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Analysis of thermal storage systems using Modelica

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Abstract

Modelica is used for the analysis of different kinds of thermal storage system for applications in power plants and process industry. The analysis includes concepts using sensible heat storage media, latent heat systems and steam accumulators. The temperature range for these systems is between 200°C – 400°C, the maximum thermal power is 100MW. For the various storage systems physical models are implemented in Modelica. Modelica is also used for system analysis simulating the interaction of the storage unit with the other components. The results of this system analysis help to improve the efficiency y of storage systems significantly.

Keywords:thermal energy storage; solar power plant; steam accumulator

1 Introduction

Thermal energy storage systems are a promising option for improving the efficiency of power plants and process heat utilization in industry. These systems represent an additional tool for energy management in thermal processes by bridging the gap between demand and availability of energy. At the present time the range of proven storage systems for providing thermal energy at temperatures exceeding 100°C is limited. Various solutions have been proposed, the selection of a concept strongly depends on the characteristics of the process. The aim of current research project is to develop storage systems for commercial applications. For three different basic storage concepts Modelica is used to identify the interaction of the storage unit with the other components of the systems. Using models from the library TechThermo Modelica proves to be an effective tool for the analysis of the dynamics of energy storage systems.

2 Storage systems for solar thermal power plants

2.1 Storage systems using sensible heat

Solarthermal power plants use concentrated solar insolation to drive a thermodynamic power cycle [1]. Today's commercial systems use trough shaped mirrors to heat a synthetic oil flowing in absorber pipes located in the focus line (Figure 1). At temperature up to 390°C the heat transported by the oil is used to generate steam to drive a turbine. The total electric capacity of these parabolic trough power plants operated in California is 350MW, by continuous optimisation the costs for electricity have been reduced to 0,14US$/kWh, so parabolic trough power plants are the most economic system for large scale generation of electricity from solar energy.

Figure 1: Parabolic trough collectors at solar test center near Almeria, Spain.

In recent years significant research activities have been initiated in Europe to improve the parabolic trough technology to promote a market introduction in areas like the Mediterranean region. Important components for increasing the efficiency of these solarthermal systems are systems for the storage of thermal energy. These storage systems help to reduce the dependence on the course of solar insolation.

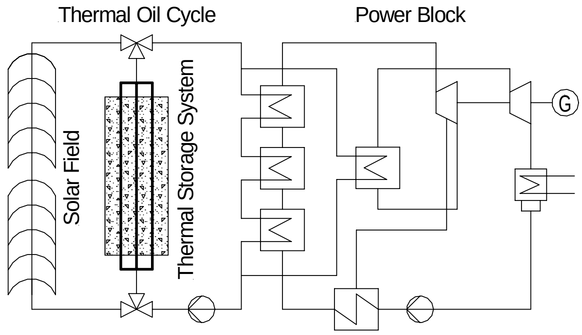

Figure 2: Schematic of parabolic trough power plant with integrated storage unit

One storage concept is based on sensible heat storage in solid media [2]. A tubular heat exchanger is integrated into the storage volume. During the charge process, hot oil from the solar collectors is used to heat up the storage mass; during the discharge cycle cold oil enters the storage unit and is heated up. Modelica is used for the simulation of the storage unit [3]. The results provide the basis for the design of a storage test facility and are applied for the development of operation strategies. This proves to be an ideal application of Modelica since

- the system combines a detailed physical model (spatial discretized storage unit) with less detailed models for the power cycle and the solar collectors
- Modelica allows continuous and discrete event modelling which is necessary for the analysis of the transition from charging to discharging
- the characteristic duration of a charge/discharge cycle is in the range of 24 hours; the computing time needed by Modelica is less than 0.1% of the simulated time interval.
- the analysis requires modifications of the structure of the power plant. The graphical interface of Modelica allows a quick variation of the number and interaction of components.
- although the storage unit represents a non-conventional component, it can be modelled by combination of well known fundamental physical processes; the extent of required additional modelling is small

TechThermo was used for the modelling of the storage unit integrated in the parabolic trough power plant. More than 90% from the lines forming the source code the complete model were taken from TechThermo; the additional modelling mostly defines characteristics of the charge/discharge process. Figure 3 shows the first model level representing the complete power plant with the three main components and a control unit that defines the mass flows in the system. The focus of the analysis lies on the storage model. Due to economic aspects low cost materials like concrete are used as storage mass. Since these candidate materials usually exhibit low values for heat conductivity the temperature of the storage mass is not homogenous.

