DYNAMIC SIMULATION OF A SOLAR TOWER SYSTEM WITH OPEN VOLUMETRIC RECEIVER - A REVIEW ON THE VICERP PROJECT -

Tobias Hirsch[1] , Nils Ahlbrink[2], Robert Pitz-Paal[2], Cristiano Teixeira Boura[3], Bernhard Hoffschmidt[3], Jan Gall[4], Dirk Abel[4], Vera Nolte[5], Manfred Wirsum[5], Joel Andersson[6], Moritz Diehl[6]

[1] German Aerospace Center (DLR), Solar Research, Stuttgart (Germany): tobias.hirsch@dlr.de

[2] German Aerospace Center (DLR), Solar Research, Cologne (Germany)

[3] University of Applied Science, Solar Institut Jülich, Jülich (Germany)

[4] RWTH Aachen University, Institute for Automation Control, Aachen (Germany)

[5] RWTH Aachen University, Institute for Power Plant Technology, Steam and Gas Turbines, Aachen (Germany)

[6] K.U. Leuven, Electrical Engineering Department, Leuven (Belgium)

Abstract

The paper presents an overview on the modeling and simulation activities of the virtual institute for central receiver power plants (vICERP). Within a three years launch period models and tools for dynamic simulation of central receiver power plants have been developed by the five research institutes involved. The models are based on the Modelica modeling language. Today, models for the heliostat field, the receiver, the air cycle, the thermal storage, and the water-steam cycle are available within the consortium. As a first application, the Solar Tower Jülich technology was used as a reference. Models are validated with real operational data from the Solar Tower Jülich.

Keywords: dynamic simulation, modeling, Solar Tower Jülich, Modelica, control, optimization

1. Introduction

While conceptual design for solar thermal power plants is mostly performed with steady-state simulation tools, detailed engineering and optimization of a plant requires taking into account transient effects. For solar plants this are short term transients induced by cloud passage as well as daily start-up and shut-downs of at least the solar part of the plant. To build up simulation capacities in this field the virtual institute of central receiver power plants (vICERP) started work in January 2008 [1]. The individual expertise of five research institutes was brought together in a so called virtual institute. The difference between a conventional project and a virtual institute is the long-term perspective. With the initial funding for three years from German Helmholtz Gemeinschaft, the state of North-Rhine-Westfalia, and the European Union, tools for dynamic simulation have been developed and co-operation between the institutes was intensified. The Solar Tower Jülich technology was used as an example application throughout the first stage of the project.

The five partners and their fields of research in this project are:

- DLR Solar Research: Coordination, Modeling of heliostat field and receiver
- FH Aachen, Solar Institut Jülich: Modeling of thermal storage, interface to plant operational data from solar tower Jülich
- RWTH Aachen University, Institute of Automation Control: Basic and advanced control schemes
- RWTH Aachen University, Institute for Steam and Gas Turbines: Modeling of steam generator and water-steam cycle
- K.U. Leuven, Electrical Engineering Department and Optimization in Engineering Center (OPTEC): Development of numerical optimization tools.

This paper presents an overview on the activities of the vICERP in the field of dynamic simulation.

2. A Modelica library for simulation of solar tower systems

There are several simulation tools on the market that allow dynamic analyses of technical processes. Commercial tools are often limited in their flexibility for new components and thus not well suited for research applications. The virtual institute decided very early to use the programming language Modelica in combination with the graphical user interface and solver Dymola. This tool has gained high attraction within the last year especially in the modeling of thermodynamic processes. As a basis for the own models, the Modelica Fluid Library was used. This library provides definitions for connectors between two components. The plant model shown in Fig. 1 was developed as a reference for all component model designs. The approach of alternating state and flow components leads to a high flexibility since component models in various levels of detail can easily be used in the same plant model.

The plant model, see Fig. 1, consist of three main sub-systems, namely the heliostat field and receiver, "A", the thermal storage, "B", and the water-steam cycle "C". Hot air with a temperature of 680 °C from the receiver can be directed to the storage or to the water-steam cycle. The cold return air (~120 °C) is blown to the front of the receiver to make use of the pre-heated air. During low irradiance periods, air can be heated by means of the thermal storage.

