A NEW TYPE OF SIMULATION SOFTWARE FOR DETAILED COMPONENT-BASED SYSTEM ANALYSIS

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Abstract

A new type of simulation software is introduced which performs sophisticated simulations on the transient thermal, and electrical and hydraulic system behaviour. In comparison to other available software, it can simulate the sensor and controller properties, and also enables hydraulic analysis. It is possible to set or influence the component parameters throughout a simulation. In addition, several open interfaces allow the use of the software in numerous fields of application, such as in particular its implementation in other software. The software core facilitates both a fixed and a variable simulation time step.

Individual system configurations can be designed by connecting single components such as in other component-based simulation tools. The program's component library contains 15 validated components. Further components can be modelled or imported by the user if required. The software was validated using TRNSYS 17 as well as analytical considerations, and very good results have been obtained.

Keywords: *Simulation software, component based, sensor and controller properties, variable time step, hydraulic circuit analysis*

1. Introduction

The demand for renewable energy sources and their availability fluctuate over time. These variations lead to a dynamic response of the respective systems. Common dynamic system simulations can be used to analyse or predict the system's behaviour, and several simulation tools have been developed in the past Connolly, D. et al. (2009). From a technical point of view, they can be divided into system-oriented and component-based tools. Component-based simulation tools are usually used in science and for sophisticated technical applications. Depending on the desired application, the potential of commercial software tools is restricted due to a number of missing functionalities or drawbacks. This motivated the development of the new component-based and detailed simulation software (MITHRA). The aim of the new software is to integrate and combine the following (partially new) features in a single program:

- Detailed modelling of sensor, controller and data logging properties
- Detailed analysis of hydraulic circuits
- Accessibility to automatically performed simulations
- Flexibility in usage: possibility to be implemented in another software, as a stand-alone or a server-based application
- Variation of component parameters during the simulation: e.g. the variation of solar thermal collector efficiency curve parameters or the heat transfer coefficient of hot water storages U = f(…)
- A variable time step
- Fast and simple modelling of new components and features
- The flexible and combined simulation of thermal, hydraulic, electrical and if required further system behaviour in one tool

In the following sections, the software structure will be introduced briefly, and the main parts "Simulation Core" as well as the "Component Liberty" will be described more specifically with a focus on the advanced methods of MITHRA.

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2. Software structure

The MITHRA software structure is shown in Fig1. It consists of a simulation core (a) and a component library (b). The simulation core processes the system information and its control strategy which are provided in two files (c). User-modelled components (d) can be simulated if necessary. The results of the simulations are dynamically written on an output file (e). Both the system file and the control file use a very simple and user-friendly syntax. However, visual interfaces like desktop or mobile apps can be applied to prepare these two files (f). The software is very well documented.

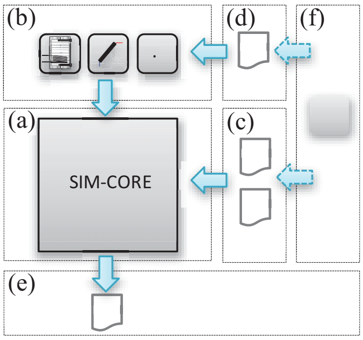

Fig. 1: Schematic structure of the software: (a) simulation core, (b) component library, (c) system file and control file, (d) user-defined components, (e) output file, (f) optional visual interfaces

Fig. 2 portrays an example of a solar thermal system which was investigated in MITHRA. It consists of a collector field with an area of 10 m^2 connected by an insulated pipe to a hot water storage with a volume of approximately 450 litre. The hot water storage has a direct temperature controlled electrical heater which is installed in the upper part. The major component details are shown in Table 1 and the measurement details are shown in Table 2. This system was modelled in MITHRA using the standard components.

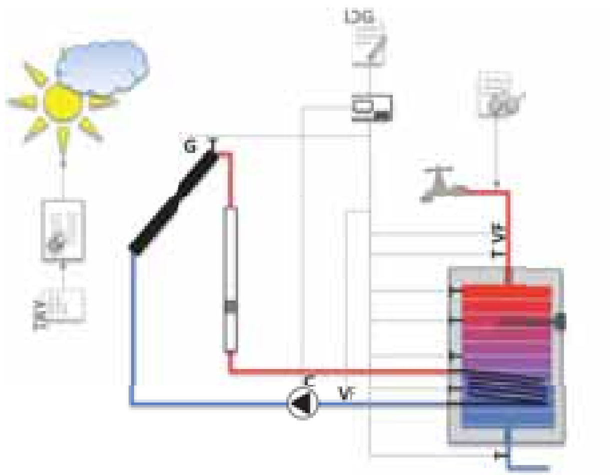

Fig. 2: Schematic structure of the exemplary solar thermal system simulated in MITHRA. The components are described in Table 1 and the sensors in Table 2

Tab. 1: Components' main information of the simulated example System shown in Fig. 2

