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Virtual Testing Stand for evaluation of car cabin indoor environment

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ABSTRACT

In the paper the authors refer to a new computational tool for the transient prediction of the car cabin environment and heat load during real operating conditions. The aim of the Virtual Testing Stand software is to support an early stage of the HVAC design process to predict demands for the heating and cooling for various operational conditions and types of car. This software was developed in Matlab as a standalone executable application including a parametric generator of car cabin geometry, a heat transfer model and a graphical user interface. The mathematical model is formed by the set of heat balance equations, which takes into account the heat accumulation, and the heat exchange between the car cabin, the outside environment, the HVAC system and the passengers. In this paper the main features of Matlab application are presented together with a selected sensitivity study of two significant parameters in a winter test case.

1. Introduction

A part of the engine power not transformed into kinetics of the car is consumed by the car's accessory systems providing safety and comfort. The HVAC (Heating, ventilation, and air conditioning) system is the main energy consumer of all cars' accessories systems [1]. The energy demand of the HVAC system is even more apparent in the case of electro vehicles, where the waste heat from a classical combustion engine is missing and must be substituted by another source of energy. If the energy for the HVAC is supplied from batteries, the driving range of electro vehicles is dramatically reduced [2]. The energy efficiency, reduction of fuel consumption and emissions of cars are still pertinent issues although the subject has been extensively studied by many engineers and researchers. The issue of energy efficiency and thermal management was dealt with in research projects such as Thermal effect of glazing in driver's cabs [3], Cool Car and other related projects of the NREL (National Renewable Energy Laboratory) [4–6]. All these projects investigated ways to provide thermal comfort inside a vehicle cabin efficiently by reducing the car cabin heat load and thus HVAC load.

The motivation of our research is to investigate and simulate a car cabin environment and its transient behaviour, which can be helpful during the HVAC design. This paper presents a newly developed design tool to predict heat loss/gains of the car cabin under real operating conditions. The software addresses design of the vehicle thermal management system during the very early stage of development of a new car, which is typically virtual. The virtual engineering process is a way to identify car cabin behaviour even before the first real prototype is made. In the early stage of the car design process it is important to find a fast, though less accurate solution of the problem. Further along in the design process more accurate and detailed studies are used to achieve the required parameters of the car. For a detailed calculation of the heat transfer and thermal comfort evaluation CFD software is commonly used, e.g. [7–9]. Unfortunately, a full 3D CFD increases the computing time enormously, thus car manufacturers often use specialized software like RadTherm or Theseus-FE namely in the early stage of the design process when energy issues of the HVAC system are considered. The aforementioned software are specialized in solving heat transfer on complex geometries except convective heat transfer, for which coupled CFD software must be used. The approach used when more numerical methods are coupled together is called the Integrated numerical modelling process, which is nowadays commonly used for the design of automotive climate control systems, e.g. [10,11].

Models based on a heat balanced approach to simulate car cabin environment are a "cheaper" alternative to previously mentioned complex approaches. Convective heat transfer in such models is not typically solved by CFD. Instead, empirical correlations with dimensionless numbers or pre-calculated CFD simulations for typical cases are used. By considering this approach, the computational time is reduced, which allows using these models in real-time applications [12–17]. Here we present a time-efficient method for predicting heat load and air temperature of car cabin

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during various operational conditions and evaluating an energy demand of HVAC to achieve conditions for thermal comfort in car cabins. These fast processing models also allow conducting sensitivity studies like Levinson [5] who investigated experimentally and numerically potential benefits of solar reflective car shells to reduce car cabin heat load in summer during parking. For an additional review of some heat balance models see [18], where the author also presents his own designed model. This class of the models is suitable as online HVAC control systems where a short computational time is necessary. Michalek et al. [19] developed a simple car cabin and HVAC unit model for real-time hardware-in-the-loop simulations. He concluded that the validated tools even with simple physical models can achieve good results in conjunction with the hardware-in-the-loop. Such kind of models requires calibration coefficients based on real experimental data which depends on the given car type and driving conditions. The neural networks method [20] is a very promising method using real data measurement. The main disadvantage of these methods is that they are designed for the specific car and conditions. The second possibility for reducing the processing time even more substantially is to create a lookup table, which is used instead of the model simulation. The lookup table contains all simulation results covering typical cases of operational conditions.

The aim of our research was to develop a simple and fast calculation method, which is capable of assessing energy balance, heat load and indoor car climate during real operating conditions of various types of car. The main advantage of our developed software is its fast calculation. It is designed mainly for the sensitivity analysis and creating lookup tables for various types of cabin geometries and operational conditions. The early version of the car cabin heat transfer model and its validation was presented in the paper [21], where the validation by measurements in real operational conditions was also presented. The model was developed in Dymola software and did not consider actual interior geometry. The model was suitable for hardware-in-loop simulations of the overall car cabin heat load, but was not able to calculate interior surface temperatures.