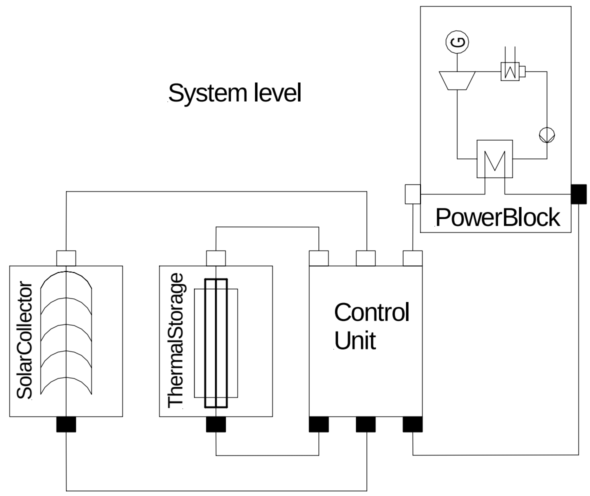

Figure 3: Main components of the Modelica model of parabolic trough power plant with integrated storage unit

Figure 4 shows the model of the storage unit: the system is assumed to be composed of parallel tubes surrounded by storage material, the radial temperature distribution and the flow field inside the tube should be identical for all tubes at the same axial position. Since characteristic lengths of the storage unit are in the range of about 500m the assumption of a radially symmetric temperature distribution around the tubes is necessary to avoid a significant increase in computing time resulting from a three dimensional calculation of the temperature inside the storage mass. The errors resulting from this assumption seem to be acceptable. The storage tube is discretized in axial direction. Modelica offers the declaration of arrays of components which are interconnected, spatial discretization is done by connecting models for a storage segment of length dz in series. The number of elements depends on the length of the storage unit and varies between 50 and 100. The build up of the model of the storage segment is shown. The model is composed of a model for the fluid volume, the tube and the surrounding storage material, heat is transferred between these three models in radial direction. There is also a heat and mass flow in axial direction to the neighbouring segments. The model for the surrounding storage material includes a spatial discretization in radial direction to account for the limited thermal heat conductivity of the storage mass.

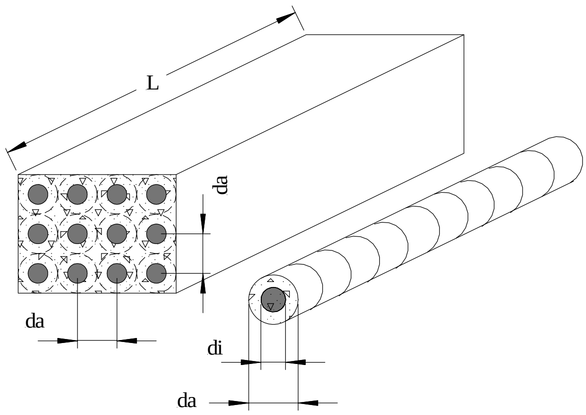

Figure 4: Physical storage model composed of parallel tubes discretized in axial direction

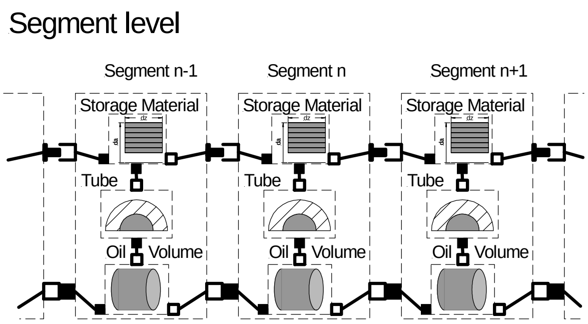

Figure5: Cut-out of the model of a single pipe of the storage system discretized in axial direction by serial connection of models for a pipe segment

Figure.5 shows the internal build up of the model for the fluid volume: the model is composed of a component including the conservation laws for mass and energy, two models calculating friction pressure loss and a model for the convective heat transfer between fluid and tube wall. These components are completed by a property model providing the correlations between the thermal state variables.

