VICERP – THE VIRTUAL INSTITUTE OF CENTRAL RECEIVER POWER PLANTS: MODELING AND SIMULATION OF AN OPEN VOLUMETRIC AIR RECEIVER POWER PLANT

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Abstract. The virtual Institute of Central Receiver Power Plants (vICERP) was founded in the beginning of 2008. It is a research network consisting of five research centers. The institute vICERP works in the field of *solar thermal energy* using *central receiver power plant systems* (CRS) with the emphasis on the *open volumetric air receiver technology*. This technology is now being realized in the research and demonstration power plant in Jülich, Germany. The focus of the work is on modeling and simulation of the dynamic system behavior as well as the development of an optimized control and operation strategy.

In order to analyze the behavior during changes in load and operation points, an object-oriented model library using Dymola /Modelica is developed. Models for the central components such as the receiver, the heliostat field, the thermal storage system and the power block are included in the library as well as additional components like pipes, compressors, and valves. The library is based on the open source Modelica library Modelica_Fluid.

The optical part of the heliostat field is modeled using the ray tracing software called STRAL. It is coupled with Dymola in a master-slave arrangement setting Dymola as the master. This way, a very detailed heliostat field model can be integrated with the option of aim point optimization. Validation of the models will be done with experimental data from the research and demonstration plant in Jülich.

Feedback control system models are being developed using Matlab/Simulink. It is intended to use a model predictive control (MPC) approach for certain control tasks in the system. For a simulation, the two environments Dymola and Simulink are coupled interfaced to each other using a co-simulation tool called TISC. That way, the models can be designed and simulated in the best-suited environments and then coupled during simulation. In addition, other tools can easily be integrated in the simulation. The control trajectories developed will be validated with experimental data from the solar power plant in Jülich.

In the paper presented, the general system setup of a central receiver system using Dymola and Simulink as well as the co-simulation with TISC is shown. The modeling of two central components, namely the open volumetric air receiver and the thermal storage, using the object-oriented modeling language Modelica are discussed. In addition, the tool coupling of Dymola and STRAL is described. Some first simulation results of the solar components are shown.

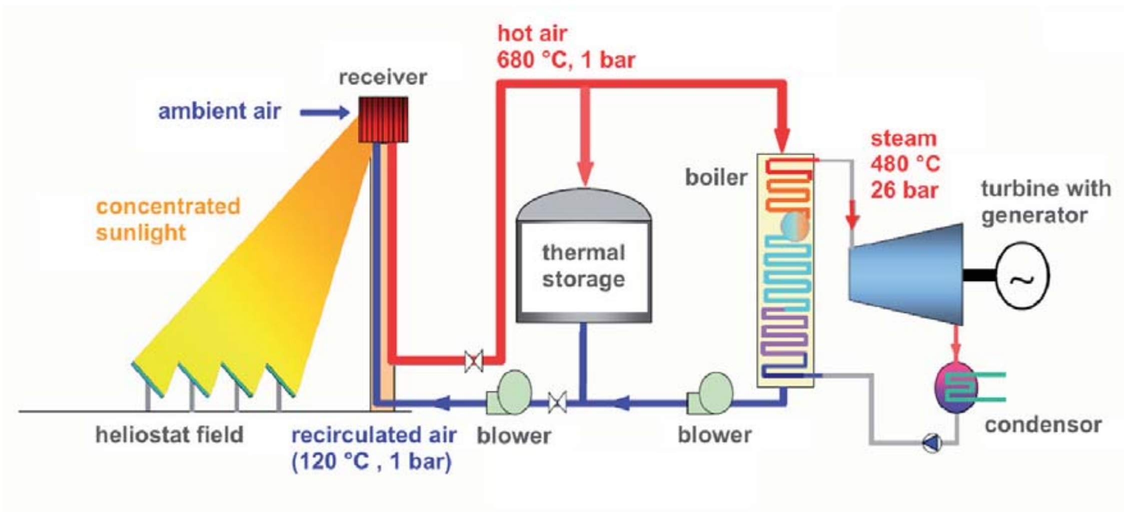

Figure 1. Central receiver power plant with open volumetric air receiver

1 Members and mission of the vICERP

The virtual Institute of Central Receiver Power Plants (vICERP) is a research network consisting of the five research centers German Aerospace Center (Solar Research Department), the RWTH Aachen University (Institute of Automatic Control and Institute of Steam and Gas Turbines), the University of Applied Sciences Aachen (Solar-Institut Jülich) and the University Leuven (OPTEC group). In the virtual institute, the five partners for the first time concentrate their capacities in the field of solar tower power plants. The mission of the cross-departmental institute is to develop and apply new computational methods for solar tower power plants. The focus is on transient processes and control of the plants. The research of the virtual institute will help to reduce existing uncertainties in the design, control and operation of solar power plants and thereby accelerate the market introduction and improve the competitiveness of the technology.