Component	Important Parameters / Values
Test Reference Years Data , TRY-Processor, Weather data in simulation environment	Time Step = 1 min
Flat Plate Collector	Collector aperture Area = 10 m^2 η_0 = 0.8 a_1 = 3.24 Wm^{-2}K^{-1} a_2 = 0.011 Wm^{-2}K^{-2}

Pipe	Internal Diameter (Pipe Wall) D_{in}= 0.03 m External Diameter (Insulation) D_{out}= 0.04 m Length L = 10.0 m
Pump	Set Volume Flow $\dot{V}$= 0.0001 m^3s^{-1}
Hot Water Storage	Internal Diameter (Tank) D_{in}= 0.6164 m External Diameter (Insulation) D_{out}= 1.0 m Height h = 1,5 m Number of Segments = 20 Electrical Heater Position = 70 % Electrical Heater Power P_{el}= 2 kW

Tab. 2: Sensors and control signal of the simulated solar thermal system shown in Fig. 2 from left to right and top to bottom

Abbreviations	Component	Unit
G	Solar Irradiance Sensor 1. in collector plane (G Collector)	W/m^2
T	Temperature Sensor 1. collector outlet (T Collector) 2. hot water storage internal - 99% height (T Storage 99%) 3. hot water storage internal - 70% height (T Storage 70%) 4. hot water storage internal - 50% height (T Storage 50%) 5. hot water storage internal - 30% height (T Storage 30%) 6. mains water(T Cold Water 99%)	° C
VF	Volume Flow Sensor 1. hot water withdraw (VF Hot Water) 2. solar primary loop (VF Solar Primary Loop)	m^3/s
C	Control Signal 1. solar primary loop pump (C Pump Solar Primary Loop)	1

The results obtained during a ten-day simulation, beginning on January 1 are shown in Fig. 3 and in Fig. 4 with more detailed measurement results for the exemplary day January 6. The components as well as the overall system show the expected qualitative behaviour. The quantitative evaluation is described in section 4 with the component validation with TRNSYS 17 standard library. For example, it can be observed that the upper set temperature of the electrical heater is 60 °C and the lower one is 55 °C, corresponding to the temperatures in the position of the electrical heater in 70% of the storage height (Fig. 3 and Fig.4). This is visualised in the temperature curve “T Storage 70%”. Due to stratification, mixing and several other modelled heat transfer phenomena, the upper storage temperature “T Storage 99%” is continuously influenced by the electrical heater but it remains in the desired temperature range. The system controller continuously compares the collector temperature “T Collector” with the temperature in the lower part of the storage “T Storage 30%”. In case of a (rather low) positive temperature difference of 5 K and more, the solar primary loop pump is turned on by setting the control signal “C Pump Primary Solar Loop” to “1”. The energy transport from the collector to the storage causes a temperature increase in the lower parts of the storage, as demonstrated by the temperature sensor T” Storage 50%” installed in the middle of the storage. In the weather dataset, January 5 is a sunny day with rather low hot water consumption. Thus, the solar thermal part of the system can fully heat up the water.

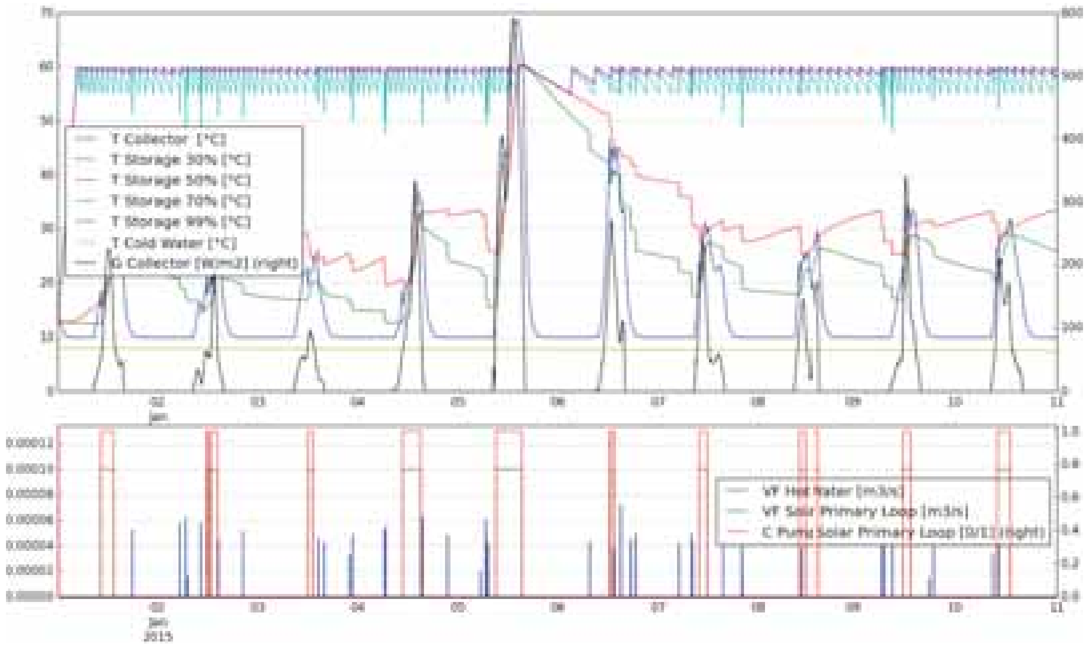

Fig. 3: Measurement results of the simulated solar thermal system shown in Fig. 2 using MITHRA. The 10 day simulation starts on January 1. The components and the sensors are described in Table 1 and Table 2.

