadays focusing on the interaction of the body with the ambient environment and the complexity of the model (realistic forms and complex geometries were introduced, virtual manikins being sometimes equipped with an air flow simulating human breath, or a generation of moisture in the skin or a control model imitating the thermo-physiologic adjustment system). The advantages of

more complex geometries are highlighted improving the study of convective flow around the human body. The bibliographic study provides an overview of the turbulence models used for different studies and comparison between them.

The generation of the computational grid, complex geometry of the human body has led to special requirements. Fairness and accuracy of the simulations are highly dependent on the quality of the calculation domain. Accuracy is actually influenced by mesh size, the shape of cells, topology, etc. The difficulty of meshing for complex geometries generation especially requires the use of unstructured cells. Since structured grids lead to better results than unstructured in our domain, the calculation volume is generally divided into two, one in which there is the manikin and the rest of the room [34]. Grid dependency study and boundary conditions parameters intervals are identified in literature.

Validation of CFD simulations and quality of the applied model remains an intrinsic part of the process, being often overlooked due to limitations of computing power or experimental cost. Indeed, the relatively limited possibilities of obtaining validation data restricts sometimes certainty of approach CFD for the study of air flow in buildings and other indoor spaces.

B. First simplified model of the car cabin

In this paragraph is present the first step in this numerical approach which consisted in the set-up of the model for the cabin car itself. The development of the numerical model was divided in a few steps: the first step - generation of the cabin geometry, the second step - generation of the numerical grid and grid independence study, the third step - validation of the numerical results.

a) *Generation of the Renault Megane geometry* - This first model comprises the interior of the car geometry with all the relevant details for our study but does not include the human geometry. The model for the vehicle geometry was designed in Catia software and then imported in Ansys Design Modeler in order to be prepared for the numerical simulation.

b) *Generation of the numerical grid and grid independence study* - The numerical mesh was developed in Ansys Workbench. In order to obtain a fairly accurate solution for the studied case at the expense of the least computational resources a mesh independence study was carried out on 5 of the numerical grids. The pressure-velocity coupling was achieved with 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 modeling we used a standard wall function. Based on the literature review [35] we selected RNG $k-\epsilon$ $k-\omega$ SST as turbulence model appropriate to be used for numerical simulation for the indoor environment.

c) *Validation of the numerical results* - The numerical model was validated with values obtained during the measurement session. Profiles with the velocities, temperatures for different grille angles and air flow are presented bellow. Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indexes were calculated

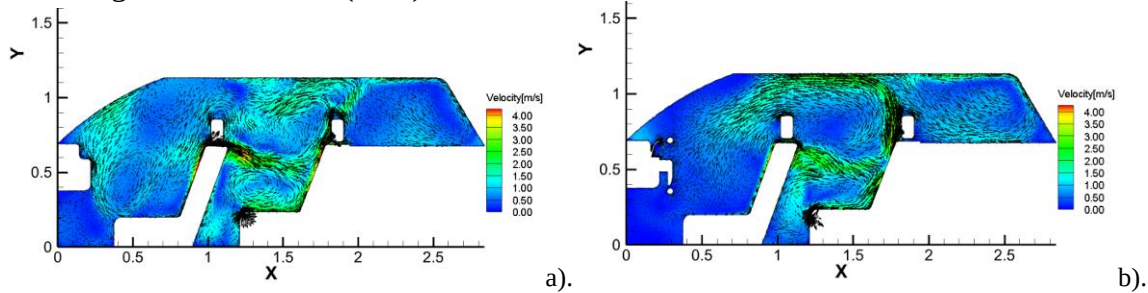


Figure 11: Velocity vectors distribution in a). the left part of the car; b). the right part of the car

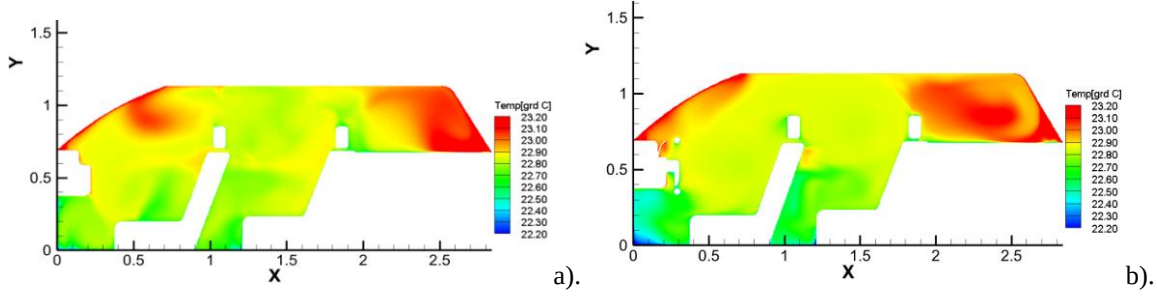


Figure 12: Temperatures contours in a). the left side of the car; b). the right part of the car

All these observations based on our preliminary tests allowed us to conclude with the following ideas:

- Having measured values for the thermal boundary conditions in quasi-steady state environment is an interesting possibility to calibrate and validate a numerical model;
- Reasonable flow patterns are obtained for the unoccupied cabin when we compare air temperature and air speed values from the numerical model with the ones measured in the real car cabin;
- The presence of the human body inside this complex and confined cabin geometry is needed in order to model a realistic situation;
- A slight change in the initial orientation of one of the air jets is generating a dramatic change in the whole cabin flow pattern. This is raising the question of the validity of the hypothesis of a uniform distribution of the velocity fields at the exit planes of the air diffusers which is the case usually in the available literature.

c. Final, complex model of car cabin with enhanced boundary conditions and human body

Once chosen the final virtual manikin geometry, prior the mesh dependency tests in the vehicle cabin geometry, the manikin was first meshed and tested in a virtual box, to simulate the evolution of the thermal plume. The imposed temperature on the manikin surface was 34°C and the ambient temperature 24°C with no air velocity, our desire being to create a natural convection flow around the virtual thermal manikin.

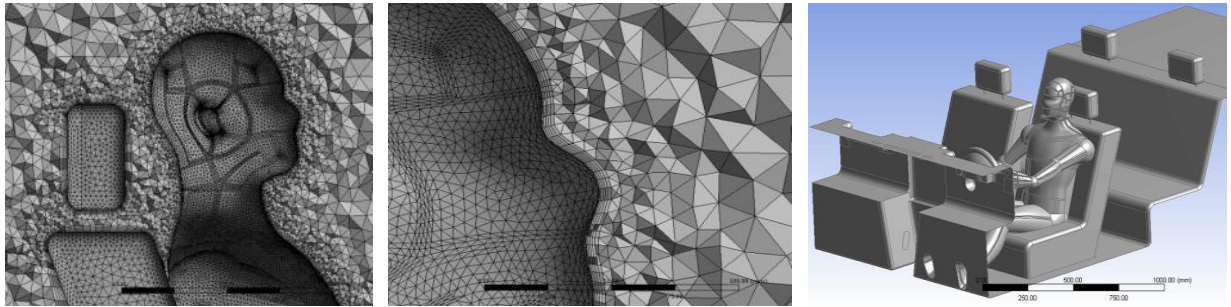


Figure 13: Numerical grid used for numerical simulation (different close-ups) and isometric view of the studied geometrical model

A fine mesh consisting of 6.5 million elements was chosen based on the experience from the previous studies where we performed the grid dependence test [36]. Several cases were studied and observed that the flow pattern changes dramatically with the angle changing, while the presence of the manikin body diminishes air velocity in the rear part of the cabin.

Comparing the velocities found in rear part of the vehicle, high velocities was found in the rear right part of the car comparing with the rear left part. The causes are the inlet angle modification and the presence of the driver. Several cases were studied and results were presented in this chapter.

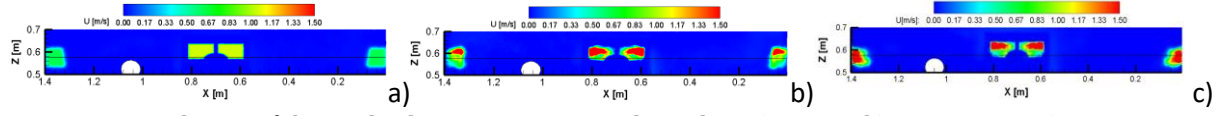


Figure 14: Distribution of the axial velocity component at the outlets: a) Case 2; b) Case 3 - CG, c) Case 4 – LAG

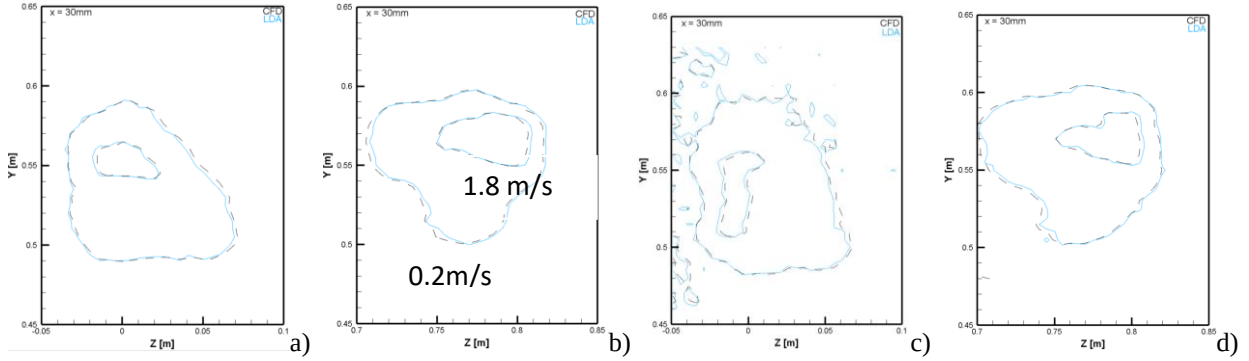


Figure 15: a,b) Side Classical grills and Center Classical grille CG (The inner contours are corresponding to 1.8m/s and the outer contours are corresponding to 0.2 m/s) and c,d) Side Lobed aileron grills and Center Lobed aileron grills grille grille LAG (The inner contours are corresponding to 1.8m/s and the outer contours are corresponding to 0.2 m/s)

