



## THE INFLUENCE OF THE GLASS MATERIAL ON THE CAR PASSENGERS THERMAL COMFORT\*

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**Abstract:** *Simulation of cabin climatic conditions is becoming increasingly important as a complement to wind tunnel and field testing to help achievement of the improved thermal comfort while reducing vehicle development cost.*

*Interaction between exchange of heat lost by convection, radiation and conduction in the cockpit is very complex. Solar radiation variability and heterogeneous influence of temperature, humidity and air velocity in ventilated vehicles or those with air conditioning systems creates a climate that vary in space and time.*

*In this paper we want to evaluate the influence of glazing properties of the thermal comfort inside the passenger's compartment. First we will simulate a soak period of one hour and then we will simulate a cool down period of 30 minutes.*

*The software used for the simulation is Theseus FE and the geometry is that of a medium class car.*

**Keywords:** numeric simulation, thermal comfort, glazing, heat transfer, Theseus FE

### INTRODUCTION

Cooling and car air conditioning affects comfort, economy, environment and safety issues.

The sensation of comfort is ensured on the one hand, by factors related to normal heat exchange between man and environment and that represent thermal comfort, and on the other hand the clean air, noise, air ionization degree etc.

The creation of thermal comfort in the cockpit is one of the most important factors to be taken into account when designing a car.

The first condition of comfort is to obtain a neutral thermal environment to which a person should feel neither too hot nor too cold.

Thermal comfort is defined in ISO 7730 as "that condition of mind which expresses satisfaction with thermal environment". It is a definition that most people can agree, because that being sensorial and not a quantitative definition cannot be easily converted into physical parameters.

The simplest way to achieve a thermal comfort is to use air conditioning systems, which ensure the necessary exchange of air passenger and air heating or cooling to desired temperature.

In addition to the positive side of air conditioning systems there are also negative sides related to increased fuel consumption by up to 2.11 l/100 km, according to ADAC [1]. This is quite important, especially in the current context of reducing pollutant emissions from passenger cars.

There are several factors that can positively or negatively affect the energy consumed by air conditioning systems among them are the physical properties of glass surfaces.

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In tests conducted by JTI (Swedish Institute of Agricultural and Environmental Engineering) and NIWL (National Institute of Labor Force) was evaluated the thermal comfort inside the passenger compartment by testing different materials for glass surfaces [2].

European Directive on Road Traffic states for a minimum visible light transmission in the car windscreens of 75% and 70% for other windows.

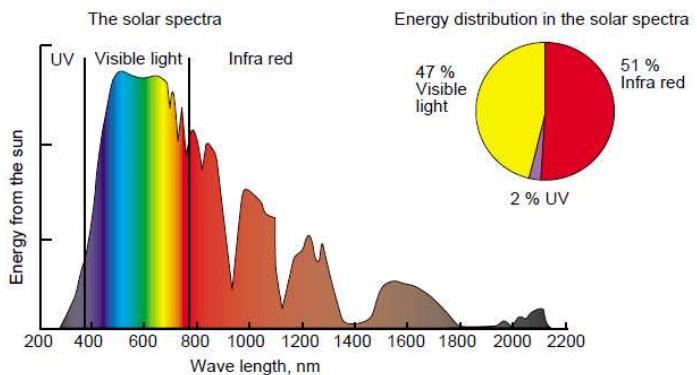
Figure 1 shows the distribution of the solar radiation, indicating the portion of the UV, Visible and IR. About half of the energy spectrum of solar radiation is visible.

Evaluation of thermal comfort depends on a number of physical parameters and not only one, such as air temperature.

For the development of air conditioning systems we need to integrate numerical simulation since the design phase.

Based on the simplified model of the car, we can establish conditions regarding the heating/cooling processes and the air flow distribution inside car.