The storage model was used to identify the influence of material and geometry parameters and provide the basis for an economic optimisation. Figure 6 is an exemplary diagram for the time course of temperature at various radial positions in the storage material. The simulated time interval includes a charge cycle, a break and a discharge cycle.

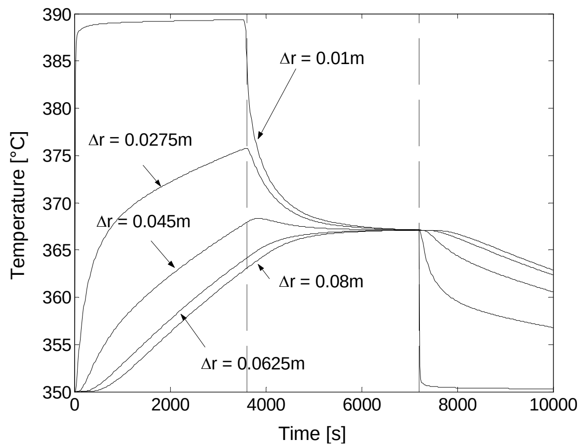

Figure 6: Example for results of storage simulation: temperature of storage material at various radial positions

The energy provided by the storage unit during discharge is used to generate electricity, so the analysis has to consider the transformation of heat into mechanical work by the Rankine cycle. The Rankine cycle demands heat at different temperature levels, the temperature of the oil flowing back to the storage unit is also dependent on the temperature of the oil at the exit of the storage unit. Modelica was used for the simulation of the complete power plant including storage and solar collectors. Figure7 shows the electric energy provided during the discharge process for different configurations of the storage unit. The total storage mass remains constant. The Modelica results show that an optimised operation strategy can lead to an increase of storage capacity of about 200%. This improvement is achieved by an adjustment of the storage unit to the specific requirements of solar collectors and the power cycle [3].

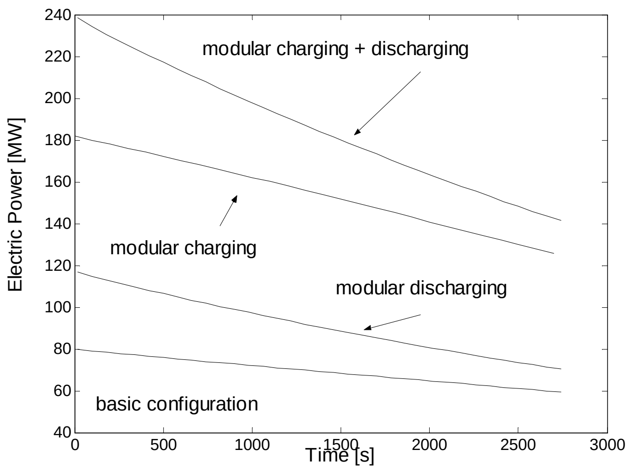

Figure7: Example for system simulation: electric power provided by the power plant during the discharge process.

The identification of this option to reduce the investment costs for the storage unit was mainly possible due to the simulation results.

2.2 Storage systems using latent heat storage media

Solarthermal power plants using thermal oil as heat transfer medium in parabolic trough absorber pipes have been optimized in recent years, a further progress demands the modification of the basic principle. The direct steam generation (DSG) in the absorber-pipes improves the efficiency of the parabolic trough technology by eliminating the synthetic oil and the heat exchanger and increasing the maximum process temperature [4]. The estimated reduction in electricity generation costs is in the range of 25%.

In DSG systems more than 50% of the thermal energy is needed for the evaporation process which takes places at nearly constant temperature. Regarding second law efficiency, a DSG system must be able to store and release thermal energy at nearly constant temperature, sensible storage systems can't be used. Instead, the utilization of latent heat from the melting / solidification process seems a promising concept for constant temperature storage systems.

