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Simulation of Operational Management for the Solar Thermal Test and Demonstration Power Plant Jülich Using Optimized Control Strategies of the Storage System

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Abstract

Electricity production costs and overall net efficiency of the system are determining factors regarding the quality and cost effectiveness of a solar tower power plant. These factors are strongly dependent on the quality of heliostats, the receiver and the thermal storage concept. This work describes the optimization of load states of a storage system through applying internal process control strategies for the air circuit of the Solar Tower Jülich which works with open volumetric air receiver technology. A concept for optimal operation of the thermal storage system was formulated and developed. Storage concepts include both technical adjustments of the existing storage system as well as the control process of the thermal storage. For simulating the optimized operating strategy of the power plant systems all main power plant components were modeled in MATLAB®/Simulink® and interconnected to form a complete system. The focus of the simulation lies in optimizing the operating strategy of a discretized thermal energy storage model.

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Keywords: thermal storage; regenerator; solar central receiver; solar tower power plant; storage concept; control strategy; operation strategy

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1. Introduction

In a research project called “Storage Optimization (SpOpt)” which is led by the Solar-Institut Jülich (SIJ), investigate and analyze methods for optimizing the thermal energy storage system of the Solar Tower Jülich (STJ) in terms of increasing the plant’s energy yield and decreasing the operational costs. Germany’s first solar tower power plant for experimental and demonstration purposes was constructed in the town of Jülich in the state of North Rhine-Westphalia and was inaugurated in autumn 2009. The STJ supplies the grid with a nominal power of 1.5 MW_e. Its installation was the essential step for demonstrating the solar power tower concept with open volumetric receiver technology, which uses ambient air as heat transfer fluid.

The receiver transforms concentrated radiation from the heliostat field into heat. Air blowers suck ambient air through the absorber modules whereby the air is heated to 680 °C. This hot air is passed through a heat recovery steam generator (HRSG) of a conventional steam Rankine cycle. An additional thermal storage system is used as a buffer storing energy in times of high irradiance and enables operation of the plant after sunset or during periods of reduced solar input.

2. Simulation and results

The thermal storage model describes and simulates the temporal and spatial behavior of the storage medium in discretized form. In each layer, the momentary energy balance and the loss mechanisms are determined using appropriate differential equations [1]. The thermal storage model is integrated into a large model which simulates the entire STJ power plant (see Fig. 1). The focus in the analysis of the plant is on simulation of storage process control strategies and calculation of the operational costs. The results of the simulated process control strategies are very valuable and shall be implemented in the operation of the STJ storage [2].

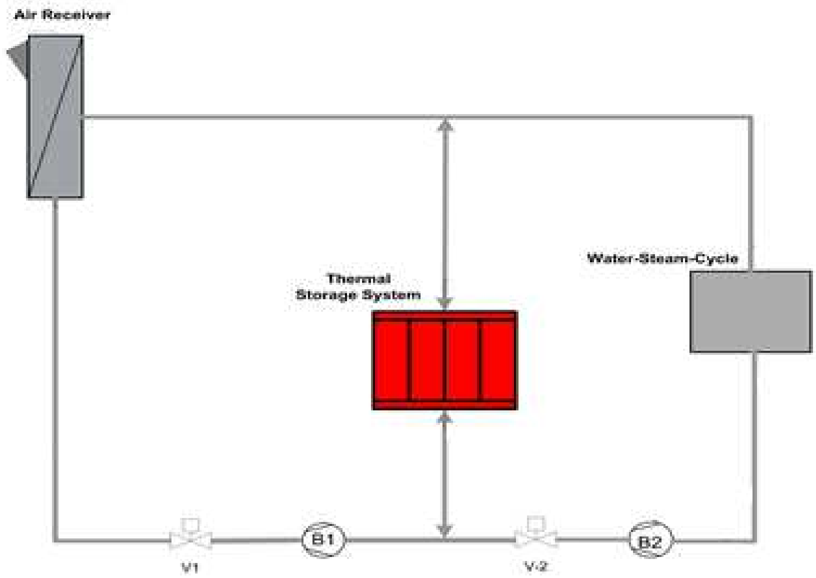


Fig. 1: Air cycle of the solar tower power plant

All storage concepts were analyzed under specific boundary conditions which include geometries, maximum expected power generation, process performance as well as temperature limits. A thermodynamic analysis of the integrated thermal storage was carried out for the entire air cycle of the solar thermal power plant by using simulation tools.

