

MODELING AND OPTIMAL DESIGN OF A CENTRAL SOLAR HEATING PLANT WITH HEAT STORAGE IN THE GROUND USING MODELICA

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Abstract

The paper discusses the modeling of a central solar heating plant with seasonal storage in the ground using the new object-oriented physical systems modeling language Modelica. Main emphasis is put on the hierarchical decomposition of the system model and on the re-engineering of an existing Fortran code for the ground store model. The object-oriented physical system model is compiled to a mathematical description in the form of ordinary differential equations (ODE). The ODE model is used to formulate and solve nonlinear optimization problems. We show design optimization results obtained for given weather conditions in Switzerland. The heating system is designed to cover the annual load of a housing area for space heating of about 500 MWh to 95% by solar. The optimization results have been validated with the help of initial-value simulations using TRNSYS, a special-purpose simulation software for thermal energy systems.

1 Introduction

Seasonal heat storage in the ground is an important opportunity for a more efficient use of energy. The idea is to store thermal energy when it is available and to use it when it is needed. Many different thermal processes and their mutual interaction have to be considered, if a ground heat store is integrated with energy systems. Advanced design tools are required in order to obtain cost-effectiveness. Related system studies are normally done with the help of detailed computer simulations.

A widely used special-purpose modular simulation software for solar energy systems is TRNSYS. Often hundreds of initial-value simulations with varied parameter values of the system components have to be performed in order to optimize a system design, see e.g. [7]. The total number of needed calculations strongly increases with the number of free parameters. That is why the approach is no longer practicable for complicated optimization problems. On the other hand, the successful application of mathematical optimization procedures to complex system models is burdened with two things: a mathematical optimization problem has to be formulated and an appropriate solver is needed. The use of the new object-oriented physical systems modeling language Modelica [1] and of an advanced optimization solver [3] simplify the application of mathematical optimization to detailed models of dynamic systems considerably.

This paper discusses, how the features of the general-purpose physical systems modeling language Modelica can be exploited to implement a complex heating system model efficiently. The model is used to solve a design optimization problem. As an example we treat a design case from [7]. In this way we are able to compare our results with the comprehensive TRNSYS simulations done there.

2 The System Model

Figure 1 shows the structure of the system, whose model implementation in the object-oriented language Modelica is discussed in this section. The system can be divided into three subsystems: a

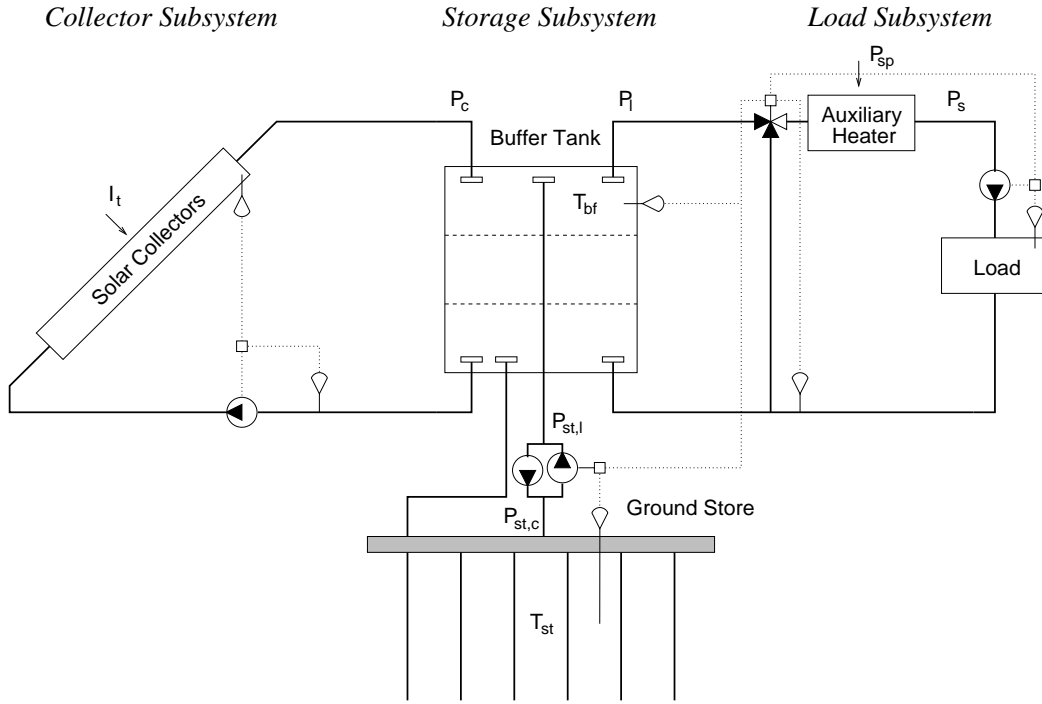


Figure 1: Structure of a central solar heating plant with seasonal duct store.

collector subsystem, a storage subsystem, and a load subsystem. Each subsystem is further subdivided, e.g. the store into a buffer tank and a duct ground store. The system is intended to collect and store solar energy during summer time and to use it for space heating in a housing area during winter time. An auxiliary heater supplements the solar energy in order to fully cover the load.