2 Solar tower power plants

Within the last years, electricity production from renewable energy resources has gained high attraction. Solar thermal power plants are one interesting option to generate electricity from solar irradiation. Several plants in operation and under construction especially in Spain and the U.S. reveal the economic potential of the technology. The open volumetric air receiver technology is one concept to further increase the upper process temperature from about 400 C to 680 C. In 2009, a demonstration plant goes into operation in the German city of Jülich. The power plant process is illustrated in Figure 1.

A field of heliostats is used to concentrate the incoming sunlight onto the receiver, which is located on the top of a tower. There, the concentrated light heats up the porous ceramic absorber cups. The heat is transferred to the air, which is sucked through the comb structure. The hot air is transported to the storage system or the heat recovery steam generator. Proportion and mass flow rate are controlled by two blowers integrated in the system. The feedback air cools the retaining construction as well as the absorber cups and is finally blown out, where it can be partly reused and sucked in again.

A thermal storage system is used as a buffer that stores energy in times of high irradiances and enables operation of the plant after sunset or during periods of reduced solar input. The storage behavior is similar to that of a regenerator. The hot air flows through a package of storage material and heats it up. During discharge, the air flows in reverse direction and cools down the storage material.

Transient effects and control aspects are of high importance for solar thermal power plants since they suffer from daily and also short time fluctuations in solar irradiance. The varying boundary conditions cause load changes and frequent start-up and shutdown processes. These processes have to be accurately controlled in order to avoid damage to components and to optimize the energetic plant output.

Research in the past was concentrated on the design of the power plant system itself and on the development of the key-components like the solar receiver. A numerical approach to transient phenomena has not yet been undertaken. The virtual institute concentrates on this topic and bundles expert knowledge from the technical disciplines solar technology, power plant operation, control and numerical optimization.

3 General system setup

The basic idea of the system setup is to model the system components in the best-suited environment. The simulation environments are coupled during simulation. This setup enables to use the advantages of each environment for the desired model and decouples system parts during simulation. The general system setup is presented in Figure 2.

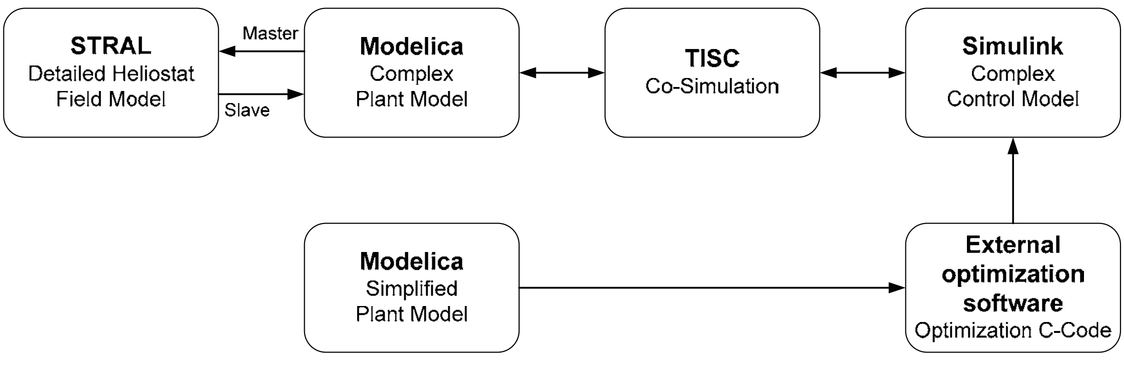

Figure 2. General system setup

A complex model of the air cycle including the thermal storage, the receiver, and the steam generator is modeled in Dymola using the object-oriented modeling language Modelica [3],[7]. As the focus is on the dynamic behavior during changes in loads, Dymola/Modelica as a strong, adequate simulation tool for complex, dynamic processes is very convenient in this field [10].

The Modelica model requests a flux density distribution as an input calculated by a heliostat field model. This model is developed using a ray tracing software namely STRAL. For the coupling of Dymola and STRAL an adequate tool coupling was developed, which will be presented in more detail in the corresponding section. The development of a control strategy for the overall power plant as well as for main components like the receiver will be done using Simulink [8]. Both environments are coupled with a co-simulation tool called TISC [6],[9]. In the following subsections, the fundamentals of the system models are described and discussed in more detail.

