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STUDIES OF THE THERMAL COMFORT INSIDE OF THE PASSENGER COMPARTMENT USING THE NUMERICAL SIMULATION

ABSTRACT: The increasing market demand for highly effective and efficient HVAC systems for automotive applications has determined a great impulse in the research and development of innovative methods and instruments to predict passengers' thermal sensation.

The interaction of convective, radiation and conduction heat exchange in a passenger's compartment is very complex. The varying radiation from the sun and the influence of inhomogeneous air temperature and air velocity from the vehicle's ventilation or air conditioning system creates a climate that may vary considerably in space and time.

According to ISO 7730, the combination of these six parameters determines the degree of general comfort: personal factors - activity level, *M* (met), thermal insulation of clothing, I_{cl} (clo) and environmental parameters - air temperature, t_a (℃), mean radiant temperature, $\bar{t}_r$, air velocity, v_a (m/s); humidity ratio, RH (%).

This paper shows the distribution of the temperature and the air flow fields of passengers' compartment starting from the body's energy balance based on Fiala's manikin (which provides all the thermo-physiological effects of the human body model) by THESEUS-FE software and the numerical simulation for air flow inside the car will be acomplished by Fluent software.

KEYWORDS: thermal comfort, temperature, air velocity, passenger compartment, numerical simulation

INTRODUCTION

One of the most important factors of comfort inside the passenger compartment in the last years is the thermal comfort. To achieve that, most car manufacturers need to demand to their HVAC providers a system that ensure better ventilation, heating and cooling that the system on the previous model, and also more complex tuning (single zone, dual zone) to please most of the customers.

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It is well known that one of the requirements to be fulfilled is that a person to be in thermal neutrality according to the comfort equation. This is described and evaluated by the following indices: DTS (**D**ynamic **T**hermal **S**ensation), TS (**T**hermal **S**ensation), PMV (**P**redicted **M**ean **V**ote) and PPD (**P**redicted **P**ercentage of **D**issatisfied). The two first indices depend of the hypothalamus temperature and the mean skin temperature and PMV - PPD indices take into account the following six parameters: activity, clothing, air temperature, mean radiant temperature, air velocity and humidity (ISO 7730).

In this paper we will simulate the passenger compartment of a medium class car and we will compare the experimental results with those obtained from the numerical simulations. For the numerical simulations we will use two softwares:

1. The evaluate the temperature distribution inside the car and the thermal comfort for the car passenger by Theseus FE;
2. The evaluate air flow fields inside the passenger compartment by Fluent 6.3.26.

The numerical simulations will be realized for 3 main cases, each one with two sub-cases. The main cases are given by the position of the button for air flow range setting and the sub-cases are given by the position where the air is introduced inside the passenger's compartment (face or face + legs).

Each simulation and experiment will last for about 1800 seconds. We will experimentally measure the velocity of air in the points given in figure 1, those values being used also as boundary conditions for the numerical simulations. The temperature will be measured in the points given in the figure 2. The temperature value that will be compared with the temperature obtained with the Theseus Fe will be an average temperature over the 12 points presented in figure 2. The position of the point where will measure experimentally the velocity of the air that will be compared with the numerical simulation will be presented later in the paper, and represents the position of the right passenger nose.