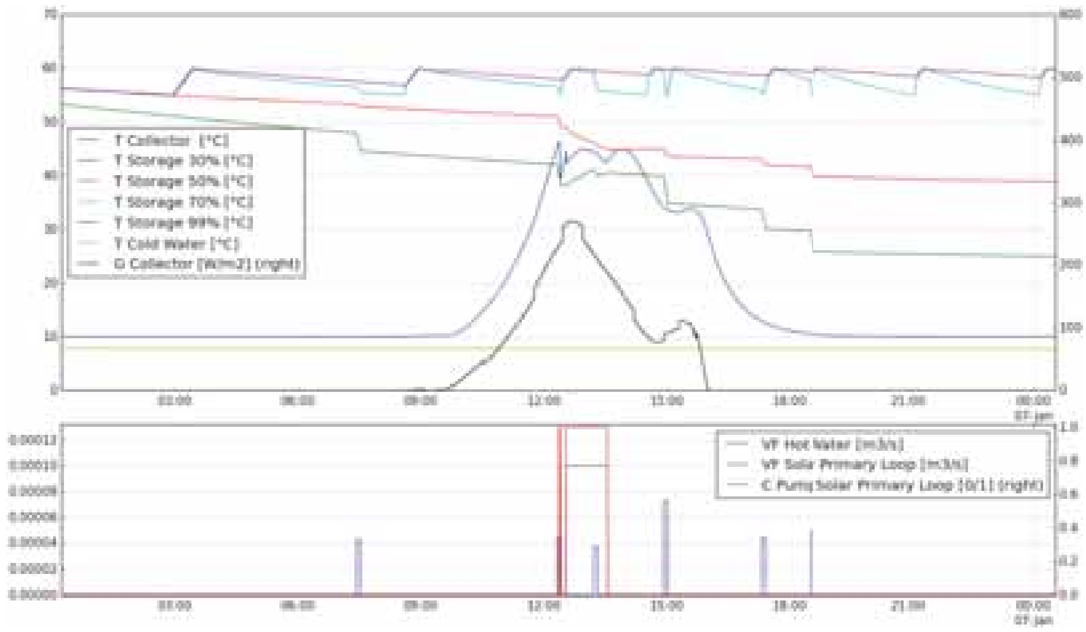

Fig. 4: Measurement results in detail for January 6 shown in Fig. 3.

3. Simulation Core

The simulation core is the most essential element of the software. In the very first step, it parses the input file, which contains the component and system description. Subsequently, a software environment is accessible where a simulation can be started manually as well as automatically by separate or wrapping software. After the simulation, an output file is generated containing the simulation results. Additionally, different implemented post processing methods for advanced plotting or data import and export are provided. In the following, the input and output files will be described before presenting the different features of the simulation core.

3.1 Input and Output Files

Figure 4 shows an example input file. The components are defined in the top of the file, and connected with each other using arrows in the bottom of the file. When defining the components, many component specific parameters can be set according to the requirements of the user. For example, to define a hot water storage tank it is possible to adjust 41 parameters, if necessary. In case the component parameters are not further defined in the input file, the component's default values will be used according to the program's manual.

An important feature is that hydraulic loops are defined (e.g. "CollectorLoop" in Fig. 5) and the components are assigned to a loop. Thereby, hydraulic circuit analysis can be performed. While some simple hydraulic analysis features are already implemented, more sophisticated features are in development.

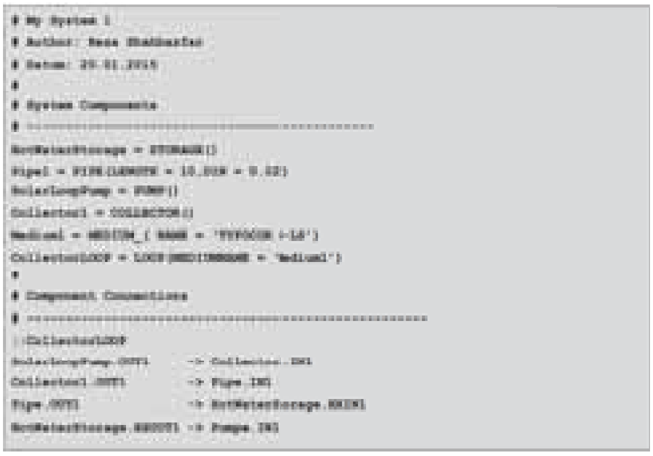

Fig. 5: Schematic structure of the simulated exemplary system in MITHRA. The components are described in Table 1 and the sensors in Table 2

The output file is generated by a data logger (see 4.9) and structured as a common csv file containing the sensor names in the first row and the time stamp in the first column (see Fig. 8). Therefore, it is easy to further process the simulation results in other programs, such as spreadsheet programs.