Thus, three-dimensional simulation of thermal comfort and helps of the prediction can be made in different circumstances, different levels of solar radiation and outdoor temperature



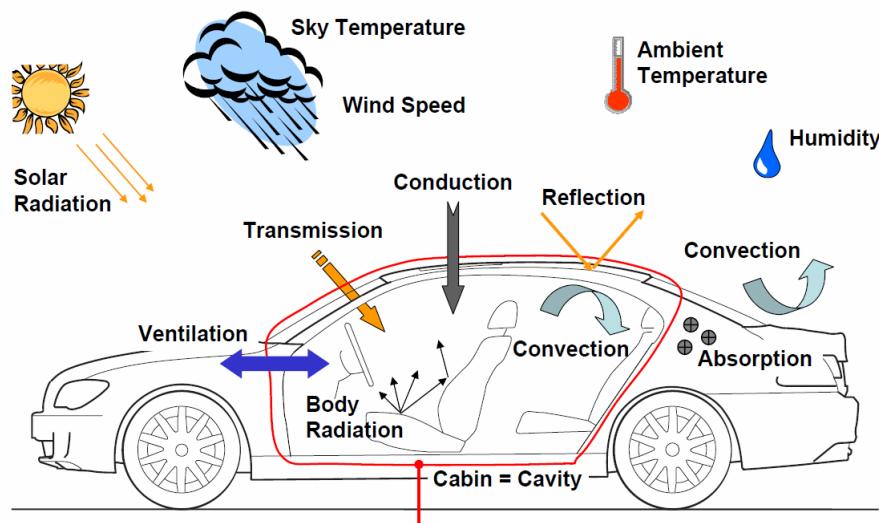
**Figure 1: The distribution of the solar radiation and the energy distribution in the solar spectra**

## THEORETICAL CONSIDERATIONS

### Cabin simulation

Climatic analysis of cabin refers to the calculation of heat transfer between the cabin components and the passengers, taking into account the heat transport mechanisms: conduction, convection and radiation.

The most important mechanisms affecting heat gains or losses are represented in Figure 2 [3]



**Figure 2: Thermodynamic system boundary for the energy conservation**

### Heat flux due to solar radiation through glazed surfaces

Since, in this paper we propose to evaluate the temperature inside a car using two types of glass elements, we present the heat flow due to solar radiation through glazed areas.

The intensity of solar radiation incident ( $I$ ) on the surface of glass has three main components:

$I_i$  - Transmitted solar radiation

$I_r$  - Reflected solar radiation

$I_a$  - Absorbed solar radiation

and the relation is.

$$I = I_i + I_r + I_a \left[ W/m^2 \right] \quad (1)$$

To calculate the heat flux through the surface of glass, we are interested only practical component  $I_i$ , whose value can be expressed by the relation:

$$I_i = \tau I \left[ W/m^2 \right] \quad (2)$$

$I$  - intensity of solar radiation incident

$\tau$  - coefficient depends on the type and quality of surface vitrate to reflect and absorb the solar radiation

The flow of heat transmitted through the interior by glass surfaces depends on:

- the effect of direct radiation, proportional to incident radiant flux  $q_s$ ;
- the effect of temperature difference between outside and inside the passenger compartment.

Pilkington has designed the glass **Siglasol**, which effectively blocks the major parts of the IR and UV content of the solar spectra, while still transmitting 77% of the visible light. The transmission of energy in the solar spectra through Siglasol is only around 50%, depending vehicle speed, or rather the cooling of the glass. Figure 3 shows how Siglasol is build by layers of clear glass and filtering layers. Because Siglasol transmits 77% of the visible light, it is not perceived as a dark glass. Still it only transmits 50% of the heat in the light. Hence, it greatly reduces the heat loading on the operator of a cab with Siglasol glazing without interfering with the European directives

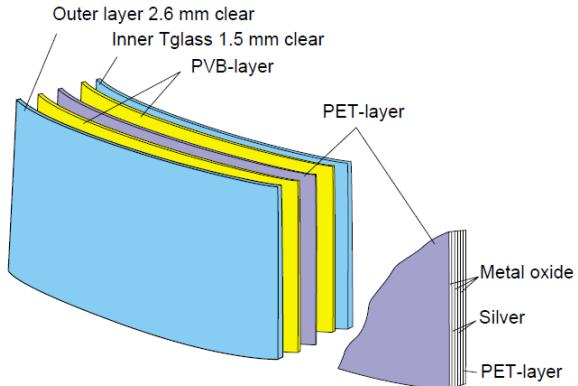


Figure 3: Construction of the sunglass Siglasol.

