SIMULATION OF SOLAR THERMAL SYSTEMS WITH CARNOT BLOCKSET IN THE ENVIRONMENT MATLAB® SIMULINK®

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Abstract – This paper describes the development of a simulation program called CARNOT (**C**onventional **A**nd **R**enewable e**N**ergy **O**ptimization **T**oolbox) for the environment MATLAB Simulink. The program combines the easy-to-use graphical environment of Simulink® with the powerful algorithms and differential equation solvers of MATLAB® for the application of solar thermal system simulation. Advantages to commercially available programs are the variable time steps, which enable long time simulation with an adequate simulation time. Furthermore the time step can decrease to sub second range, which is a key feature for short time resolution that is important in highly dynamic systems, e.g. for controller design.

The concept of the library CARNOT is similar to the Simulink® standard library. The models are organized in so called subsets that contain the components of conventional and renewable heating systems. The program performs simultaneous calculation of heat transfer and hydraulics. New systems configurations can be created entirely by mouse operations, just drag-and-drop the respective blocks from the library. Interconnection of the blocks is done by lines that represent vectors of the physical properties. The included models can be easily extend to own components, which can be integrated as graphical Simulink® models (subsystems) or in C-, Fortran- or MATLAB® M-scripting language. In the same way completely new models of components can be included.

1. INTRODUCTION

The paper presents a new simulation tool for solar thermal application which has been developed by Solar Institute Juelich and is commercially available since November 1999. The tool uses the commercial software MATLAB® Simulink® as environment. The program overcomes the actual market situation in simulation tools for solar thermal application:

On the one hand, easy to use tools are commercially available which are well suited for design of standard systems but with poor possibility to user adaptation.

On the other hand, sophisticated programs with a lot of possibilities of user specifications and extensions are available, but they require detailed knowledge of the program internal processes.

Moreover most of the programs are quite restricted concerning the simulation time step which is a key feature for system design that is sensitive for short-time dynamic resolution, e.g. for controller design.

To overcome this disadvantages, a new approach using a commercial software was chosen to enhance features concerning time step, user interface, user extension possibility and support.

2. APPROACH

2.1 Project background
Background of the actual development of the program was a lack of simulation programs to calculate, design and optimize a solar district heating within a research project for extension of the university campus, the Solar Campus Juelich. Commercial programs could not resolve relevant short time dynamics and calculate simultaneously the hydraulics and heat transfer of the network. Moreover, the adaptation to the system configuration was time consuming and model extensions could be integrated only with difficulties.

2.2 Basic software MATLAB®-Simulink®
The software MATLAB® developed from the mathematical library EISPACK and LINPACK. Actually it is a powerful mathematical software with an integrated scripting language and huge mathematical function libraries based on matrix calculation. During the 20 years of the lifetime of MATLAB®, various scientific groups worldwide began to extend MATLAB® in particular applications, which are added to the MATLAB® Package as so called Toolboxes. Actually there are around 150 of these Toolboxes covering various kinds of applications like financial calculations, statistics, fuzzy logic etc. The calculations are performed in a so called workspace on the basis of command line processing.

Simulink® is a Toolbox extension for MATLAB®, too. The toolboxes are distributed by the American distributor, the firm The MathWorks®. Simulink® is used for system modeling and simulation on the basis of MATLAB®. It is organized as a graphical library, which includes the basic components of control circuits, e.g. integrator, mathematical functions (e.g. trigonometric functions and arithmetic operations), signal generators (Dirac pulse, sine wave, chirp signal) and visualization (scopes, file output). Simulink® works with a graphical

interface which is similar to data flow diagrams: The components are represented as blocks that are connected by arrow lines corresponding to vectors, that are passed from block to block and contain all information to enable a continuous calculation. All operations are performed in the graphical interface: components were connected by mouse operations and blocks are copied from the library by drag and drop. Running Simulink® implies that MATLAB® is running in the background, so that Simulink® is just an interface, the calculation and the mathematical operations are performed in MATLAB®. Therefore all function of the MATLAB® basis can be called from the Simulink® interface, too. The parameters of simulation can be controlled from files, executed in the workspace of MATLAB, as well, which enables a grade of automation of various simulations with different parameter sets as needed for optimization algorithms.

2.3 Particular advantages of the software basis
In relation with the systems design problems at Solar Campus Juelich, a new software was needed. MATLAB® Simulink was chosen because of the following specific features:

- graphical interface
- worldwide spread standard for simulation in control system design in particular in automotive and aeronautic industries
- mathematical update and support by the MathWorks®
- up-to-date numerical algorithms and solvers
- toolboxes for most areas of mathematical fields, in particular systems behaviour (optimization, parameter identification, control systems (predictive control, fuzzy logic, etc.), financial, statistics etc.)
- enhanced features concerning the time step by variable step size and sub second range.
- enhanced error handling by windowed messaging
- context sensible help documentation and hotline

The development was initiated by financial support of Viessmann GmbH, a German manufacturer and market leaders of house heating equipment, who needed models of conventional and renewable components of house heating systems to accelerate the design process of the control systems.