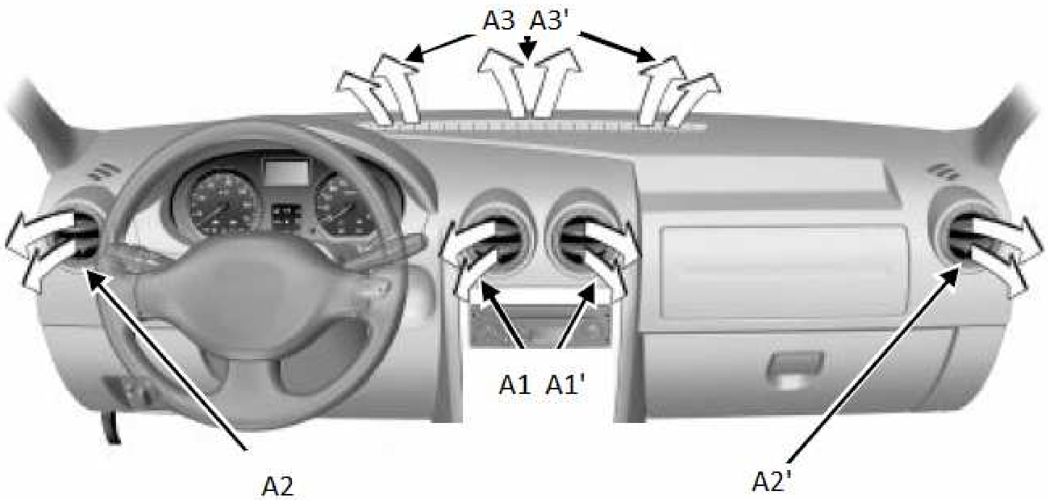


Figure 1 *The position of velocity measuring points*

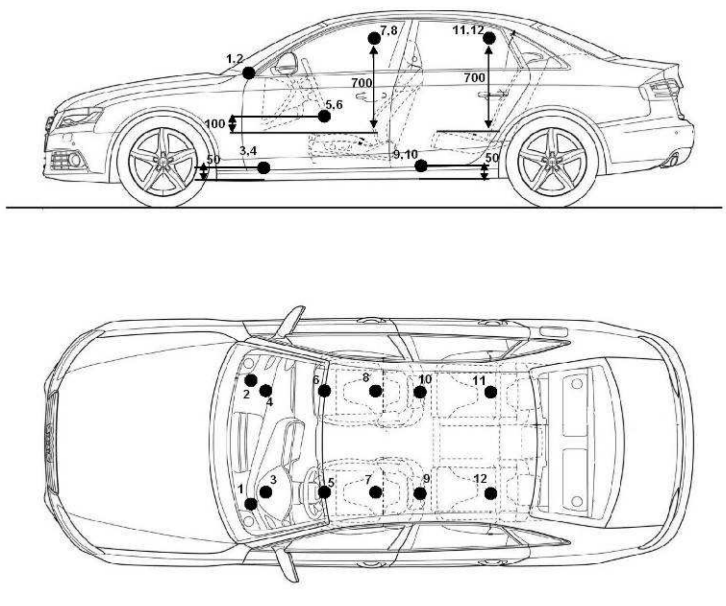
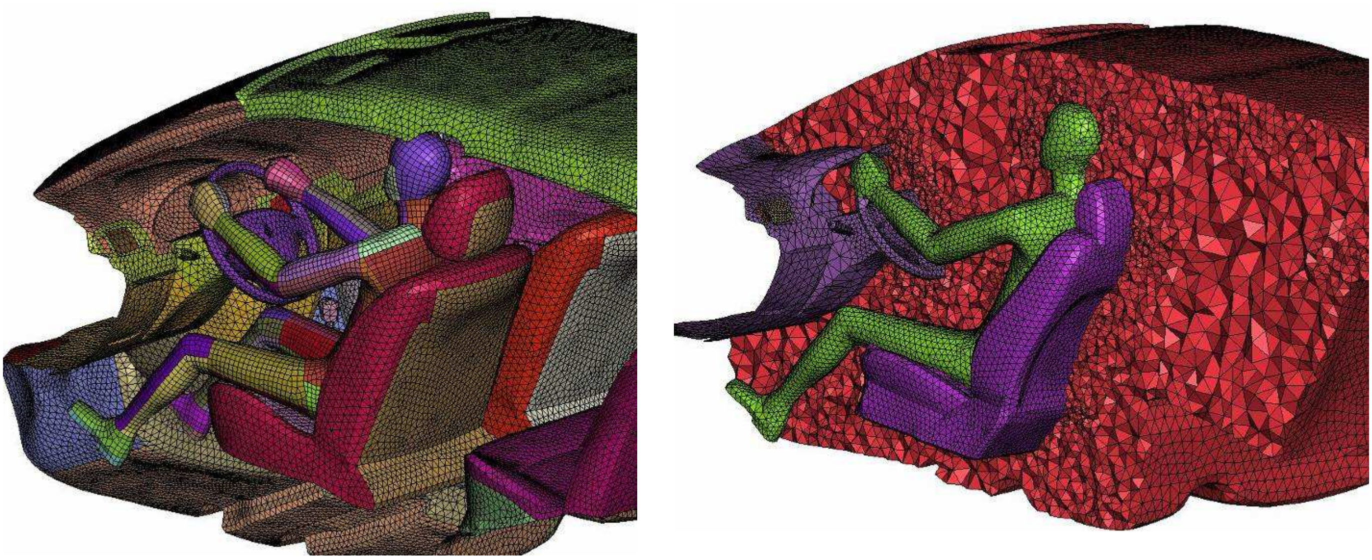


Figure 2 *Temperature measuring points*

GEOMETRY PREPARATION

Because our aim is to evaluate the comfort parameters inside the cabin, we have used only the elements that describe the interior of the car. For both software, Theseus FE and Fluent we have used the same mesh of the model realized using Beta Cae ANSA, the only differences being given by the domain needed: for Theseus FE the shell elements and for Fluent the inside volume, and also by the FEM model of FIALA FE Manikin, a section through this two models can be seen in figure 3.



a) Section through Theseus model *b) Section through Fluent model*

***Figure 3** Mesh details*

Simulation set-up

Because our experimental simulation consists of evaluating the thermal comfort parameters inside the habitacle for three positions of the air flow rate knob as can be seen in table 1, each position having two posibilities, we will have to do three Theseus FE numerical simulations and six Fluent numerical simulations.

***Table 1** General boundary conditions*

The position of the button for the air flow range setting	Position	Air flow rate [m^3/h]	A1/A1'	A2/A2'	A3/A3'
			Air velocity [m/s]		
2		180	3.2	4.2	0
			3.5	3.4	0.2
3		330	6.8	6.9	0.8
			5.4	5.5	1.0
4		450	9.6	9.5	0.8
			8.3	8.3	1.4

The air conditioning unit characteristics are presented in table 2, and in table 3 the external boundary conditions.

***Table 2** AC system characteristics*

Time[s]	0	300	600	900	1200	1500	1800
Temperature[℃]	26	18	12.8	11.7	10.6	10.1	9.6

***Table 3** External boundary conditions*

Ambient temperature[℃]	Ambient humidity[%]	Sun load[W/m^2]	T_{sky} [℃]	Sun Azimuth [°]	Sun Altitude[°]
32	40	600	11.9	90	180

With this given boundary conditions, the obtained results for the velocity in the point P4, point positioned at passenger head level, as can be seen from figure 4, are presented in table 4.