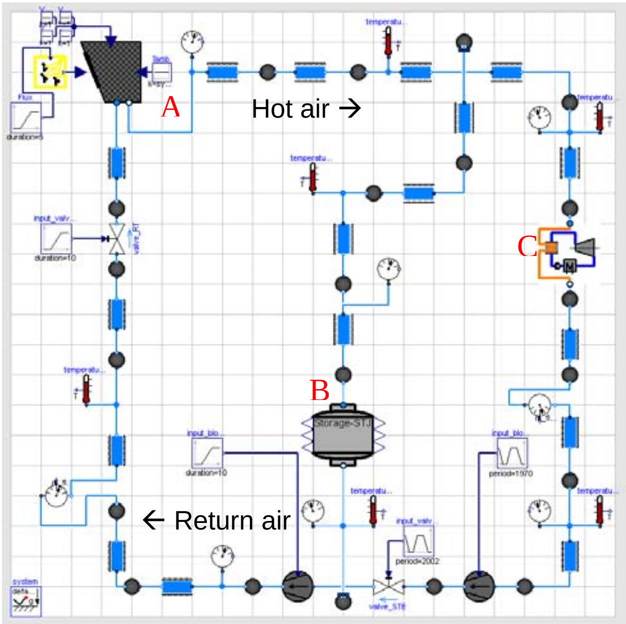

Fig. 1: Screenshot of the Modelica plant model

3. Modeling of heliostat field and receiver

Heliostat field and receiver setup the solar sub-system and rank first in the energy conversion chain of the power plant. The component models are developed with the intention to analyze transient effects in the receiver during start up/ shut down, aim point changes, or cloud passage and to calculate the essential quantities and their dynamic behavior for the subsequent components in the air cycle, which are the temperature of the air at the outlet of the receiver, the corresponding air mass flow rate and their dynamic behavior. Modeling of the components of the sub-system focused on the dynamic behavior of the receiver, as the time constants of the receiver are considerably greater than the time constants of the heliostat field to change the flux density distribution on the receiver surface. Thus, for the heliostat field a static model is used. For the receiver, a dynamic thermal model is developed with an adjustable discretization depending on the simulation purpose, which can be a detailed analysis of the receiver with a high discretization or the provision of data for the air cycle with a lower discretization.

The heliostat field is modeled in STRAL [2], which is a powerful and fast ray tracing tool for solar thermal power plants. STRAL enables to setup heliostat field models in great detail using specific heliostat data including a model for the heliostat drive system [3], data for shading objects, receiver data, and sun shape data. The heliostat field model can be used to calculate very accurate flux density distributions on the receiver surface or among others for optimization of the operational strategy (aim point optimization) [4]. STRAL and Dymola are coupled via a TCP/IP network connection using a classical client server approach to use the heliostat field model in STRAL and the dynamic receiver model in Dymola in an overall simulation [3]. During the simulation, Dymola, which acts as the client, sends flux density calculation requests including the simulation time to STRAL, which acts as the server. STRAL considering the heliostat states and the heliostat drive model calculates the new flux density distribution. The calculated flux density distribution is send back to the requesting Dymola application. The overall simulation enables to analyze transient effects during start up or shut down procedures, during cloud passage, or aim point changes.

The thermal model of the open volumetric air receiver is setup out of thermal models for absorber modules including the absorber comb, absorber cup, support construction, and insulation. The module models as the smallest model unit are used for an adjustable receiver discretization. The absorption and heat transfer processes in the absorber comb are modeled using an efficiency matrix, which is based on a more detailed absorber channel model to complex to be included in this dynamic receiver model. The absorber module is subdivided into finite volumes for the air and the solids. The balance equations are formulated dynamically for the volumes. Heat transfer between the components is considered with Nusselt correlations. Additional receiver components like pipes, headers, and valves are represented with dynamic lumped models. The receiver model was validated with data from the solar tower in Jülich. Figure 2 displays the measured and simulated specific enthalpy of the air at the outlet of the receiver normalized with the maximal occurred specific enthalpy for a single day in Jülich. It points out a very good agreement between measured and simulated data in terms of absolute and dynamic behavior, which could also be detected for other temperatures or specific enthalpies in the receiver, e.g. at the outlet of the sub-receivers, and for additional days.

