MODELING AND VALIDATION OF THE ENERGYbase SOLAR THERMAL COLLECTOR FIELD

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Synopsis

The next generation modeling language Modelica, in conjunction with the simulation tool Dymola, is currently used by the Sustainable Building Technologies (SBT) business unit in the Energy Department of the Austrian Institute of Technology (AIT) for the scientific support of the ENERGYbase office complex. As a first step, an appropriate model for the solar thermal collector array was created, calibrated and validated using Dymola as well as the Generic Optimization Tool (GenOpt) multipurpose optimization software, showing that a quite complex system can be simulated with adequate results using a simplified model and a reasonable amount of data.

1 Introduction

The ENERGYbase[1] office building is an office complex, housing several small companies, laboratories and a university of applied science in the 21st district of Vienna. It is certified to German “Passivhaus” standard. Employed technologies to achieve this low energy standard are solar thermal heating and cooling, heat pumps utilizing the aquifer below the building as well as a large photovoltaic array, placed on the façade sections which provide shading on the south side of the building.

The AIT provided scientific support during the planning phase, and is now advising the operators to further improve efficiency. To test alternative control strategies, dynamic models of all the major components are created in various software packages and validated using data from ENERGYbase building information system connected to nearly 500 sensors within the building and its HVAC system.

2 The collector field and its model

2.1 Solar thermal collector field and monitoring equipment

The solar thermal collector field of the ENERGYbase consists of 19 GREENoneTEC IMKXS fields installed in parallel configuration, totaling in an area of 284.4 m² (274 m² aperture). The approximate temperature of the collectors is measured by temperature sensors mounted on the back side of every other collector using thermal conductance paste, while the inlet and outlet temperatures are only measured for the whole system, around 15 meters away from the tee connection of the two main pipes distributing the media to the 19 collector fields. Readings for the mass flow rate in the primary loop are also recorded. All data are collected by the building management system, and stored into the Siemens Advanced Data Processing (ADP) database where the SBT business unit has constant access to the data.

Also connected to this database is a weather station on the roof of the ENERGYbase building, providing amongst other things temperature and radiation data for the exact position of the building,

2.2 The simulation model

The model of a solar collector computing the dynamic or steady-state response was developed in Modelica[2], based on existing models developed in other simulation tools specialized in solar system modeling[3,4]. The Modelica language is an open source modeling language, consisting of a language standard definition along with a large collection of basic model components from various fields, the so-called Modelica Standard Library. The Modelica language is built around the two basic concepts of algebraic and acausal modelling. This allows the user to specify his or her models using algebraic equations, either from literature or actually derived from the basic physical properties, and enter them directly into the simulation environment without the need of adaption to the algorithms behind the software. Furthermore, all models are a priori acausal, and allow taking phenomena like changing flow directions into account without having to specify them explicitly in the model. The Modelica language is implemented in several tools, from which Dymola was chosen for the implementation.

The efficiency η of a solar collector mostly depends on the difference between the outlet temperature of the collector (Tout) and the ambient temperature (Tamb) and is described by the following equation valid for glass-covered flat-plate collectors [5]:

$$\eta = c_0 - c_1 \cdot \frac{(T_{out} - T_{amb})}{G_k} - c_2 \cdot \frac{(T_{out} - T_{amb})^2}{G_k}$$

The efficiency rate parameters c_0, c_1 and c_2 are usually obtained by performing standard laboratory tests on the actual component. The total irradiated specific energy G_k is calculated as:

$$G_k = I_{beam} \cdot IAM(1 - GSC) + I_{diffuse}$$

where IAM is the incidence angle modifier, I_{beam} and I_{diff} are respectively the beam and diffuse components of the solar radiation and GSC represents the geometrical shading coefficient. The Modelica model enables the user to choose among different correlations, presented in [4], for the calculation of the incidence angle modifier.

The total heat flow rate $\dot{Q}$ impacting on the solar panels is given by:

$$\dot{Q} = A_c \cdot G_k \cdot \eta$$

where A_c is the total area of the solar collector panel. The equation governing the time evolution of the collector outlet temperature is finally given by:

$$dhc \cdot \frac{dT_{out}}{dt} = \dot{Q} + \dot{m} \cdot c_p (T_{in} - T_{out})$$

where dhc and c_p are the dynamic heat capacity of the collector and the specific heat capacity of water - the latter considered for simplicity's sake as function of the thermodynamic state of the fluid at the outlet only - and T_{in} and $\dot{m}$ are respectively the inlet temperature of the water and the mass flow rate.