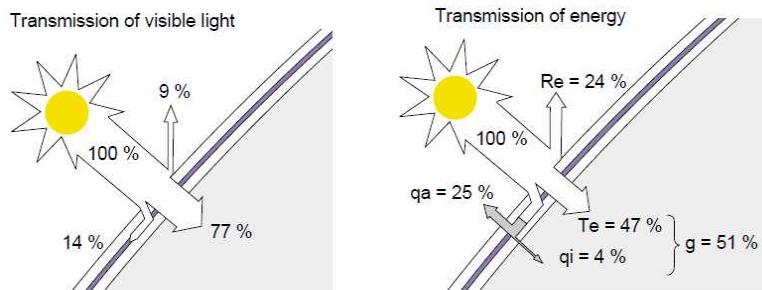


Figure 4: This figure shows the function of Siglasol and the difference between the transmission of visible light (77%) and transmission of the energy in the sun light (51%).

## Thermal comfort prediction

DTS and PMV are both thermal comfort indices related to the global state, whilst the equivalent temperature can be derived for each body element sector of a human body. Local thermal comfort in THESEUS-FE should be based on equivalent temperatures.

### - DTS

One part of the post-processing in Theseus-Fe is the evaluation of the dynamic thermal comfort index, DTS. This index has been validated by a huge number of experiments, where humans' bodies had been exposed to cold and warm environmental conditions. The index has been validated under dynamic conditions with suddenly changing environmental temperatures and more steady-state-like conditions. Thermal comfort experiments run with test persons that mark the actual state of thermal sensation on a 7-point ASHRAE scale. Under dramatically changing conditions, test persons must be asked for thermal sensation at defined time steps.

### - PMV

The predicted mean vote (PMV) calculation takes into account the following variables:

$R^{cl} = I_{cl} * 0.155$	- thermal resistance of human clothing [ $m^2K/W$ ]
$I_{cl}$	- thermal resistance of clothing, in [ $m^2K/W$ ], [clo]
$M$	- metabolic rate [ $W/m^2$ ]
$W$	- external work [ $W/m^2$ ]
$t_a$	- mean adjacent air temperature [ $^{\circ}C$ ]
$t_r$	- mean adjacent mean radiant temperature [ $^{\circ}C$ ]
$v_a$	- Mean adjacent relative air velocity [m/s]
$p_a$	- Partial water vapor pressure of the adjacent air [Pa]

The PMV is recommended for use only for the following range of conditions:

$I_{cl}$	= 0 to 0.310 $m^2K/W$ (0 - 2 clo)
$M$	= 46 to 232 $W/m^2$ (0.8 – 4 met)
$t_a$	= 10..30 $^{\circ}C$
$t_r$	= 10..40 $^{\circ}C$
$v_a$	= 0..1 m/s
$p_a$	= 0 .. 2700 Pa (relative humidity should be between 30 and 70%)

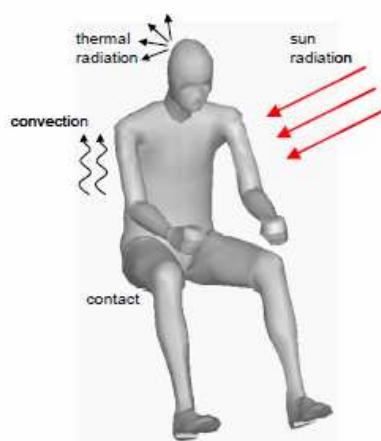
### - Local equivalent temperatures and Comfort Indices

The ISO 14505-2 contains guidelines for the assessment of the thermal conditions in automobiles. A typical application is HVAC system testing.

The equivalent temperature ( $T_{eq}$ ) is the temperature of a homogeneous room with a radiation background temperature equal to the air temperature and low relative air speed.