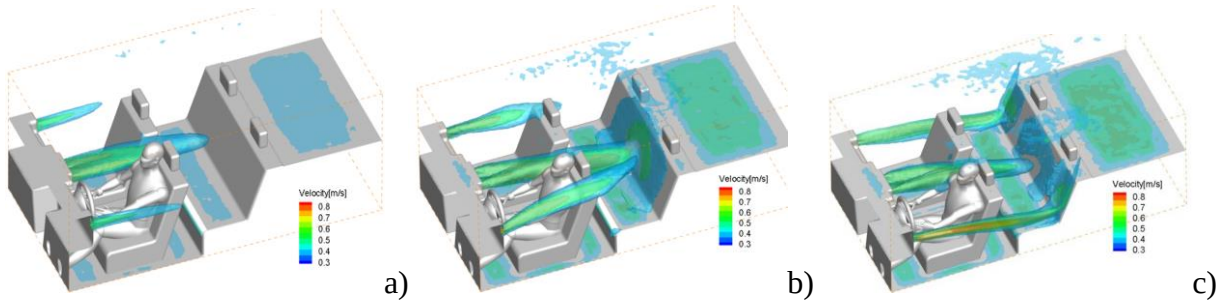


Figure 16: Velocity isocontours : a) Case 2; b) Case 3 - CG, c) Case 4 - LAG
Legend: blue – 0.3 m/s green – 0.55 m/s; red – 0.75 m/s

For finishing this chapter, once again, the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indexes were calculated. The final numerical models that we retained, with virtual manikin as a driver, in non-isothermal conditions, allowed us to simulate six cases that we will present in the next chapter. Three of them are dedicated to the classical air diffusers – CG, and three of them are dedicated with the new air diffusers – LAG.

In Tables 7, 8 and 9 we present the synthesis of the boundary conditions that we applied to these models apart the measured velocity fields that we discussed earlier. The imposed temperatures on the surfaces and at the inlets are temporal mean values from the experimental set-up presented in Chapter 3, B, d). Note that, the imposed flow rates in these cases are also different between the diffusers in this case. In order to obtain the corresponding values, we have used a weighting coefficient that we applied to the velocity fields.

Table 1: Mean air temperatures from measurements for the three fan controller positions such as imposed as boundary conditions in the final model

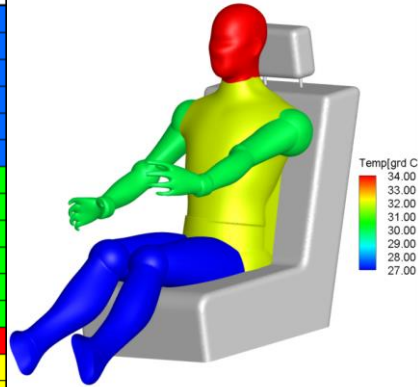
Diffuser position	V1	V2	V3	V1	V2	V3
	Temperature [°C]			Q [m ³ /s]		
Left diffuser	9.85	9.83	12.07	0.0131	0.0258	0.0380
Right diffuser	6.99	8.02	12.57	0.0068	0.0124	0.0197
Central diffusers	2.96	5.79	11.14	0.0047	0.0093	0.0158

Table 2: Mean surface temperatures from measurements for the three fan controller positions such as imposed as boundary conditions in the final model

Vehicle interior surface	V1	V2	V3
	Temperature [°C]		
Windshield	28.83	28.62	27.63
Ceiling	26.63	26.23	22.37
Right side	25.16	25.72	24.70
Left side	25.16	25.72	24.70
Rear window	28.41	28.13	27.29
Floor	21.08	21.05	22.65
Driver seat	29.00	28.00	27.00
Passenger seat	29.00	28.00	27.00
Back seat	29.00	28.00	27.00
Trunk	27.44	26.86	25.92
Dashboard	25.23	24.93	23.77

Table 3: Surface temperatures of the virtual manikin

Region	Temperature [°C]
1. Right foot	27
2. Right leg	27
3. Right thigh	27
4. Left foot	27
5. Left leg	27
6. Left thigh	27
7. Right hand	30
8. Right arm	30
9. Right upper arm	30
10. Left hand	30
11. Left arm	30
12. Left upper arm	30
13. Head	34
14. Pelvic region	32
15. Chest	32
16. Back	32



CHAPTER 5 – RESULTS AND DISCUSSION

With the previously elaborated complex models we can proceed in our final quest: *finding which the influence of the inlet conditions is determined by the two types of air diffusers.* This way, we wanted to check first what is happening with the global distribution of the flow inside the cabin in non-isothermal conditions. Next, we wanted to gain a deeper perspective in the thermal comfort aspects. To this end we compared thermal indexes from the numerical data

with the measured values of the parameters characterizing the thermal environment from the car such as described in the experimental set-up from Chapter 3.

We finish this last chapter dedicated to our study with a comparison between the numerical study and the experimental results obtained in the real car cabin from measurements and from the subjective studies.

D. Numerical results obtained using the complex model with realistic boundary conditions and virtual manikins

As it has been shown by Fanger [37], the velocities and the turbulent characteristics of the flows may generate a thermal discomfort translated by the sensation of “draught” as “an undesired cooling of the human body caused by air movement” [37, 38]. This way, we wanted to check first, the influence of the different boundary conditions and of the variation initial flow rate on the behavior of the global temperature and velocity fields inside the car cabin.

In Figure 17 we represented once again, for the isothermal case, for both diffusers (CG and LAG) the velocity magnitude distributions respectively in the median plane of the driver, in the median horizontal plane of the right passenger’s place, and in the median horizontal planes of the central diffusers and of the side diffusers. This case was considered only for V2.

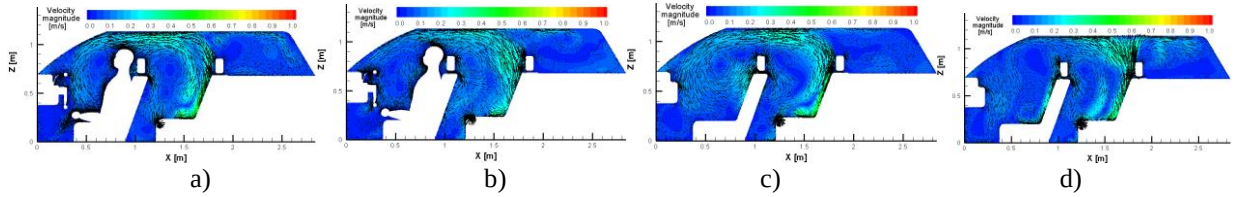


Figure 17: Velocity magnitude and in plane components distribution in the median plane of the driver a) CG ; b) LAG and in the median plane of the right passenger place a) CG ; b) LAG for the isothermal case, V2

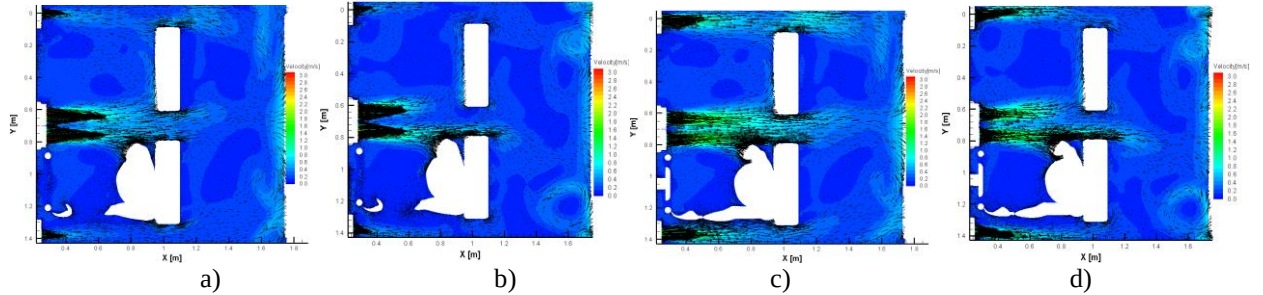


Figure 18: Velocity magnitude and in plane components distribution in the median horizontal plane of the central diffusers driver a) CG ; b) LAG and in the median horizontal plane of the side diffusers a) CG ; b) LAG for the isothermal case, V2:

An interesting result is observed for V2 running position of the fan controller. As in the case of the throw of another lobed air diffuser flow [39] the LAG jet throw is not reduced despite its higher induction. The results presented in Figure 168 provide us with valuable information, giving an indication on the entrainment and the throw improvement by the lobed grille. For the other flow rates, no distinctive advantage of the LAG diffusers compared to the CG could be observed.