This paper presents more complex GUI-driven Matlab application, which contains a parametric modelling tool to create a generic CAD geometry of any car cabin including interior parts (e.g. seats, dashboard). This tool allows simulating thermal behaviour of various car cabins provided its geometry, cabin body structure and composition, material properties and driving cycle data are given. Some of the main benefits of this application are easy sensitivity studies (influence of material properties, geometry) and creation of lookup tables (variation of boundary conditions). In the next chapter the main features of application are described.

2. Methods

The Virtual Testing Stand of Car Cabin (VTSCC) was developed in Matlab as a stand-alone windows application, which includes the model for prediction of the thermal behaviour of a given car cabin during various operational conditions. In Fig. 1 there is a basic structure of the model input/output interface.

Each test case is defined for a given car and its operational conditions. The car is characterized by its geometry and materials composition and properties and by the operational conditions, which include GPS data, weather data, HVAC system data and number of passengers inside the cabin. All these input data are processed by the Matlab modules i.e. the parameterized geometry generator, the solver of the heat transfer, the view factor solver for radiation heat transfer, the GUI and the modules for post processing and import and export data to .csv or .xls file. The results of the application are predicted surface temperatures, relative humidity and, air temperature inside the cabin. If the SHL (stationary heat load) mode is switched on (see menu item simulation/SHL simulation in Fig. 2), it is possible to predict car cabin heat load, which expresses how much cooling/heating energy the HVAC system needs to keep a selected target set point temperature inside the cabin. The GUI of the application is split into several parts:

- Main menu (see Fig. 2).
- Control panel – the same for all workspace panels.
- Workspace panels: geometry (see Fig. 4), material composition (Fig. 5), boundary conditions, driving cycle (Fig. 6), processing, and post-processing (Fig. 7).
- Other windows – geometry editor and post processing plots.

The Matlab application is controlled via the main menu where the user can operate with car cabin geometry, simulation post-processing and view setup – see Fig. 2.

Additional setup of the application is in the following files: Setup.csv, Batch.xls, and PlotSetup.csv. There is also the possibility to plot a graph of any variables used in processing and export data to an Excel file. On the left side there is the control panel, which allows the user to choose a given scenario by selecting a car and its driving cycle, and after that to run the simulation. Part of the control panel is a command line which allows the user to set up some of the options and also the slide bar to visualize post processed data at the selected time of simulation. The rest of the screen belongs to a specific selected panel, which will be described in the following subchapters.

2.1. Parametric geometry

The simplified geometry is one of the most important drawbacks to providing a fast calculation tool for car cabin heat loads. Instead of using 3D detailed geometry the main car cabin features were selected as determining, i.e. dimensions of the cabin such as length, width, height of the side door and side windows, geometry of interior surfaces – dashboard, front and rear seats, area of glazing given by its dimensions and position, etc. The considered geometry features are defined by large sets of parameters (about 70), where all of the geometrical parameters are dimensioned for the specific case. The length, width and height of the cabin come from an official car blueprint. Other parameters, which are not given in the blueprint, can be linearly extrapolated from the blueprint using AutoCAD. Based on these parameters the Geometry generator allows us to generate three types of car body work: hatchback, combi, and sedan/liftback. The geometry is generated into .nas (Nastran) format, .mat and .stl format. The reasons why these formats were chosen are the following: Nastran file is easy to read in the text editor, .mat file is a general structure to store data in Matlab and .stl is a common file format for transferring 3D geometries between CAD software. The parameterized cabin geometry consists of 18 parts see Fig. 3, where an example of generated parameterized geometry is shown for the car Škoda Felicia Combi.

The parameterized geometry is used to calculate surface areas and cavity volumes of a given car, which are used for the heat transfer calculations. The surface area is calculated as a sum of the areas of the triangular patches forming the given surface. The volume of the cabin cavity is calculated by the divergence (Gauss) theorem, which allows to calculate volume of enclosure based on the knowledge of the surrounding surfaces. These surfaces have to be ordered properly; in our case all normal vectors were defined as outwards. For the simulation, only volume of the cabin cavity was considered; other cavities such as engine compartment, trunk and dashboard cavity were not integrated into the current heat transfer model. The geometry can be interactively modified in