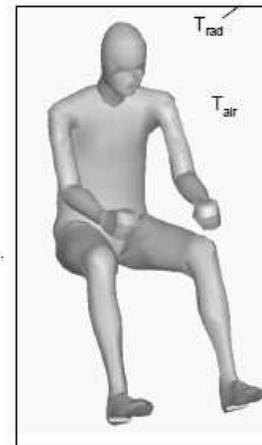
$$T_{eq}=T_{rad}=T_{air} \quad (3)$$

Realistic conditions



Global heat loss:  $Q_{real}$

Homogeneous conditions

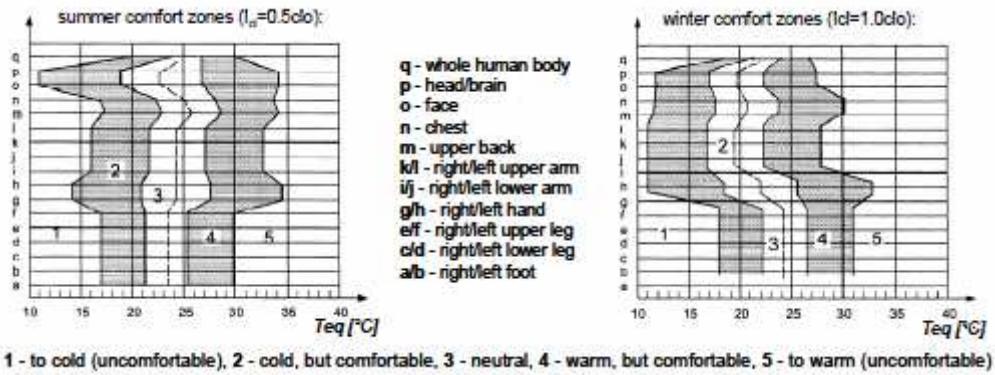


Global heat loss:  $Q_{eq}(T_{eq})$

Figure 6. Equivalent temperature

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Figure 5. The 7-point ASHRAE scale



**Figure 7: Local thermal comfort zones(ISO 14505-2)**

In figure 7 are represented the local thermal comfort zones (ISO 14505-2). Those diagrams are based on a huge number of experiments at winter and summer conditions with samples of test persons and measured equivalent temperatures.

## NUMERICAL SIMULATION

The software used for the simulation was Theseus-Fe 3.0 and its benefits are represented by the short time needed to solve the problem, the good approximation of thermal comfort and heat transfer and the reliability of results.

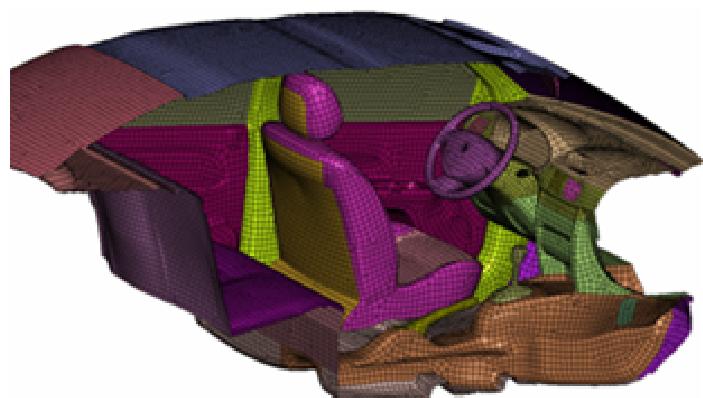
### Model creation

The simulation was based mainly on finding the impact on thermal comfort inside the passenger compartment by using two types of glass for car windows.

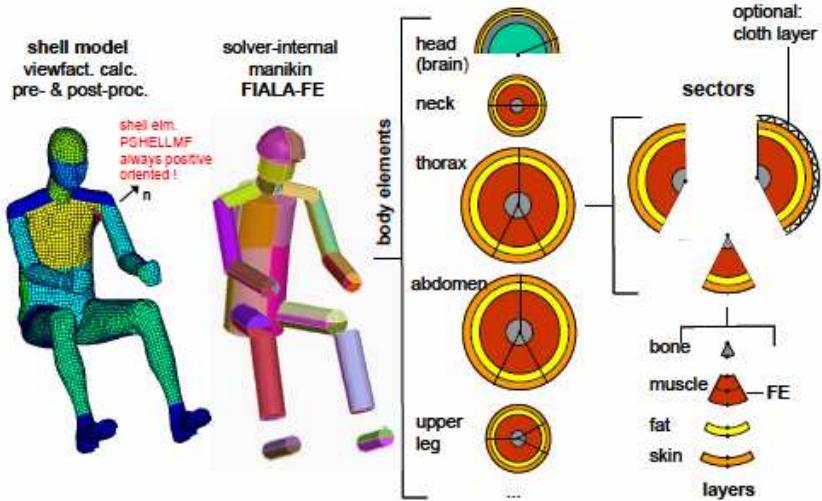
The CAD model used for the simulation represents a medium class car, but because we wanted to evaluate only the temperature of the cabin, we kept just the elements that compose the interior of the car.

Meshing of the model was made by Beta CAE ANSA software, obtaining a number of about 48000 elements with an average size of 20mm and distributed to 40 groups, each group being characterized by its material properties. A section in the thermal finite-element model is presented in Figure 8.

Also, the model includes two Fiala-FE manikins (Figure 9), each one containing 8365 elements which are distributed in 48 groups.