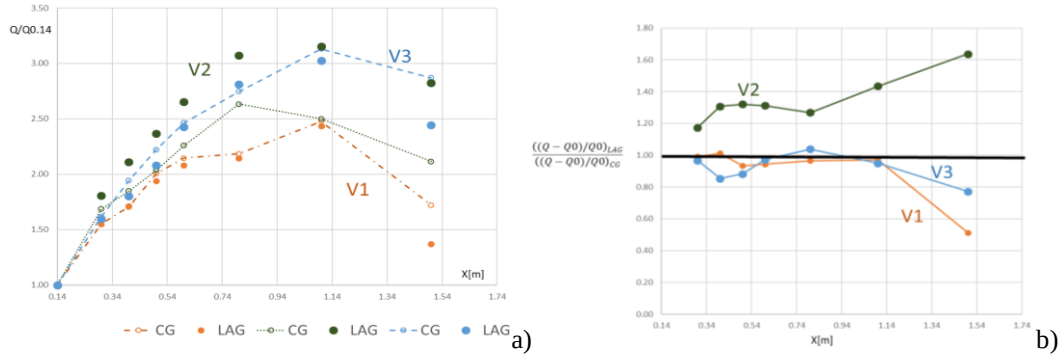


Figure 19: a) Global normalized volumetric flow rates for the three fan controller positions and for the two types of diffusers, b) normalized entrainment rates (LAG compared to CG)

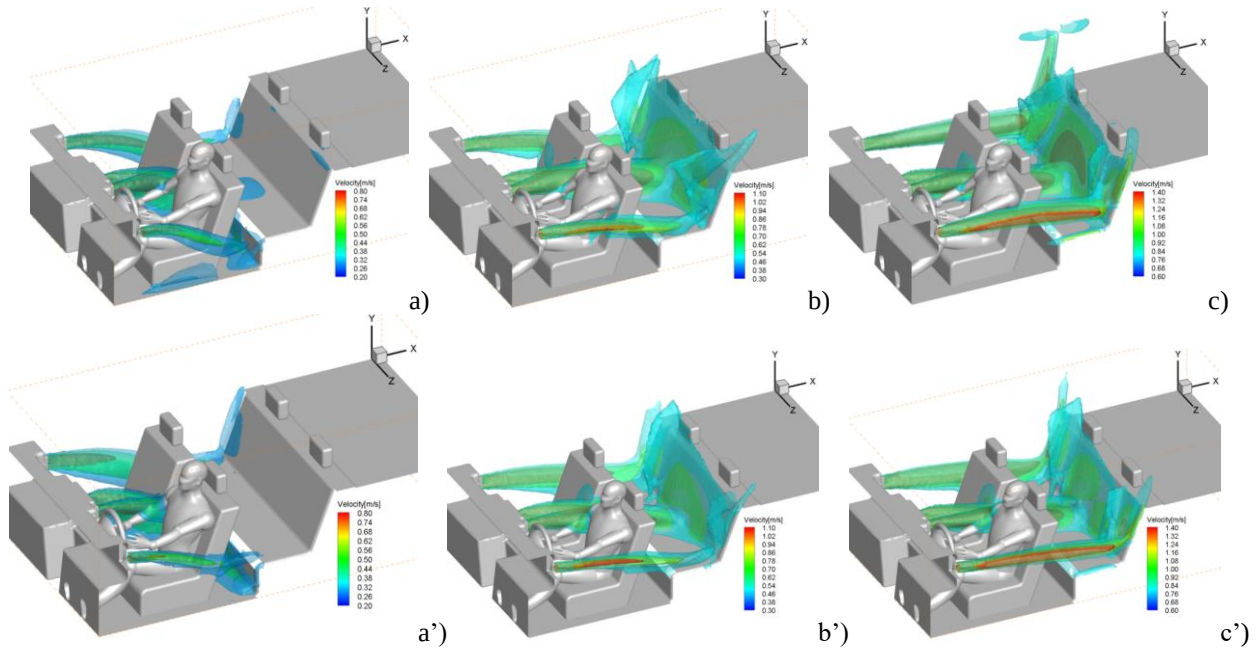


Figure 20: Velocity magnitude isocontours for the non-isothermal case, V1: a) CG; a') LAG; V2: b) CG; b') LAG; V3: c) CG; c') LAG

Legend: a) red – 0.3 m/s; green - 0.5 m/s; blue – 0.8 m/s
b) red – 0.5 m/s; green - 0.8 m/s; blue – 1.1 m/s
c) red – 0.8 m/s; green - 1.1 m/s; blue – 1.4 m/s

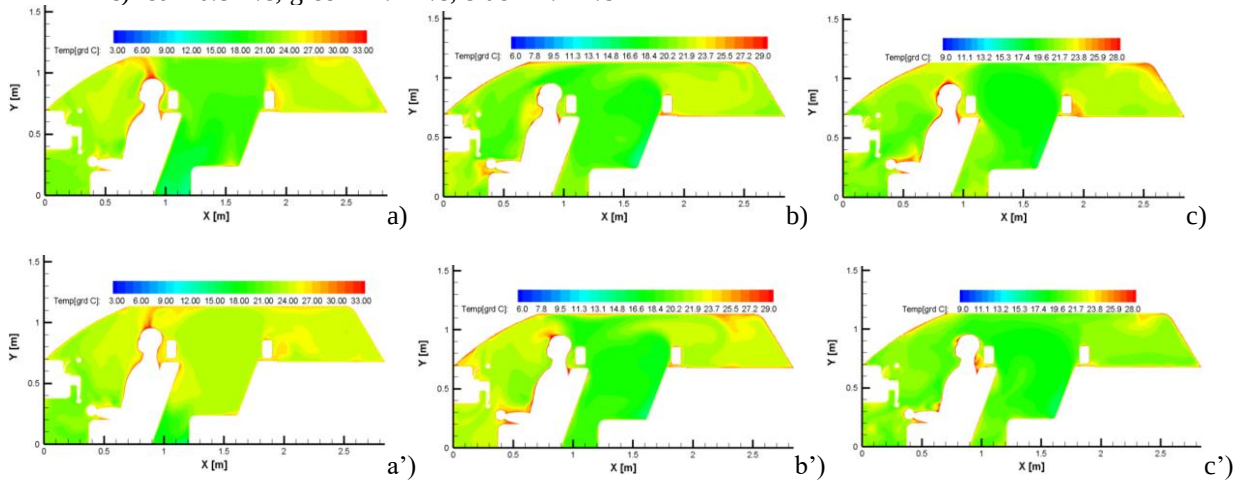


Figure 21: Temperature distribution in the median plane of the driver for the non-isothermal Velocity magnitude isocontours for the non-isothermal case, V1: a) CG; a') LAG; V2: b) CG; b') LAG; V3: c) CG; c') LAG

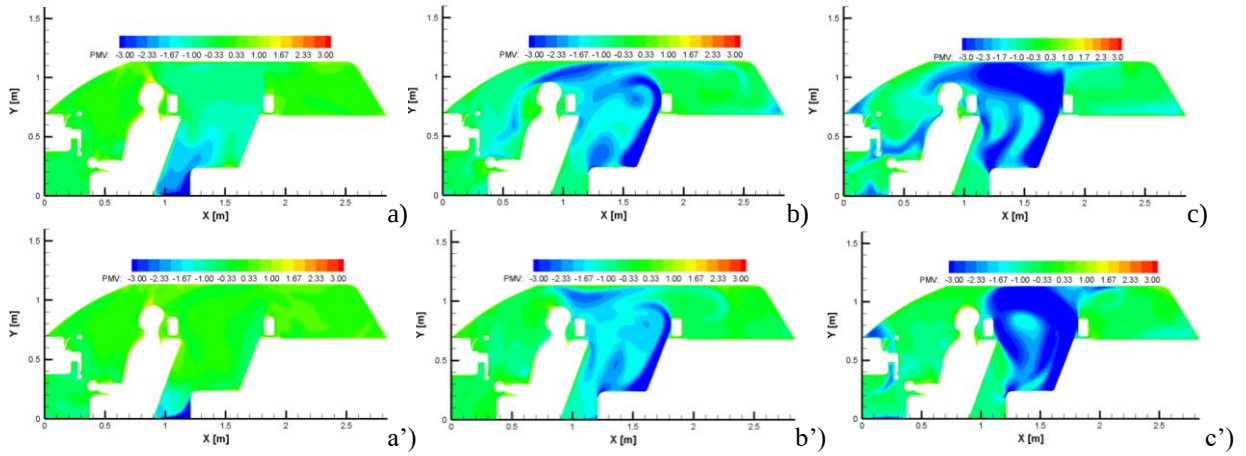


Figure 22: Local PMV distribution in the median plane of the driver for the non-isothermal case, V1: a) CG; a') LAG; V2: b) CG; b') LAG; V3: c) CG; c') LAG

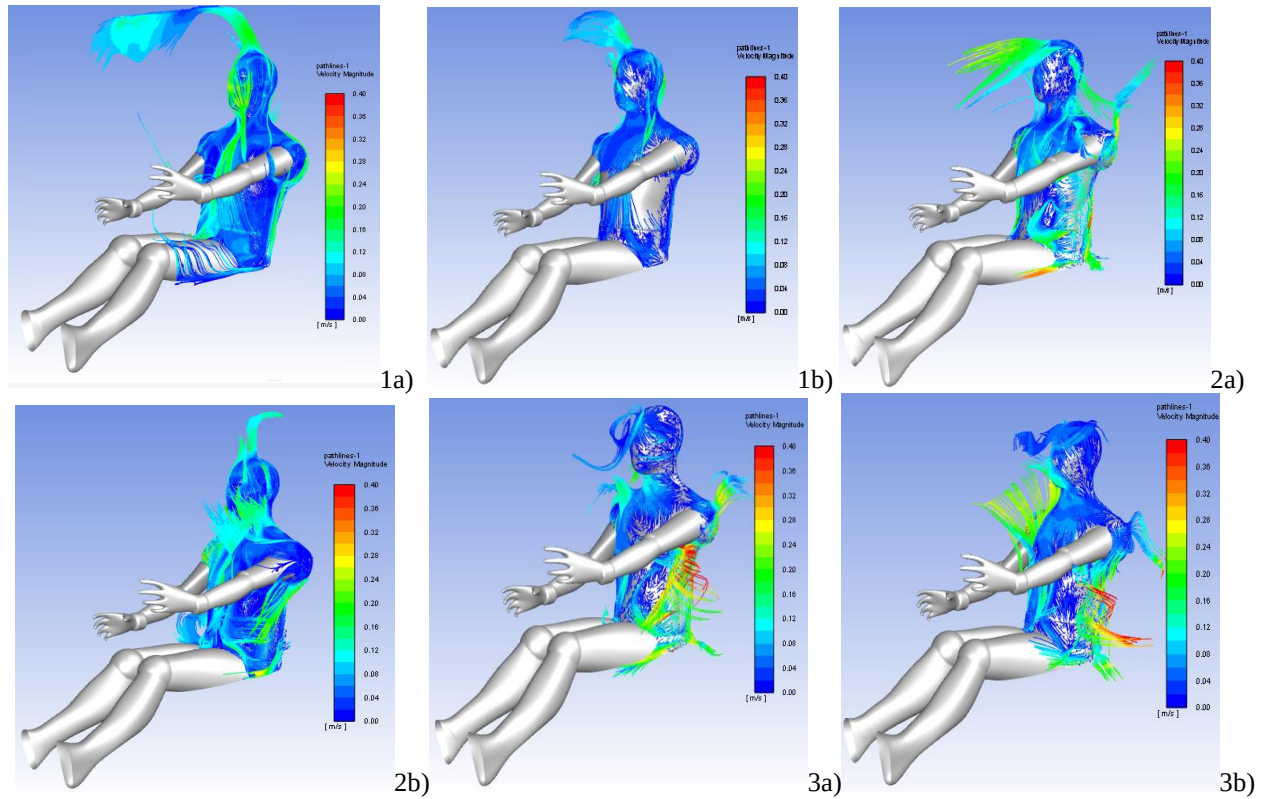


Figure 23: Pathlines showing the thermal plumes from the virtual thermal driver's body: a) CG ; b) LAG; 1) V1, 2) V2, 3) V3