3.2 Port Concept

In each simulation time step, component states are linked to each other according to the system description in the input file. A port concept has been developed to enable the components to not only generate a value but also to interact with each other. Different type of ports can be distinguished:

1. Hydraulic Port
2. Energetic Port
3. Sensor Port
4. Free Port

Through a hydraulic port, energy and mass exchange including pressure is performed. The energetic port enables a non-mass-linked energetic exchange. The sensor port plays a special role since it only has a one-way interaction mode. The last category of ports is the free port, which is automatically defined by the simulation core according to the user's specific requirements; for example, when using a file reader to import different kinds of values.

3.3 Variable Simulation Time Step

Throughout system operation and respectively during simulation, there are times of high process dynamics causing highly fluctuating state values, but there are also less dynamic conditions with rather stationary conditions. In the solar thermal system (Fig. 2), one can observe typical dynamic system conditions. For example, they are caused by variations in solar radiation caused by clouds passing by, after a power-on of the solar primary pump or after a hot water withdraw. On the other hand, in the night and in the absence of a hot water withdraw the system temperatures are less dynamic.

The simulation core was designed in order to facilitate a variable simulation time step to enable the simulation to speed up under less dynamic conditions. Therefore, three different speed levels with different speedup factors can be defined at the beginning of a simulation. A suitable simulation time step is automatically chosen depending on the automatically reported component states and the required tolerance accuracy. In Fig. 6, the collector temperature and the control signal of the solar primary pump of the solar thermal system (Fig.2) are shown. The simulation was performed using a variable time step. Two short time ranges of the diagram (left dotted rectangle) are shown in Fig. 7. (left) The calculated points of the collector temperature are marked by a "+". It can be noted that the activation of the solar primary loop pump leads to more dynamic system conditions slowing down the simulation speed. Shortly after the disconnection of the solar primary loop pump, the system is less dynamic and the simulation speeds up once again (right dotted rectangle, see Fig. 7 right).

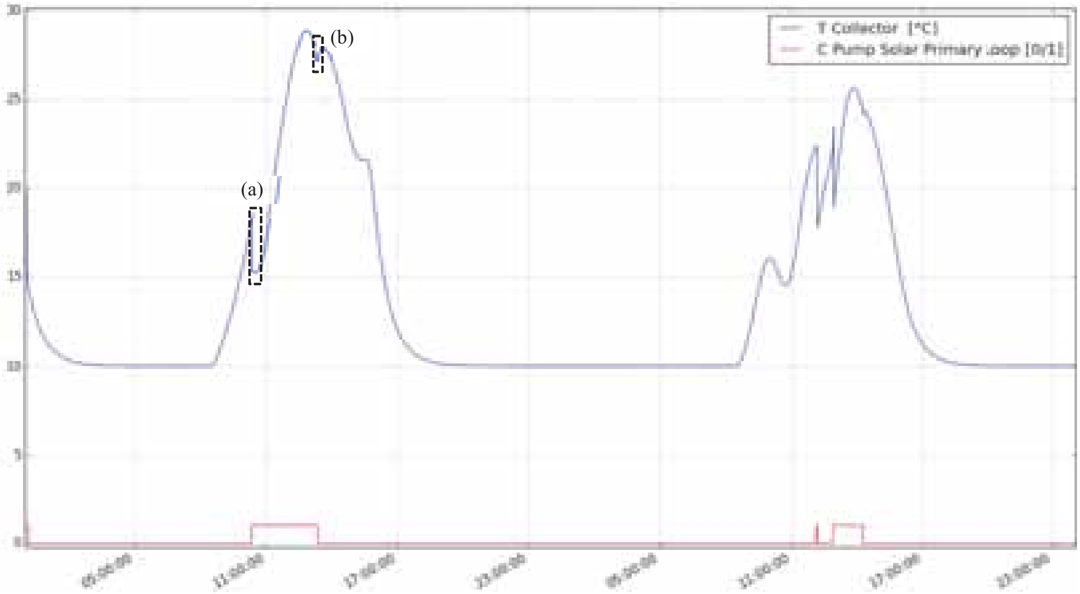

Fig. 6: Two days simulated in MITHRA using variable time steps. Two exemplary positions showing the automatic simulation speed change have been chosen (dotted rectangles) and are shown in Fig. 7 (left dotted rectangle) and Fig. 7 (right dotted rectangle).