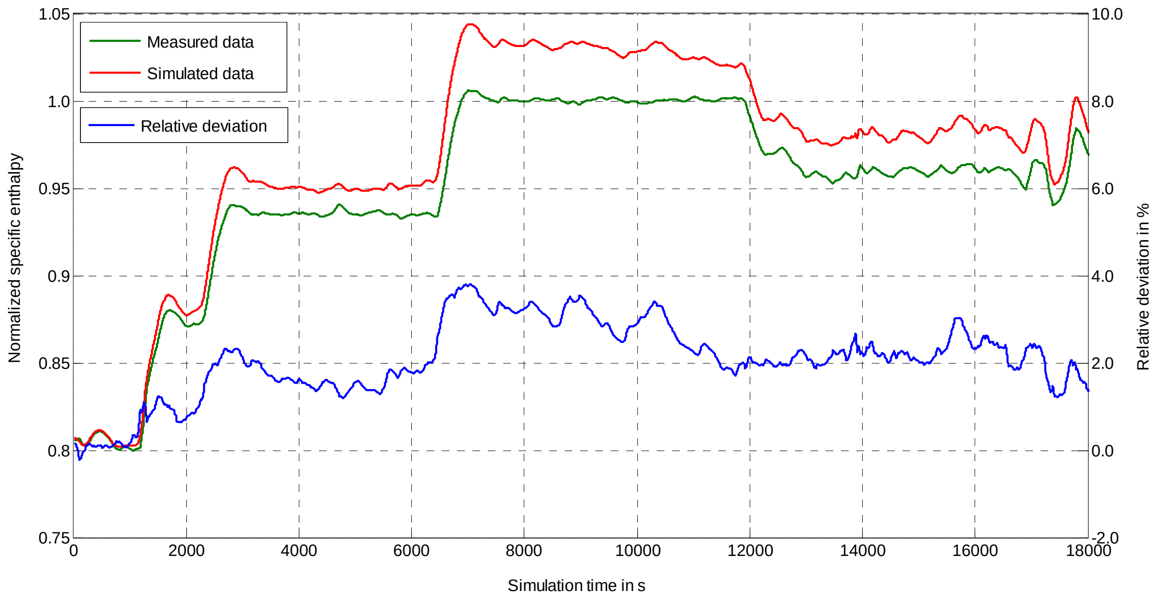

Fig. 2: Comparison of simulated and measured specific enthalpy of the air stream at the receiver outlet and the relative deviation of the specific enthalpies

4. Modeling of the thermal storage system

Intention of the modeling was to submit a dynamical state simulation of the thermal storage system during load and discharge process as well as to switch between these processes in a continuous simulation run. The storage unit in Jülich is often used as a buffer storage [6]. Thus, especially the ability of simulating the switching process between loading and discharging should be reached.

Each MWh of heat, which is stored inside the storage, causes a finite quantity of exergy destruction. This is directly dependent on the pressure drop during storage processing. The storage behavior is similar to a regenerator. On the one hand, the outlet temperature of this kind of storage is directly dependent on the temperature profile inside the storage. On the other hand, the temperature profile depends on boundary conditions. These are the inlet temperature, fluid mass flow, solid geometry, solid material, initial material temperatures and fluid medium. By equal mass flow and inlet temperature the storage needs to be loaded and discharged several times before the inside temperature profile reaches an equilibrium steady state. After reaching this state, the temperature profile stays constant if the boundary conditions remain unchanged.

In order to describe numerically the storage unit, it is divided in discrete elements in which the energy and momentum balance is solved. The number of discrete elements is variable and is set as a parameter. The temperature profile and pressure drop inside of the storage is calculated for each time step.

For the energy balance, the required heat transfer coefficient is calculated thermodynamically by storage geometry and flow parameters. The heat conduction in 3 dimensions is considered and implemented as well [5]. Fig. 3 shows exemplarily the measurement positions of one chamber at the research storage at Solar Tower Jülich (STJ). The pressure drop is measured on top of and above the storage material. There are eight levels with three temperature measurements each, generating a representative average level temperature. On top and above the storage material is also one temperature measurement. These temperature values are used to validate the storage model, represented by crosses in fig. 4. The continuous line represents the simulated temperature profiles. Fig. 4 compares the simulated values with the measured ones at the beginning of the charge (left) and at the nearly end of the following discharge process (right). Airflow pressure drop comparison between measurement and simulation is shown in figure 3, right.

The model allows computing the outlet temperature of the thermal storage at any process time. Further more the model is capable to take into account flow direction changes inside the storage. All results were generated with a storage discretization level of 450 elements in airflow direction. A computational time of 100 seconds, on an actual ordinary notebook, was needed to simulate 8 real-time hours. The pressure computation is close to measured values. The difference between simulated and measured temperature profile is less than 5 %. This is within the acceptable range for the dynamic simulation of the storage system.

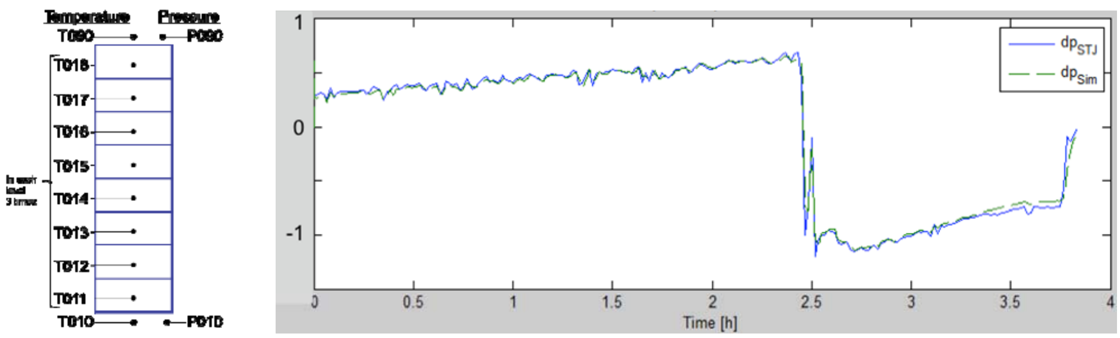

Fig. 3: Temperature measurement test rig (left) and normalized pressure drops from measurement and simulation (right)