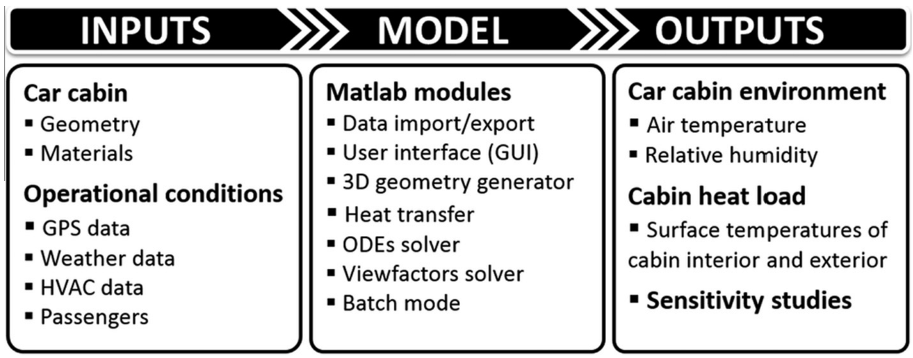

Fig. 1. Scheme of the model input/output interface and overview of the Matlab modules.

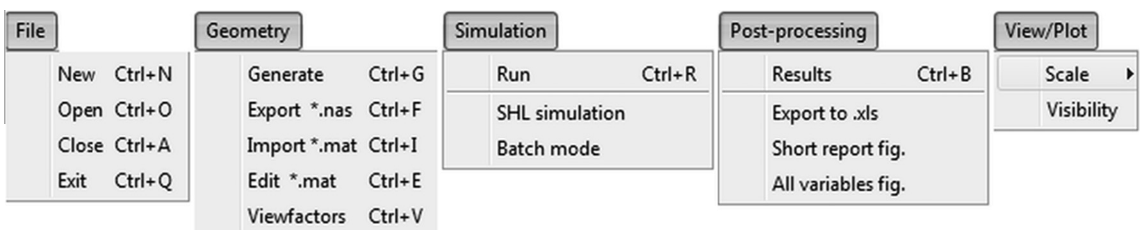

Fig. 2. The main menu of the VTSCC.

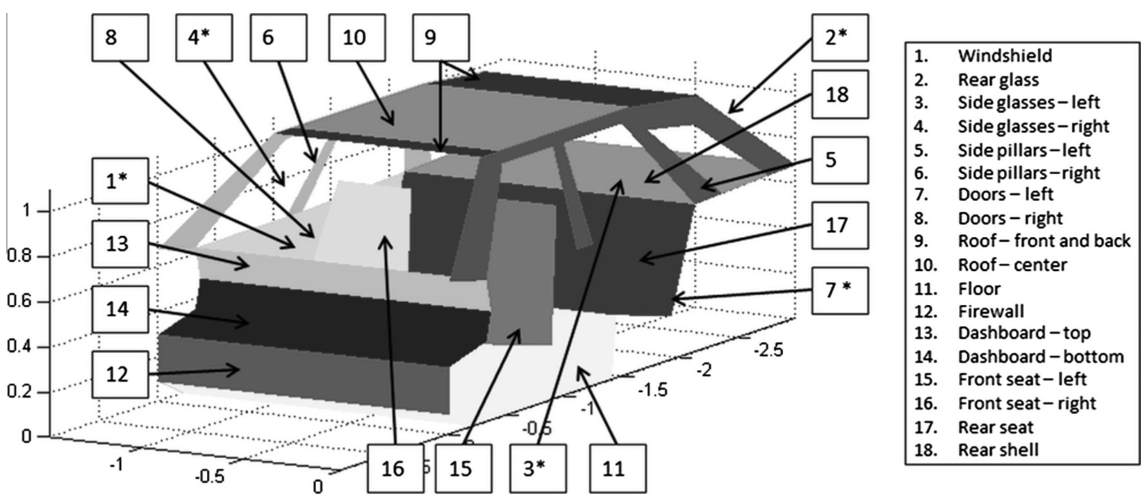

Fig. 3. Škoda Felicia Combi parameterized geometry (marked surfaces $*$ are hidden on the current plot).

the GUI with the editor of the parametric geometry, see menu item Geometry/Edit (Fig. 2). Part of the model is our developed view factors solver [22], which can be initialized by selecting item Geometry/Viewfactors. The solver calculates view factors of generated geometry, which are necessary for the simulation of the radiation heat transfer. The algorithm was validated on the benchmark tests, for which the analytical solutions are known: box (non-shading) and Shapiro test (shading) [23]. Other more complex tests (i.e. cube in box, car cabin geometry) were validated using the solver of commercial software Star-CCM+. The accuracy of our solver is comparable with the commercial software in case of non-shading and it is limited only by the precision of the Matlab function dblquad, which calculates a view factor integral see [24]. However it is not optimized for the efficient calculation of the shading in the extensive geometries; nevertheless it fits for simple parametric geometries generated by our application.