Observing the results presented in these figures it appears that the thermal plume generated by the virtual manikin is very sensitive to the inlet velocity condition. Indeed, initially, for the low velocity values (Figure 22) the plume has a slender, symmetric shape. We observe however that for the two types of diffusers its orientation is different – for the CG it is oriented towards the windshield, for the LAG it is oriented towards the backseats of the car. Another representation of the thermal plume, but in its integrity, is proposed in Figure 23, where are given for the six cases, the pathlines starting from the virtual body and coloured by the velocity magnitude. The same observation as in the case of the air temperature distributions could be done – for the CG it is oriented towards the windshield, for the LAG it is oriented towards the

backseats of the car.

As the thermal environment in this study is non-uniform we also decided to estimate the local Predicted Mean Vote (PMV) distributions in the test cell [40]. This zone is very reduced in dimensions for V1, for both CG and LAG cases. For V2 and V3 cases the discomfort zone is extended in the back part of the car cabin. If we compare CG with LAG we could observe that the discomfort zone tends to extend also in the front region of the car cabin in front of the virtual driver in the first case. As it could be observed, the innovative diffusers a larger zone with high comfort level and a more reduced region in the driver zone corresponding to unacceptable conditions. However, in both cases the zone corresponding to the backseats seems to be more uncomfortable.

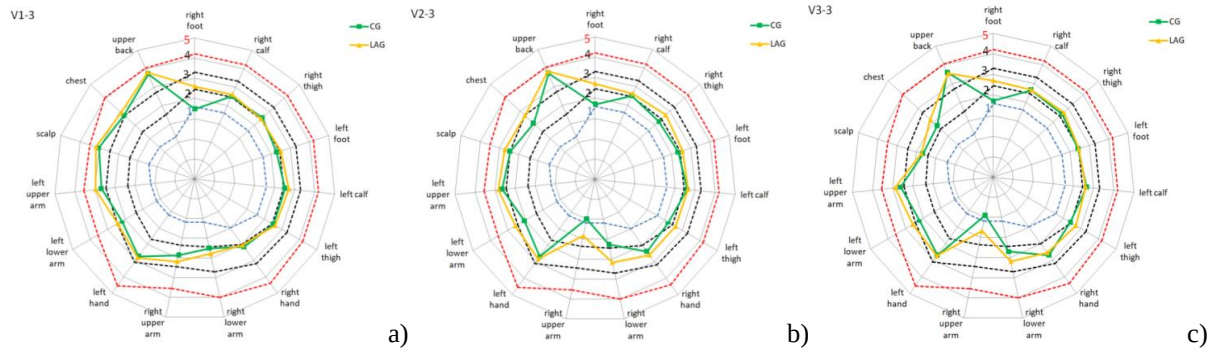


Figure 24: Equivalent temperatures on the surface of the virtual thermal manikin: a) V1, b) V2, c) V3

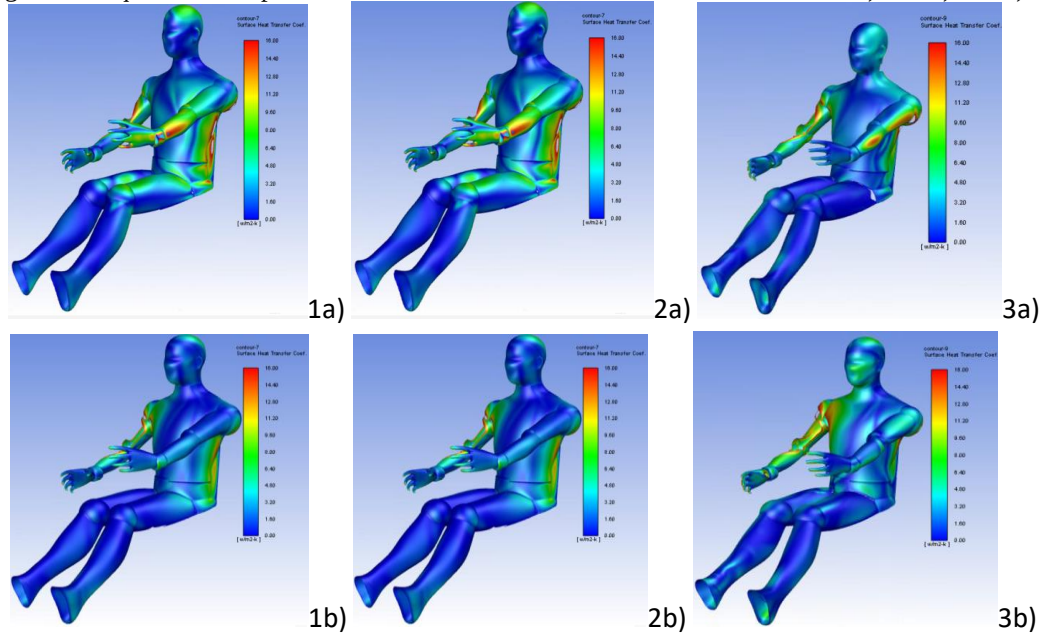


Figure 25: Distribution of the convective fluxes on the virtual body: a) CG ; b) LAG; 1) V1, 2) V2, 3) V3

In Figure 24 is represented the equivalent temperature distributions for each part of the body for the five cases with jet flow. 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 convective fluxes on the surface of the manikin [41]. This remark brought us to represent in Figure 25 of the manuscript the distributions of the convective fluxes on the surface of the manikin for the five main studied cases. Figure 25 allows observing the convective flux dynamics on the 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. [42]. It allows also

to qualitatively observe that thermal transfer occurs differently for each part of the body and each considered case. If we look to the right hand of the manikin which is exposed to the flow of the central air diffusers, it could be observed that in the case of the LAG the heat transfer between the body and the air flow is less intense. In the same time the results are consistent with the previous distributions of the PMV and DR values that were displaying that in the case of the LAG, in the front part of the cabin the thermal discomfort related to draught would be reduced.

E. Experimental results obtained from the third experimental campaign

The second experimental set-up that is presented in Chapter 3, was in fact our third experimental campaign and was designed partially for the calibration and the validation of our final numerical models, partially in order to gain insight on the phenomena from the car cabin reported to the subjective human component of the thermal sensation.

The following part of this subchapter is organized around the three types of experimental approaches:

- Comfort Sense system on the driver's place;
- Thermal manikin as driver and Comfort Sense system placed in the center of the cabin;
- Human subjects as driver and Comfort Sense system placed in the center of the cabin.

In the Figure 181 is presented a synthesis of the experimental setup sketches with the locations of the evoked measurement equipment and subjects.

The experimental sessions can be divided into three categories, studying the CG and LAG impact on thermal comfort and these three cases will be detailed further.

We have measured the temperature of inlet airflow for the three intervals. We can observe that the temperatures can be different for certain airflow ranges for the two grilles cases. However, no significant differences can be identified.

Regarding the temperature variations on the vertical, temperature sensors were placed at the level of different sensitive human parts, as head, chest, abdomen, knee and feet. The results are presented in pictures below. During the first and second airflow range, there is not a significant difference in terms of temperatures for the 2 grille cases. In the case of the third airflow range, all the sensors installed at the level of the head show a faster decrease of temperature, indicating a different thermal behavior for the case of the lobed grilles.

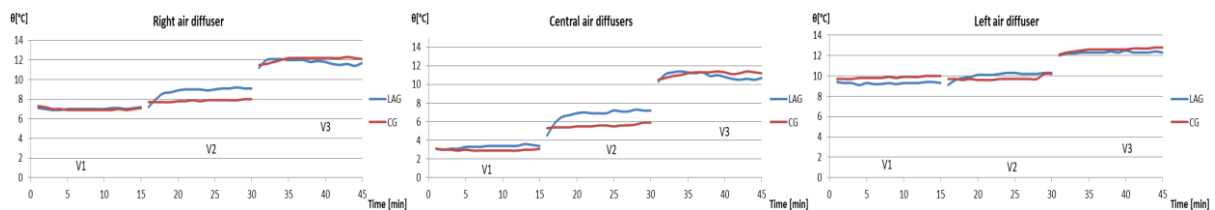


Figure 26: Temperature evolution in 15 minutes intervals for each airflow range, at measured at diffuser grille level. Comparison between CG and LAG case

a) Configuration 1: Comfort Sense placed on driver seat

The Comfort Sense system was installed on the driver place in order to assess thermal comfort and compare the results with Suzy manikin results and with the survey answers from the questionnaires. The big disadvantage of PMV index obtained with Comfort Sense is that the related global assessment of thermal comfort in a single point in such non-uniform and transient. In Figure 27 there are compared PMV values for the two types of investigated air diffusers: classical grille CG and lobed ailerons grille LAG. By imposing a Metabolic rate of 1.2 met and a clothing insulation of 0,7 clo, the PMV index was calculated for a fixed point correlated to the driver seat. We have to note here that the Comfort Sense system was placed exactly in the same place during all the experimental campaigns with the two types of grilles.