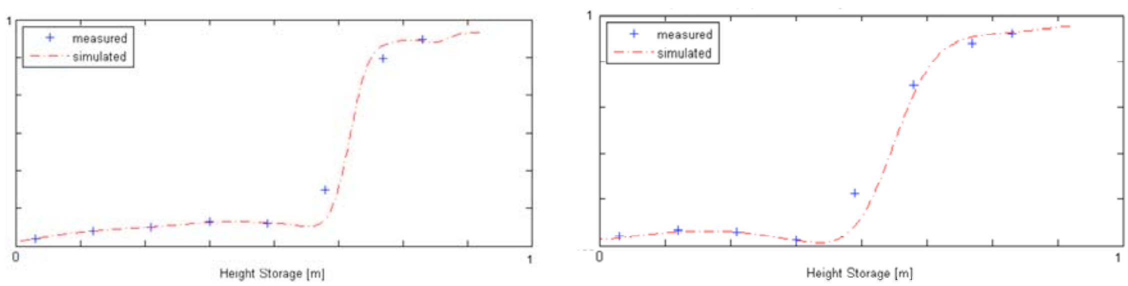

Fig. 4: Storage temperature profile during the load process (left) and the discharge process (right) (both axes normalized)

5. Modeling of water-steam cycle

In comparison to the water-steam cycle of a conventional power plant the water-steam cycle of a solar tower is started daily and sees several load changes due to fluctuations in solar irradiation. Therefore the start-up behavior and the reactions to changes in power input are the most interesting features to analyze with a numeric model. To create such a model the influence of the components on the transient behavior of the cycle has been analyzed. Fig. 5 shows the water steam cycle of the solar tower Jülich.

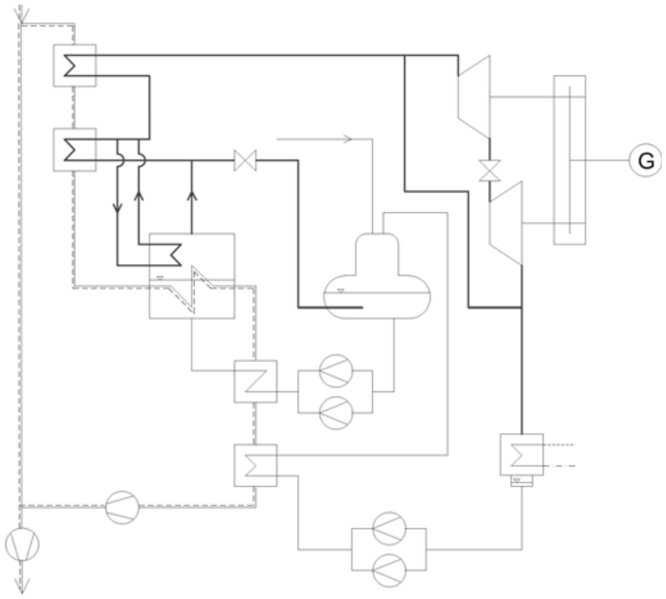

Fig. 5: Water-steam cycle of the STJ

In small power plants, like the one in Jülich, turbine and pumps have almost no influence on the cycle behavior. Therefore they were modeled as steady-state models. All other components, steam generator, pre- and superheaters, condenser and feed water tank, were modeled transient. As the steam generator has the biggest inertia and the most influence on the cycle behavior, Particular care was taken to capture the main dynamic influences by the model. The model and its validation shall be discussed in the following.

The steam generator of the solar tower in Jülich is designed as a fire tube boiler, where water is heated and evaporated by a bundle of flue gas tubes arranged inside a drum.

The boiler is modeled with a nonequilibrium model, which means that conservation equations for water and steam phase are formulated separately. Therefore it is not necessary that both phases are in saturated state at the same time. Mass and a heat transfer models are used to describe the interface between the steam and the water volume. Heat transfer and heat storage over the drum wall are taken into account. Convective heat transfer models connect the wall with the environment, the steam and the water. The heat transfer between the bundle of tubes and the water is also simulated with an interchangeable convective heat transfer model.