2.2. Material composition

Material composition of the car cabin is essential for heat transfer calculations. For each cabin part we define its material structure and composition with individual layers of given thickness and type of the material with appropriate thermo-physical properties. Each part is split into interior and exterior sides of the surface, which are separated by the imaginary EXT/INT layer. For example in the case of the doors, the imaginary layer represents the air gap. The material properties are imported from our material database, which was established from the literature survey and manufacturers' database. The types of material in our material database are split in several categories:

- Transmitting materials (various types of glazing).
- Surface materials (colours, varnishes).

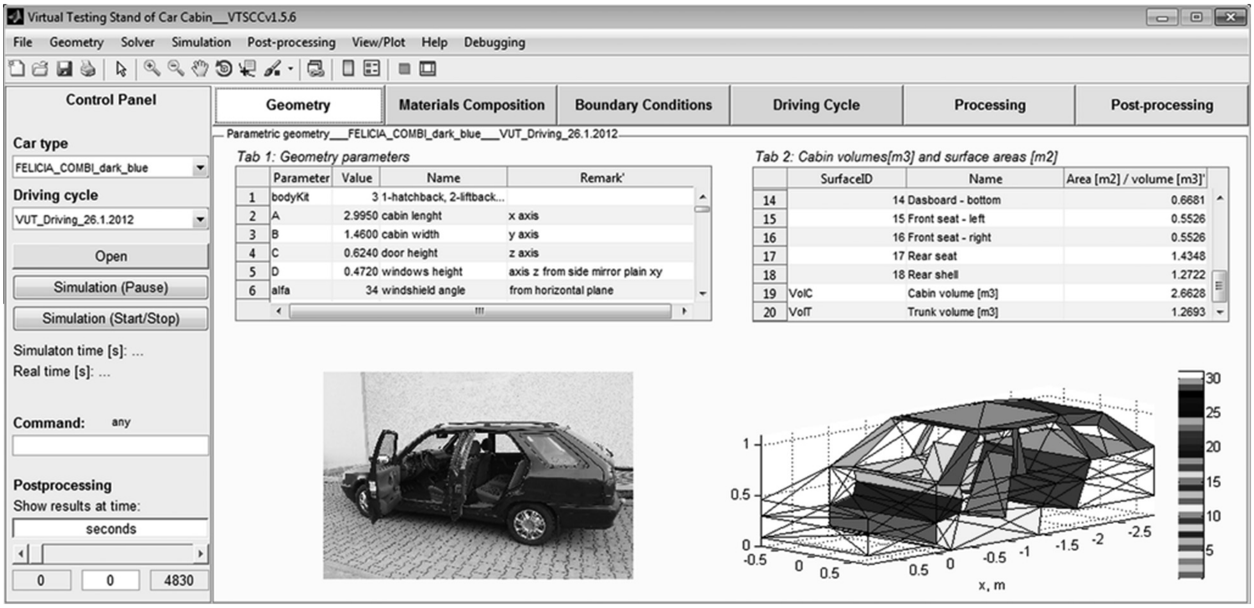

Fig. 4. VTSCC – geometry panel.