3.1 Complex plant model

The complex plant model consists of detailed models of the air cycle including the open volumetric receiver, the thermal storage, the conventional power block, and additional components like blowers and valves. The models are based on the open source library Modelica_Fluid [2]. The vICERP library uses a finite volume approach with staggered grid method implemented with flow and volumes elements [10]. The mass and energy balances are considered in the volume element. A formulation of the balance equations from Hirsch [4] is implemented using pressure and specific enthalpy as state variables. The momentum equation is reduced to a pressure drop equation and formulated in a flow element.

<u>Open volumetric air receiver model</u>

An open volumetric air receiver uses ambient air sucked through a hot porous volumetric absorber, where the air is heated up. The receiver installed in the Jülich power plant is set up of parallel absorber modules, shown exemplary in Figure 3 a). Such absorber modules consist of an absorber comb at the front, where the solar irradiation is absorbed. In the case under consideration, the Jülich absorber is a volumetric, porous ceramic with flow channels. An absorber module is illustrated in Figure 3 b). The comb is attached to an absorber cup made out of the ceramic material. This absorber cup is inserted into a metal holding pipe with internal insulation. An orifice is installed inside the pipe to affect the mass flow distribution through the absorber modules. These pipes are assembled in a retaining construction. The air is merged after the pipes in union frame collecting the air of each sub receiver. Each of them possesses a controllable air valve to control the mass flow rate through the sub receiver. The return air is feed back through the retaining construction in flow channels aligned perpendicular to the absorber pipes. An annular gap formed by a second pipe is installed around the holding pipe. The return air streams crosswise over the absorber pipes cooling the retaining construction and the pipes, through the annular gaps, and along the outer surface of the cups to the outside.

The absorber modules are modeled by circular pipe segments (four segments) and annular gaps (two segments) simplifying the real geometry. Each segment has two independent thermodynamic states, pressure and specific enthalpy respectively. Models for the wall material are included (seven segments) having the temperature as one state each. The mass flow rate is calculated out of the pressure drop over each segment. Pressure drop calculations as well as heat exchange calculations are based on analogous cases like laminar or turbulent flow through a pipe or an annular gap. Convectional heat exchange and conductional heat exchange perpendicular to the flow are considered. Inside the absorber cup, conduction along with the flow is also taken into account, as the ab

a) b)

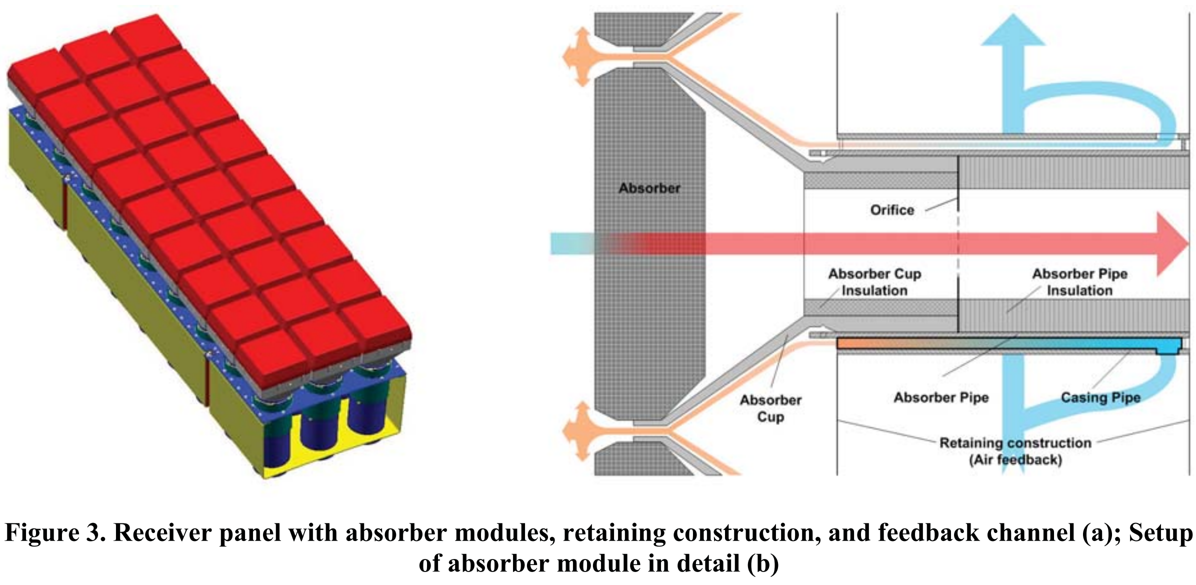

Figure 3. Receiver panel with absorber modules, retaining construction, and feedback channel (a); Setup of absorber module in detail (b)

