THREE DIMENSIONAL NUMERICAL ANALYSIS OF TEMPERATURE DISTRIBUTION IN AN AUTOMOBILE CABIN

by

Gokhan SEVILGEN **and Muhsin KILIC***

Department of Mechanical Engineering, Faculty of Engineering and Architecture, Uludag University, Bursa, Turkey

Short paper
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In this study, 3-D numerical analysis of temperature distribution in the automobile cabin were performed by using computational fluid dynamics method. For this purpose, a 3-D automobile cabin including window and outer surfaces was modeled by using the real dimensions of a car. To evaluate the results of numerical analysis according to thermal comfort, a virtual manikin divided into 17 parts with real dimensions and physiological shape was added to the model of the automobile cabin. Temperature distributions of the automobile cabin were obtained from the results of the 3-D steady and transient numerical analyses for standard heating and cooling period. Validations of the results were achieved by comparing to the results of the experimental studies performed simultaneously with the numerical analyses.

Key words: *computational fluid dynamics, automobile cabin, virtual manikin*

Introduction

With progressive changes in vehicle styling, tightening fuel economy constraints, the replacement of the environmentally unsafe refrigerants and corresponding reductions in the heat available for the passenger heating system, there is interest in the development of more effective heating, ventilating, and air conditioning (HVAC) systems to ensure passengers thermal comfort even in extreme conditions by considering market situation. However, the complexity of human thermo-physiological model and physiological shape of the human body and highly transient conditions in the vehicle cabin make the computational fluid dynamics (CFD) analysis more difficult [1]. Analysis of complex HVAC systems based on numerical calculations with sufficient accuracy and acceptable results is now possible for HVAC researchers by using improved computer technology and CFD techniques [1-8]. In these studies, numerical simulations were computed under different environmental conditions such as standard heating and cooling periods.

Computational grid and boundary conditions

The dimensions of the computer-aided design (CAD) model of the vehicle cabin were obtained from the test car which was a 2005 model 1600 cm^3 FIAT Albea. The CAD

* Corresponding author; e-mail: gsevilgen@mail.uludag.edu.tr

model of the vehicle cabin is shown in fig. 1(a). Virtual manikin added to the CAD model to predict the local heat characteristics of the human body surfaces. The manikin used in this study has a height of 1.70 m and a total surface area of 1.81 m^2 at the standing position. Different types of mesh structures were used to achieve optimum mesh structure in terms of computing time and precision results. We used hex-core mesh structure which had hexahedron elements in the center volume region and tetrahedron elements near the boundary surface. This computational domain consists of about 900000 volume cells and the section view of the mesh structure is shown in fig. 1(b). Generally, at the interior and exterior surfaces of the vehicle cabin, various boundary conditions can be used for numerical simulations. In these numerical simulations, constant heat flux or constant temperature boundary conditions were applied at the manikin surfaces. In this numerical study, we just shown the results of the simulations where the constant temperature boundary condition was used for manikin surfaces. Temperature of the surfaces without clothes such as head and hands was set a value of 33.7 °C; the temperature of the surfaces with clothes was set a value of 24.4 °C for all cases. This value corresponds to the thermal resistance of the clothes was 1 clo (0.155 m^2°C/W). Convective boundary condition was considered at the glazing surfaces

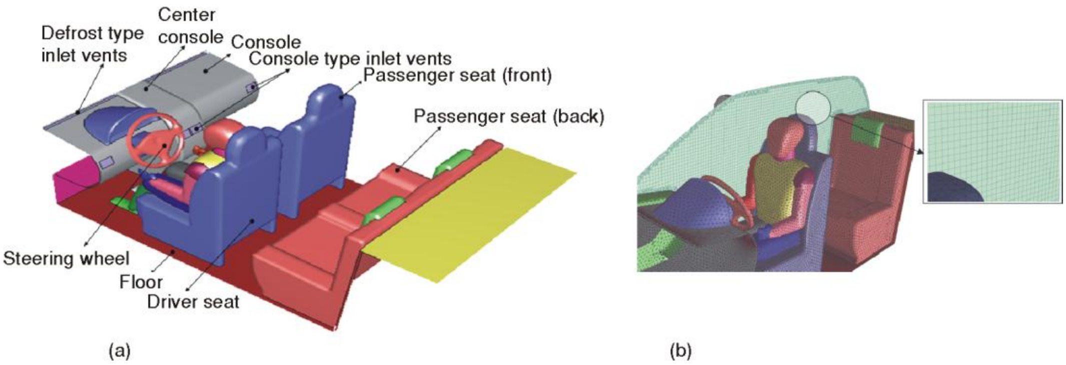


Figure 1. (a) CAD model of the vehicle cabin, (b) the section view of the computational grid