First concepts for latent heat storage systems a similar to the sensible heat storage systems using concrete: a heat exchanger is embedded in the storage material (phase change material - PCM). Instead of the thermal oil, steam flows in the heat exchanger.

Modelica is also used for the initial analysis of the PCM –storage system. The first model is a modified version of the model for sensible heat storage: the concrete storage material is replaced by the model for the PCM storage material, the thermal oil in the pipe volume is replaced by a steam flow. Due to the reuse of already existing models, the development time for the first model of the PCM storage model could be reduced significantly.

3 Steam accumulator systems

Due to its high volumetric heat capacity and low mass specific costs water represents an ideal storage medium. Unfortunately, it can't be applied under atmospheric conditions at temperatures exceeding 100°C. In order to extend the application range of water based thermal storage system, water was stored in pressurized vessels to increase the saturation temperature. These storage systems are called steam accumulators since usually they are intended for supplying saturated steam [5].

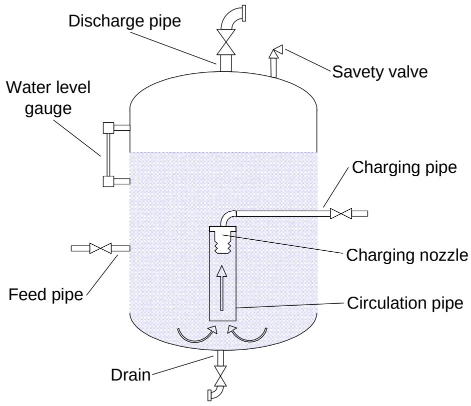

Figure 8: Cross section steam accumulator

Figure8 shows the cross-section of a steam accumulator. Most of the volume is filled by the liquid phase that is covered by the saturated steam phase at the top of the vessel.

Both phases are in thermodynamic equilibrium. If the steam is discharged directly from the accumulator, steam is produced by evaporation from the boiling liquid part. The latent heat of evaporation is cooling down the content of the storage vessel. This leads to a new thermodynamic equilibrium and accordingly to a lower pressure. To charge the accumulator steam is brought into intimate contact with the water content, in order to distribute the heat, released from the condensing steam, uniformly throughout the liquid.

The main parts of a steam storage installation are:

- Storage vessel for holding the storage medium
- Devices for charging and discharging the steam
- Accessories for carrying out the storage operation
- Regulators for the automatic control of the storage installation

Storage Vessels

The production costs of the vessel are the most important item in the total cost. For this reason the design of the storage vessel is central to the layout of the installation as a whole. The best shape provides minimum weight, is simplest to produce and takes up the least floor space. From considerations of strength the storage vessels are best made circular in cross-section, i. e. their basic shape is that of a cylinder. The ends are elliptic or hemispherical in shape. In practice an average length-to-diameter ratio of 4 has been found to be the best.

3.1 Charging and Discharging Devices

Indirect steam accumulators use a liquid as the storage medium, so that the steam must be condensed to be stored. This can be achieved by blowing it into the liquid contained in the accumulator. The incoming steam bubbles condense in the liquid or pass into the steam space, depending on the thermodynamic equilibrium in the vessel. The bubbles which rise to the steam space increase the pressure and lead to a higher saturation temperature, so that the next bubble might condense. To use the entire storage content, the charging process requires circulation. Ruth invented a method that consists of nozzles which turn the flow of steam upwards. The nozzles are surrounded by a circulation pipe, wherein the water flows upwards. The minimum temperature loss is composed of the difference between the steam space and the uppermost liquid layer and the difference between the saturation temperatures due to the additional pressure of the water at lower depths. Depending on the accumulator pressure and the steam intake there is a certain depth for the nozzles which minimizes the overall temperature loss. To avoid introducing charging steam into the storage vessel itself an external condenser and evaporator can be used.

3.2 Accessories

All storage installations require efficient thermal insulation to reduce cooling losses to an economic level. The fittings on the pressure vessel itself are the safety valve, the anti-vacuum valve and the blow-down valve. The thermal expansion of the vessel can be considerable in all directions and simultaneous adjustment must be provided in the piping by smooth or curved pipe bends or by bellow-type compensators. Measuring instruments for indicating the charging state in the accumulator are of special importance.