During the operation of the solar tower the air temperature is kept stable, whereas the mass flow changes according to incoming radiation. During start-up on the other hand the temperature is increased stepwise to warm the steam generator up.

To simulate a start-up of the steam generator the air temperature is increased when certain pressures conditions are reached. As shown in Fig. 6 the pressure in the simulation rises slower than the real one. As the steam mass flow is regulated by the pressure, it also rises slower than in reality. The incoming air temperature had to be approximated by steps. The higher temperature of the outgoing air matches the lower temperature of the outgoing steam. The temperature difference is due to the lower saturation temperature with lower pressure. The validation example shows that the dynamic behavior of the water/steam cycle of the solar thermal power plant in Jülich can de predicted with sufficient accuracy and with replication of the main dynamic reaction.

During the project all components were modeled and connected to a complete model of the cycle. Due to missing data only single components could be validated.

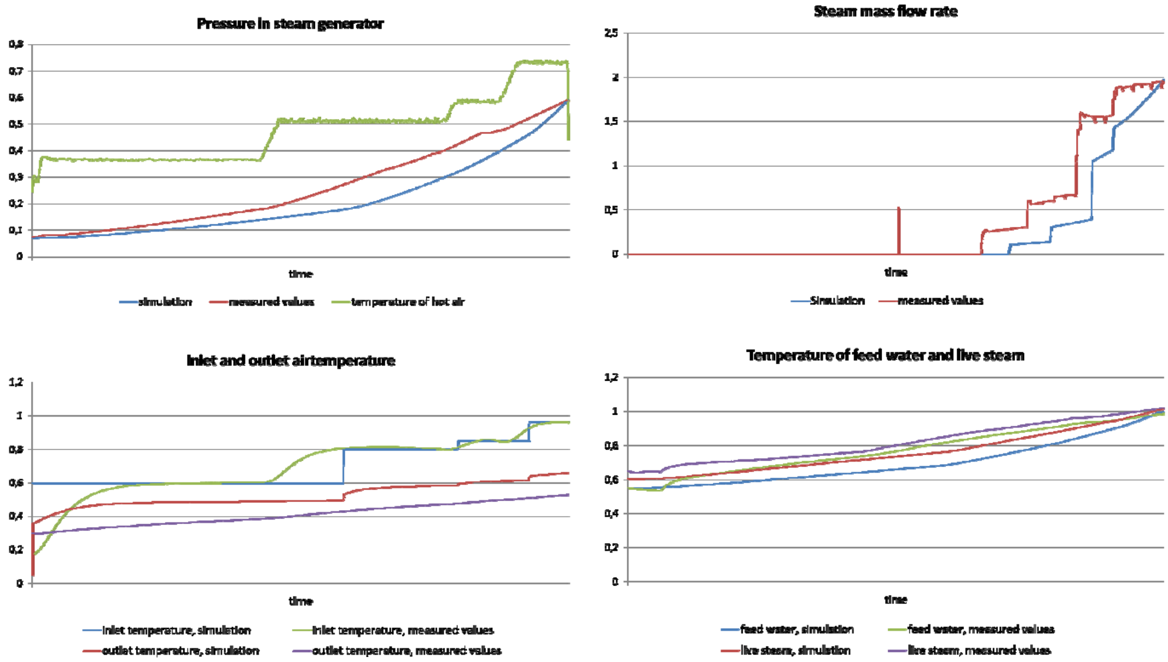

Fig. 6: Start-up of the steam generator

6. Design and simulation of plant control

The simulation of the operational behavior of the complete plant requires an integrated control scheme within the model to ensure compliance with given limits of absolute and gradient values. As a first concept, a basic automation scheme has been developed based on a wiring of SISO control loops with PID controllers. This scheme should on one hand assure a safe operation of the plant under normal operation conditions and on the other hand be a measure of performance for more sophisticated control schemes. The tuning of the different controllers has been done in MATLAB using a response optimization technique.

The measurement signals for the control scheme are different volume flows and temperature information. Actuating variables are the speed of the blowers and different valves located in the air cycle.

The main goal of the control scheme is to maintain the outlet air temperature of the receiver constant at about 680 °C. This is achieved by controlling the air volume flow through the receiver. The temperature difference from the reference point is used in an outer control loop of a cascaded structure, which feeds the required volume flow as setpoint to the inner control loop. The inner loop accesses the blowers and valves to set the demanded air flow.

The vICERP project also includes the application of a model predictive controller (MPC). This approach makes use of the dynamic model of the plant that has been developed for the simulation to predict future behavior with respect to changes in actuating variables.