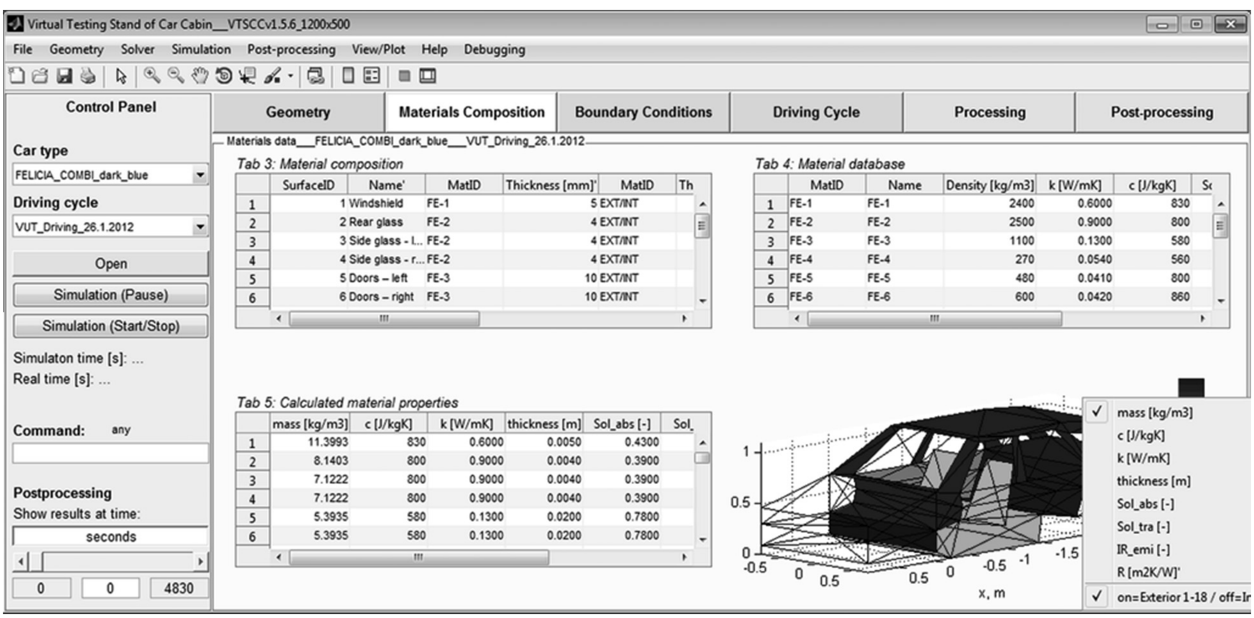

Fig. 5. VTSCC – material composition panel.

- Solid materials (plastic, metals, etc.).
- Air properties.

For the calculation of heat transfer, the following quantities are essential: thermal conductivity, density, and specific heat capacity, surface properties such as longwave emissivity, shortwave transmissivity, reflectivity and absorptivity. From the density and thickness of each cabin surface layer it is possible to calculate its mass. In Fig. 5, there is the screen shot of the material composition panel with the information about the selected car cabin. In the upper left corner we show the definition of material composition by type of material and its layer thickness; on the right side it is a table with material properties. In the right bottom table are calculated values of overall material properties of the specific part of the car cabin, and additionally the mass and thermal resistance are evaluated. All values of material properties can be visualized by the user on the car cabin as coloured patches.

2.3. Driving cycle definition

Fig. 6 shows the graphical user interface of the application, when the driving cycle panel is active. The driving cycle is defined by date/time data of the latitude, longitude, altitude, car speed, meteorological data, HVAC setup, occupancy of cabin by passengers, etc., see table on the left side of the panel. All these data are imported from the TimeTable.csv of the selected driving cycle folder, which generally contains experimental data. However, the user can also create or modify this file to obtain various even virtual scenarios. On the left side of the panel is the current Timetable and on the right side is shown in the map a current geographical

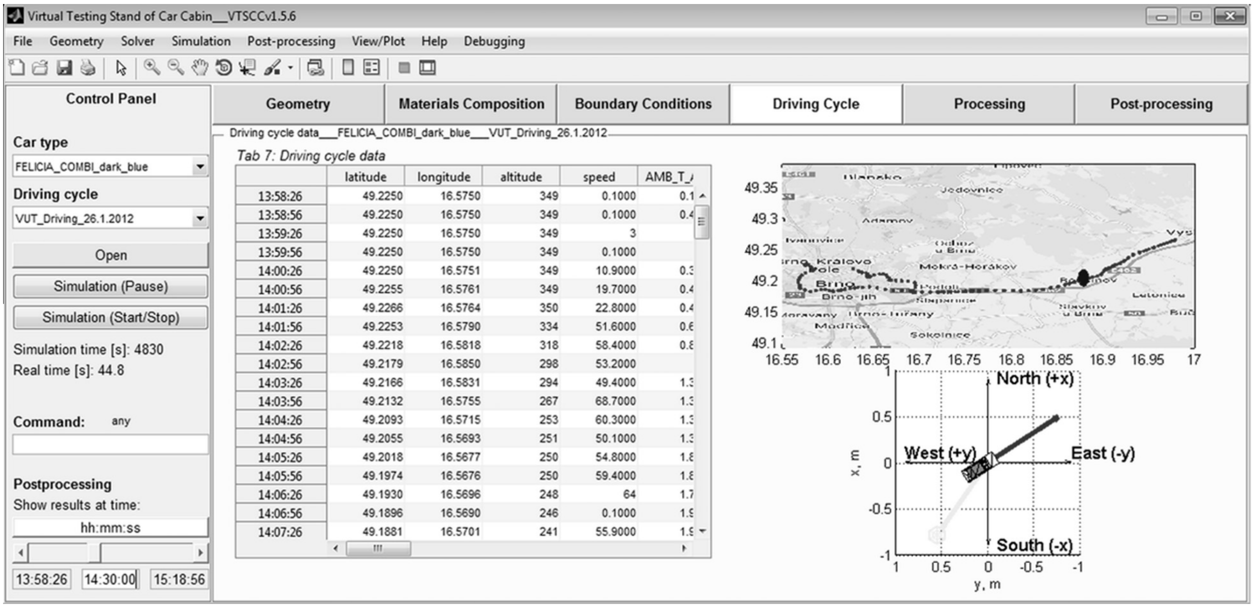

Fig. 6. VTSCC – driving cycle panel.