We observe that for lower values of the airflow (V1 and V2), the LAG performs slightly better, indicating a better PMV value. However, for the highest airflow, the situation is reversed.

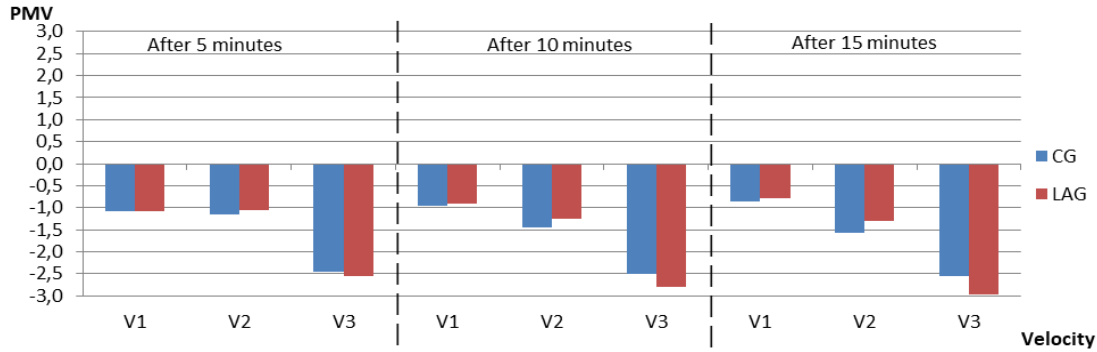


Figure 27: PMV as given by the Comfort Sense system, each 5 minutes during the experiments - Comparison between CG and LAG case

b) Configuration 2: Thermal manikin placed on driver seat and Comfort Sense placed in the center of the cabin

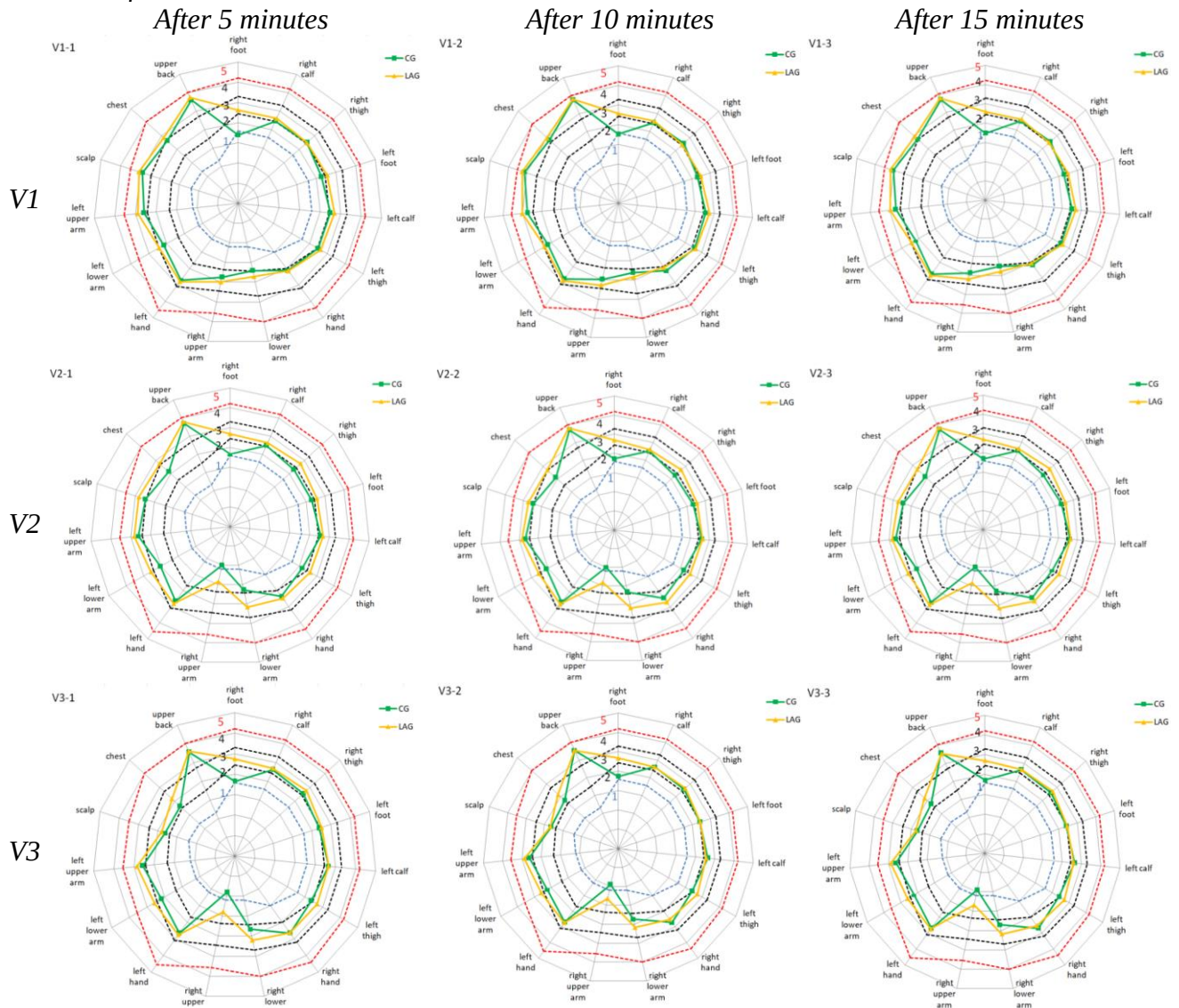


Figure 28: Equivalent temperature for different parts of the body, for CG and LAG case measured for all three ranges of airflows during 5, 10 and 15 minutes

In the next configuration, the thermal manikin was placed on the driver seat and the

Comfort Sense system was installed in the center if cabin vehicle. Figure 28 represents the equivalent temperature distribution for each airflow range (V1, V2, V3) during 3 intervals (after 5, 10 and 15 minutes). The equivalent temperature should be placed between lines 2 and 3, in order to consider achieved thermal comfort. We can observe that, for the LAG case, the equivalent temperature indicates an increased thermal comfort state in comparison with CG case, especially for the right foot, right arm, left thigh etc.

Table 4: Experimental values obtained for t_{eq} using the thermal manikin

Experimental t_{eq} values						
Body part/Velocity step/Diffuser type	V1		V2		V3	
	CG	LAG	CG	LAG	CG	LAG
Whole Body	27.8	27.0	27.7	27.2	27.7	27.2
Right Foot	22.4	23.4	21.2	23.2	21.3	22.6
Right Leg	17.3	23.0	18.4	23.5	18.5	23.5
Right Thigh	22.4	23.0	22.5	23.0	23.1	23.2
Left Foot	22.7	22.3	21.3	23.6	22.8	23.5
Left Leg	21.4	22.6	21.6	22.8	22.1	22.3
Left Thigh	22.6	23.6	22.9	23.3	23.3	23.0
Left Hand	22.6	23.1	21.0	23.1	22.0	23.5
Right Forearm	20.9	20.4	22.0	22.9	23.4	22.8
Right Arm	17.6	18.9	16.4	20.9	18.5	20.9
Hand	19.3	20.8	10.0	14.2	9.4	13.5
Left Forearm	23.7	24.2	23.4	24.1	23.4	23.7
Left Arm	20.9	22.1	20.3	22.9	21.0	22.9
Head	23.3	24.8	23.2	24.2	23.0	24.3
Pelvic region	25.0	25.8	22.2	23.7	18.2	18.7
Chest	23.6	24.6	20.6	23.6	18.5	20.9
Upper back	28.4	28.9	28.5	29.0	27.8	27.8

c) *Configuration 3: Human Subjects placed on driver seat and Comfort Sense placed in the center of the cabin*

After the thermal manikin measurements, several human subjects campaigns were performed, to obtain the Thermal Sensation Vote. Multiple sessions were performed to avoid subjective responses. In parallel, the Comfort Sense monitored the PMV index in the center of the cabin's vehicle. The majority of votes resulting from the questionnaires are indicating a neutral thermal state. However, this environment cannot be considered comfortable because it is necessary to have at least 80% of the votes to be neutral. The resulting TSV index range is between +2 (warm) and -3 (cold).

In the first part of the tests, when the airflow range was set on the first position, most of the TSV was neutral (69% for CG; 56% for LAG) while some of human subjects rated the vehicle environment like warm (11% for CG; 4% for LAG), slightly warm (20% for CG; 25% for LAG) and slightly cool 15% only for the LAG grilles measurements. From these results we can conclude the Lobed Aileron Grills have the tendency to faster cool down cockpit environment due to the 15% of "Slightly cool" votes more than CG case. In the first period after the entrance in the vehicle from a exterior warm environment, passengers are experiencing "alliesthesia" of the cool indoor environment, a state of thermal pleasure, even if the initial TSV is warm.

"Alliesthesia" is one of the recent concepts of researchers that are studying physiology and psychology in dynamic state, which proposes that any thermal stimuli sensed by the skin that diminishes or balances the effect of contrary thermal stimuli will be perceived as pleasant [12]. "Alliesthesia" can be positive or negative depending on people's current thermo-physiological state and the effect of the thermal stimuli caused by their immediate environment on their thermoregulation. For example, when the core body temperature is raised above the normal value, a cold stimulus will be perceived as pleasant. The same cold stimulus will be unpleasant if the core temperature is below the normal value. From this perspective, a thermal sensation

cannot be correlated to specific situations, it is connected to a dynamic equilibrium between human thermoregulation and the thermal impulse of the thermal environment [111] at which in our opinion is added the psychological component.

