Advances in Engineering Software 76 (2014) 48–55

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Virtual Testing Stand for evaluation of car cabin indoor environment

Jan Pokorny, Jan Fiser, Miroslav Jicha *

Brno University of Technology, Faculty of Mechanical Engineering, Department of Thermodynamics and Environmental Engineering, Technicka 2896/2, 616 69 Brno, Czech Republic

ARTICLE INFO

Article history:
Received 14 March 2014
Received in revised form 3 June 2014
Accepted 5 June 2014
Available online 28 June 2014

Keywords:
Car cabin
Indoor environment
Matlab
Thermal comfort
HVAC design
Computational tool

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

* Corresponding author. Tel.: +420 541143271; fax: +420 541143365.
E-mail address: jicha@fme.vutbr.cz (M. Jicha).

http://dx.doi.org/10.1016/j.advengsoft.2014.06.002

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