2.1 Interfaces

First we define interfaces and an abstract system model. The according Modelica code is listed in Figure 2. We are mainly interested in the energy balance of the system. Accordingly a `HeatingConnector` for the interconnection of several components is modeled by using variables and parameters that are needed to describe the transport of energy with a heat carrier fluid. That is the fluid temperature T , the mass flow rate q_m , and the specific heat capacity of the fluid c_p . The used types are predefined in the standard package `Modelica.SIunit`.

Many components have two connectors, one inflow and one outflow. Examples are the collector model and the load model. A `HeatingTwoPort` serves as common base class. The storage model has four ports: two for the collector loop and two for the load loop. Using the base classes `LoadModelShell`, `CollectorModelShell`, and `StorageModelShell` for the three main subsystems, the abstract solar heating model `SolarHeatingModelShell` can be defined. The specialization of the system components is discussed in the following subsections.

2.2 The Duct Ground Store

The model described here is based on the DST model [6], which is currently available as Fortran and Pascal version and which has a size of about 100 KB source code. Using the high-level features of Modelica, an efficient re-engineering of the model has been possible. The new implementation is divided into several subcomponents to consider convective and conductive thermal processes in the ducts and in the store, respectively.

```

connector HeatingConnector
  Temperature      T;
  flow MassFlowRate qm;
  SpecificHeatCapacity cp;
end HeatingConnector;

partial model HeatingTwoPort
  HeatingConnector a, b;
end HeatingTwoPort;

partial model LoadModelShell
  = HeatingTwoPort;

partial model CollectorModelShell
  = HeatingTwoPort;

partial model StorageModelShell
  HeatingConnector al, bl "load loop";
  HeatingConnector ac, bc "coll loop";
end StorageModelShell;

partial model SolarHeatingModelShell
  LoadModelShell lm;
  CollectorModelShell cm;
  StorageModelShell sm;

equation
  // load loop
  connect(sm.bl, lm.a);
  connect(lm.b, sm.al);

  // collector loop
  connect(sm.bc, cm.a);
  connect(cm.b, sm.ac);
end SolarHeatingModelShell;

```

Figure 2: Connector and model interface definitions for a solar heating system model

In a duct store, an array of boreholes is drilled vertically into the ground. Water is used as heat carrier fluid and is circulated through these ducts in order to exchange heat. In the model, the store is divided into a number of sections (6 in our case). One representative duct component is defined for each section.

The main model complexity is caused by the spatially distributed thermal process in the ground, which can be described for constant thermal properties by the heat equation

$$\frac{1}{a} \frac{\partial T}{\partial t} = \nabla^2 T \quad (1)$$

with T the ground temperature and a the thermal diffusivity. The method of finite differences is a famous tool to treat partial differential equations (PDE) of the form (1) numerically by calculating the temperature field at several grid points. However, the number of temperature variables introduced in this way can be very high. In order to keep the model complexity as small as possible, we first divide the total thermal process in the ground into two subprocesses: a small-scale local thermal process around each duct and a large-scale global thermal process in the overall store. Each subprocess is treated separately. The total thermal process is given by superposition of the subprocesses.

One component for the local thermal process is defined for each section of the storage model and is attached to the corresponding duct component. Considering the radial temperature distribution around the duct during heat injection or extraction, the model can be implemented by a radial, one-dimensional mesh of ground cells (e.g. 10 cells per component). But after a comparable short time of operation (some days) it can be seen that the shape of the local temperature field will become steady. Furthermore the small-scale dynamics in the ground is damped by the buffer tank. Neglecting the time variation, the dynamic model for the local thermal process can be replaced by an analytical description of the local temperature field under steady-flux conditions. Accordingly the heat transfer is assumed here to occur via time-invariant thermal resistances between the ducts and the ground store volume. The resistances are given by a logarithmic function of the duct spacing, see [5].

The large-scale thermal process in the ground is modeled by a rectangular mesh of a few hundred ground cells. In system simulations we are mainly interested in the interaction between the defined

storage sections and the resting system. The actual temperature distribution in the ground, as approximated by the mesh, is of less importance. That is why we are applying model order reduction to the state-space model describing the temperature field in the ground. In the example discussed here, the number of temperature variables could be reduced from 220 to 15 by applying a singular perturbation approximation, see e.g. [8].