Figure 4 *Control point position*

Table 4 *Experimental results and simulation results for passenger head velocities*

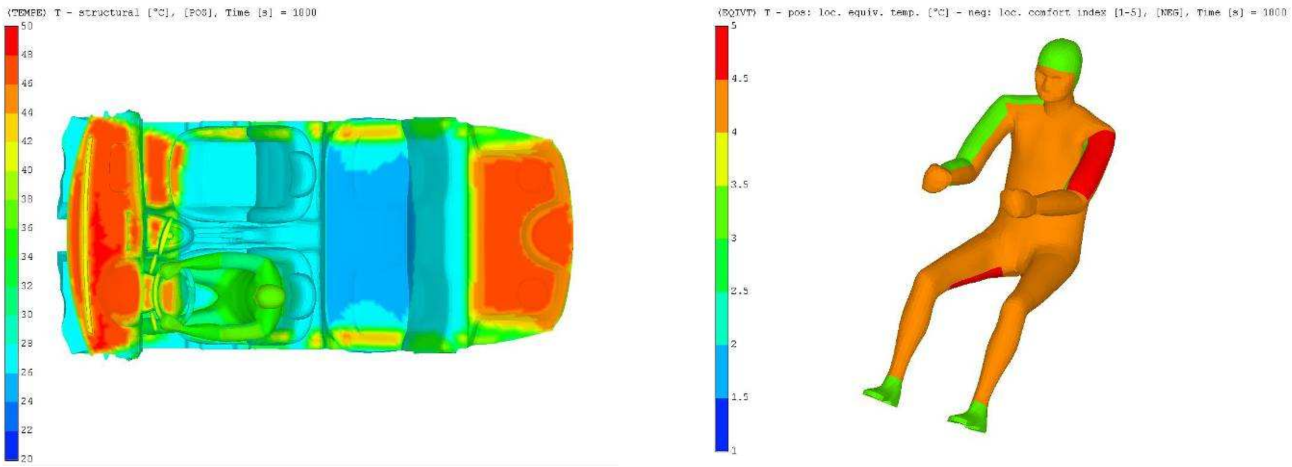
The position of the knob for the air flow range setting	Position	Experimental (P4)	Simulation
		Air velocity [m/s]	
		1.1	1
2		0.2	0.71
		1.7	1.55
3		1.2	1.22
		2.5	2.2
4		1.2	1.7

The temperature results for the simulation of the cool down inside the car cabin are given in table 5.

Table 5 *Experimental results and simulation results for the average temperature inside cabin*

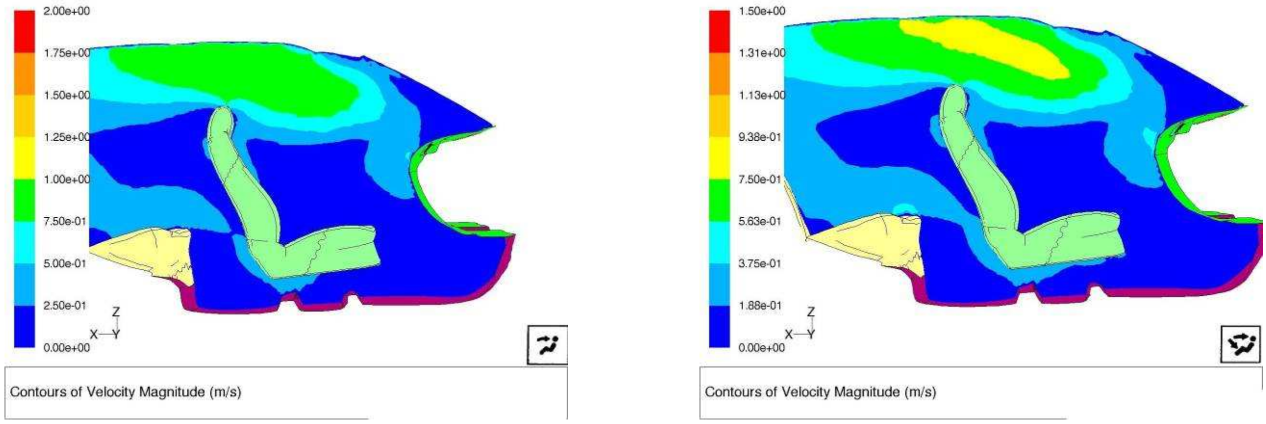
Knob position	Time[s]	0	300	600	900	1200	1500	1800
2	Simulation[℃]	33.9	28.1	25.2	23.7	22.7	21.9	21.3
	Experimental[℃]	35	29.0	25.7	24.0	23.1	22.2	21.5
3	Simulation[℃]	33.9	25.6	21.8	20.1	18.9	18.1	17.5
	Experimental[℃]	35.1	26	22.2	20.3	19.2	18.6	17.8
4	Simulation[℃]	33.9	23.7	19.4	17.7	16.4	15.6	14.9
	Experimental[℃]	34.9	24.2	19.7	18.3	16.8	16.0	15.0

From figures 5 to 7 we can see the temperature distribution inside the cabin after 1800s, the and also the velocity profiles inside the cabin.