3.3 Regulators

To maintain a certain state in the accumulator or in the piping system regulation by valves is required. The regulator can be acting as a reducing valve, opening with falling pressure in the downstream controlled piping. It can also be acting as an overflow valve with increasing pressure in upstream controlled piping.

Figure 9 shows the Modelica model for the varying-pressure accumulator. The central part of the model is the vessel. In the vessel the mass and energy balance for an open control volume is solved. The volumetric and caloric properties are calculated within the equation of state model that is connected to the vessel model via a thermal state connector. All connectors are defined in the TechThermo library. To represent the mass of the vessel shell a heat capacity is connected due a thermal resistance to the vessel. The pressure loss of the mass flow during charging the accumulator is represented by two models. The first is used to calculate the static pressure increase below the water line in the vessel. The second model computes the pressure loss of a flow due friction with a coefficient called Zeta.

3.4 Simulation Model and Results

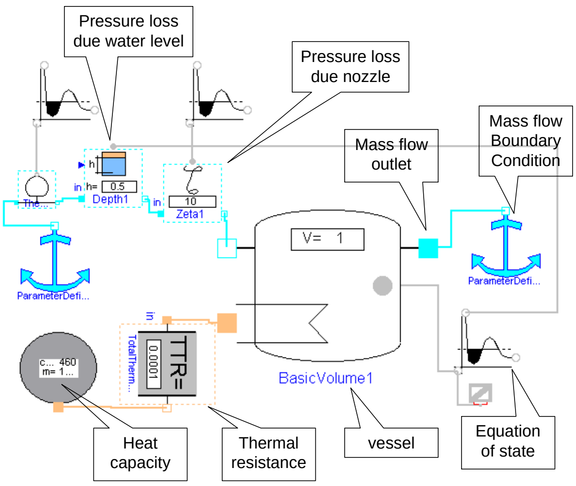

Figure 9: Modelica model of steam accumulator

3.5 Mass and energy balance in the vessel

The energy equation for a control volume that relates energy and mass flows has following form

$$\frac{dE}{dt} = \dot{m}_{in} \cdot \left(\frac{w_{in}^2}{2} + g \cdot z_{in} + u_{in} + \frac{p_{in}}{\rho_{in}} \right) - \dot{m}_{out} \cdot \left(\frac{w_{out}^2}{2} + g \cdot z_{out} + u_{out} + \frac{p_{out}}{\rho_{out}} \right) + \dot{Q} - \dot{W}_e$$

If we assume that the changes in kinetic and potential energy are zero and there is no external work we obtain an equation for the internal energy of the control volume

$$\frac{dU}{dt} = h_{in} \cdot \dot{m}_{in} - m_{out} \cdot \dot{m}_{out} + \dot{Q}$$

Conservation of mass means that the change of mass in the control volume must equal the difference between the mass entering the system and the mass leaving the system

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

The specific internal energy in the control volume consists of the internal energy of the liquid part and the internal energy of the vapour part

$$u = (1-x) \cdot u_{liq} + x \cdot u_{vap}$$

with the steam quality x in the following form

$$x = \frac{m_{vap}}{m_{liq} + m_{vap}}$$

3.6 Thermophysical properties of steam

The volumetric and caloric properties are calculated with the Soave-Redlich-Kwong cubic equation of state, the departure function for the cubic equation of state, the Antoine saturation pressure correlation and the enthalpy of the ideal gas. The results are within an error of 5 %.

A closed system that consists of a liquid and its vapour in thermodynamic equilibrium has 1 degree of freedom. So if e.g. the temperature is known the pressure, the enthalpy, etc. can be calculated in the following way.