**Figure 8: Section in the thermal finite-element model of the vehicle**



**Figure 9:** Fiala FE manikin

### Boundary conditions

In table 1 we present the physical properties of the glass used in the two simulations.

**Table 1.** Glass properties

	Case A	Case B
Parameter	Standard	SIGLASOL
Emission ( $\epsilon$ )	0,8	0,9
Absorption ( $\alpha$ )	0,8	0,9
Transmission ( $\tau$ )	0,55	0,06

The environment parameters are presented in table 2, and the airzones description in table 3.

**Table 2.** Boundary conditions

Environment characteristics	
Sun Intensity [W/m <sup>2</sup> ]	1000
Azimuth angle [°]	180
Altitude angle [°]	90
Exterior temperature [°C]	35
Exterior humidity [%]	40
Sky temperature [°C]	15,6

**Table 3.** Airzones characteristics

Name	Volume[m <sup>3</sup> ]	Humidity[%]	Temperature[°C]
<i>Interior</i>	3.00	40	35
<i>Trunk</i>	0.51	40	35
<i>Dashboard</i>	0.30	40	35

Because we want to simulate a soak period of one hour followed by a cool down period of 30 minutes, we must define the air conditioning system properties. These are presented in the table 4.

**Table 4.** Air conditioning properties

Time [s]	Temperature[°C]	Air Flow [m <sup>3</sup> /s]
0	50,0	0,125
60	40,0	0,125
600	20,0	0,125
1200	10,0	0,125
1800	7,0	0,125

## Results

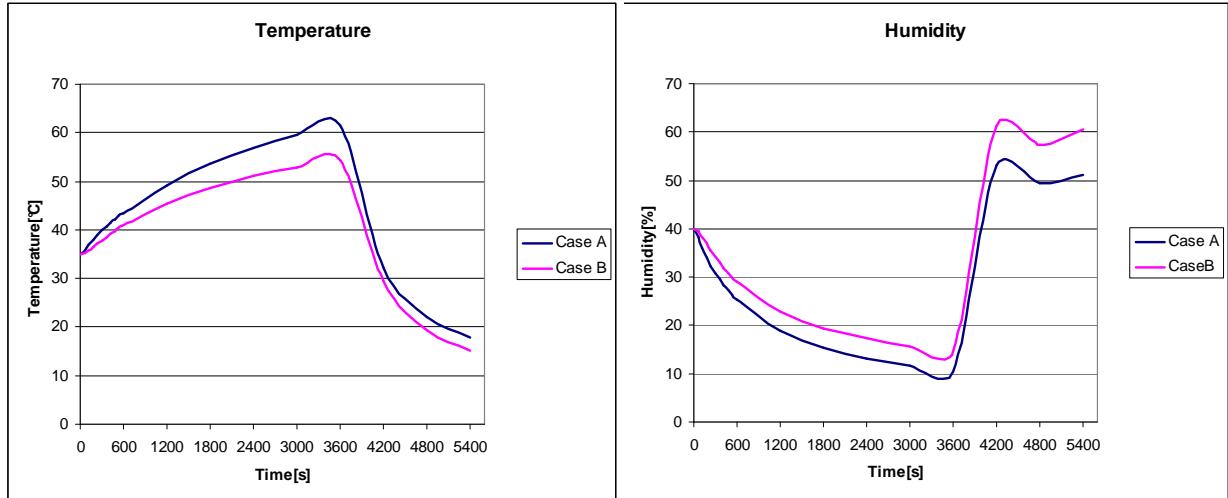
### Cabin

In table 5, we have the values for temperature and humidity inside car for both cases.