2.3 The Water Tank

The buffer tank is modeled by three uniformly mixed water layers. Each layer is described by one temperature variable and an energy balance equation taking into account water inflows, water outflows, and conductive heat transfers with neighboring layers and with the environment. The natural convection inside the tank is modeled by nonlinear conductances between neighboring layers using an arc tangent function. Variations of the buffer tank volume influence heat capacities and heat losses of the layers.

2.4 The Solar Collector Array and the Heat Load

In order to simplify this study, we use TRNSYS as preprocessor together with the solar collector subsystem and the load model developed in [7].

The solar collector subsystem is simulated for a number of constant fluid temperatures over the year. Afterwards the specific gained energy and the circulated water amount are approximated for periods of 3 hours by cubic polynomials using the fluid temperature as free variable. The total collector area is used as multiplier.

The heat load as well as the fluid forward and return temperatures in the load model are calculated as functions of the ambient temperature.

3 System Optimization

With the help of the object-oriented modeling tool we automatically compile a mathematical system model of the form

$$\dot{\mathbf{x}}(t) = \mathbf{f}[t, \mathbf{x}(t), \mathbf{z}(t), \mathbf{p}], \quad \mathbf{x}(t_0) = \bar{\mathbf{x}}(t_0). \quad (2)$$

The state variables $\mathbf{x} \in \mathbb{R}^{n_x}$ are 24 temperatures and 6 energy quantities. An additional state is used to integrate violations of a given limit by the buffer temperature. The disturbances $\mathbf{z} \in \mathbb{R}^{m_z}$ are the weather conditions during the year. The time-invariant parameters $\mathbf{p} \in \mathbb{R}^{m_p}$ are the collector area, the buffer tank volume, the duct store volume, and the duct spacing. The model is translated into C-code as it can be imported by the applied optimization tool.

The optimization problem is to find the minimum-cost system design that fulfills a given solar fraction, i.e. that supplements a given fraction of the total heat load by solar, during the operational period $[t_0, t_1]$ of one year. The system costs are described by the cost function

$$J[\mathbf{x}(t_1), \mathbf{p}] \rightarrow \min_{\mathbf{p}}, \quad J : \mathbb{R}^{n_x} \times \mathbb{R}^{m_p} \mapsto \mathbb{R}^1, \quad (3)$$

which includes prices for the solar collector array, the buffer tank considering cost decreases for larger volumes, and the duct store considering e.g. drilling costs, land area costs and piping costs. Furthermore we added a term to consider the energy needed for the thermal build-up process of the ground store during the first years of operation. We are interested in a solution that minimizes J subject to the system model behavior (2) and additional constraints of the form

$$\mathbf{c}_l \leq \mathbf{c}[\mathbf{x}(t_0), \mathbf{x}(t_1), \mathbf{p}] \leq \mathbf{c}_u, \quad \mathbf{c} : \mathbb{R}^{n_x} \times \mathbb{R}^{n_x} \times \mathbb{R}^{m_p} \mapsto \mathbb{R}^m. \quad (4)$$

One final state constraint results from the solar fraction. Other constraints are restrictions on the design parameters and on the state trajectories, e.g. to avoid boiling. Moreover we do not know initial values for the 24 storage temperatures $\bar{\mathbf{x}}_T(t_0)$ at the beginning of the year. They are the result of the thermal build-up process. That is why the initial temperatures are not fixed, but they are defined with the help of the equalities

$$\bar{\mathbf{x}}_T(t_0) = \mathbf{x}_T(t_1). \quad (5)$$

The solution we are specifying in this way is called the steady-state operation of the system.

The nonlinear, constrained optimization problem (2)–(4) is solved numerically with the sequential quadratic programming (SQP) software Omuses [3]. The optimization algorithm requires sensitivities of the system equations (2), the criterion (3), and the constraints (4) with respect to the parameters and the unknown initial states. They are calculated internally by the solver by using automatic differentiation. The system equations (2) and their extension by sensitivity equations are solved numerically with the procedure RKsuite, which is available in the Netlib.