For a known temperature the pressure is given by the Antoine pressure correlation

$$\ln(p) = A_A - \frac{B_A}{T + C_A}$$

With the known temperature and the calculated pressure the specific volume of the liquid part and the vapour part is received from the Soave-Redlich-Kwong cubic equation of state

$$p = \frac{RT}{v-b} - \frac{a(T)}{v(v+b)}$$

by rearrangement to the normal form

$$v^3 - \left[\frac{RT}{p}\right] \cdot v^2 + \left[\frac{a(T) - RTb}{p} - b^2\right] \cdot v - \left[\frac{a(T)b}{p}\right] = 0$$

and using Cardano's method. R and b are material dependent constants. a(T) is a temperature dependent variable.

The enthalpy is estimated with the departure function for the Soave-Redlich-Kwong cubic equation of state

$$h - h^\circ = \left[T \cdot \frac{\partial a(T)}{\partial T} - a(T)\right] \cdot \frac{1}{b} \cdot \ln\left(\frac{v+b}{v}\right) - \frac{a(T)}{v+b}$$
$$+ R \cdot T \cdot \left(\frac{v}{v-b} - 1\right)$$

and a polynomial equation for the enthalpy of the ideal gas

$$h - h_{T_0} = A_{IG}(T - T_0) + \frac{B_{IG}}{2}(T^2 - T_0{}^2) + \frac{C_{IG}}{3}(T_3 - T_0{}^3)$$
$$+ \frac{D_{IG}}{4}(T_4 - T_0{}^4)$$

For the enthalpy of the liquid part the results are not satisfying. A better approach is to calculate the latent heat of evaporation and subtract it from the enthalpy of the vapour. The latent heat of evaporation is received from the Antoine vapour pressure correlation in combination with the Clausius-Clapeyron equation

$$\Delta h_{lv} = \frac{B_A \cdot \Delta v_{lv}}{T} \cdot \left(\frac{T}{T + C_A}\right)^2 \cdot e^{A_A - \frac{B_A}{T + C_A}}$$

The differentiation between the state of superheated steam and the state of wet steam is realised by an if-clause.

```
if (x > 1 and p < p_sat) then
   x = 1;
else
   p = p_sat;
end if;
```

If the steam is superheated the steam quality x is fixed to 1. Else the system pressure is calculated with the saturation pressure correlation.

3.7 First Results

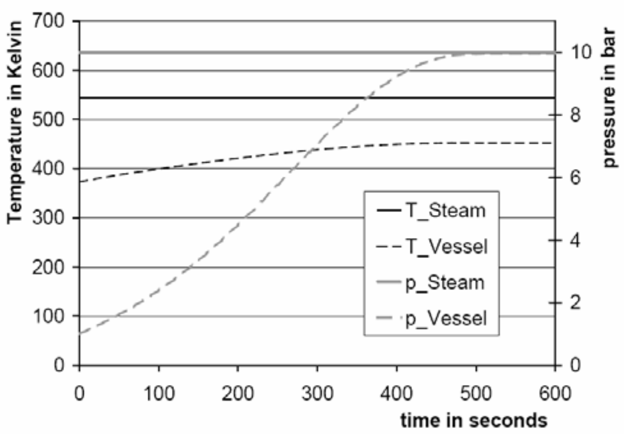

Figure 10: Temperature and pressure rise in steam accumulator during charging process

In Figure 10 first simulation results of the varying-pressure accumulator model are shown. The vessel is charged with superheated steam at a temperature of about 550 Kelvin and a pressure of 10 bar. The initial temperature of the vessel is 373 Kelvin. If the vessel is in thermodynamic equilibrium the temperature of the vessel will not exceed the saturation temperature belonging to the pressure in the vessel. As it can be seen, limiting for the charging procedure is the pressure of the superheated steam. A bigger amount of energy could be stored if an indirect charging device is used.

4 Conclusions

In particular the results of the system analysis of storage units prove to be a very useful tool for the optimization. For a selected application, the thermal energy provided by the storage system must be evaluated regarding the requirements of the specific process. Often, the duration of a charging / discharging cycle often exceeds durations of 24h. The capability of Modelica to simulate efficiently the transient behaviour of systems over such periods offers an important option for optimization.

Further development will also include steam accumulator with integrated phase change material. This concept is intended to increase the storage capacity of steam accumulators. Here, most of the needed models are already available from the current simulation projects.

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