sorber cup is extremely hot during operation and exchanges heat with the return air. The absorption of the concentrated irradiation in the absorber is implemented with an external function, as the complete absorption process would be too complex for implementation. The external function is based on an existent absorber model, where irradiation, multiple reflections in the flow channels, conduction and convection in the absorber comb are taken into account [5]. Unfortunately, at this point the models are not yet validated, but will be with experimental data from the power plant in Jülich.

From this type of receiver setup, some important requirements arise for the receiver model. In the model, the mass flow distribution through the absorber modules has to be taken care of under the consideration of an inhomogeneous flux distribution causing transients in temperature for the absorber material and the air. Less mass flow rate is needed in less irradiated areas, whereas more mass flow rate is needed in higher irradiated areas to result in an almost homogenous temperature profile for the receiver. This is one criterion for high receiver efficiency. However, in reality hot air has a higher flow resistance through the absorber modules depending on density and viscosity resulting in the opposite effect. Thus, mass flow rate distribution and temperature distribution are an important issue for open volumetric receiver and are going to be analyzed in the vICERP. In practice, an individual orifice is implemented in the absorber pipes to homogenize the temperature distribution by adjusting the mass flow rate distribution for one design point additional to a controllable air flap for each sub receiver.

The severe modular concept of absorber modules is transferred to the receiver model. Depending on the discretization, the open volumetric receiver is represented by a matrix [n,m] of absorber modules. The absorber modules itself are not further discretized in the n,m-plane. Thus, one module has one value for a solar irradiation as an input. To reduce computational time a number of adjacent absorber modules can be represented by just one single model assuming homogeneous flux distribution in this area.

Thermal storage model

A thermal storage system is used as a buffer that stores energy in times of high irradiances and enables operation of the plant after sunset or during periods of reduced solar input. The developed storage model enables the analysis of different operation conditions of the power plant. The storage behavior is similar to that of a regenerator. The hot air flows through the storage material and heats it up. During discharge, the air flows in reverse direction and cools down the storage material, while heating the fluid.

The storage model is divided into storage cells. Each cell element includes the characteristic material and flow phenomena. The flow conditions are described with a volume and flow element, the material behavior is calculated within a material element.

In the energy equation convection between the material and the gas fluid and conduction inside the storage material in two dimensions are considered. The model includes also storage surface losses. For the calculation of the convection coefficient and the pressure drop, empirical equations are used for each flow pattern. The model includes also storage heat losses at the outer surface.

The simulation model describes the dynamic behavior of a heat storage component in two dimensions (parallel and perpendicular to the flow) which can be extended to three dimensions. The developed model can be applied for channel geometries and for different medium properties. For the medium properties, standard polynomial

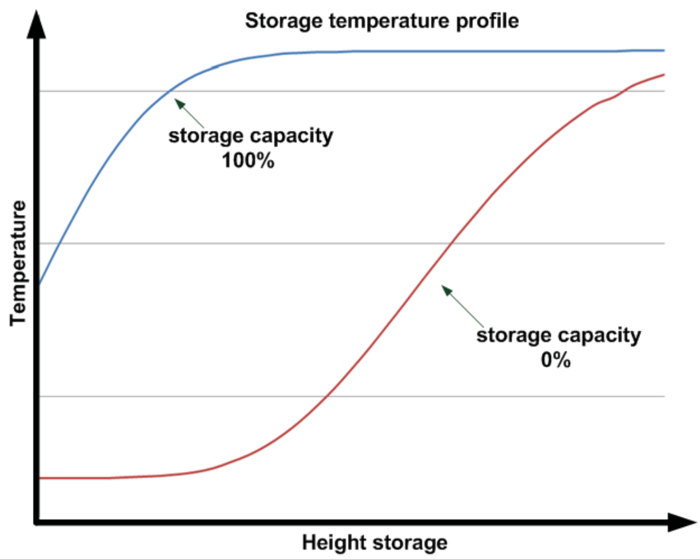

Figure 4. Temperature profile of the storage system for 100%- and 0%- storage capacity

functions from the model library are used. In addition, the flow direction can be changed during simulation. This enables the description of charging, discharging and stand-by operation mode. Additionally heat losses during standby periods are also calculated.