As Dymola has a block oriented GUI, this solar collector model was connected to a table with the measured data, as well as with a mass flow source and sink and a block computing the mean square error between measured and simulated enthalpy flow rate.

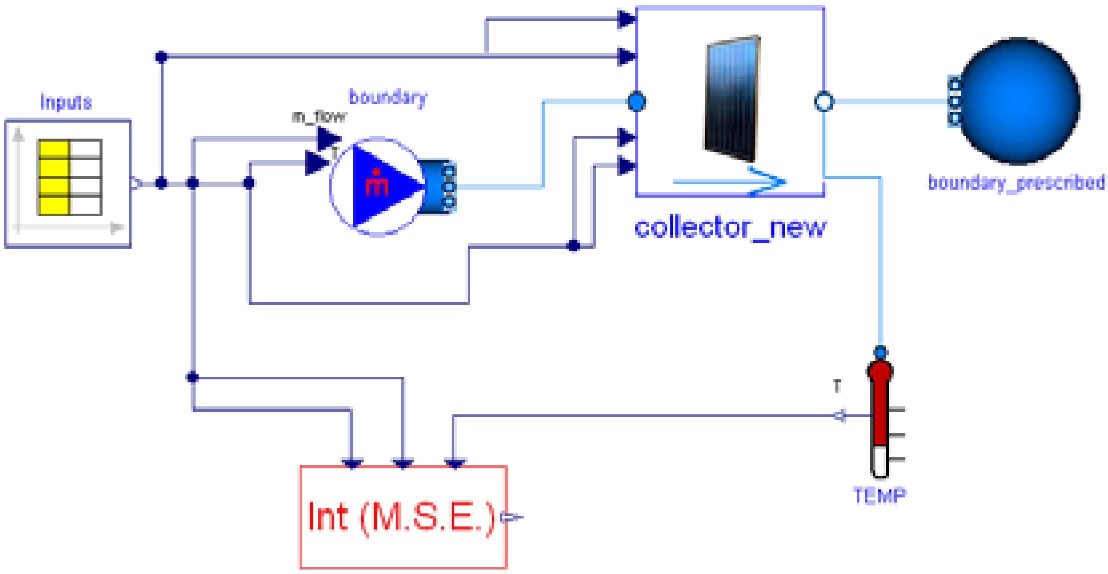

Figure 1: Complete Dymola model

2.3 Calibration

As only every second panel has a sensor, and the pressure valves of the individual field inlets were only adjusted manually without any documentation when the collector array was installed, the chosen approach was to model the whole collector field as a single array. The parameters with respect to the coefficients of the efficiency curve and the dynamic heat capacity will vary from the data given on the calibrations sheets and the data sheet of the individual collectors, as the adjustments lead to different actual mass flows in the single collectors, which may be far from optimal. Before performing the calibration process on the model, further simplifications turned out to be necessary: since the monitoring data available didn't include separate values for the beam and the diffuse radiation, but solely the global radiation, a fixed value of 1 was used for IAM and the value of GSC was set to 0. The term G_k appearing in the equations presented in the previous section is therefore equivalent to the global radiation input.

Based on this assumptions, the simulation model itself was calibrated, using the in- and outflow temperatures of the medium, the overall mass flow rate through the collector field and the climate data measured, with the goal of minimizing the error between the enthalpy flow rate measured by the sensor between solar thermal array and heat exchanger with the values computed by the simulation model.

GenOpt, a java-based open source optimization program developed by the LBNL, was used to implement the calibration. GenOpt communicates with simulation software through text files, using defined templates to provide input to the simulation software and reading the value of the target function from text files provided by the simulation software. It is able to utilize multi-core systems for better performance, which is very important as the current version of Dymola (7.4) is unable to do so. For this calibration

$$\int (H_{out} data - H_{out} simulation)^2 \, dt$$

was chosen as the target function.