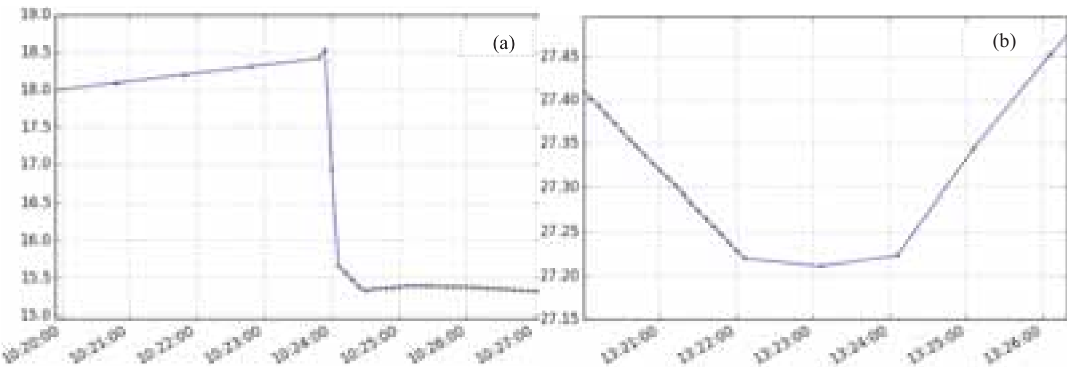

Fig. 7: X-zoom on left (a) and right (b) dotted rectangle displayed in Fig. 6. After the activation and disconnection of the primary solar loop pump the simulation time step (marked by "+") is reduced and increased, respectively.

3.4 Numerical Solver

In MITHRA, there is no global numerical solver. The numerical process is executed in the components. An explicit numerical solver has been developed to enable a fast modelling of new components. It is an automatically self-controlled solver, which reduces the simulation time on the one hand, and achieves the expected simulation accuracy on the other. This is achieved by an algorithmic manipulation of the calculated control points. It is possible to implement implicit numerical methods or to combine them.

3.6 Process Analyser

A process analyser to detect the simulation time (complexity) of each component and to plot the results if required has been developed. It detects malfunctioning components or other problems of the simulation. Additionally, warnings and errors are displayed and can be written to a file.

3.7 Hydraulic Circuit Analyser

Throughout a simulation, the hydraulic circuit analyser automatically investigates the hydraulic system behaviour. It can analyse the components of each loop and pre-calculate the pressure and the pressure drop due to a fictive volume flow. This makes it possible to automatically iterate the expected volume flow and flow direction in distribution manifolds. Therefore, the loops and the fluid within the loops are separately declared in the input file (see Fig. 5). Some components are modelled slightly different: For example, a pump can provide a pressure difference instead of a constant volume flow (see. 4.4), or new components like a safety valve and expansion vessel are modelled and can be used in loops. The hydraulic analyser works in a simple mode and its further development is possible.

4. Components

For a simulation, the system has to be described by its single components according to the input file shown in Fig. 5. While it is possible to create new components, a number of ready-to-use components are contained in the program's component library. Table 3 provides an overview of the available components. These components are quite flexible: By setting a parameter (usually called MODE), a wide range of different component constructions can be reproduced. Thus, the number of the components is not directly comparable with some existing programs. All components are validated using analytical methods or numerical methods with TRNSYS 17. A detailed mathematical and syntactical description of the components, including the validation results, is provided in the program's documentation with more than 100 pages.

Tab. 3: Component Library Overview – Ready-to-use components

Components	
Pipe	Sensor
Medium (e.g. Heat Transfer)	Equation Processor
Hot Water Storage	Numeric Function Generator
Pump	File Reader
Solar Thermal Collector	Safety Valve
Boiler	Expansion Tank
Distribution Manifold & Flow Mixer	Multi Zone Building Modell (in process)
Weather Processor / TRY	Heat Pump (in process)
Controller with Data Logger	Photovoltaic (in process)

The components are briefly described in the following sections with a focus on their advanced features.

4.1 Pipe

The component pipe is realized as a plug-flow-model. Additionally to the common features (for example, the calculation of the thermal losses to the environment), this component determines the hydraulic losses as well as the internal heat transfer between the single segments at different temperatures. The inlet and outlet heights can be defined. Thus, a thermal stratification in the pipe can be simulated if required. As an additional special feature, any pipe bends and a number of different hydronic components like elbows and ball or block valves can be defined and will be taken into account when the hydraulic losses are calculated.

4.2 Medium

In MITHRA, the heat transfer medium within the system hydraulics itself is considered to be a component. Therefore, the relevant required hydraulic and thermodynamic features like fluid density, viscosity, specific heat or aggregate state can be calculated dynamically with respect to the current individual system conditions. Different common mediums are already modelled, and the user can create new fluids if necessary.

4.3 Hot Water Storage

Heating applications often use hot water storage to ensure the user's thermal energy demand and to enable the system to bypass the time between energy availability on the one side and energy demand on the other. The system behaviour implies many different overlapping heat and mass transfer phenomena, which makes it rather complex to model. In MITHRA, detailed and very flexible hot water storage was modelled. In simulations, the storage medium is divided into nodes. For every node, a complex mass and energy balance is calculated. Besides the energy and mass calculations, the stratification of the storage medium including mixing effects is also considered.