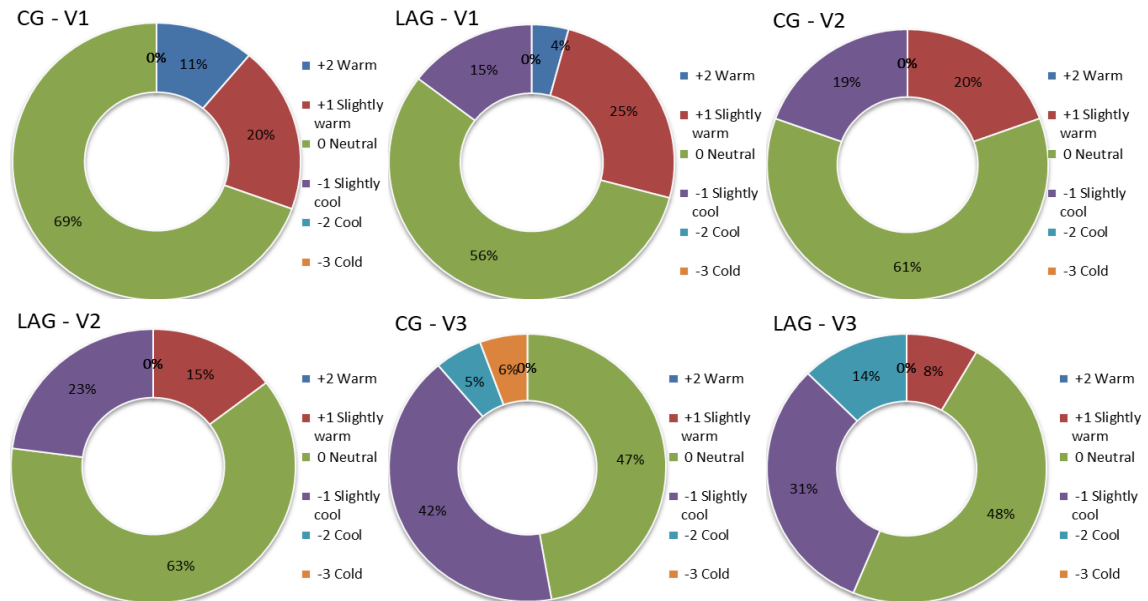


Figure 29: Thermal state percentages field at the level of whole body, from TSV, for both cases CG and LAG in all three airflow ranges

After this period, the subjects are experiencing all other thermal states previously described. The TSV for all the cases, at different time periods are written in the tables below:

Table 5: TSV values for different parts of the body for CG

Table: TSV index obtained for CG												
Time	0			5			10			15		
Velocity step	V1	V2	V3	V1	V2	V3	V1	V2	V3	V1	V2	V3
Body parts	1	2	3	4	5	6	7	8	9	10	11	12
Whole Body	0.56	0.22	-0.56	0.44	0.11	-0.56	0.33	0.00	-0.78	0.33	-0.39	-0.89
Right Foot	0.67	0.44	-0.11	0.33	0.44	-0.22	0.56	0.44	-0.22	0.22	0.56	-0.22
Right Leg	0.44	0.33	-0.22	0.22	0.33	-0.22	0.44	-0.11	-0.56	0.11	0.22	-0.56
Right Thigh	0.67	-0.22	-0.33	0.11	-0.11	-0.33	0.11	-0.33	-0.56	0.11	0.00	-0.78
Left Foot	0.67	0.67	0.22	0.78	0.56	0.00	0.67	0.78	0.11	0.67	0.44	-0.22
Left Leg	0.78	0.56	0.00	0.78	0.44	-0.11	0.56	0.44	-0.33	0.78	0.22	-0.33
Left Thigh	0.78	0.33	-0.11	0.67	0.22	-0.22	0.44	0.33	-0.22	0.78	-0.11	-0.22
Left Hand	-0.11	-0.22	-0.67	-0.33	-0.44	-1.00	0.00	-0.44	-1.00	-0.11	-0.56	-0.89
Right Forearm	-0.22	-0.67	-1.00	-0.44	-0.89	-1.33	-0.33	-0.89	-1.33	-0.67	-1.00	-1.22
Right Arm	0.00	-0.67	-1.22	-0.22	-0.89	-1.33	-0.33	-0.89	-1.44	-0.44	-0.89	-1.33
Hand	0.44	0.33	-0.11	0.33	0.33	-0.56	0.33	0.22	-0.56	0.44	0.11	-0.89
Left Forearm	0.56	0.33	-0.44	0.33	0.22	-0.78	0.44	0.11	-0.56	0.44	-0.22	-0.56
Left Arm	0.56	0.33	-0.56	0.44	0.22	-0.78	0.44	0.11	-0.67	0.44	-0.22	-0.78
Head	0.78	-0.11	-0.78	0.44	-0.11	-0.89	0.56	0.11	-0.89	0.56	0.11	-0.89
Abdomen	0.78	0.00	-0.22	0.56	0.22	-0.22	0.44	0.33	-0.22	0.44	0.00	-0.33
Chest	0.56	-0.11	-0.56	0.33	-0.22	-0.56	0.44	-0.22	-0.78	0.44	-0.33	-0.78
Upper back	0.67	0.56	0.22	0.33	0.56	0.22	0.67	0.56	0.22	0.89	0.33	0.22

Table: TSV index obtained for LAG												
Time	0			5			10			15		
Velocity step	V1	V2	V3	V1	V2	V3	V1	V2	V3	V1	V2	V3
Body parts	1	2	3	4	5	6	7	8	9	10	11	12
Whole Body	0.08	0.00	-0.38	0.08	0.00	-0.50	0.17	-0.08	-0.46	0.42	-0.17	-0.46
Right Foot	0.25	0.00	0.00	0.33	0.00	-0.33	0.08	-0.25	-0.25	0.00	-0.33	-0.42
Right Leg	0.33	0.08	-0.25	-0.08	-0.42	-0.42	0.08	-0.42	-0.42	0.00	-0.58	-0.33
Right Thigh	0.17	-0.08	-0.42	-0.08	-0.42	-0.58	0.00	-0.42	-0.75	-0.25	-0.42	-0.67
Left Foot	0.42	0.25	-0.08	0.33	0.00	0.08	0.25	0.08	-0.08	0.33	0.00	-0.08
Left Leg	0.50	0.25	-0.17	0.08	0.08	-0.08	0.33	0.00	0.00	0.25	-0.17	-0.08
Left Thigh	0.25	0.00	-0.33	0.17	-0.17	-0.33	0.25	-0.25	-0.25	0.08	-0.25	-0.33
Left Hand	-0.25	-0.33	-0.75	-0.33	-0.71	-0.82	-0.33	-0.50	-0.92	-0.42	-0.67	-0.92
Right Forearm	-0.50	-0.58	-0.75	-0.50	-0.96	-0.83	-0.42	-0.50	-0.83	-0.33	-0.63	-0.83
Right Arm	-0.50	-0.67	-0.92	-0.50	-0.63	-0.92	-0.42	-0.67	-0.67	-0.25	-0.79	-0.92
Hand	0.00	-0.08	-0.17	-0.08	0.00	-0.50	-0.08	-0.25	-0.36	-0.17	-0.17	-0.42
Left Forearm	-0.17	-0.08	-0.25	-0.08	-0.08	-0.33	-0.08	0.00	-0.25	0.08	0.00	-0.25
Left Arm	-0.33	-0.08	-0.42	-0.17	-0.17	-0.50	-0.08	-0.25	-0.42	0.08	-0.25	-0.42
Head	0.58	-0.50	-0.92	0.33	-0.54	-0.75	0.00	-0.58	-0.75	0.25	-0.71	-0.92
Abdomen	0.25	0.17	0.08	0.25	0.00	0.00	0.17	0.17	0.00	0.42	-0.08	-0.08
Chest	0.25	-0.67	-0.83	-0.08	-0.54	-0.58	-0.42	-0.50	-0.58	0.08	-0.54	-0.58
Upper back	0.33	0.00	-0.25	0.25	0.17	-0.08	0.17	0.33	0.00	0.33	0.25	0.00

The questionnaire survey reveals that the lobed air diffusers are improving thermal comfort state. The most sensible human body parts are feet, ankles, head and the neck. To these sensitive parts we can add arms, forearms and hands which are on the direction of the jet flow from the diffusers. In the following graphics we have compared Thermal Sensation Vote from questionnaires at the level of these body parts for the CG and LAG case.