**Table 5.** Temperature and humidity values inside car

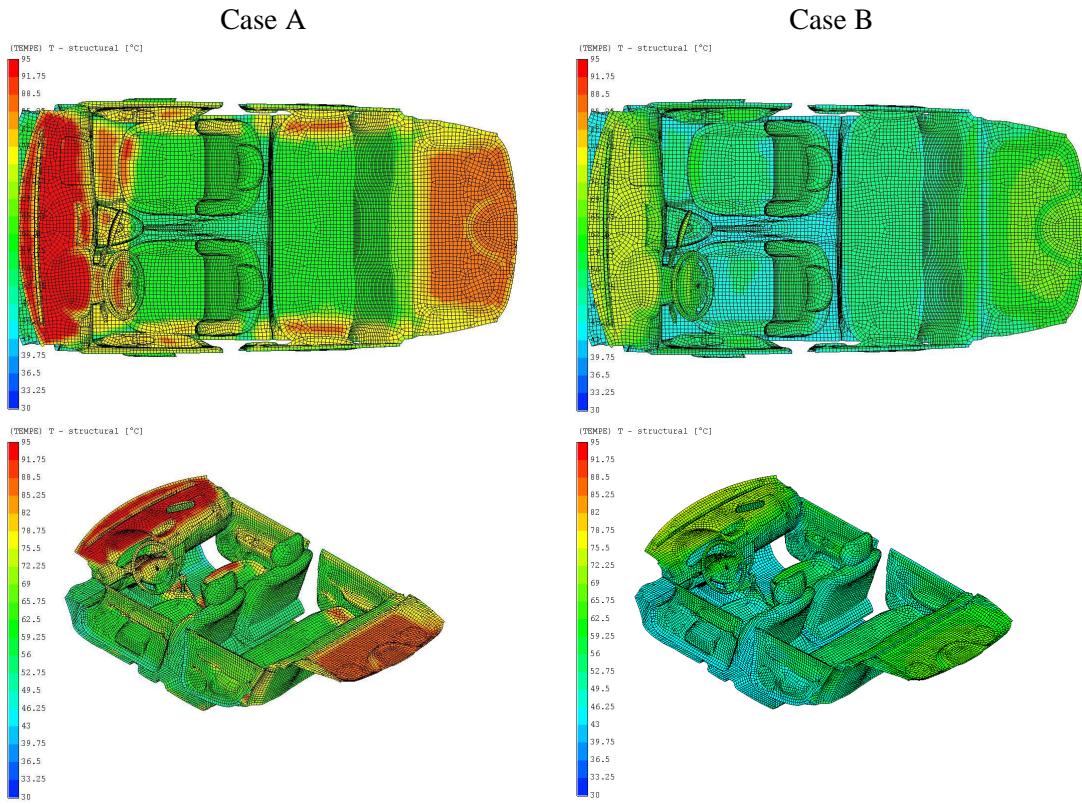
Time[s]	Temperature[°C]		Humidity[%]	
	Case A	Case B	Case A	Case B
3600	61,60	54,47	10,50	14,65
5400	17,76	15,05	51,24	60,60

In figures 10 and 11 we present the temperature and humidity variation during the simulation