3. THE CARNOT BLOCKSET

3.1 Basic features
The CARNOT Blockset is organised as modular library similar to the Simulink® standard library.
New system configurations can be created in the graphical interface by mouse operations. Blocks are optically connected by arrow lines in the interface.
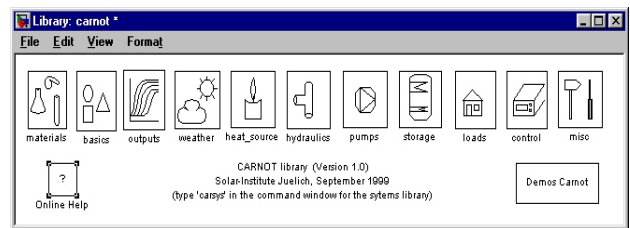

Fig. 3.1: Interface of the CARNOT Blockset

The physical meaning of the lines is the THV (thermo-hydraulic vector), the common data structure, by which the data exchange among the blocks is performed. The THV contains all thermal and hydraulic information about the flow, e.g. temperature, mass flow rate, system pressure. New model integration is only limited by keeping this data structure to secure communication with the other models.
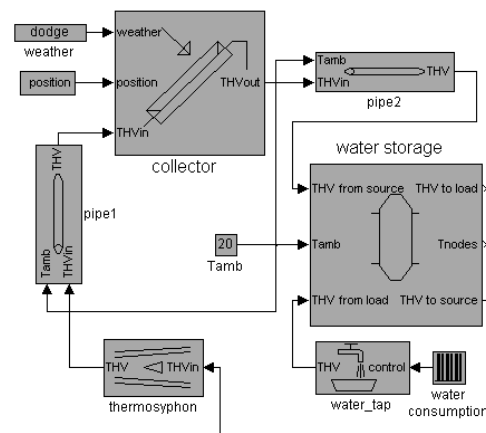

Fig. 3.2: Scheme of solar system

The CARNOT Blockset contains two libraries, the Carnot and the Carsys library, which are described in detail in the next paragraph.
Demo models of systems configurations are provided which can be started from a special demo window. The demos are commentated to get familiar with the interface.
Help is provided in parallel in various systems:
The program is delivered with a written manual. There are two online manuals, one in pdf-format and one in HTML, which can be called directly from the blocks by pressing a help button. HTML includes a keywords search mechanism and contents frames that facilitates the search process. Moreover a text oriented help of basic introduction and functions is integrated in the workspace.

3.2 Components of the CARNOT Blockset
The CARNOT Blocksets consists of 9 subsets, in which the components are structured into groups. The following subsets with the respective components and the related functionalities are included:

materials: This blocksets provides material properties of commonly used fluids in conventional and solar heating systems (water, air, oil, water-glycol). Also calculation of moist air and vaporous phase of water is possible. The materials properties are also accessible from the workspace, i.e. they can be used for calculation as well, if Simulink® or CARNOT is not active.

basics: In this blocksets, basic functions in hydrodynamics and heat transfer can be encountered, e.g. blocks for calculation of characteristic numbers (Reynolds, Prandtl etc.), pressure drop of laminar flow, velocity, conversion of relative humidity to absolute humidity etc.

outputs: In "outputs" the blocks for online-visualisation and results encapsulated. The subset contains scope blocks that are adapted to the data structure of CARNOT, efficiency meter which can be connected to source blocks and blocks for writing simulation results to files or to the workspace.

weather: This subset comprehends basic weather models, interfaces to common weather data formats (meteonorm, TRY), calculation of sun position, incidence angle and axis tracking. Weather data are stored in a special CARNOT format, so before using external data, they have to be preprocessed.

heat source: Common conventional and renewable heat sources are integrated in this subset:

solar collectors (flat plate collector, evacuated tube collector, parabolic trough) and as functionality of the collectors a surface tracking respectively a fixed surface position.

In case of the collectors the optical characteristics (single or double glazing have to be adapted by exchanging blocks in the subsystem. The pressure drop is treated in the same way.

conventional heat sources (furnace, heat exchanger, heat pump, radiator, electric heating).

hydraulics: This subset comprises the passive hydraulic elements of heating cycles (pipes, valves, flow diverter)

pumps: The subset consists of three different pump models (constant massflow, user defined characteristic, characteristic of German manufacturer Wilo) and a thermosyphon model.

control: The control subset contains the component of control systems like measurement sensors and a bang-bang controller

storages: The storage subset provides different kinds of thermal storages.

water storages: simple storage, multiport storage with internal heat exchangers, combi storage.

ground storages: 3D ground storage, U-tube ground storage, surface models (isotropic sky, Hay Davies model)

loads: This subset covers loads: A simple building model is integrated, one with a radiator heating, another with a floor heating system. To model the load of solar thermal system, a water tap as symbol for a user-definable water consumption is included.

misc: The misc(ellaneous) subset consists of utility blocks and templates for creation of own component models. A typical utility block is the phase check block which displays a warning when a phase change in the working fluid is detected.