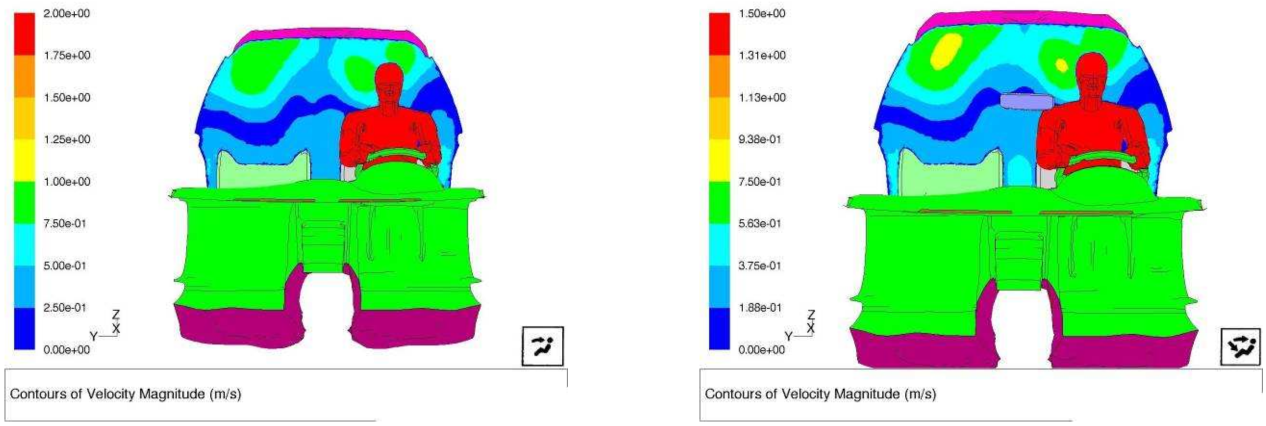


Temperature distribution on the interior

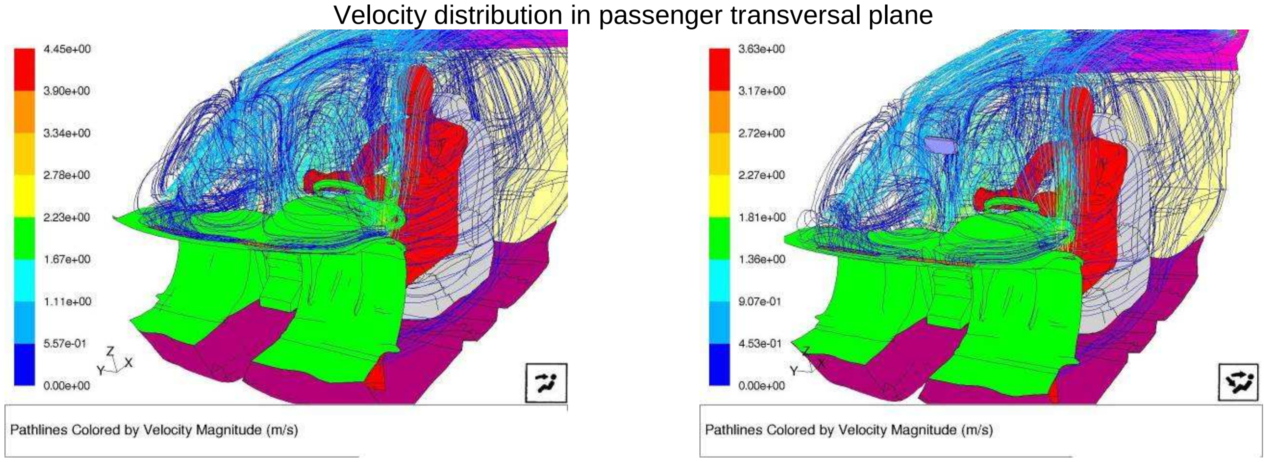
ISO Comfort index



Velocity distribution in passenger longitudinal plane

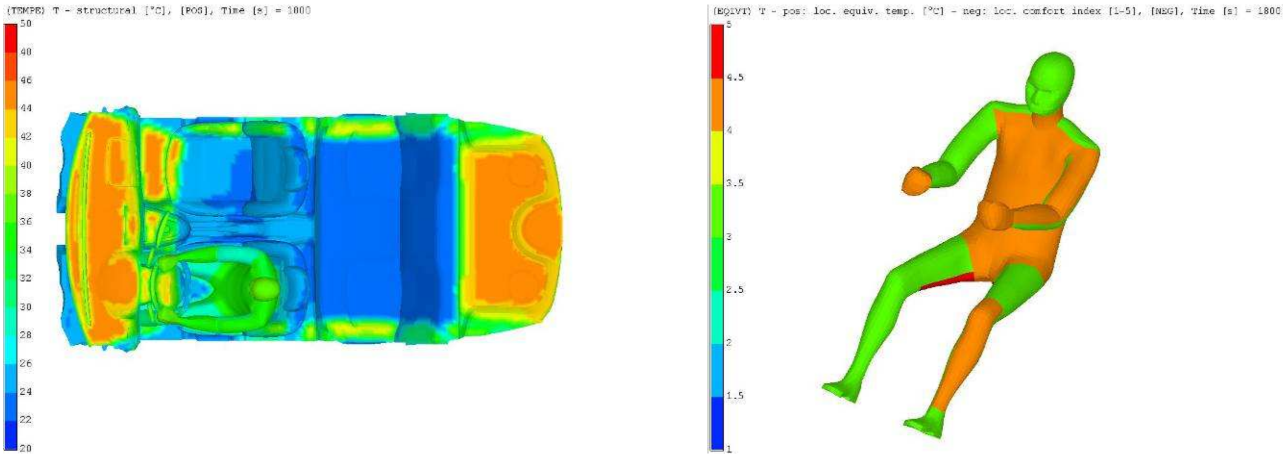


Velocity distribution in passenger transversal plane



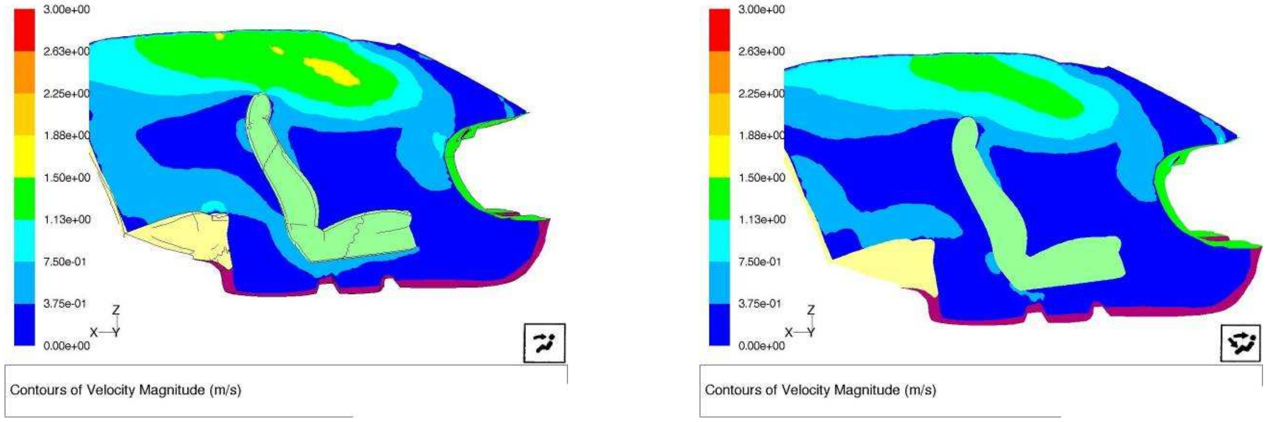
Velocity pathlines

Figure 5 *Temperature and velocity distribution for setting knob in position 2*

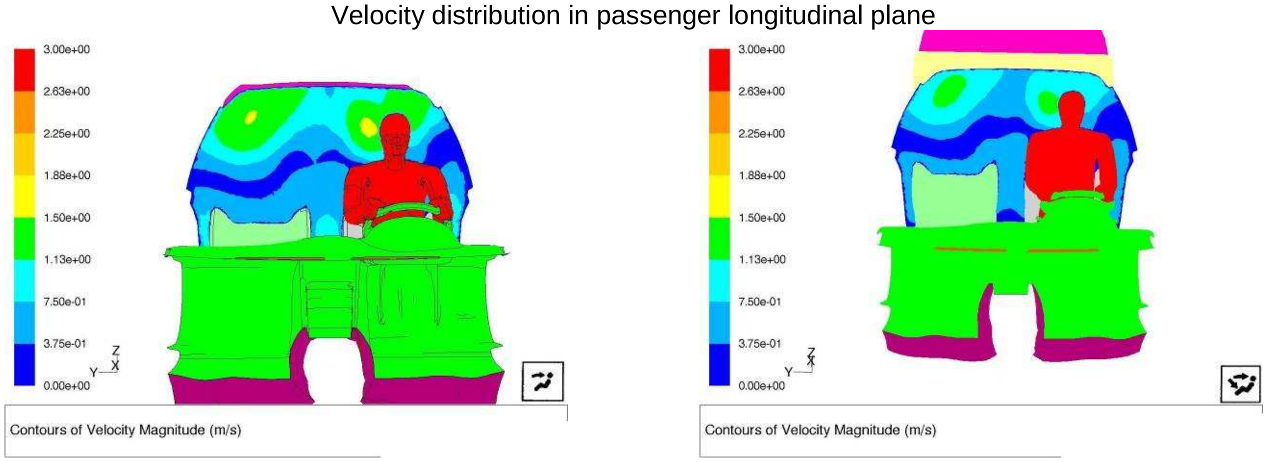


Temperature distribution on the interior

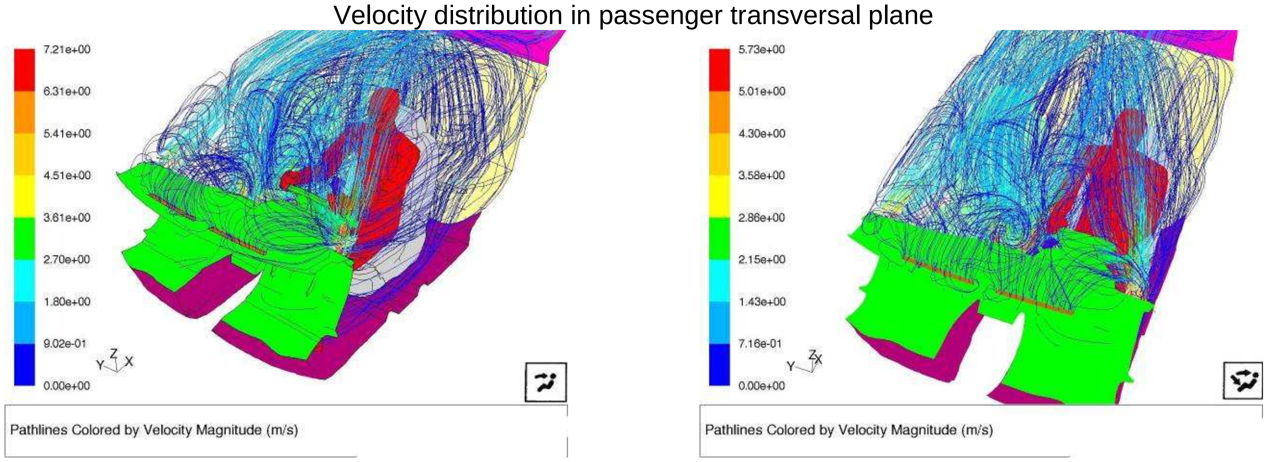
ISO Comfort index



Velocity distribution in passenger longitudinal plane

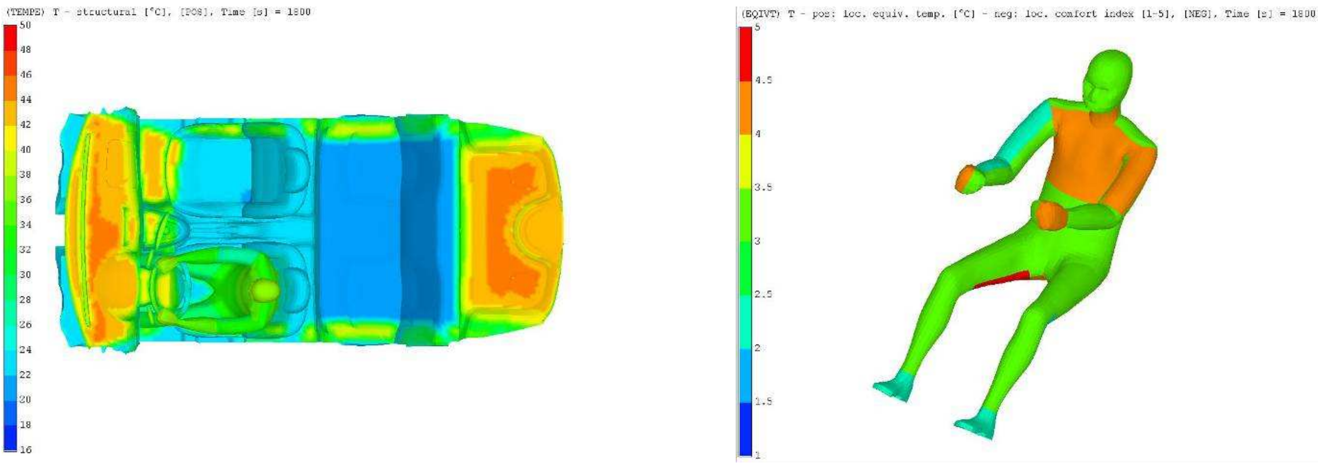