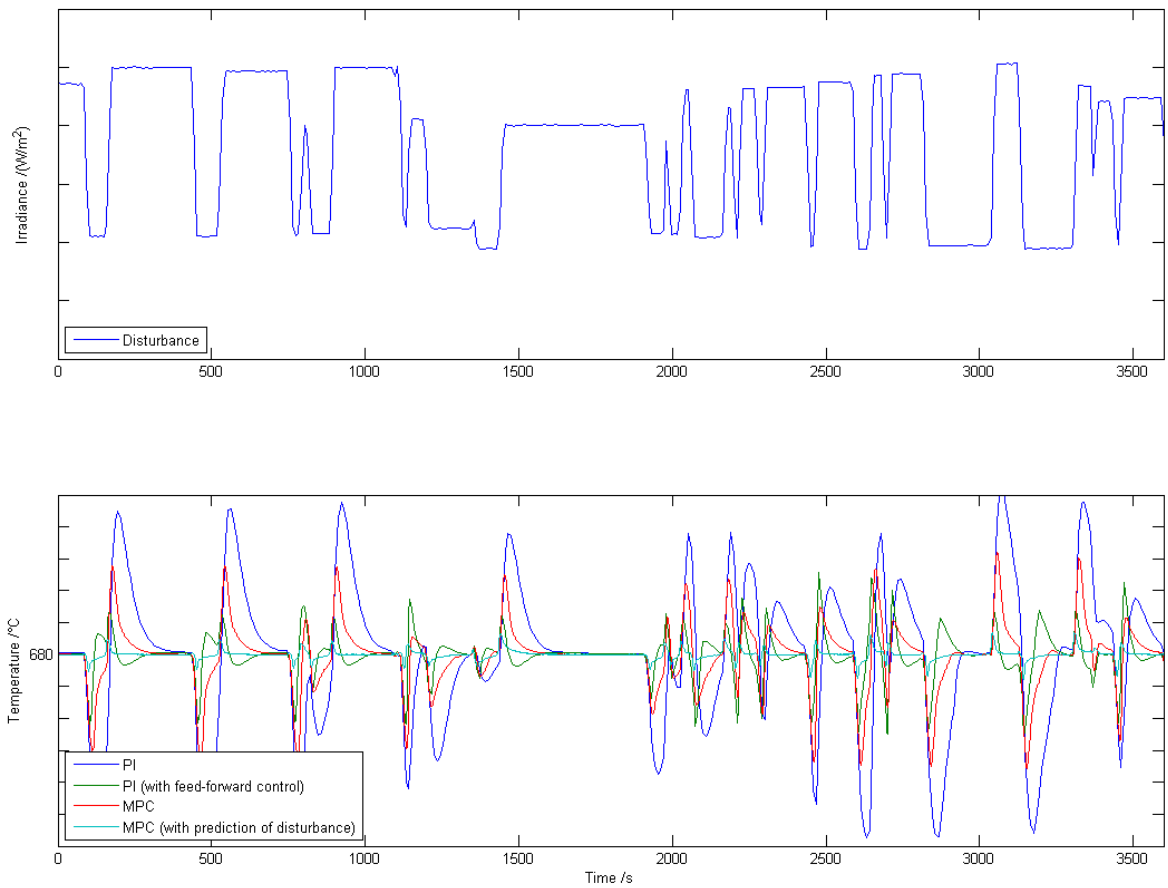

Fig. 7. Simulation results for different control approaches

With an MPC approach, it is also possible to include a natural objective function (maximize produced energy, minimize risk of boiler shutdown during transients, minimize time to start-up etc.) as well as imposing constraints such as bounds on variables or periodicity constraints.

The main difference between the control of a conventional compared to a solar plant is that the energy input in the first case is an actuating variable, whereas in the second case it (the solar irradiation) acts as a disturbance. However, this disturbance is not completely random, but may be measurable or even predictable. This information can also be included in the different controllers. For the basic automation scheme this has been accomplished by adding a nonlinear feed-forward control based on a Hammerstein-model which calculates from a given solar irradiation the necessary air volume flow through the receiver which results in the desired air outlet temperature. In case of the MPC, it is straightforward to include the solar irradiation by using it also in the prediction of the plant output.

Due to the lack of measurement data, a stochastic test signal for the solar irradiance is used for evaluation of the model and different control schemes. The test signal is depicted in the upper part of Fig. . Although the direct radiation may drop to zero if the heliostat field is completely covered with clouds, the above signal is used since a comparison of the different control schemes would not be particularly significant if all schemes run into their lower saturation during periods with no direct radiation. The parameterization for the model generating the test signal was chosen in such a way that the control schemes probably saturate during periods with low irradiation.