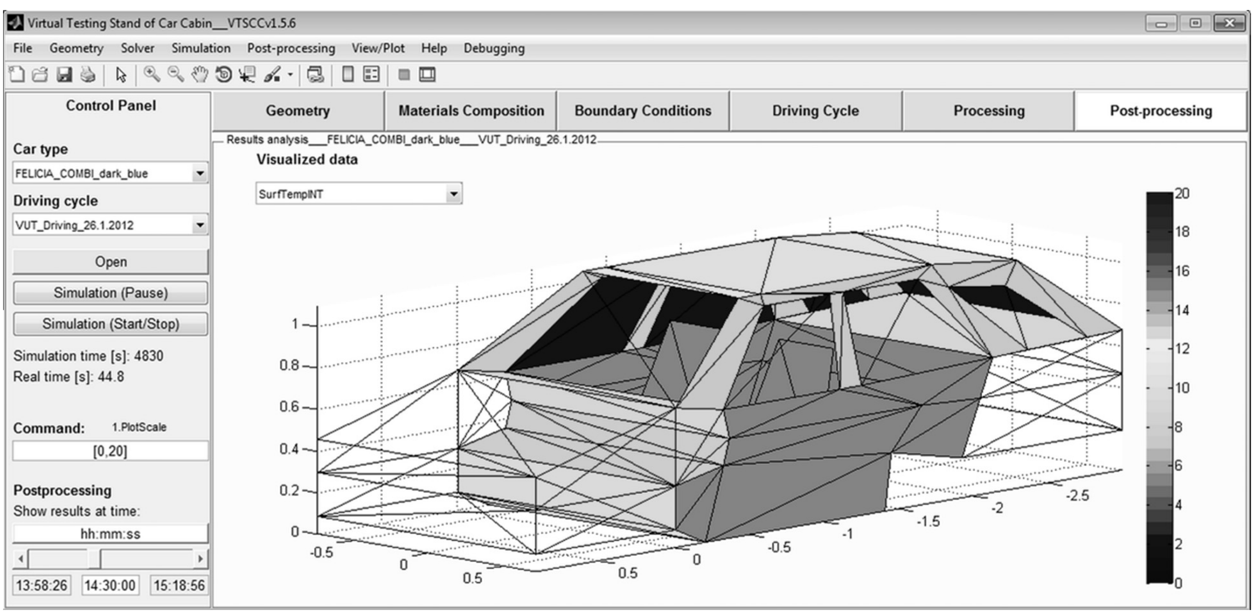

Fig. 7. VTSCC – post-processing panel. Example of the winter driving test case, plot shows interior surface temperature.

position (big dot) and the overall route (small dots). Zohar Bar–Yehuda's plot google map application [25] was used to visualize the route in the map. In the plot below the current car azimuth at a given time is displayed (in this case at 14:30, see sidebar at the bottom of control panel) and also the current position of the Sun. The car bearing is calculated from the current and the previous positions of car. The Sun position is calculated by the algorithm available from [26] and it depends on the current geographic position of the car and time data.

2.4. Processing

The Processing panel contains a message dialog with information about processing of the heat transfer solver, which is the main part of the VTSCC. The heat transfer calculations are done in the parameterized 3D geometry. The main idea for how to calculate heat transfer of the car cabin is inspired by the previously published paper [21]. The presented model was extended into 18 parts instead of 10, considering the geometry cabin interior as seats and the dashboard. For each cabin surface the type of boundary conditions defining neighbouring air zone, cavity and type of solar radiation have to be declared. The definition of boundary conditions can be found in the boundary conditions panel. In the current model there are ambient, cabin, trunk, and engine space and dashboard cavity and air zone. Solar radiation is split into three groups by the type of solar radiation impacting on a given surface: no solar radiation, outside and inside transmitted solar radiation. The model is able to simulate mutual position of the sun's rays and the car, i.e. normal vectors of all exterior and interior surfaces of the car cabin. The heat transfer is simulated by the set of heat balance equations, considering the accumulation/storage in the materials. The Matlab solver ode15 is used to solve a system of 38 ordinary differential equations (18 $*$ 2 – surface temperatures, 1 – air temperature, 1 – specific humidity. The development of the multi air zone model is still ongoing and the advection scheme between air zones is under development. The ode's system requires specifying initial conditions, i.e. start value of unknown parameters as specific humidity, air temperature and surface temperatures. If experimental data are available the value for initial conditions are automatically taken from the first line of experiments. If it is only a virtual case the initial temperature can be set up manually or equals to the outside ambient temperature. The user is informed about the running simulation by the elapsed real and simulation time and in the panel "Processing" the user can see the report about the running simulation or errors.