It has to be underlined that in this model the number and positions of internal heat exchangers, electrical heating elements, inlets and outlets as well as the number of the nodes are not limited or restricted. The internal heat exchanger and the storage body can be described analytically by typing in the single parameters, or they can be described using overall values like U or U*A. The shape of the storage can be switched from cylindrical to cuboid.

4.4 Pump

The component pump converts electrical power into a pressure difference or to a pre-defined volume flow depending on the simulation mode and the fact whether the hydraulic circuit needs to be analysed or not. In the latter case, the pump characteristics dp = f(Vd, Pumplevel) can be defined. The pump is switched on by a control signal that is continuously variable or digital in the rage of 0…1.

The efficiency behaviour of the pump is described by two parameters: A first parameter describes the efficiency of the electromotor in terms of converting electrical energy into rotatory mechanical energy, and the latter factor describes the efficiency of the mechanical components of the pump in terms of converting the rotatory mechanical energy into a hydraulic pressure difference. Alternatively, it is possible to describe the pump's overall behaviour with a single parameter. Furthermore, the temperature increase of the fluid due to the pump inefficiency is also modelled.

4.5 Solar Thermal Collector

Several different approaches exist on how a solar thermal collector can be modelled. When performing a simulation and setting up these models, it is often problematic to get all the required parameters. Thus, many parameters need to be assumed which leads to an increase of the model uncertainty. To avoid this, a converse approach has been chosen in DSMIN for the development of the solar thermal collector model. Firstly, the data sheets of different available collectors on the market were analysed. The collector model was developed according to the identified and easily obtainable parameters. It primarily depends on the efficiency curve parameters, but also on the collector heat capacity and the incident angle of the solar irradiation. Moreover, the hydraulic collector behaviour was also taken into account. It is described by one or multiple parameters available in the collector datasheet or in the collector testing report.

4.6 Boiler

A boiler ensures that the thermal energy demand is met. Oil-fired or gas-fired boilers are two common types. Their system integration can vary as well. Usually, they are separate external devices heating up a medium in a closed loop and pumping the heated medium to the load.

In MITHRA, a flexible component model of a boiler was developed. It can convert an external energy source into thermal energy and supply it to the load using a pump. The temperature behaviour is regulated by setting an upper and lower temperature. The heat capacity, a constant or a variable efficiency function depending on the boiler's return temperature can also be taken into account in the simulation process.

4.7 Distribution Manifold / Flow Mixer

To split one inlet volume flow into multiple outlet flow rates a distribution manifold can be used. The outlet flow rates can be adjusted individually using valves. In MITHRA, a distribution manifold was modelled where the flow rate factors can dynamically be controlled by an external function during the simulation. A flow mixer is also available enabling the reverse process: Multiple inlet volume flows are mixed and provided as a single flow at the outlet.

4.8 Weather Processor

The climatic conditions play a key role for thermal or energy simulations. Thus, several methods and different sources have been developed in the past providing weather data especially for simulation purposes. Typically, solar diffuse and beam irradiance in the horizontal plane, ambient temperature, wind speed and air humidity are part of the weather information. In MITHRA, a weather processor was created as a component. It reads the weather data and is able to calculate the irradiance on the surface at any desired orientation. Therefor a complex calculation of the sun's position in the sky is internally performed and isotropic or non-isotropic sky models are utilised.

For Germany the "test reference years" (TRY) DWD (2014) is one of the most popular and free available sources for weather data used in simulations. A special "TRY mode" has been programmed in the component that enables the direct use of the TRY data without any intermediate step.

4.9 Controller and Data Logger

Energy and hydronic systems usually have a controller to ensure an appropriate operation. Usually the controller utilizes sensors, actuators and a control strategy. Common controllers provide the opportunity to log and transfer the current sensor an actuator values in a file or they analyse the data just in time. The controller in MITHRA was programmed to have these functionalities and be freely programmable.

The number of sensor inputs and actuator outputs can be chosen freely. For each input and output, the sensor type (e.g. temperature or flow sensor etc. or control signal) needs to be defined. Different simple and predefined control strategies are available, or user may define their own control strategy. An example of a control file is shown in Fig. 8. At the beginning of the file, the controller inputs are assigned to a local variable in order to be handled more easily. The solar primary loop pump is then controlled with four different if-statements using a delta-T switch-on (8 K) and switch off (4 K) including the protection of the solar loop components (100 °C) and of the storage protection at 95 °C. An example of a controller's logging file is provided in Fig. 9.

Fig. 8: Example of a simple control strategy for the controller.