The simulation can start with a predefined gradient for the storage temperature or a homogenous value. Figure 4 shows the temperature profile for the 100%- and 0%-storage capacity load situation.

3.2 Complex control model

Feedback control system models are developed using Matlab/Simulink. After application of a basic automation concept based on classical PID controllers, it is intended to use a model-based predictive controller (MPC) for certain control tasks in the system. The MPC uses an internal, simplified dynamic plant model to calculate the prospective output of the plant. By converting a simplified Modelica model to a compilable language such as C/C++, state-of-the-art algorithms for non-linear optimization and optimal control can be used, including, but not limited to (possibly stochastic) weather forecasts and complex objective functions taking into account risks and electricity demand. By optimizing the use of the heat storage, it is possible to avoid shutdowns of the turbine in the event of passing clouds, extend the electricity production into the evening (when the demand of electricity is high). It is also possible to store heat overnight and use this to warm-start the plant the next morning.

Thus, an optimal trajectory of the actuating variables is calculated minimizing a specific cost function. This makes the MPC very suitable for the given, strongly coupled multivariable control system. The main advantages are the feasibility of feeding the knowledge of future set points (load requests) and future disturbances (weather forecast) directly into the controller and optimize thereby optimize the operational behavior of the plant under the expected future conditions. Moreover, the MPC is capable to handle constraints given by limits of the controlled and actuating variables by integrating them into the optimization problem. Additionally, when nonlinearities become important in transients due to load request changes, plant start-up or shutdown, the MPC can be extended to work with nonlinear dynamic system models.

3.3 Detailed heliostat field model

The heliostat field model is implemented in a new ray tracing software for solar towers, namely STRAL (solar tower ray tracing laboratory) [1]. Using STRAL, a detailed model of each individual heliostat can be integrated as it supports the integration of mirror error matrices and an individual geometry setup of the facets. The dynamic behavior of the heliostats, especially the time delay during rotation, can be realized using tracking functions taking the geometry of the heliostats and the characteristics of the actuators into account. Tracking functions use the geometrical transformation from the actuator to the rotary motion and the characteristics of the actuator like maximum speed.

Additionally, aim points can be defined on the target and shifted during the simulation to react on the change in solar irradiation during a day. Another feature of STRAL is the option of aim point optimization during operation. That way, the configuration of heliostat pointing at an aim point can be optimized regarding spillage, temperature distribution, power or additional criterions. A layout of the heliostat field model for the power plant in Jülich is shown in Figure 5. A tower model is implemented representing the shading on the heliostats. The target can be seen at the top of the tower showing a flux distribution during operation.

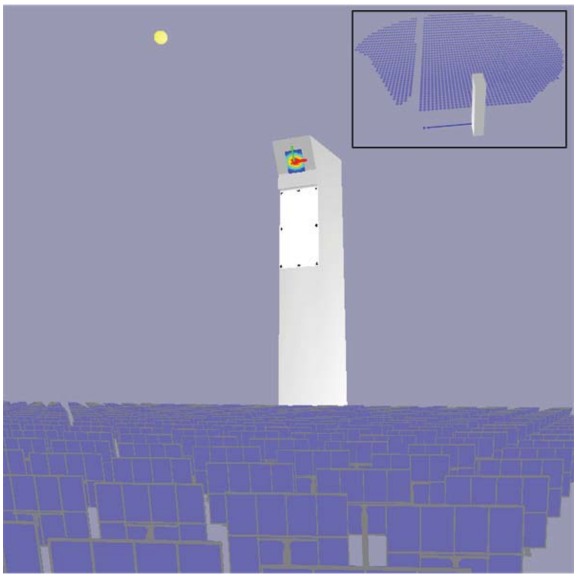

Figure 5. Heliostat field modeled in STRAL

4 Coupling of Dymola and STRAL

One important goal of the virtual institute vICERP is to develop a control strategy for the solar tower technology. The heliostat field and the receiver, as main components of the solar tower power plant, have a big impact on the efficiency of the power plant. It is a difficult task to develop an overall control strategy for the system out of heliostat field and receiver for its complexity. An optimization of the flux density on the receiver, which is a major problem in this field, has a wide range of possible combinations of aim points for each individual heliostat. Thus, in the first place it is necessary to be able to model such a system in detail with adequate software before starting to develop a control strategy. Dymola and STRAL have been chosen to deal with that problem.