2.5. Post-processing

After the successful accomplishment of the simulation all results are saved into the .mat file. These data can be analysed and visualized in the post-processing panel (Fig. 7) or in the Matlab plot. On the post-processing panel is the plot with the coloured patches, where the user can choose to visualize exterior/interior surface temperatures, exterior/interior solar intensities, air temperature, specific humidity, etc. at a specific time given by the position of the slide bar in the control panel. If the experimental data are available it is also possible to generate a short report with comparison of the experimental and simulated data. The software allows exporting processed data into .csv or .xls file for further analysis in Excel.

3. Results and discussion

3.1. Experimental tests

The car cabin model was tested and validated for the Škoda Felicia Combi car in situations of summer parking, the autumn and winter driving. The summer and autumn tests were already presented in [21]; the simulation of the winter test from the 26th of January is presented in this paper to illustrate the main features of the software. The weather during the test was dry, cold (air temperature 0.5 °C) and the sky was fully covered by clouds (solar intensity 48 W/m^2). The experiment was performed on the route from Brno to Vyškov and back and it started at 13:58 and ended at 15:18 (UTC + 01:00), i.e. it took 4830 s. The operational conditions during the driving cycle were the following: Maximum speed of the car was 86.8 km/h and average speed was 54.6 km/h. During the driving test the car cabin was occupied by two persons, the ventilation was switched on and the fan controller was set up on the 2nd level. Volumetric flow of the ventilation air was 27 l/s and its temperature started on 10 °C and after 10 min its value was stabilized at 36 °C. More details about the experimental part of the research can be found in [27]. In Fig. 8 there is a comparison between predicted and measured mean air temperatures inside the car cabin.

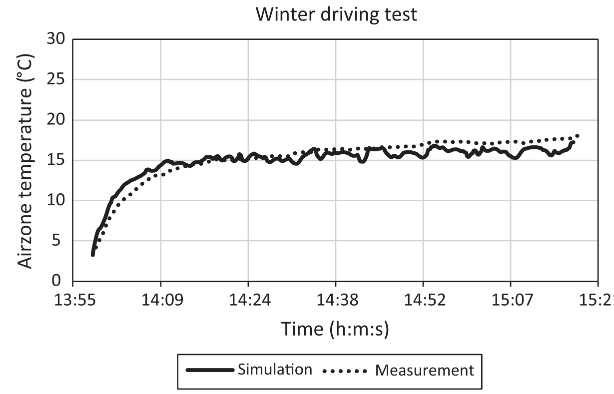

Fig. 8. Cabin air temperature – simulation compared with measurement.

3.2. Sensitivity studies

The following example demonstrates the main advantage of the application VTSCC i.e. fast analysis of various parameters on the car cabin environment. The above mentioned scenario can be analysed by the sensitivity study to explore the effect of:

- Geometrical parameters of the cabin body (areas, angles, length).
- Influence of material properties (density, specific heat capacity, radiation surface properties, etc.) – see the study for the winter test presented in [28].
- Influence of boundary conditions (GPS, weather, HVAC data etc.) – presented in this paper.

In Table 1, there is a demonstration of how the batch simulation cases are defined for the sensitivity studies. The table contains the definition of the selected CAR, DRIVING CYCLE, the input FILE where the selected PARAMETERS (defined by the "Excel" position) are substituted by the value (#) or CHANGE ($*$) and REMARK. The main objective of the parametric study is to determine what is the specific effect of boundary conditions i.e. ventilation volumetric air flow rate, solar intensity, ambient temperature, number of passengers and car speed on the cabin temperatures (air and interior surfaces). As an example of the parametric study, the influence of the ventilation volumetric flow rate as a significant interior parameter (Fig. 9) and solar intensity as a significant external parameter (Fig. 10) are presented.

Standard setting with the volumetric flow rate 27 l/s kept the cabin air temperature slightly below 20 °C. Without heating, the predicted air temperature was below 5 °C, and with four times higher volumetric flow i.e. 108 l/s the cabin air reaches the temperature above 25 °C.

In the winter season the solar intensity is rather low; however if the sky is clear it can also substantially affect the cabin environment. During the measurement the sky was fully covered by clouds and the measured solar intensity was 48 W/m^2. In the sensitivity study the effect of solar intensity was tested from 0 up to 500 W/m^2. For the sunny weather conditions (500 W/m^2) the predicted average cabin air temperature was 20 °C. The numerically computed temperature is about 3.1 °C larger than the average inner temperature from the basic test case (50 W/m^2).

It should be noted that this study was focused on the cabin air temperature only; however thermal comfort is also influenced by other parameters like mean radiant temperature. In the case of the car high speed the cabin air temperature is not the main problem; what is more important is the decrease of the windows surface temperature. So the objectives of the parametric study can focus on the investigation of other parameters as mean radiant temperature, humidity, car cabin heat load, etc.