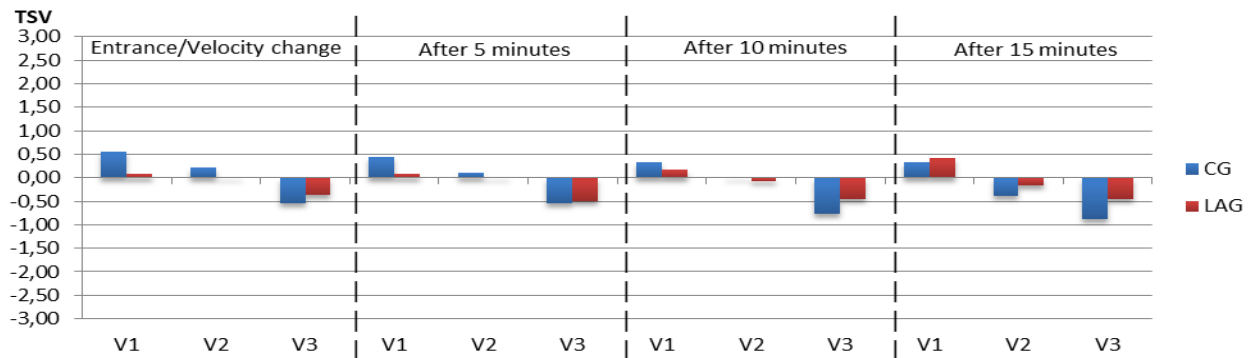
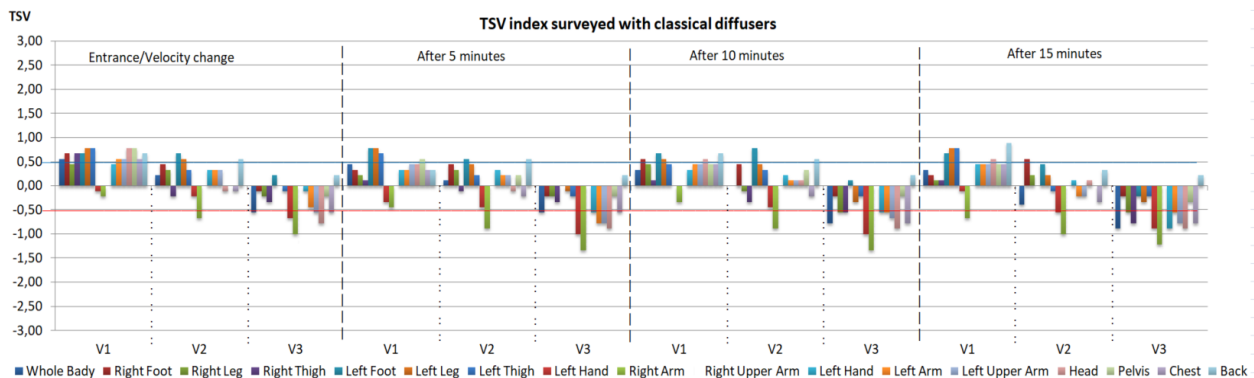


Figure 30 : Whole body TSV for CG and LAG cases

We can observe the CG TSV evolution to “cold” for the largest airflow V3, while for LAG case, the TSV remains the same, while for V2 airflow the TSV is close to neutral. Close to the head of the driver, the LAG case indicates a more comfortable environment.



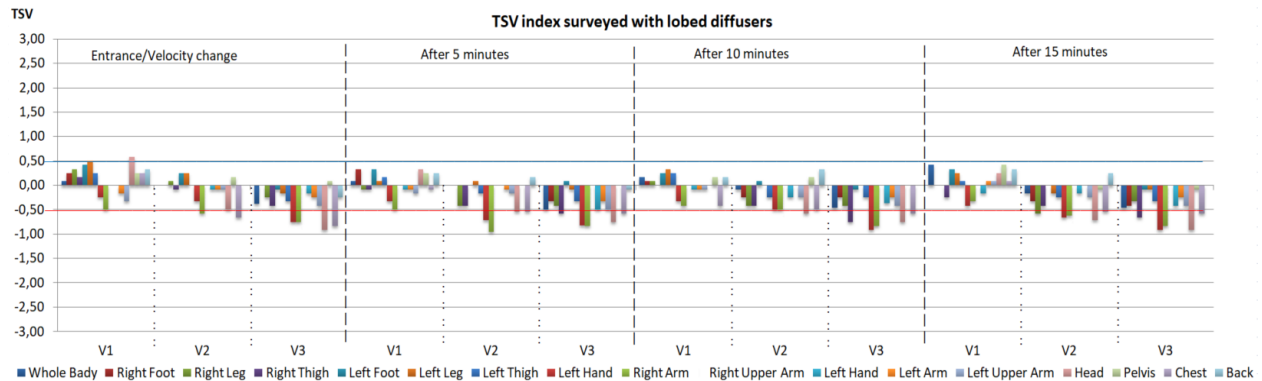


Figure 31: All local TSV values for CG and LAG cases

F. Discussion of the results

In Tables 25 and 26 we are presenting a synthesis of the data recorded by the Comfort Sense system for the CG case and for the LAG case. In Tables 27 and 28 we gathered all data regarding all recorded thermal indexes for CG and LAG cases. A direct interpretation of the values seems to be difficult. The TSV index captures besides the subjective nature of the persons that are filling in the questionnaires, the inherent dynamics of the environmental parameters, such as the protocol was designed after the prescriptions of the standard.

Tables 6: Synthesis of the data recorded by the Comfort Sense system placed on the driver seat for the CG and LAG case

Velocity step	θ_{op}	θ_{MRT}	PMV	PPD	Velocity	θ_{air}	DR
[-]	[°C]	[°C]	[-]	[%]	[m/s]	[°C]	[%]
V1	24	24	-0.70	16	0.02	25	0
V2	26	23	-1.79	66	0.18	22	21
V3	22	22	-1.78	66	0.15	22	20

Velocity step	θ_{op}	θ_{MRT}	PMV	PPD	Velocity	θ_{air}	DR
[-]	[°C]	[°C]	[-]	[%]	[m/s]	[°C]	[%]
V1	24	23	-0.92	23	0.01	49	25
V2	23	22	-1.20	35	0.03	60	24
V3	21	23	-2.78	97	0.37	60	20

The majority of studies using human subjects in dynamic states, for buildings mainly, have been conducted in climatic chambers, and only a few of them have been validated in real in situ conditions. However, an accurate prediction of people's thermal perception in dynamic state does not yet exist and PPD and PMV models do not accurately reflect people's thermal perception in such a state like passengers that are experiencing "alliesthesia" of the cool indoor environment.

Some important discrepancies can be noticed between the results derived from the Comfort Sense and the Thermal Manikin measurements and the subjective ones from questionnaires. Generally, sensations of coldness are amplified in the response of the Comfort Sense system, in comparison with the TSV and the thermal manikin. Moreover, it can be

observed that the correlation is not significant.

Tables 7: Synthesis of the data recorded by the Comfort Sense system for the CG case

Time	Velocity	PMV CS driver seat		TSV		PMV Suzy		PMV center CS	
		CG	LAG	CG	LAG	CG	LAG	CG	LAG
after 5 min	V1	-0.85	-0.51	0.44	0.08	0.26	0.20	-0.11	-0.32
after 10 min		-0.69	-0.30	0.33	0.17	0.27	0.39		
after 15 min		-0.56	-0.15	0.33	0.42	0.28	0.41		
after 5 min	V2	-1.54	-0.89	0.11	0.00	0.39	0.41	-0.61	-0.92
after 10 min		-1.85	-1.37	0.00	-0.08	-0.09	0.39		
after 15 min		-1.97	-1.44	-0.39	-0.17	-0.22	0.28		
after 5 min	V3	-1.75	-1.67	-0.56	-0.50	-0.23	0.15	-2.37	-1.93
after 10 min		-1.76	-1.71	-0.78	-0.46	-0.21	0.04		
after 15 min		-1.82	-1.89	-0.89	-0.46	-0.22	0.04		

This result is a confirmation of previous analysis carried out in another typology of environment [43]. In the same time the figures 198 and 199 we are representing values of the TSV from the questionnaire survey and the PMV estimated from measured data from the Manikin and the Comfort Sense system versus the operative temperature for the entire experimental campaign show once again a great dispersion of the data collected from the questionnaire survey compared to the measured and predicted comfort indexes. However, the subjective data and the thermal manikin are giving globally very close responses. This finding correlated with the evidence of the same discomfort zones put in evidence by the subjects, the manikin and the numerical results, shows that the thermal manikin represents a worthy tool for the thermal comfort analysis in laboratory configurations and in real field case studies.

CHAPTER 6 – PERSONAL CONTRIBUTIONS

Before going to the general conclusions chapter, we wanted to review the main original contributions developed in the research study.

The doctoral thesis addresses a complex, interdisciplinary subject, which required the synthesis of a large amount of specialized literature. In the first part, the thesis is organized around the study of current research, mainly aiming two directions: methods, models and indicators for prediction of vehicular thermal comfort and numerical simulation techniques for turbulent flows. Thus Chapter 1, offers an overview of the main concepts and results of numerous studies from literature for numerical and experimental research in the field of thermal comfort. This chapter is the summary of our initial search of landmarks in the literature that allowed us to get directions and to choose a specific numerical and experimental validation cases, based on the existing results and on the available means. The first chapter is a bibliographical one, proposing an extensive and exhaustive introduction in the thermal comfort research field with focus on cabin thermal environment, a synthesis of theoretical aspects concerning thermal comfort, vehicle environments and related environmental factors, that have a major effect on the vehicular space mainly aiming two directions: methods, models and indicators for the prediction of indoor thermal comfort and numerical simulation techniques for the turbulent flows used for the study of air flow in the cabin environment. It represents the summary of our initial extensive search of milestones in the existing literature. It allowed us to set the main directions for our research and to define specific numerical and experimental validation based on the existing data and on the available methods. *Thus, a first personal contribution consists of the bibliographic synthesis in Chapter 1, given the absence of such an analysis at present for the vehicular spaces, in the literature, taking into account all the aspects mentioned above.*

In this study, the numerical approach was focused on CFD (Computational Fluid Dynamics) and experimental studies. The CFD type approach has the advantage of providing the

opportunity to analyze a large number of cases, thus filling costs related to the need for a relatively large number of experiments whenever a parametric study is required. In this context, CFDs have gained great popularity in our field over the last decade. A problem presented in the literature is related to the fact that insufficient importance is still given to convective flows generated by heat sources such as the human body, which can themselves affect the distribution of room air [280]. Generally speaking, when it comes to studies that perform simulations of the thermo-aeration behavior of ventilated spaces, the investigators' attention is captured by the airflows generated by the air intake devices, although the location of the maximum speed values in a room is influenced by the intensity of heat sources and their distribution in the room. Consequently, the interaction between the different flow types (convection currents, uniform flows and / or air jets) should be taken into account when a study focuses on estimating comfort from these simulations. *One of the main contributions of this study is related to the fine modeling of convective flow generated by the human body and the study of its interaction with the environment in terms of flow dynamics in the vehicular spaces.*