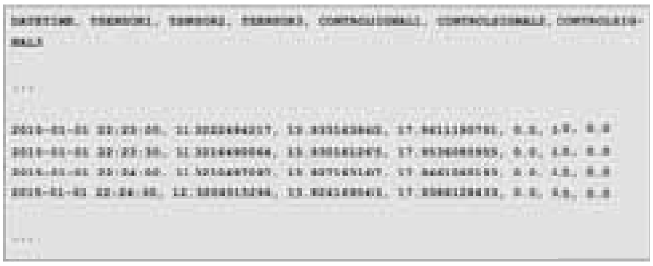

Fig. 9: Example of a logging file generated by the controller. In the first column, the time stamp and the column names are provided in the first row

4.10 Sensors

As a special feature, the sensors are considered to be stand-alone components in MITHRA. Thus, it becomes easily possible to describe and numerically investigate their temporal response and measurement uncertainty in interaction with the rest of the system. In MITHRA, the measurement uncertainty is distinguished in systematic and random errors. Systematic deviation can be modelled as constant offset or can be function of the measured value or a function of simulation time. The random errors are defined by a maximum and minimum limiting function that may also vary depending on the measured value and the simulation time. In between these two limits, a probability distribution function like a rectangular or a normal distribution function can be selected. The influence of the sensor's behaviour in terms of the logging file depends on the controller's data fetching mode (sampling or averaging and thresholding) and logging speed.

When performing detailed simulations, sometimes it can be necessary to take the sensors response behaviour into account. Hence, in MITHRA the physical sensor behaviour is provided. In Fig. 10, the overall behaviour of a simulated exemplary temperature sensor in different configurations is shown. Sensor "T_IDEAL" shows the values of the simulated system, assuming an ideal sensor. The thermal response behaviour of the sensor is modelled for the second sensor "T_SEN1". In the case of the third sensor "T_SEN2", random errors of the sensor are modelled additionally.

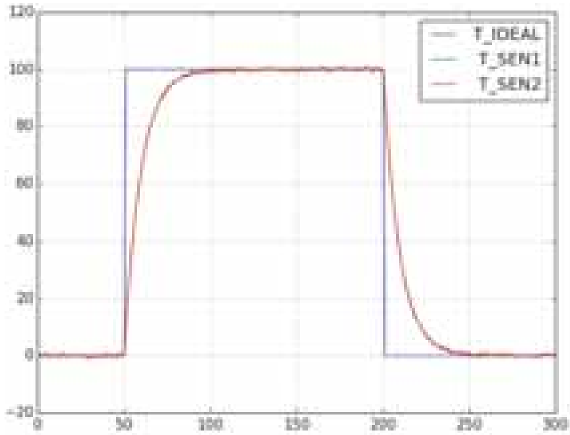

Fig. 10: Simulated temperature sensor in three different configurations: 1. Ideal ("T_IDEAL") 2. With a thermal response time (T_SEN1) 3. With thermal response time and random errors (T_SEN2)

4.11 Equation Processor

User-defined calculation can be performed using the equation processor component. The results are available at the output of the component. The number of used inputs has to be defined and the respective values must be connected in advance. It uses a similar syntax to the control file shown in Fig. 9.

4.12 Numeric Function Generator

For testing purposes or for basic control functions, it is sometimes necessary to quickly generate a value during the simulation. Thus, a value generator was modelled in MITHRA. It provides the opportunity to generate constant values, step functions or interpolations between given points and given time steps.

4.13 File Reader

The file reader makes it possible to read in external data into the simulation. The external file can contain a single value, multiple values or multiple time series provided in columns like in a csv format. In the latter case, the column separator can be defined manually. The file reader provides several mathematical and numerical functions like looping the file or using a simulation time depended or independent transfer function.

4.14 Safety Valve

A safety valve can be built into each loop to keep a maximum set pressure. In MITHRA it can be used for more sophisticated simulations including hydraulic circuit analysis. The component distinguishes an upper and a lower response pressure of the valve.

4.15 Expansion Vessels

Expansion vessels compensate the thermally caused volume variations of the fluid within the system. As expansions vessels typically have their pressure – volume characteristics, the volume compensation leads to a pressure variation in the system. To be able to simulate this behaviour, an expansion vessel has been modelled. Two different modes exist: In the first mode, a simple parametric approach is used that interpolates the "delta pressure" as a function of the "delta volume" with a predefined lookup table. The second mode is for gas-filled membrane expansion vessels where the “delta pressure” can be calculated as a function of the “delta volume” using the ideal gas law of thermodynamics.

4.16 Component Validation

The component validation was performed by using analytical or numerical methods. For the latter, TRNSYS 17 standard library (see UW–Madison, 2009) was used to validate the component’s pipe, collector, hot water storage and weather processor. Different tests have been chosen that can isolate the component’s elementary behaviour as good as possible. For the variations within the test, a normal operation range was chosen. Additionally, two points (one extremely low and on extremely high) were considered. The component tests are described in Tab. 4.