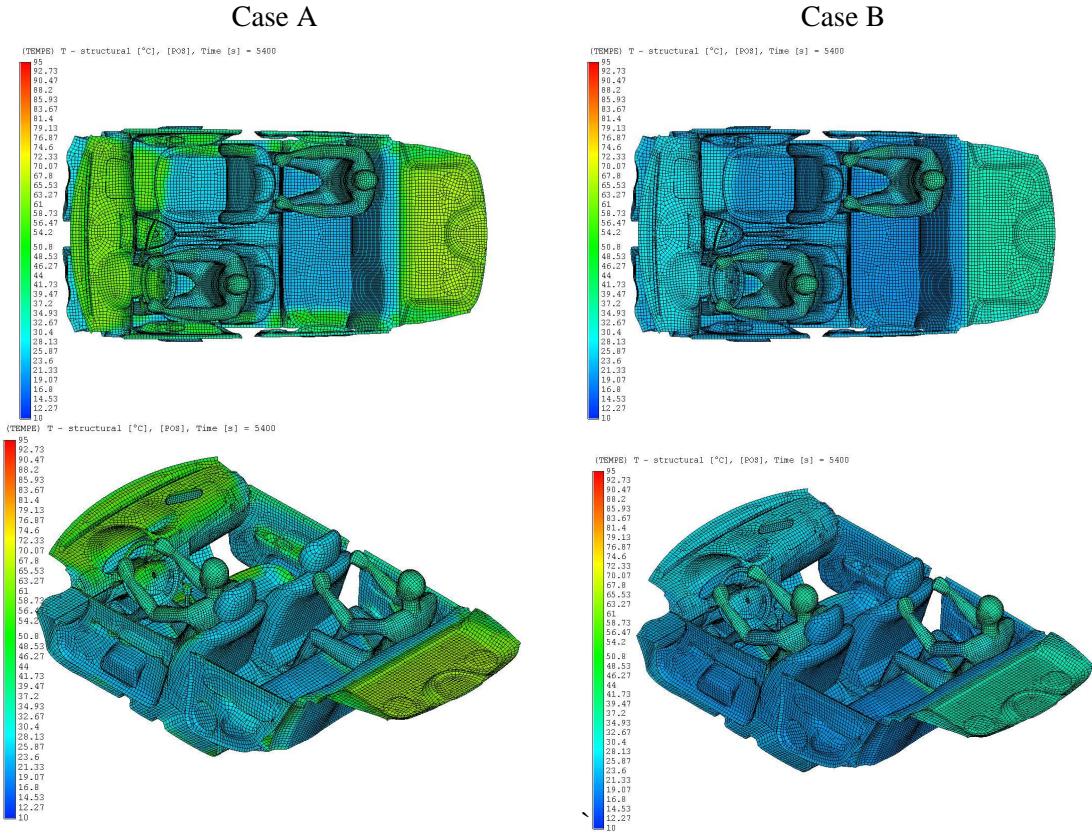


**Figure 10: Temperature variation for case A and Case B**

**Figure 11: Humidity variation for case A and Case B**



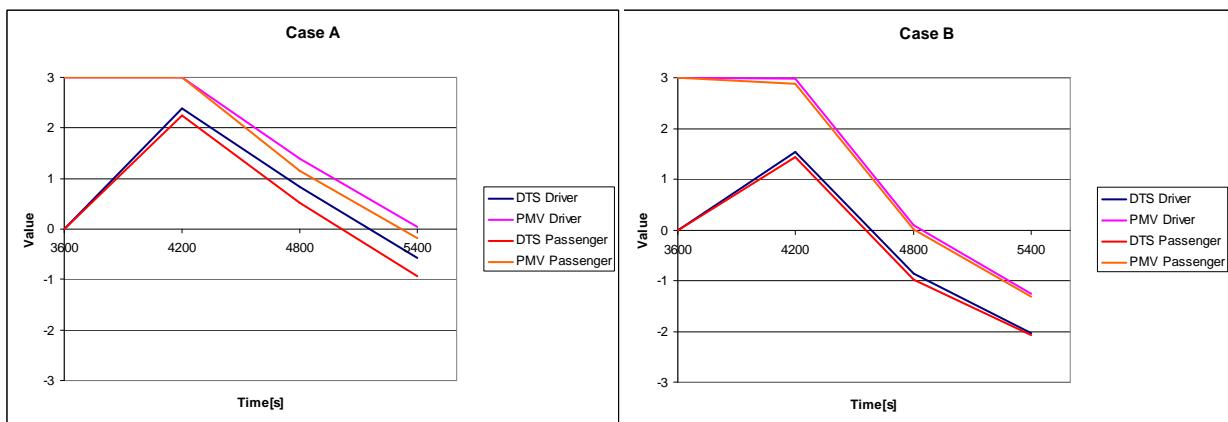
**Figure 12: Temperature distribution after 3600s**



**Figure 13: Temperature distribution after 5400s**

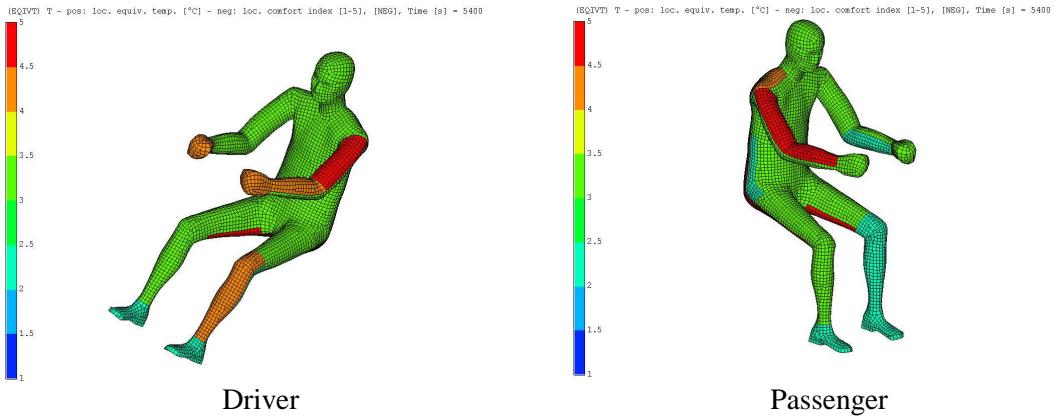
### Manikin

In figure 14 and 15 we can see the comfort index PMV and DTS for Case A and respectively Case B and in figure 16 and 17 the local comfort index for passenger and driver in the same cases.