Moreover a block for economical and ecological calculation is included which can be connected to source blocks.

The CARNOT library addresses to more sophisticated, scientific application, e.g. for testing of own models, parameter adaption/optimization/identification

3.3 CARSYS Library

The CARSYS (**CAR**NOT **SYS**TEM) library is similar to the subsets of the CARNOT library, but all the components already have the parameter sets of the manufacturers, i.e. systems of commercially available components can be build-up. The CARSYS library should be used to design commercial systems, that means, the CARSYS addresses to more applied and practical use in planning, system design, economic analyses etc. Therefore the demos of CARSYS contain standard system configurations where the commercial component can be chosen by pull-down menus. As only commercial systems should be investigate with this library, the subsets, that refer to own model integration, (basics, materials, utility functions, templates) are not included in this library.

3.4 Data structures

Data sets which have a physical connection, e.g. weather data, or the above mentioned Thermo-Hydraulic Vector, are encapsulated in vector structures. The following vectors have been integrated, dependent on the requirements of calculation.

THV (Thermo-hydraulic vector)
This vector contains all characteristic data for the flow and heat transfer calculation, e.g. fluid type, mass flow rate, temperature, etc.

Weather data vector
The weather data vector consists of all relevant characteristics of weather data sets, e.g. ambient temperature, solar radiation, relative humidity, wind speed etc.

Fuel vector
The fuel vector comprehends the characteristic values for calculation of systems with conventional fuels, e.g. ratio of chemical components, air demand, etc. It is used in ecological calculation.

AIV (**A**ir **I**nfiltration **V**ector)
The AIV contains all important values that characterizes the air flow in buildings. The vector is used in building calculation with the building model as load.

S-Vector
The S-Vector defines the incoming energy flows for a room node in building calculation, e.g. heat from inner sources (computers, illumination, human beings etc.), mass flow into the room etc.

Eco vector
The Eco vector defines the output of a conventional fuel system, e.g. mass flow of CO_2, H_2O, temperature, electric power, thermal power etc. It is used in ecological and economical calculation.

4. MODELS OF THE CARNOT BLOCKSET

There are two main ways to integrate models in the library:
On the one hand, models can be integrated by creating subsystems consisting of basic blocks of the Simulink® standard library. Subsystems can be masked, so that the parameters of the respective model can be entered in self-created menus to facilitate entering of parameters. This way of building a model is graphical oriented and corresponds to system configuration.
On the other hand, models can be integrated as C, Fortran or MATLAB® M-Script files, which are called from the Simulink® model by blocks called S-functions or M-functions. To secure correct communication between the file and the block, templates are integrated in Simulink® with definition of the position, where certain parts of the model, e.g. the differential equation have to be implemented in the respective language.
To shorten the simulation time, the time consuming calculations have been integrated as C-file in S-function blocks which accelerates the simulation. Smaller calculations are programmed as graphical Simulink® models.
Models in CARNOT can be distinguished by their complexity. There are three main types introduced in the following paragraphs

4.1 Characteristic curve models
Simple component behaviour can be modeled by using the component characteristic which is integrated as mathematical functions or look-up tables. Examples for models using a characteristic are the pumps, valves, material properties etc.

4.2 Transfer functions
Transfer functions describe the systems answer to standard signal by solving the differential equation of the physical behaviour. Transfer function can be build with Simulink® blocks from the standard library. Example of this model type is the heat pump, where the coefficients for the transfer function can be calculated by a utility function in the workspace as preprocessing.

4.3 Differential equation
The last kind of modeling uses the differential equation, that is brought in a discrete form and solved as a node scheme by numerical algorithms. In the CARNOT library, an upwind scheme by Patankar [1] is used. The calculation is bases on finite differences. Two of these models, the collector and the multiport storage, are described in detail below. As this procedure is time consuming concerning the simulation time, models based on the differential equation are implemented in C which is advantageous with regard to calculation time.

4.3.1 Collector Model
The model was set up during a study of solar collectors [2]. The aim was to identify the collector parameters from measurement during operation of the solar system. It should be possible to decide if a lower efficiency is due to sand or dust on the glazing or due to increased thermal losses.
The model is based on the physical parameters of the collector based on the model description of Per Isakson [3]. It is implemented in the language C and linked to the simulation environment via an S-function.
The model parameters were identified using a MATLAB® optimisation function by comparing measured and calculated temperature at the collector outlet. By this method it was possible to determine the reason of decreasing efficiencies during operation by online monitoring.