Velocity distribution in passenger transversal plane



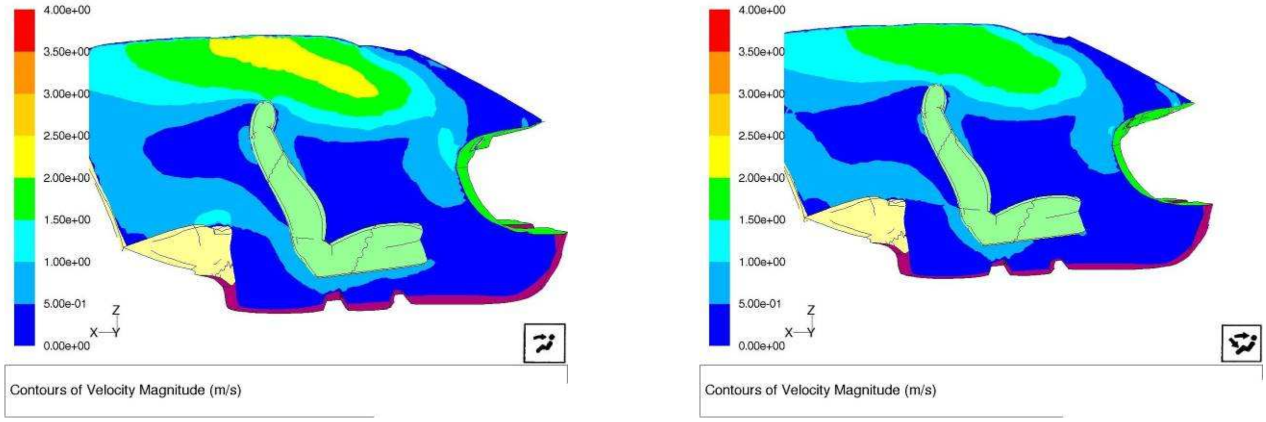
Velocity pathlines

Figure 6 *Temperature and velocity distribution for setting knob in position 3*

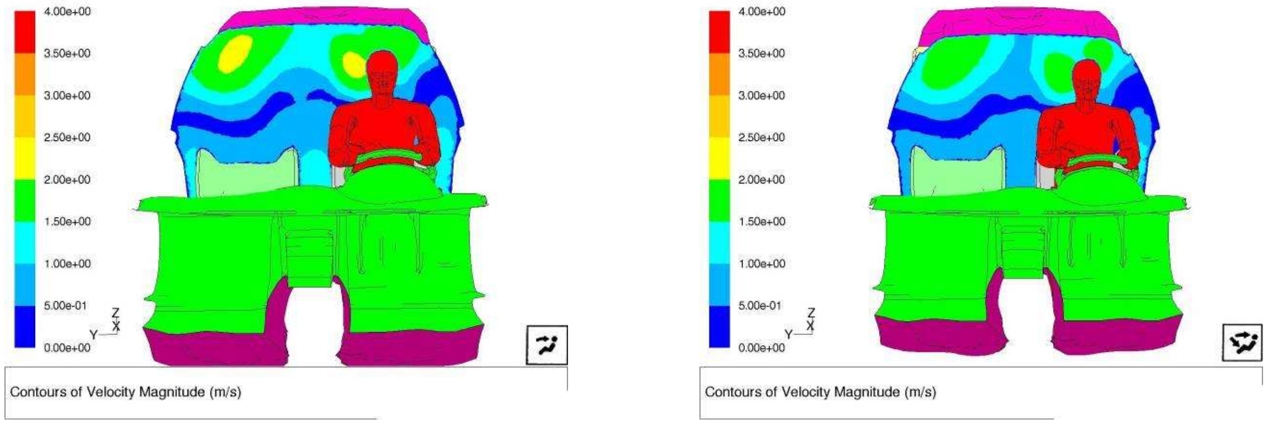


Temperature distribution on the interior

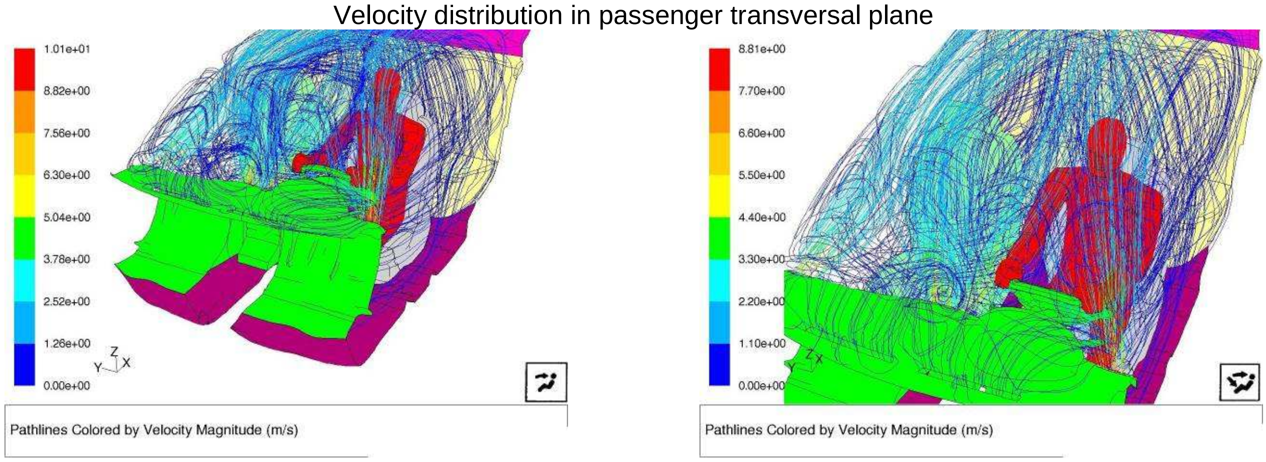
ISO Comfort index



Velocity distribution in passenger longitudinal plane



Velocity distribution in passenger transversal plane



Velocity pathlines

Figure 7 *Temperature and velocity distribution for setting knob in position 4*

The Theseus FE Software has integrated functions that help finding directly the comfort indices: DTS, TS, PMV and PPD which are showed in tables 6 to 8 for and in figures 8 to 10 for each knob position.