In the lower part of Fig. the responses of the air outlet temperature at the receiver with the different controllers are depicted. The main goal of this feedback control is disturbance rejection, i. e. it should assure a constant outlet temperature by adjusting the air volume flow through the receiver appropriately.

As one can see, the model-based controller achieves superior performance compared to the scheme based on

PID controllers in both cases, i. e. if the additional knowledge about the actual or future solar irradiation is taken into account or not. However, this knowledge does improve the quality of both controllers tremendously. Also note that especially the PI controller suffers from the all-pass behavior of the receiver regarding steps in the volume flow. Thus, the adjustment of the controller parameters is always a tradeoff between responsiveness and the maximal overshoot of the temperature.

7. Tool to solve dynamic optimization problems

The Modelica modeling language used to describe the dynamical behavior of the power plant within the vICERP project is designed in a way that models can be translated into systems of differential-algebraic equations (DAE), a standard format which is supported by several numerical tools. While the simulation of the plant behavior, as described in previous sections, is interesting in its own right, a further use of the equations is to solve decision making problems, or *dynamic optimization* problems.

In the Modelica community, dynamic optimization has attracted a great deal of attention in the past years, as practitioners seek to use their developed simulation models based on first-principle to fit parameter values or finding optimal control strategies. These models represent a great challenge even for state-of-the-art numerical codes for dynamic optimization as involved equations are often nonlinear and may contain continuous as well as discrete variables.

To solve optimization problems in vICERP, a general framework for dynamic optimization of Modelica models was developed. This framework, publically available as the open-source tool CasADi, is based on a novel implementation of *algorithmic differentiation* inside a powerful symbolic environment. The tool contains a set of sub-tools intended to facilitate the implementation of a wide range of state-of-the-art dynamic optimization algorithms, including *direct multiple shooting* and *direct collocation*.

8. Simulation of the integrated system

Having prepared the individual component models, it is possible to simulate the performance of the whole plant. Due to the object-oriented modelling approach simple component models can be replaced by more complex models within the same overall plant model.
One example run is chosen to present the simulation capabilities and illustrate the fundamental plant behaviour. The test run includes the following periods:

- Heating up the receiver in the morning (about 30 min)
- Regular operation with storage charge (about 45 min)
- Regular operation at reduced irradiance with storage discharge (about 30 min)
- Again regular operation with storage charge (about 60 min)

A simple power block model that uses any heat directed to the steam generator, was used in this simulation. The simulation is based on thermodynamic equations and does not yet include any restrictions in tolerated temperature transients. It is very well suited to illustrate the buffering behaviour of the storage. Fig. 8 shows the simulated process in terms of representative temperatures and mass flows. For confidentiality reasons only normalized values are plotted.
The virtual test case starts from a cold plant with the activation of the two blowers for receiver and steam cycle, respectively. The blowers soon establish constant mass flows in all three branches (receiver, storage, steam generator). Three minutes later the receiver is heated with constant (nominal) power. The receiver outlet temperature slowly rises up to nominal operation conditions. Hot air is directed to the steam generator and to the storage. Inside the storage the temperature front moves from top to bottom. After some delay time, the temperature at 70% height starts to rise. The same holds for the temperature at 50% height with an additional time delay.
Before the storage is fully charged (temperature at 15% and 0% height have not yet changed) the irradiance is reduced and the plant falls into storage operated mode. From the simulation, it can be seen that the transition is very smooth without significant steps in the temperature. During discharge, the temperatures in the storage drop. The lower end temperatures rise since the return air from the steam generator has a higher temperature than the starting temperature. The discharge temperature of the storage sinks slightly. An adapted mass flow

through the storage will be able to further stabilize this temperature. After about 30 min the irradiance is again increased and the system falls back into regular operation with storage charge.
The simulations indicate that the complex plant model can be used to simulate transient behaviour like start-up of the plant. A next step would be to include the detailed water-steam cycle model in order to simulate the combined start-up of solar system and power block. Such a model can then be used to perform optimization runs for plant start-up.