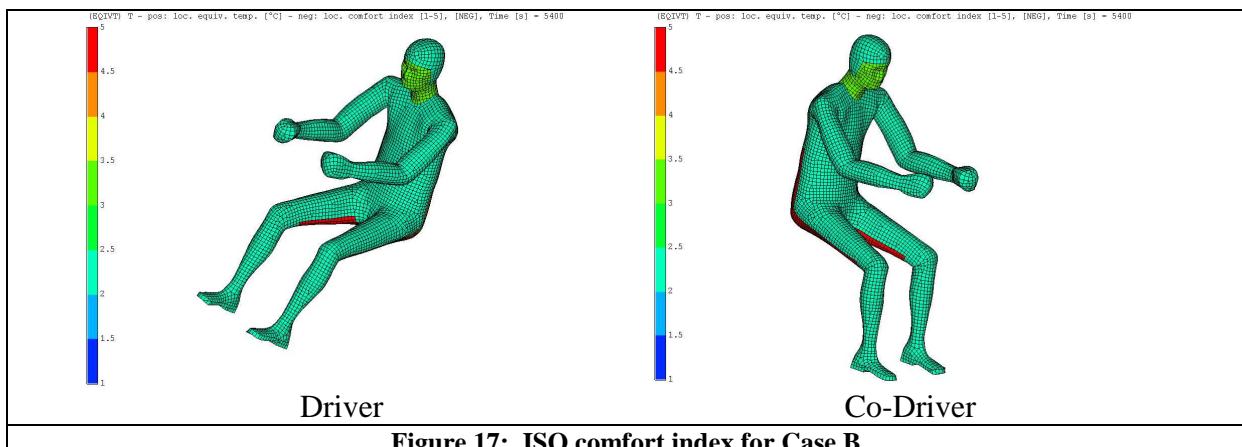


**Figure 14: DTS and PMV index for driver and passenger for Case A**

**Figure 15: DTS and PMV index for driver and passenger for Case B**



**Figure 16:** ISO comfort index for Case A



**Figure 17: ISO comfort index for Case B**

## CONCLUSION

In this paper we have evaluated using Theseus FE software the influence of glazing material over the thermal comfort inside a passenger compartment of a medium sized car.

The results obtained in the numerical simulation prove that there is a close link between the glass material physical properties and the thermal comfort experienced inside the vehicle. Looking at table 5 and figures 10, 12 and 13 we can observe that after the soak cycle, the temperature inside the car with insulating windows is 54,47°C compared to 61,60°C, value that is inside the car with standard windows, a difference of over 7°C. After the cool down period of 1800s, the temperature inside the insulated car is 15,05°C compared to 17,75°C inside the car with standard windows, a difference in temperature of about 2.5°C.

Regarding the humidity inside the car, its variation can be observed by looking at table 5 and figure 11. We can first observe a drop in the value of humidity, drop caused by the soak cycle. After that period, the humidity is 14.65% in the Case B, compared to 10.50% from the car with standard windows. After the cool-down period, the humidity arrives to 51.24% in Case A and 60.60% in Case B.

Regarding the PMV values obtained for both cases, we can conclude that for Case A, after a cool-down period of 1800s, the value is close to 0, that means optimum comfort, and for Case B, after the same period, the value is close to -1, that means the temperature is cool but comfortable. Analyzing the graph, we can see that in case B we have values close to 0 after only 1200s of cool down, this means we can obtain the same comfort index in a shorter period of time, in our case 20 minutes instead of 30 by using insulating windows.

Regarding the DTS comfort index, we can conclude that for the insulated windows we need a time shorter to 1800 seconds than in the case of normal windows to achieve the same value for thermal comfort. In our experiment, that amount of time is equal to a third of the total time of the cool down simulation.

Looking at figures 16 and 17 we can see that in the Case A, the value for ISO thermal comfort is between 2.5 and 3.5 which means a neutral comfort, and in the Case B, the value is between 2 and 2.5 after a cool down period of 1800s.

This numerical simulation has showed us the importance of the glass physical properties on obtaining a good thermal comfort inside a vehicle. Also, we have observed that by using a insulted window instead a standard one, we can reduce the time needed to obtain the same amount of thermal comfort. Also, by shortening the time, we will obtain a fuel economy.

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