Table 6 Values for comfort indices with the knob on position 2

Time[s]	DTS	TS	PMV	PPD[%]
0	0	0	3	99.34786
150	2,598689	0.74157	2.50428	93.52094
300	2,640739	0.985932	2.171009	83.84898
450	2,648365	1.092501	1.8505	69.59726
600	2,626376	1.10863	1.488338	50.26705
750	2,566786	1.073332	1.257148	38.08553
900	2,513203	1.012359	1.07952	29.58486
1050	0,959708	0.940969	0.920856	22.90852
1200	0,768973	0.873818	0.774983	17.6555
1350	0,629684	0.802553	0.659505	14.1365
1500	0,50282	0.728611	0.559256	11.54933
1650	0,424832	0.655807	0.468645	9.585693
1800	0,354561	0.58464	0.385358	8.092819

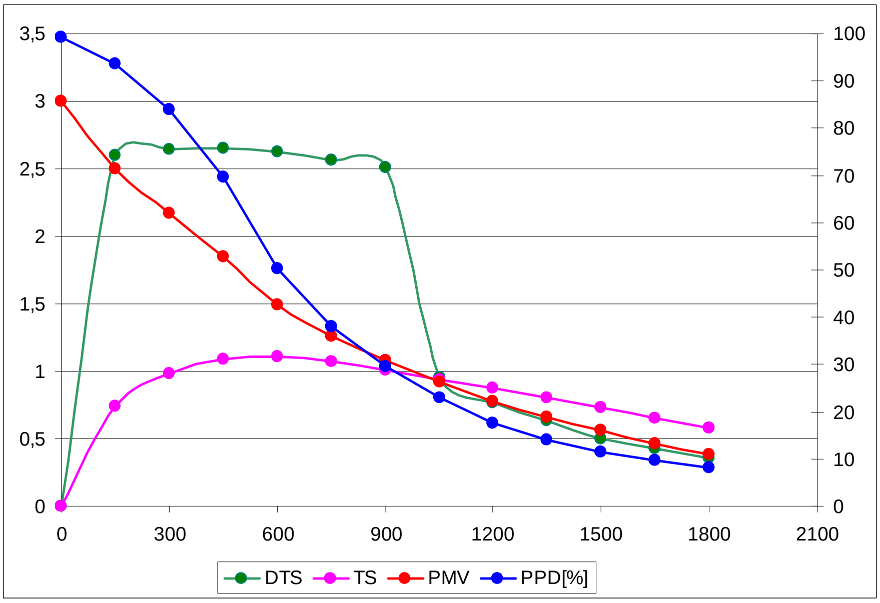


Figure 8 The variation of the comfort indices depending on time with the knob in position 2

Table 7 Values for comfort indices with the knob on position 3

Time[s]	DTS	TS	PMV	PPD[%]
0	0	0	3	99.34786
150	2.578358	0.666369	2.189823	84.54475
300	2.602035	0.837303	1.705367	62.03882
450	2.544139	0.851515	1.263595	38.41108
600	2.44546	0.774307	0.788753	18.11327
750	0.322423	0.656268	0.515193	10.5501
900	0.171848	0.528208	0.30487	6.931633
1050	0.02431	0.393309	0.117018	5.283623
1200	-0.12024	0.254484	-0.05511	5.062882
1350	-0.29645	0.107164	-0.18546	5.713097
1500	-0.43877	-0.01458	-0.29798	6.845024
1650	-0.50275	-0.0626	-0.39953	8.325882
1800	-0.56612	-0.11224	-0.493	10.07869