At the same time, the results obtained from any type of numerical approach should be validated experimentally in conditions as close as possible to real ones, to allow their exploitation. Knowing that experimental studies using human subjects are costly, long lasting and subjective, being hard to validate, a good compromise is the use of thermal manikins. *This is the motivation of developing thermal manikins in our research group and thus one of the most important objectives of the thesis was consisted by the development of the thermal manikin.*

Apart the thermal manikin in the experimental part of the study was used different measurement equipment. In our study we used state of the art equipment in order to measure and characterize the flow patterns inside the cabin. *This is the first time at our acknowledgement when such a detailed characterization of the flow rates discharging from the dashboard of a real car is proposed in the literature.*

The flow patterns and their effect on thermal sensation are not completely considered by manufacturers or by users, given that flow trajectory might substantially differ from the direction imposed by the guiding vanes of the air vents. This is related on one hand to these previously mentioned convective effects but might be also an intrinsic characteristic of the air vent itself. No studies combining passive induction control via the conception of air diffusers were found in the literature. The proposal of some innovative designs of air vents for the present studies was based on the previous findings of the French and Romanian research teams were the doctoral project was developed. *A part of the manuscript is dealing with the development of an innovative thermal manikin and of new concepts of air diffusers. The approach is based on both experimental and numerical approach.*

A complex numerical model has been developed. This model includes a passenger with anatomic shape and takes into consideration to types of air diffusers: one which is the reference – the classic air grilles that were originally designed in the cabin and one innovative set of air diffusers that we wanted to test. The validation of the chosen approach for introducing the effect of the flows generated by the two types of diffusers is also presented in this chapter. *This is the first study at our knowledge in the literature using a large number of human subjects for the vehicular environment assessment.*

CHAPTER 7 – CONCLUSIONS AND PERSPECTIVES

Designers in the automotive field started to be focused on comfortable mobility only over the last decades given the lowering of production costs and the increasing safety of vehicles. Their approach was mainly based on methods used in the field of building systems. 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 also because that the time that people spend in

vehicles (private or public transport) has grown substantially. Thermal comfort in vehicular spaces acquired more importance due to the growing of the distances between home and workplace [1] with a direct impact on the time that people spend in vehicles [2].

Prediction of conformable thermal conditions inside a vehicle cabin is still a challenge due to the transient behavior of this environment. The understanding of flow patterns is still a provocation for nowadays researchers due to the interior cabin complex geometry and also to the ventilation system complexity (flow rate, location and geometry of vents) [8]. Flow patterns and their effect on thermal sensation are not completely considered by manufacturers or by users, given that flow trajectory might substantially differ from the direction imposed by the guiding vanes of the air vents. This is related on one hand to these previously mentioned convective effects but might be also an intrinsic characteristic of the air vent itself. The grilles design and fan characteristics are not taken into consideration by the manufacturers when designing the air conditioning system, these being a source of noise [44] with impact on passenger's state of mind.

The currently available standard intended for evaluation of vehicle thermal environment, EN ISO 14505 [9-11], propose buildings evaluation models, which do not meet the demands of for cabin environment evaluation. Unlike the indoor environment from buildings, the vehicular cabin climate is dominated by thermal transient conditions: the strongly non-uniform thermal environment associated with the high localized air velocities that might fluctuate if we are in the presence of an automatically controlled air conditioning system, the higher levels of relative humidity, the solar heat flux, and the radiative heat flux from the interior surfaces, the solar intensity and its scattering over the different material types and surface niches in the cabin, the angles of incidence of the solar radiation etc. [5], [6]. In the absence of evaluation models adapted to this environment, the available literature is dispersed around those papers dealing with environmental conditions inside the vehicle that might affect the human thermal comfort and those concerning the human's response and perception of its interaction with the environment. The available literature is equally divided within experimental and numerical approaches. Due to complexity of this environment and due to unadapted models of evaluation from standards, this process experimental and numerical is divided in three subcategories of studies. The first category is represented by studies that deal with the idea of thermal environment assessment without considering any comfort assessment. The second subcategory include those studies where thermal comfort assessment models proposed by standards are used. The third subcategory covers the articles using or proposing new thermal comfort assessment methods.

In this context, we decided to orient the subject of the thesis around the complex problematic of cabin thermal environment and its effect on driver's and passenger's thermal state. Thermal comfort has been widely studied in build environments, while thermal comfort in vehicles is a relatively new subject, there have been relatively few studies. In the manuscript are presented numerical and experimental studies of the effects of different passive grills over passengers' thermal comfort. Thus, the general objectives of the doctoral research project could be summarized as following: (1) The first general objective of this thesis was **to deepen the knowledge and to understand thermal phenomena that occur in cabin thermal environment**. (2) The second general objective of this doctoral study was **to develop an advanced thermal manikin able to evaluate cabin thermal comfort** knowing that thermal manikins are the most proper measurement tool in the case of non-uniform and transient environments. (3) The third general objective was **to develop and validate a complex numerical model in order to get insight into the complex phenomena previously evoked**.

These three general objectives were intended to sustain the main goal of the doctoral research that is: **improvement of thermal sensation of vehicle occupants, by implementation of innovative air diffusers**. To this end we oriented our research towards diffusers with a special geometry that allows flow control mechanisms resulting in the improvement of mixing

between air supply by the ventilation system and the ambient air in the cabin.

During all this quest we tried to stay on a line that would ultimately allow to respond to a set of fundamental questions, namely: *To what extent this kind of parameters can affect the perceiving of comfort, and also the consequences of an "incomplete" assessment proposed by the existing evaluation models? How is in this context affected the ventilation and air conditioning design due to the use of current models for pre-evaluating a good functioning of the HVAC systems – in particular for vehicles - and an acceptable environment for their users?*

The second chapter is dedicated to the design and development of an advanced thermal manikin with 79 independent zones and neuro-fuzzy control. The concept and the development are presented step by step as well as the preliminary tests of this prototype. I was directly involved in designing and manufacturing of this particular thermal manikin that was conceived and developed with the help of the Systems and Mechatronics department from the National Institute of Research Aerospace Elie Carafoli (INCAS) from Bucharest.

The third chapter is dedicated in a first part to the measuring principles of all used measuring instruments and in a second part to the three main experimental set-ups used during the entire study. All the experimental tests were made with the car was kept inside a hall. The main reason for this choice was related to our desire to maintain constant values of external factors, to decouple the in-cabin conditions from the solar radiation effect and to protect measurement equipment from the outdoor meteorological conditions. As a result, indoor thermal conditions varied much slower than outside. The objective of the experimental campaign was multiple:

- to record in different conditions, like previously, the evolutions of the temperatures on the surfaces inside the cabin and in different points in the air;
- to test the effect on different flow rates and cold air temperatures on the air distribution inside the cabin;
- to « measure » thermal comfort indices using the Comfort Sense system and the thermal manikin previously developed for different flow rates and two geometries of air diffusers in cooling conditions, and thus to provide data for validation purposes of the numerical models developed in Chapter 4;
- to perform subjective thermal comfort evaluations for the same flow rates and the two geometries of air diffusers in cooling conditions allowing a direct comparison between the subjective response and the dedicated measurement systems;
- to provide data recording air speed values and temperatures in different points inside the car cabin for validation purposes of the numerical models developed in Chapter 4.

In the introduction of the fourth chapter we propose to pass briefly through the current developments related to Computational Fluid Dynamics applied to air distribution and thermal comfort. In the bibliographical chapter we put in evidence all numerical studies that we found in literature relevant for our subject. Still, the great majority of these studies lacks details and explanations of modeling choices, this way we decided to rely on the knowledge gained in the much more studied field of air distribution and thermal comfort in buildings. In the following parts of the chapter we present the steps employed in our numerical approach. In a first time a simple car-cabin numerical model was designed and in our quest of methods of calibration of the correct boundary conditions, we used temperature and air flow measurements in a real car-cabin. In a second time, a complex numerical model has been developed. This model includes a passenger with anatomic shape and takes into consideration to types of air diffusers: one which is the reference – the classic air grilles that were originally designed in the cabin and one innovative set of air diffusers that we wanted to test. The validation of the chosen approach for introducing the effect of the flows generated by the two types of diffusers is also presented in this chapter.

With the previously elaborated complex numerical models we could proceed in the fifth chapter to our final quest: finding which is the influence of the inlet conditions determined by the two types of air diffusers. This way, we wanted to check first what is happening with the global distribution of the flow inside the cabin in non-isothermal conditions. Next, we wanted to gain a deeper perspective in the thermal comfort aspects. To this end we compared thermal indexes from the numerical data with the measured values of the parameters characterizing the thermal environment from the car such as described in the experimental set-up from Chapter 3.

We finish the last chapter dedicated to our study with a comparison between the numerical study and the experimental results obtained in the real car cabin from measurements and from the subjective studies.

Given the originality of this research study, a first stage of analysis that opens interesting study perspectives for the continuation of several research directions. First of all, with regard to the experimental part, a short-term perspective is to continue the experimental studies in winter conditions using both the developed thermal manikin and human subjects. Also, other geometries of diffusers that we already adapted to the real studied car, will be tested in the near future.



Figure 32 Other geometries of diffusers to be explored....

From a numerical point of view, first we would like to implement a LES model to capture the temporal and spatial dynamics of convective natural current and the influence of scale and frequency of whirlpools present in airflows. We also want to connect the RANS with a nodal model for body thermoregulation and adaptive comfort simulations. We would like to modify the geometrical models in order to resolve the flows through the grilles. A long-term perspective is given by the coupling of these researches with numerical and experimental studies related to the quality of indoor air and especially to the particular dispersion inside the vehicle. More virtual manikins should also be introduced in the vehicle.

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