Results of the sensitivity studies are saved as .mat file and also exported to the .xls, which can be used for additional statistical analysis. The sensitivity study outlined in Table 1 contains 25 various hypothetical scenario of the original winter test driving. The sensitivity study was focused on the variation of the only input parameter. The computational time of one case was 40.8 s i.e. much lower than the real time of 4830 s. The calculation of all 25

Table 1
Batch file for definition of the object of the sensitivity studies.

CAR	DRIVING CYCLE	FILE	PARAMETER	∗X CHANGE	REMARK
Škoda Felicia Combi dark blue	Driving 26.1.2012 Brno Vyškov and back	TimeTable.csv	O2:O163	∗0, 0.25, 0.5, 1, 2, 4	Vent. volume
		TimeTable.csv	I2:I163	#0, 50, 100, 300, 500	Solar intensity
		TimeTable.csv	G2:G163	#−20, −10, 0, 10, 20	Ambient temperature
		TimeTable.csv	F2:F163	#0, 50, 90, 130	Car speed
		TimeTable.csv	J2:J163	#1, 2, 3, 4, 5	Passengers

∗ – Multiplied parameter, # – Redefined parameter.

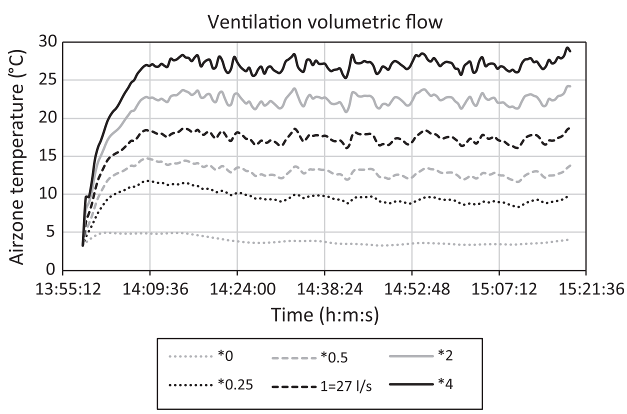

Fig. 9. Sensitivity study: influence of ventilation volumetric flow.

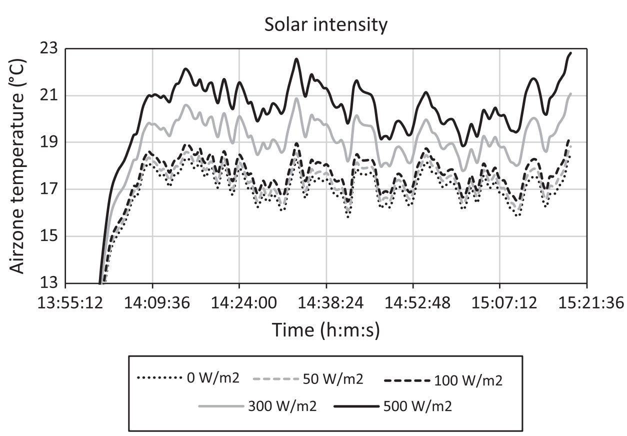

Fig. 10. Sensitivity study: influence of solar intensity.

cases took 25 min. The VTSCC application can be easily used also to study the effect of more boundary conditions simultaneously. Then the amount of considered cases will rise to $6 * 5 * 5 * 4 * 5 = 3000$ cases and the computational time will take approximately 50 h. By this application it is possible to perform extensive sensitivity studies to create complex lookup tables in a few days.

4. Conclusions

In the article the authors present a new computational tool for the simulation of the car cabin heat load and cabin air temperature during real operating conditions. The main features of the simulation tool are shown together with the software structure. The simulation tool aims at designing an HVAC system and the overall thermal management of the car cabin, during the early stage of a new car development. It is possible to rapidly analyse thermal behaviour of a car cabin during real operating conditions. It also allows managing sensitivity studies of the cabin environment with respect to the change of various material properties, cabin geometries and boundary conditions. The short sensitivity study was presented to illustrate how the application could be used and what benefits it brings. Also we have shown in the paper a comparison of predicted and experimental data for a winter driving test case. This test case was used as original data for the presented sensitivity study, which was focused on the influence of change of boundary conditions on the cabin air temperature. The model also has a special mode for the calculation of the heat load with respect to the set point temperature inside a car with the objectives to predict energy requirement for HVAC during various operational conditions.

The software was developed in Matlab as a windows standalone application, with a graphical user interface. The GUI provides visualisation of the input data as material composition of the car cabin, GPS data, and mutual position of the car and Sun and also output processed data as temperatures of surfaces, impacted solar radiation, air temperature and specific humidity. The output data can be visualized at each time step of the scenario.

The heat transfer model was validated on the Škoda Felicia Combi for winter, autumn and summer tests including parking and driving. Further development of the simulation tool and its validation in a climatic chamber is underway, aiming mainly at a multizone cabin.

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