4.3.2 Storage Model
In the model the storage-tank is subdivided into a number of layers which are defined by the user (multi-node one-dimensional model). Any number of ports (pipes or heat exchangers) can be connected to the model. The internal heat exchangers may be used as stratified charging heat exchangers.
The model is also available as a combi-storage. In this case two parallel one-dimensional models are calculated.

4.4 Validation of models
Every software has the problem, that only long time application can prove the reliability of the obtained results. Though models may be tested and certified, there is no guarantee for correct calculation due to possible programming bugs.
Nevertheless basic validation has been performed for the CARNOT blocks, even though validation is not complete and still in progress. Besides of consistence checking of simulation results, two kinds of testing have been performed:

Evaluation of comparison to measured data
- The house model has been compared to the measured and calculated data of the SOPASIM-project (Balters 1995)[10]. Comparison to measurements has also been done with data from a project in Argentina (Müller 1999)[9].

Comparison to other simulation programs

- The collector model was checked with results of earlier TRNSYS simulations of the Solar Campus Juelich, where the Isakson collector model (Type 101) was used. The discrepancy in the yearly delivered energy between the models was less than 2 %.
- The storage with heat exchanger model was checked with the TRNSYS Type 74 by Harald Drück [14]. The simulation showed an yearly energy difference of the storage of about 3 %.
- The sun angles were compared with TRNSYS radiation processor (Type 16) and showed good congruence.
- The house model has not yet been tested under all conditions. It has been compared to the results given by Feist (Feist 1994) [11].
- The property functions were compared to data in the literature (Bernd Glück [10], VDI Wärmeatlas [15] and Schmidt [12]) and corresponded very well to the literature.
- The 3D ground storage model has not yet been thoroughly tested. There is only few measured data available for this type of storage. The model has been compared with the data published by Reuss [13]

5. APPLICATION OF THE CARNOT BLOCKSET

A wide range of application can be performed with the CARNOT Toolbox based on the variety of functionality of the basis software MATLAB-Simulink®. In the following paragraph some of possible applications from the author's horizon are discussed in detail

5.1 Simulation and system design

The classical application of the Blockset is the simulation of a configured system to judge the capability. By an iterative process of simulation, the design can be adapted and the system output can be maximized.

Further application in this context are energetic (energy consumption of conventional system), economic (rentability of system, return of investment costs, amortization time) and ecological analysis (avoidance of CO_2 production).

Component certification by approval of solar energy gain can be performed, as well [4] by simulation of the system for the respective weather conditions.

5.2 System Identification, component testing

Identification of component or system parameters on the basis of measured data. The application enables dynamic component and system testing and physical modeling of new components. The process allows as well black box modeling with identified parameters.

5.3 Development and improvement of innovative components

Component behaviour can be modeled and optimized by simulation before prototypes are build. In this way, hardware costs can be reduced.

5.4 "Hardware in the loop" test of components

Hardware in the loop testing refers to testing of components connected to a computer. The test conditions are simulated and fed via an I/O card to the hardware component. Development cycles can be considerably shortened by this method.

5.5 Creation of libraries with manufacturer data sets

The idea of the CARSYS library can be user-extended by just entering the data sets of component tests or of manufacturer catalogues. This can be used to design systems using commercially available components or for easy analysis and optimization of existing systems.

5.6 Optimization by use of MATLAB algorithms[1]

By combination of MATLAB optimization algorithms with system models, optimization processes can be automatized. Systems and components parameters can be optimized and investigated under various boundary conditions. Of course, self written optimization routines can be used, as well.

5.7 Controller algorithm development and design

Above optimization results can serve to develop control algorithm. Because of the variable time step of MATLAB down to sub-second range, short time dynamic can be resolved, which enables controller design for sophisticated systems.

5.8 Model extension to evaluate side effects

The easy-to-use graphical environment of Simulink® facilitates model extension to side effects, e.g. bacteria growth in a water tank.

The CARNOT Blockset has been successfully used in the following cases:

- design of a district-heating with co-generation
- controller design for house-heating systems at Viessmann
- design of a latent heat storage (research project of BMBF (German research ministry)[5])
- parameter-identification for solar collector [2] and hot water storage-tanks [6],[7]for dynamic testing
- parameter-identification for solar collector and hot water storage-tanks for dynamic system testing (ISTT method) (co-operation with ZAE Bayern)

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[1] with MATLAB optimization toolbox

6. CONCLUSIONS

A new tool for simulation of thermal systems with conventional and renewable components is commercially available for the environment MATLAB®-Simulink®. It has enhanced features concerning range of time steps, system specification, graphical interface and user-defined model integration. A further extension to similar applications, e.g. simulation of buildings or electrical systems is planned and partially in progress.

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