STRAL has a wide range of features. It was developed at the DLR for the purpose of a detailed description of the optical behavior of the heliostat field and an accurate calculation of the flux density. Its strict object-oriented structure proved to be very convenient as it is easy to implement additional features. In order to be able to use STRAL in combination with Dymola, a convenient coupling of both tools had to be developed. The coupling has to be flexible regarding extension and usage, less time consuming, as well as easy to implement in both simulation environments. For these requirements, the coupling was designed to use a TCP/IP connection to allow divided simulations on separated computers via network connection. The communication is based on commands on the binary level to keep the coupling simple and easy to adapt for other tools. In Dymola, the option to implement external functions and libraries is used to communicate with STRAL. In such a library, a number of commands was developed in C++ for example to account for initialization of the tool coupling, opening a project, starting a calculation, shifting of aim points.

The communication of the two environments was tested with a simple receiver model in Dymola and a complex heliostat field model representing the field of the solar tower in Jülich on two separated computers via TCP/IP. The tool coupling showed a stable and fast performance even at full discretization of the receiver surface (30x36 absorber modules).

5 Simulation results

In this section, some first simulation results are presented and discussed. In the simulation, a co-simulation of STRAL and Dymola was performed using a complete heliostat field model (2150 heliostats) of the solar tower power plant of Jülich and a simplified receiver model. The receiver model uses nine absorber modules distributed over the receiver surface. Their position is shown in Figure 7. The remaining surface area of the receiver is not used in this simulation. Thus, the nine absorber absorber modules do not represent any other adjacent receiver surface. The azimuth and elevation angle of the sun are kept constant at az_Ang=0° and el_Ang=45.8°. The same orifice diameter (d=0.022m) is used for the nine absorber modules.

At the beginning of the simulation, the mass flow rate through the receiver is increased from zero to the overall design mass flow rate of 0.078kg/s. A PID controller is used to control the mass flow rate. The heliostats aim at a safety aim point outside of the receiver surface at the beginning of the simulation and are shifted to six aim points distributed over the receiver surface at time t=2100s representing a step function in the flux density. Simulation end time is 6000s.

Figure 6 shows the overall mass flow rate of the nine absorber modules as well as the highest and the lowest individual mass flow rate of an absorber module in the upper graph for the simulation time of 6000s. The lower graph presents the average air receiver outlet temperature and the highest and lowest air outlet temperature of an individual absorber module.

Figure 7 illustrates the flux density distribution on the receiver surface at t=6000s. An average flux density for each absorber module is used corresponding to the receiver discretization. If needed, STRAL could provide a much more detailed calculation of the flux density. In addition, the position of the nine absorber cups, the individual mass flow rate through the absorber module, and the absorber comb material surface temperatures are included in the figure.

Before the shifting of the heliostats, the mass flow rates of the absorber modules are almost identically due to similar solar irradiation on the absorber surface. The mass flow rate is equally distributed on the nine absorber modules. At t=2100s, the aim point of the heliostats are shifted from the safety position to six aim points on the receiver surface. Rotation time of the heliostats is neglected in this simulation. In consequence, a step in the solar irradiation on the receiver surface is generated.