4 Case Study

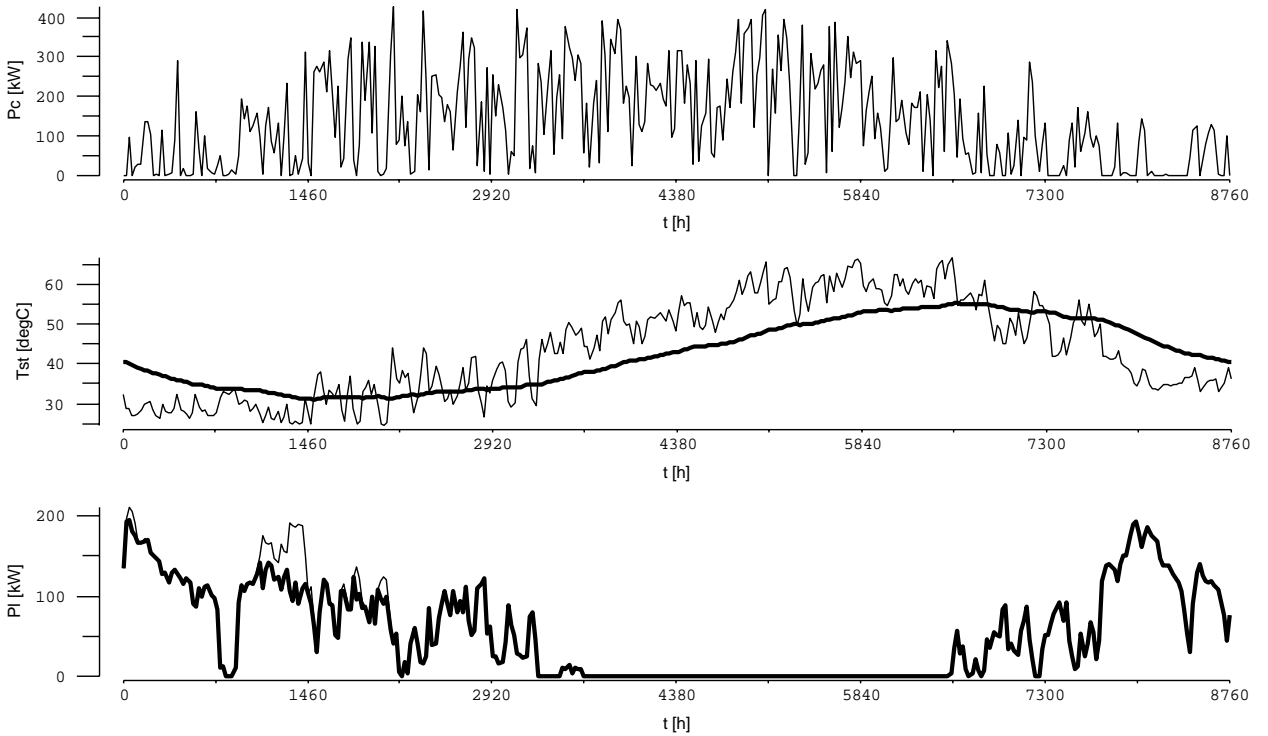


Figure 3: Simulated daily mean values for a solar fraction of 95% in steady state operation. The diagrams show the collected solar heat P_c , the average temperatures T_{bf} of the buffer tank and T_{st} of the ground store (thick), as well as the heat load P_s and the solar contribution P_l (thick).

We apply the methodology to the low temperature case of the study [7]. The system has a total annual heat load of 500 MWh corresponding to 120 housing units. The heat is only used for floor space heating. Weather data and prices for Geneva, Switzerland are assumed.

In [4] we have discussed optimization results for a solar fraction ranging from 40% up to 100% assuming 25 years of operation and an annuity factor of 0.1. There we used a version of the model formulated in the modeling language Omola. However, the compiled ODE-model is identical to the

one used here. According to the results, there is almost no cost increase for solar fractions up to 95%. The solar cost is less than 325 CHF per MWh.

Figure 3 shows the steady state behavior of the system for a solar fraction of 95%. The seasonal heat store has to bridge the gap between availability of solar energy during summer time and the need for space heating during winter time. It can be seen, how the large ground store and the small buffer tank inter-operate in order to fulfill this task efficiently. The supplementary heat is mainly needed in February. The optimal system parameters have been validated with the help of TRNSYS simulations.

5 Conclusions

Modern algorithms can considerably improve the efficiency of computer simulations. Here we successfully solved a design optimization problem for a sophisticated system model. Other areas of application of the method are nonlinear parameter estimation and optimal control, see e.g. [2].

The modeling done in this study is concentrated on seasonal heat storage. The use of the general-purpose high-level modeling language Modelica and the exploitation of automated symbolic processing of model equations simplify the model development and allow the efficient application of recently developed mathematical algorithms to complex dynamical system models.

The main goal of the re-engineering done for an existing Fortran code of the ground store model has been to reduce the model complexity in system simulations. New features introduced in the Modelica version are the description of small-scale thermal processes by analytical expressions and the application of model order reduction to the state space model of the large-scale thermal process in the ground. Such modifications can be expressed in Modelica by replacing submodels with alternative implementations. As the treatment of PDEs is not yet covered by Modelica, a model generator program has been developed that generates a numerical mesh and performs the model order reduction.

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