Table 1: parameters obtained from the calibration

a1	c0	c2	dhc
3.53	$6{,}42 \cdot 10^{-1}$	$2{,}21 \cdot 10^{-3}$	$6{,}49 \cdot 10^{5}$

As the system to be calibrated has no discontinuities, the discrete Armijo gradient algorithm was chosen, as it is known to be stable and quite cost effective in terms of target evaluations needed. The calibration converged to the parameters shown in Table 1 after 173 iterations: Figures 2 and 3 show the temperatures and enthalpy flow rates at the outlet during the calibration period.

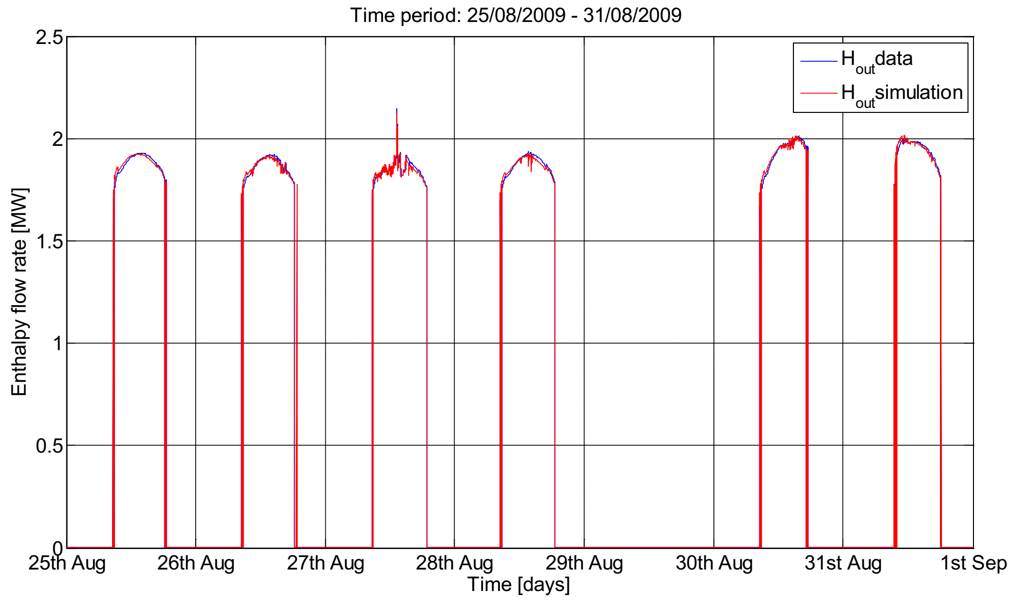

Figure 2: Comparison of enthalpy flow rates for the calibration period

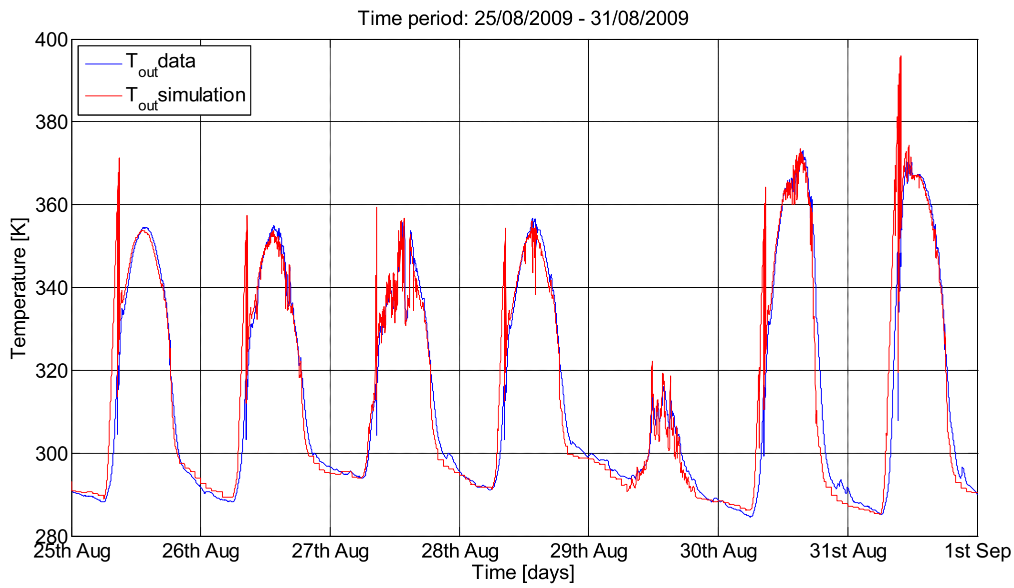

Figure 3: Comparison of temperatures for the calibration period

3 Validation and results

To proof that the parameters found by GenOpt represent the solar collector array not only for the week chosen for the calibration of the model, but are in general a good representation of the system, the system was simulated for a longer time period. As can be seen in Figure 4, the overall energy produced by the solar thermal collector array during August 2009 is nearly indistinguishable from the simulated results for the same time period, using again the data from the ADP database. Numerically, a gain of 368.36 MWh was measured, while the simulation result was 367.80 MWh, resulting in a relative error of only 0.15 percent.

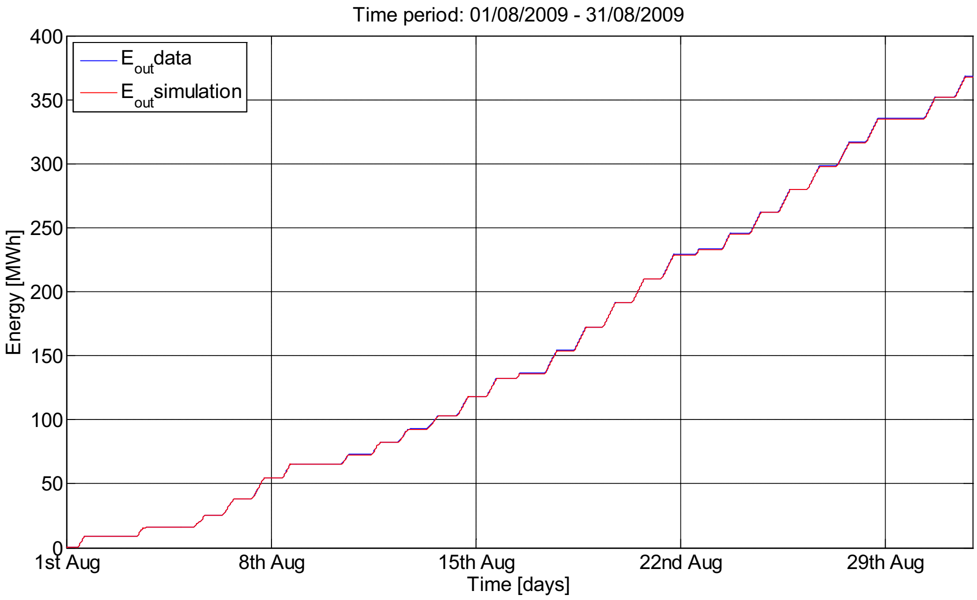

Figure 4: Simulated and measured energy match for the month of August

3.1 Conclusions and outlook

As shown by the validation, the behavior of the simplified model of the solar thermal collector field is close enough to the measured data in terms of energy to be used for forecasts and control refinement. A simulation model which would not simplify the collector field, but would take into account all 19 individual collectors would not only cause a 19 fold increase of simulation time, but would also require the availability of additional sensors. The resulting effort and expenses are not justified, especially as the long term goal of the modeling and simulation work done on the ENERGYBase is the implementation of weather predictive control, and the error produced by the simulation model is well within the range of accuracy reached by forecasts for temperature and especially solar radiation.

The next steps towards the weather predictive control mentioned above are models for the heat exchanger, the thermal storage and the control algorithms currently implemented. All of those are currently being developed by the Energy department.

[1] http://www.ENERGYbase.at

[2] http://www.modelica.org

[3] Velasolaris AG, POLYSUN Simulation Software User Manual, 2009

[4] Christian Hoffmann, Objektorientierte Simulation und Dynamische Optimierung von Energieversorgungsanlagen auf der Basis regenerativer Energien, 2000

[5] John A. Duffie, William A. Beckman, Solar Engineering of Thermal Processes, Third Edition, Wiley, John & Sons, Incorporated, 2006

[6] http://simulationresearch.lbl.gov/GO/