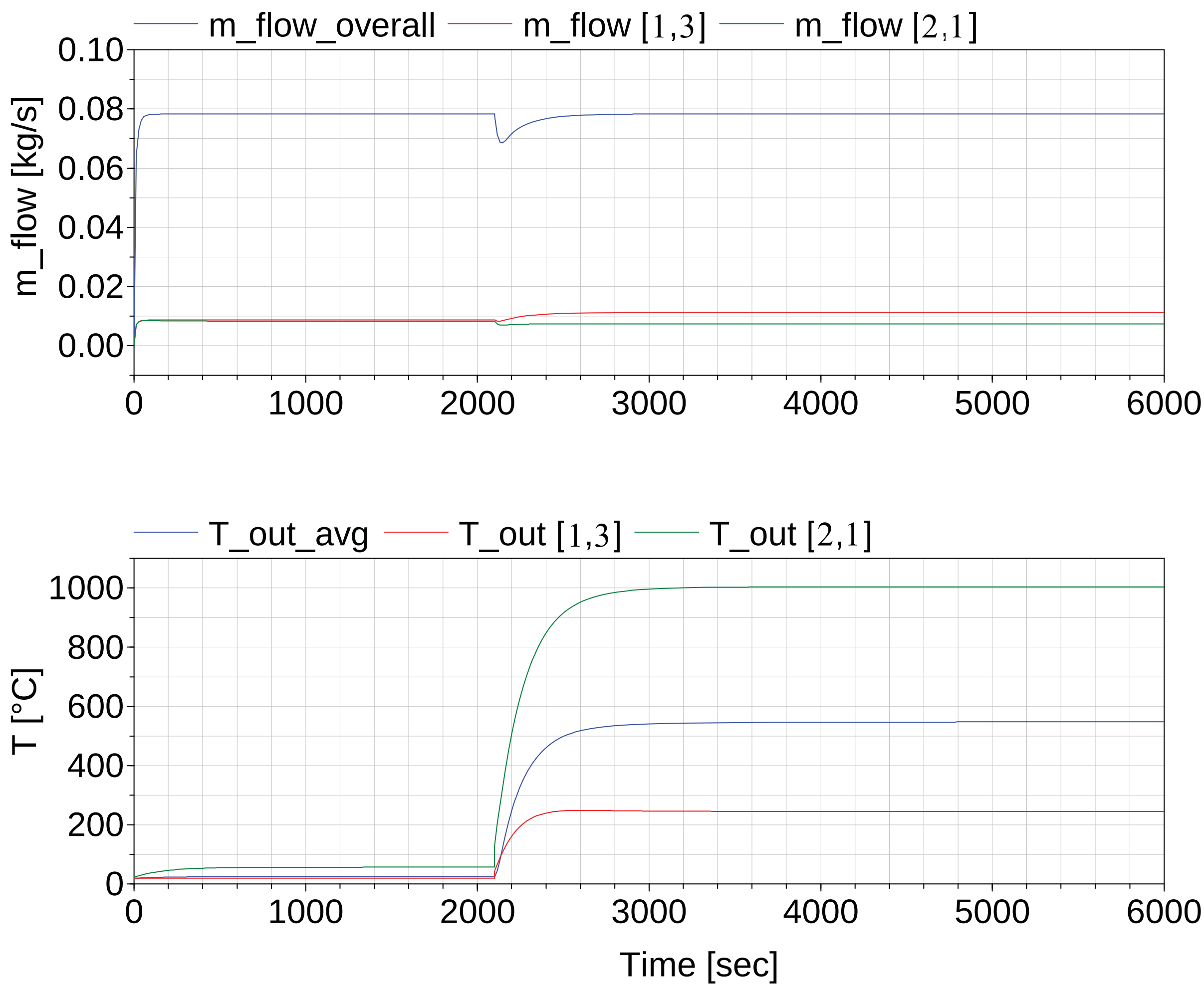

Figure 6. Overall mass flow rate (upper graph) and average air outlet temperature (lower graph) compared to the lowest and highest individual value of the absorber modules

After the step, a higher irradiation is absorbed in the absorber comb. The mass flow rates shown in Figure 6 drop due to the fact that the air temperatures increase. This leads to a decreasing density. The mass flow rate is adjusted back to the design mass flow rate by the controller. The inhomogeneous flux density on the receiver surface causes an unequally distributed absorption in the absorber comp. The distribution of the mass flow rate is not controlled or impacted by adjusted orifice diameters. Therefore, the mass flow rate distribution demonstrates the assumed effect of having a lower mass flow rate in the highly irradiated and hotter areas in the center and a higher mass flow rate in the less irradiated and cooler regions at the border of the receiver. The highest mass flow rate can be found for the absorber module at the lower right side [1,3] of 0.0113kg/s at 144345W/m². The lowest mass flow rate of 0.00734kg/s occurs in the center on the left [2,1] with an irradiation of 455329W/m². This effect lowers the average air outlet temperature decisively leading to a dramatic loss in efficiency. The average air outlet temperature is 18.39% lower than the design average air outlet temperature of 680°C. Therefore, a control strategy for the receiver is inevitable.

One attempt to result in a higher average air outlet temperature is an adjustment of the orifice diameters for a design flux distribution. Larger diameters are chosen for the more irradiated areas in the center of the receiver, and smaller diameters are installed for the less irradiated areas at the border of the receiver. Unfortunately, these adjustments are only valid for one specific design case. A dynamic control strategy has to be developed to react flexibly on fluctuations in the flux density distribution as well as changes in load. Intensive work will be done in this area during the next two years to control the mass flow rate distribution.