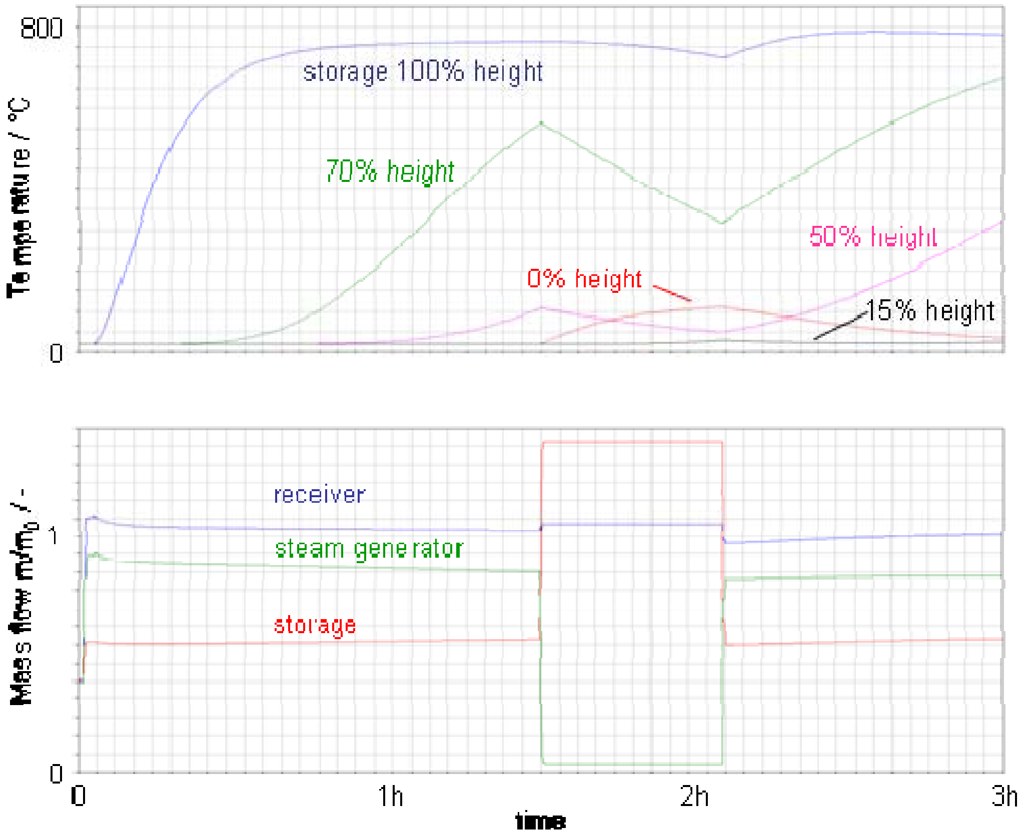

Fig. 8. Plant simulation of an artificial test configuration

9. Summary

Intense work within the virtual institute vICERP lead to a comprehensive Modelica library for the simulation of solar tower systems. The models have been developed for the example of the Solar Tower Jülich but can be transferred to any other type of plant. Validation with laboratory as well as power plant data reveal the accuracy of the models. In parallel to the component modeling, methods and capacities in the field of tool coupling, optimization and control have been worked out. A follow-up project will concentrate on control aspects of the heliostat field and operator assistance systems for the plant.

Acknowledgements

The authors would like to thank for financial support granted by the Initiative and Networking Fund of the Helmholtz Association, the state of North Rhine-Westfalia, and the European Union/European regional development fund. Special thanks to the Solar Tower Jülich consortium especially Kraftanlagen München for providing plant operational data.

References

[1] Abel, D., Bohn, D., Diehl, M., Hirsch, T., Hoffschmidt, B., Pitz-Paal, R.: The virtual institute for central receiver power plants-vICERP, In: Proceedings of the SolarPACES 2009 conference. 2009, 15-18 September 2009, Berlin, Germany

[2] Belhomme, B., Pitz-Paal, R., Schwarzbözl, P., Ulmer, S.: A new fast ray tracing tool for high-precision simulation of heliostat fields, In: Journal of Solar Energy Engineering, 131 (3), 2009

[3] Ahlbrink, N., Belhomme, B., Pitz-Paal, R.: Transient simulation of solar tower power plant with open volumetric air receiver, In: Proceedings of the SolarPACES 2009 conference. 2009, 15-18 September 2009, Berlin, Germany

[4] Ahlbrink, N., Andersson, J., Diehl, M., Maldonado Quinto, D., Pitz-Paal, R.: Optimized operation of an open volumetric air receiver, In: Proceedings of the SolarPACES 2010 conference. 2010, 21-24 September 2010, Perpignan, France

[5] Gall, J., Abel, D., Ahlbrink, N., Pitz-Paal, R., Andersson, J., Diehl, M., Boura, C.T., Schmitz, M., Hoffschmidt, B.: Optimized Control of Hot-Gas Cycle for Solar Thermal Power Plants, In: Proceedings 7th International Modelica Conference, 2009, Como, Italy

[6] Ahlbrink, N., Alexopoulos, S., Andersson, J., Belhomme, B., Boura, C.T., Gall, J., Hirsch, T.: The virtual institute for central receiver power plants: Modeling and simulation of an open volumetric air receiver power plant, In: Proceedings MathMod 2009, Vienna.