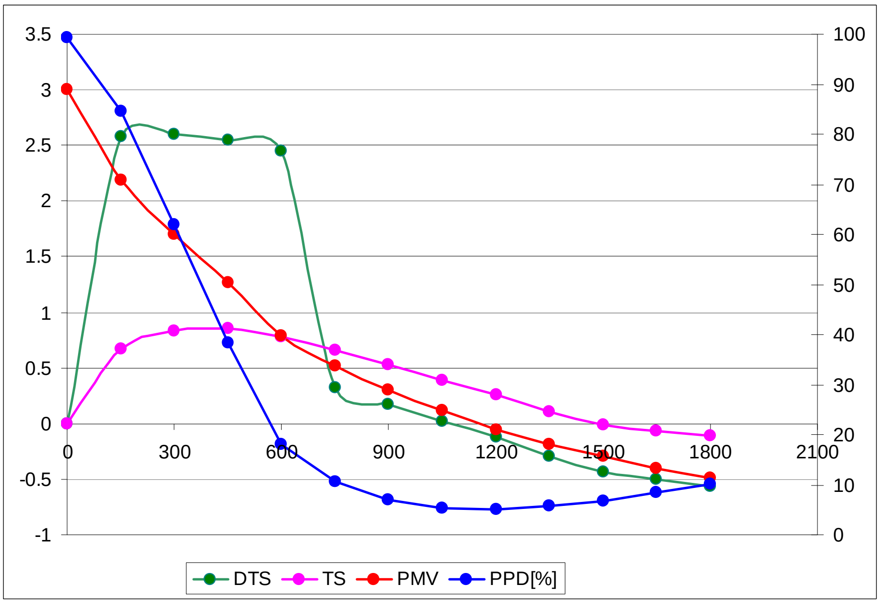


Figure 9 *The variation of the comfort indices depending on time with the knob in position 3*

Table 8 Values for comfort indices with the knob on position 4

Time[s]	DTS	TS	PMV	PPD[%]
0	0	0	3	99.34786
150	2.562908	0.610863	1.963334	75.07838
300	2.570346	0.72223	1.381996	44.55466
450	2.454938	0.683284	0.869673	20.96491
600	0.064047	0.54339	0.331268	7.282143
750	-0.10718	0.367413	0.044163	5.040382
900	-0.33472	0.183211	-0.1785	5.6605
1050	-0.58593	-0.0083	-0.37726	7.963486
1200	-0.70975	-0.07657	-0.5594	11.55282
1350	-0.79317	-0.14847	-0.69281	15.09244
1500	-0.86008	-0.22059	-0.80756	18.75137
1650	-0.91765	-0.29188	-0.91142	22.54215
1800	-0.97087	-0.36164	-1.00702	26.41637

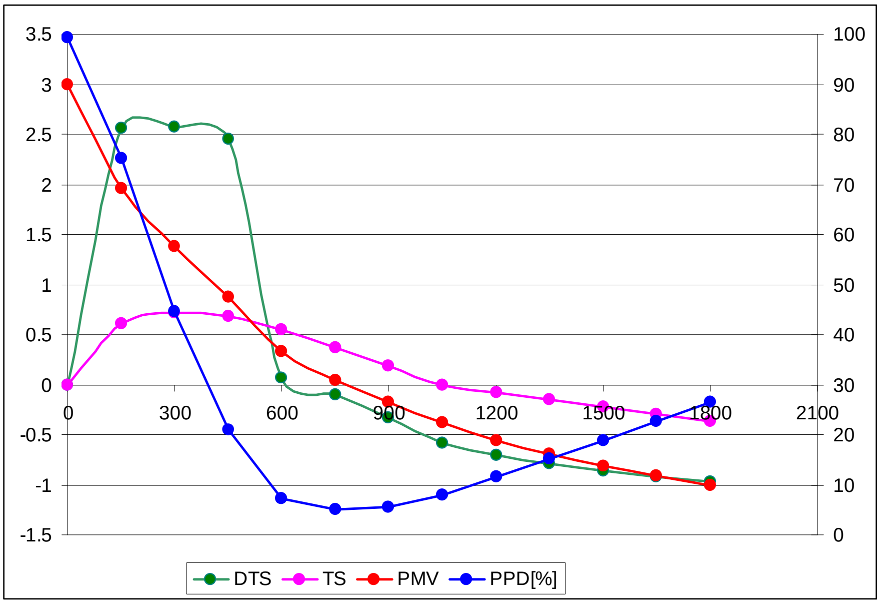


Figure 10 *The variation of the comfort indices depending on time with the knob in position 4*

CONCLUSIONS

The climate in the passenger compartment is very inhomogeneous.The influence of inhomogeneous air temperature and air velocity from the vehicle’s ventilation or air conditioning system creates a climate that may vary considerably in space and time.

Thermal comfort models allow to assess the thermo-physiologic interaction of a human body with its environment in terms of feeling cold, neutral or warm, comfortable or un-comfortable. Global models consider the complete thermal state, and local models hold for certain body parts, e.g. for the seat contact zone at the human back. In simulations those comfort models are part of the post-processing, because temperatures or heat fluxes must be derived first. Mathematical models for thermal manikin simulations and comfort models should be compatible, e.g. the meaningful use of local comfort models requires manikins with well validated response functions for the local skin temperatures. On the other hand, simple global comfort models (like PMV) make an advanced simulation based on Fiala's manikin more or less dispensable.

Analyzing the results obtained for the given cases, we can conclude that thermal comfort is reached faster in the case where the air flow rate is bigger, but keeping the same air temperature.

We will reache a neutral sensation(PMV and DTS lower than 1) in 600 seconds for maximum flow rate, wich will be 150 seconds faster than for the case where the knob will be in position 3 and 450 seconds faster than the knob being in position 2.

Comparing the experimentally values for velocity with those obtained by numerical simulation, we can conclude that the numerical simulation gives us a good aproximation of velocity fields inside the passenger compartment.

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