Tab. 4: The components‘ main information of the simulated exemplary system shown in Fig. 2

Component	Variations
Pipe	Test 1: ambient temperature, Test 2: thickness of insulation , Test 3: thermal conductivity of insulation material, Test 4: inner diameter
Collector	Test 1: ambient temperature, Tests 2: irradiance, Test 3: flow rate, Test 4: collector return temperature, Test 5:incident angle, Test 6: maximum stagnation temperature (3 % max, not typical operation condition)
Hot Water Storage	Test 1: electrical heating in the upper of the storage, the vertical thermal conductivity over the time is compared, Tests 2: variations in the insulation U-Value, temperature of each node over time is compared , Test3: variation of the power of electrical heater in the bottom of the storage tank, the stratification over time is compared, Test 4: Variation of the volume flow in the internal heat exchanger, temperature over time of all nodes is compared, Test 5: hot water withdraw in the top of the tank is simulated and varied, the temperature over time of all nodes is compared
Weather Processor	Multiple test and the comparison of direct and diffuse radiation, variation of plans orientations and models anisotropic diffuse radiation calculation

In Fig. 11, an overview of the numerical validation results for typical operation ranges is shown. There are only small deviations in the range less than 0.5 percent. In very extreme situations, like a collector stagnation temperature, deviations up to 3,0 percent may occur. However, they are not of importance and the question which of the models is closer to the realty remains unanswered.

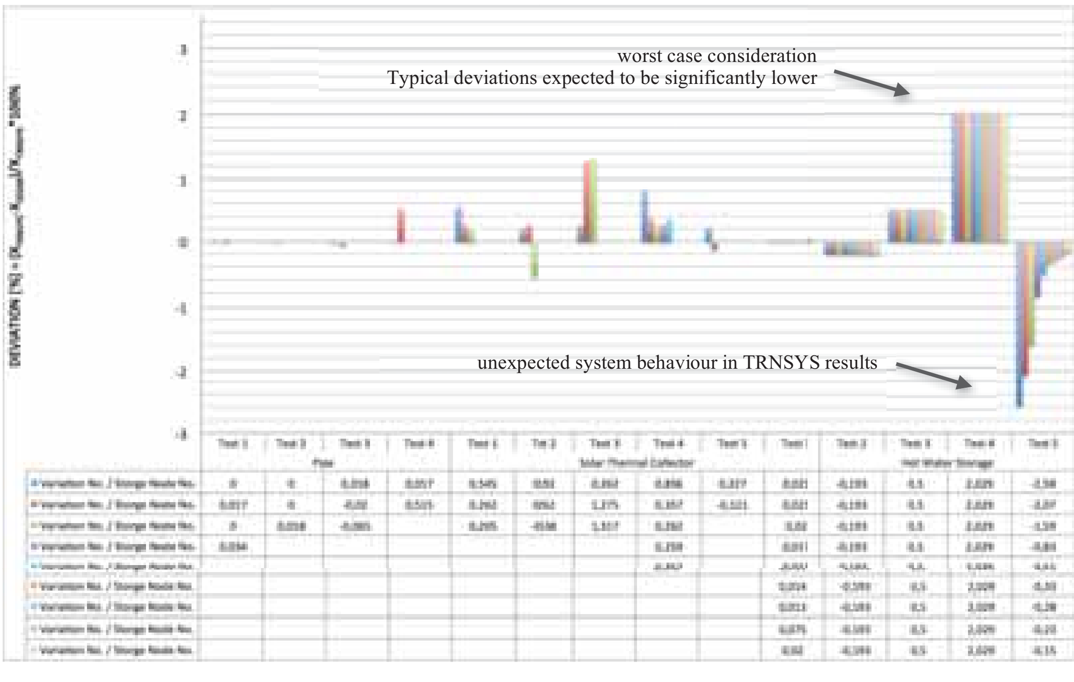

Fig. 11: Overview of the deviation in results for typical operation conditions. Tests according to Tab. 4.

5. Summary and conclusion

In this paper, a new type of flexible component-based simulation software for thermal, hydraulic and electric system simulations is introduced with many advanced methods from today's point of view. Among them, the measurement uncertainty of sensors and the controller can be modelled and investigated in interaction with the system in detail. The controller is freely programmable. Additionally, the basis for an automatic hydraulic circuit investigation is provided and can be further developed. The software can be used as stand-alone application, server-based or can even be implemented in other software. During a simulation, the component parameters can be changed. The simulation time step is variable. This tool enables a fast component or system modelling. In the software, a component library containing 15 flexible components is introduced. The components are analytically or numerically validated using TRNSYS 17 standard components. A detailed software manual containing detailed mathematical description and validation results of the components in more than 100 pages is available.

The development of this software took approximately one year of intensive programming. The experience shows that it is possible to further develop simulation tools with respect to the above named features, when considering these features from the first development steps of the simulation core and of the components. It is planned to use this software for some stand-alone and server based software applications. Three more sophisticated components will be finished by the end of spring 2016. The commercial use of MITHRA is possible but not available yet.

6. References and Acknowledgements

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DWD Deutscher Wetterdienst, BBR Bundesamt für Bauwesen und Raumordnung, Climate & Environment Consulting Potsdam GmbH., 2014. Handbuch Testreferenzjahre von Deutschland für mittlere, extreme und zukünftige Witterungsverhältnisse. Last retrieved August 26, 2015, from http://www.bbsr-energieeinsparung.de/EnEVPortal/DE/Regelungen/Testreferenzjahre/Testreferenzjahre/TRY_Handbuch.pdf

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