and outer surfaces of the cabin for all simulations. Air temperature profile obtained from the measured data was used as the boundary condition at the inlet vents. The temperature profiles used for heating and cooling simulations are shown in fig. 2. Air velocity at the inlet vents was chosen as a constant value considering the grade of heating or cooling system of automobile cabin. Surface-to-surface model, including view factors, and discrete ordinate model were used for the calculation of radiation heat transfer among the interior surfaces of the cabin and the results were compared each other. In numerical solutions, second order discretization method was used for convection terms and SIMPLE algorithm was chosen for pressure velocity coupling. For the turbulence modelling, the random number generation (RNG) k-ε model was chosen for the numerical calculations. This turbulence model is generally used for such calculations due to stability and precision of numerical results in literature [3-5]. The detailed information about these boundary conditions and the numerical results can be found in references [2, 5, 8, 9]. We also determined discrete measurement points in the cabin environment for validating numerical results. These points are shown in tab. 1.

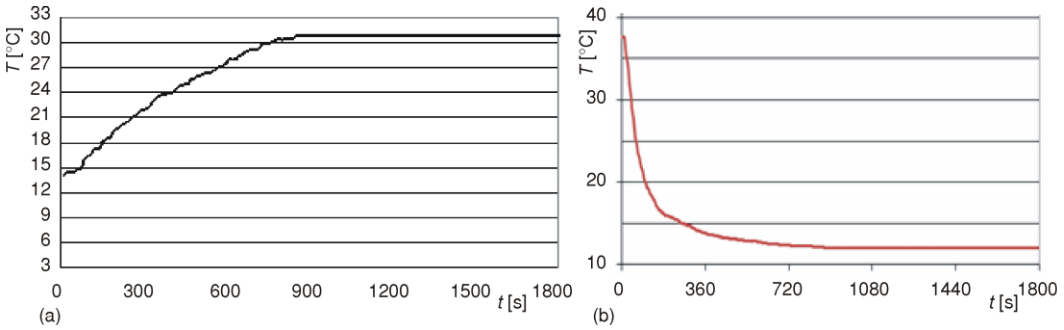
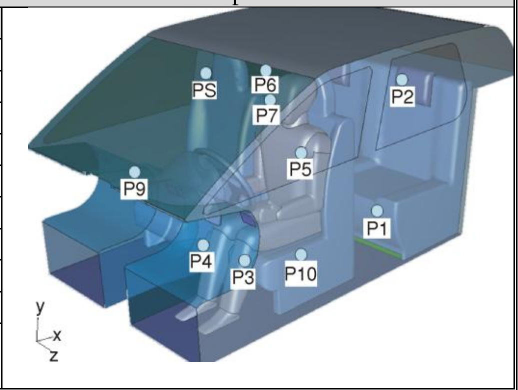


Figure 2. Measured transient temperature profile at inlet vents; (a) Heating period, (b) Cooling period

Table 1. The location of the measuring points in the cabin of the test car during heating period

The definition and the location of the measurement points		
Points	Location	
P1	Knee level (the left rear)	
P2	Head level (the left rear)	
P3	Knee level (the left front)	
P4	Knee level (the right front)	
P5	Shoulder level (the left front)	
P6	Head level (Between two front seats)	
P7	Head level (the left front)	
P8	Head level (the right front)	
P9	The point at the center console surface	
P10	The point at the left side door inner surface	

Numerical results

The temperature predictions at 20 and 30 minutes of heating and cooling period at the vertical centre plane of the automobile cabin are shown in figs. 3(a)-(d), respectively. Although, higher temperature gradients were computed in ten minutes of heating period, temperature changed slowly down after this period and almost steady-state conditions were reached about 30 minutes of heating period.