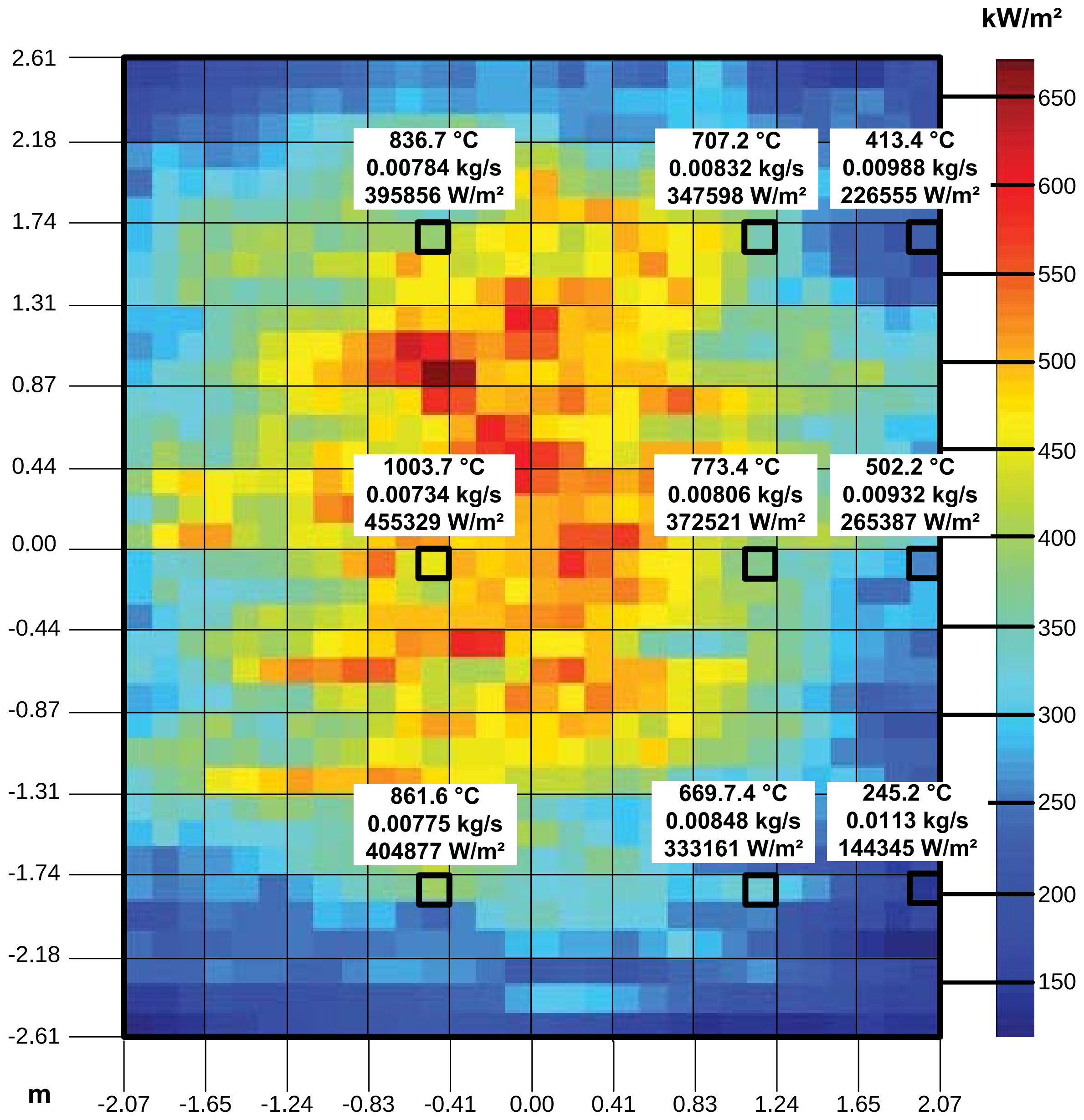

Figure 7. Average absorber module flux density on the receiver surface, position of the nine representative absorber modules with surface temperature of the absorber comp, mass flow rate, and irradiation

6 Conclusions

For analyzing the transient behavior of a solar thermal power plant, a simulation system including three different tools (Dymola, STRAL, MATLAB/ SIMULINK) is developed. Interaction between Dymola and Simulink is realized with the co-simulation tool TISC. A coupling is developed for Dymola and the ray tracing software STRAL. Some first results are shown demonstrating the capabilities of the system. Within the next two years, intensive work will be done on the dynamic simulation and control of such a power plant. Non-linear model predictive control methods are foreseen for the complex control tasks.

7 Acknowledgements

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