From the results of the simulation, the temperature the temperature values were decreased with cooling time and in the front region of the vertical plane, a temperature value of 30 °C was calculated at the chest level. High temperature values were computed near the glazing or ceiling surfaces which were more affected from the solar radiation. The mean temperature predictions at the surfaces of the vehicle cabin for heating and cooling periods are shown in tab. 2. The surface temperature of the cabin surfaces were computed nearly about ambient temperature for heating period, however, the surface temperature values computed for cooling period were quite different from ambient temperature due to solar radiation effects and radiation heat transfer among the interior surfaces of the cabin. The comparisons of the experimental data to the predicted temperature values for heating period at the sample points (P1, P2, P3, and P8) is shown in fig. 4 and the comparison of the experimental data to the surface temperature values for cooling period is shown in tab. 3. Both the measured and

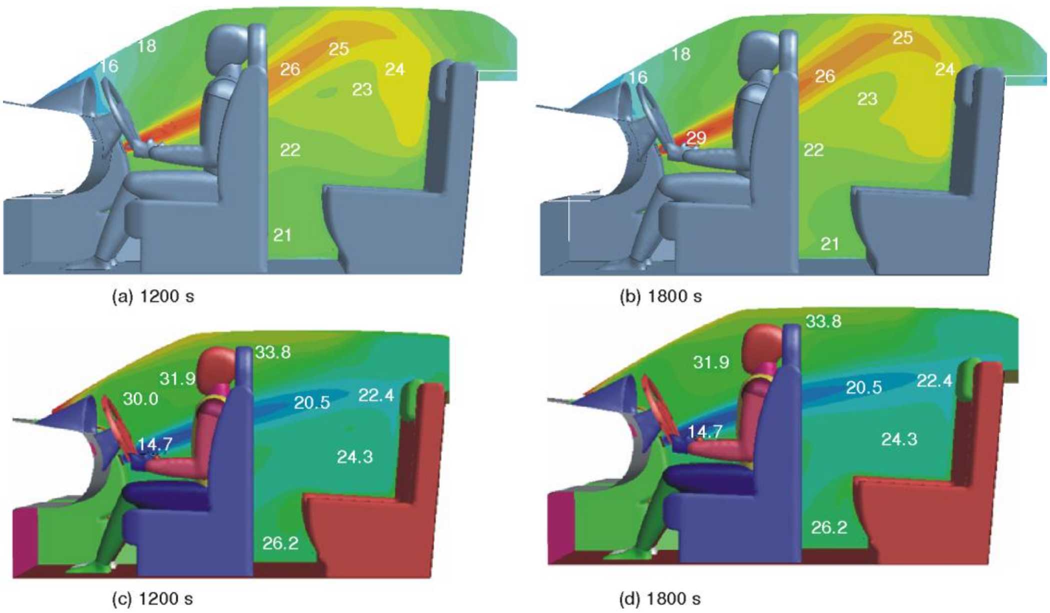


Figure 3. Temperature [°C] predictions at the central plane of the vehicle cabin for heating (a, b) and cooling period (c, d)

Table 2. Calculated temperature values at the surfaces of the vehicle cabin interior during standard heating (a) and cooling (b) period of the vehicle cabin

Surfaces of the vehicle cabin	Heating period			Cooling period		
	t = 600 s	*t* = 1200 s	*t* = 1800 s	*t* = 600 s	*t* = 1200 s	*t* = 1800 s
Windshield (front)	12.6	15.2	16.1	42.4	42.0	41.5
Rear glass (back)	12.4	15.0	15.7	33.0	33.3	31.6
Front door glass (right side)	12.0	14.5	15.3	35.0	34.3	34.5
Back door glass (right side)	12.5	15.3	16.1	31.2	31.3	30.9
Front door glass (left side)	12.9	15.1	15.9	34.2	34.0	33.9
Back door glass (left side)	13.3	16.0	16.9	31.7	31.3	31.4
Driver seat	16.2	18.1	18.8	33.0	33.0	32.4
Passenger seat (front)	16.2	18.1	18.8	40.7	39.4	39.3
Passenger seat (back)	15.1	17.7	18.6	31.8	31.4	31.6
Console	13.4	15.5	16.2	44.3	43.0	42.7
Center console	14.2	16.1	16.8	39.1	38.3	38.1
Steering wheel	16.8	19.2	20.1	42.6	42.8	41.1
Floor	11.3	12.5	13.1	32.4	31.9	31.9
Ceiling	16.3	19.3	20.2	33.6	33.6	33.1
Ambient temperature	16.7	19.5	20.2	28.7	28.1	27.9

Table 3. The computed and measured surface temperature [°C] values at 1800 s of cooling period

Surfaces	Num. t = 1800s	Exp. t = 1800s	Surfaces	Num. t = 1800s	Exp. t = 1800s
Windshield	41.5	45.5	Front door glass (right side)	34.5	37.6
Rear glass	31.6	31.6	Front door glass (left side)	33.9	36.2
Console	42.7	43.9	Ceiling	33.1	34.2
Passenger seat (F)	39.3	36.5	Steering wheel	41.1	38.1

computed data curves present same trend with the time in fig. 4 and the predicted surface temperature values for cooling period were nearly about experimental data. The heat transfer characteristics of the whole body for heating period are shown in the tab. 4. With increasing time, radiation and convection heat fluxes approach each other and total heat flux on the manikin is decreasing from about 95 to 65 W/m^2.

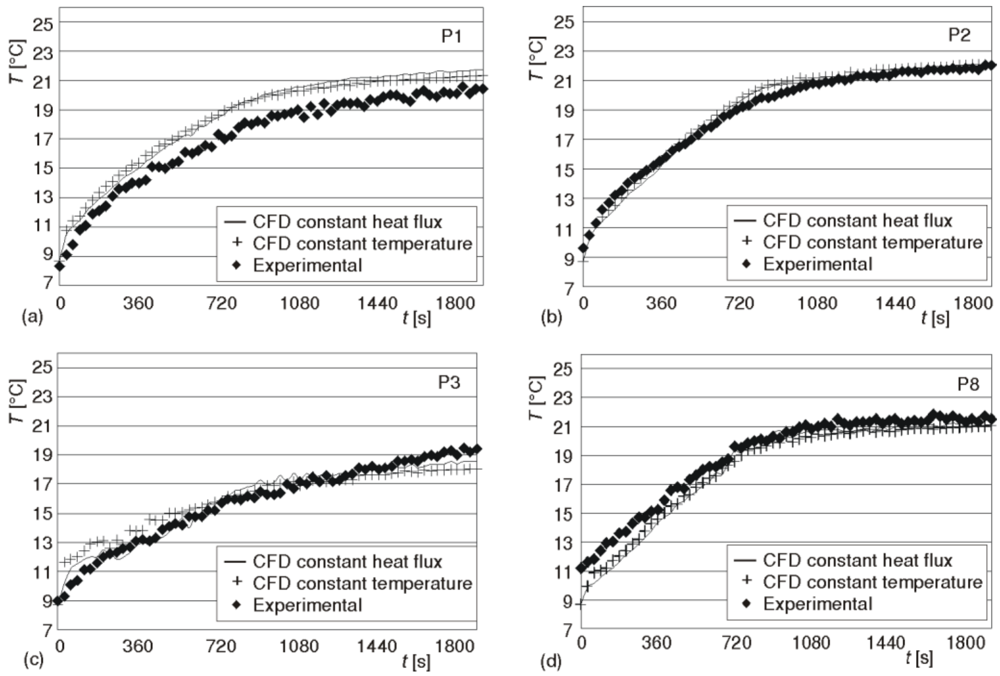


Figure 4. The comparison of the predicted temperature values to the experimental data during heating period

Table 4. Heat transfer characteristics of the whole body for thirty minutes of heating period

t [s]	Whole body			
	q_c [Wm^{-2}]	q_r [Wm^{-2}]	q_t [Wm^{-2}]	T_r [°C]
600	51.3	43.2	94.5	18.2
900	39.4	37.8	77.2	19.2
1200	36.3	35.5	71.8	19.6
1800	32.0	32.7	64.7	20.1

Conclusions

Highly transient conditions were obtained in the first 15 and 20 minutes of heating and cooling periods in the automobile cabin. Considering the physiological models of the human body, it can be said that using the constant temperature boundary condition on the human body surfaces is more realistic compared to the constant heat flux boundary condition for evaluating the thermal characteristics of the human body surfaces. Surface-to-surface or discrete ordinate model can be used for the calculations of the radiation heat transfer among the cabin interior surfaces but these models show differences in terms of computation and preprocessing time. Considering the heat interactions between human body surfaces and cabin environment, convective heat transfer has a great effect on the human body at the beginning of the heating period but radiation heat transfer has an important role on human body. Higher temperature values were calculated at the surfaces directly affected by the solar radiation in the automobile cabin thus mean temperature of these surfaces was decreased slowly compared to the other surfaces during the cooling period.

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