A reduction of electricity production costs, an increase of the storage availability and an increase of amount of electricity produced can only be achieved with a customized operating strategy. In order to increase the amount of generated electricity, two approaches were analyzed. Two simulation approaches for different storage concepts were considered for this paper:

- STJ thermal storage with a homogeneous storage material
- STJ thermal storage with inhomogeneous storage materials.

Both concepts are based on the structural design of the STJ storage system. For each concept a corresponding operation strategy mode was developed. The difference between these two approaches is the particular composition and arrangement of the storage materials.

For the storage concept with homogeneous storage materials, the thermal storage is equipped with alumina porcelain stones which can be heated to high temperatures and possess good thermal conductivity properties. For the storage concept with inhomogeneous storage materials, the thermal storage is equipped with three types of materials which have different thermal and mechanical properties.

The differences lie in the properties of the storage stones and are mainly characterized by the density, the porosity, size of the heat transfer surface as well as the weight of the storage elements. Figure 2 shows measured values of the receiver mass flow of the STJ for an operation day with high solar irradiation and no irradiation fluctuations. The measured values are normalized to the nominal mass flow of the boiler. It can be seen that the maximum mass flow passing the receiver is about 80 % of the design value. For this case the first strategy applies, whereby the boiler should be operated at nominal power with the application of the thermal storage. According to this design point, the highest thermal efficiency of the boiler is reached. Figure 2 shows the representation of this operating strategy. The thermal storage is charged during the first half of the day until the maximum filling level is reached. The storage is discharged during the second half of the day to compensate the difference between receiver's mass flow rate und the nominal mass flow. When solar radiation is no longer available, the boiler can be operated through the discharge of the thermal storage. Two strategies have been developed.

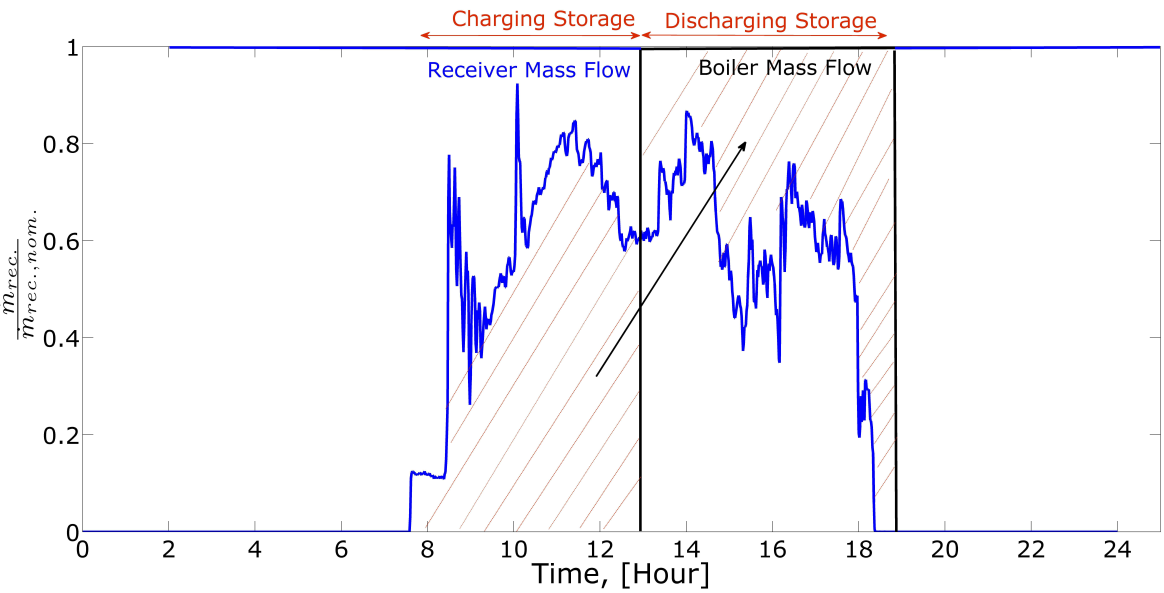


Fig. 2: Receiver mass flow and mass flow at the boiler - Strategy 1

The aim of the second strategy is to maintain as long as possible a constant boiler operation. Strong fluctuations of the air mass flow in the boiler lead to fluctuations of the steam mass flow at the turbine or may even produce a shutdown of the turbine. These factors cause an effect on the life time of the components and therefore it should be avoided. The implementation of the second strategy is shown in Figure 3, with this strategy the boiler can be operated through the discharge of the thermal storage.

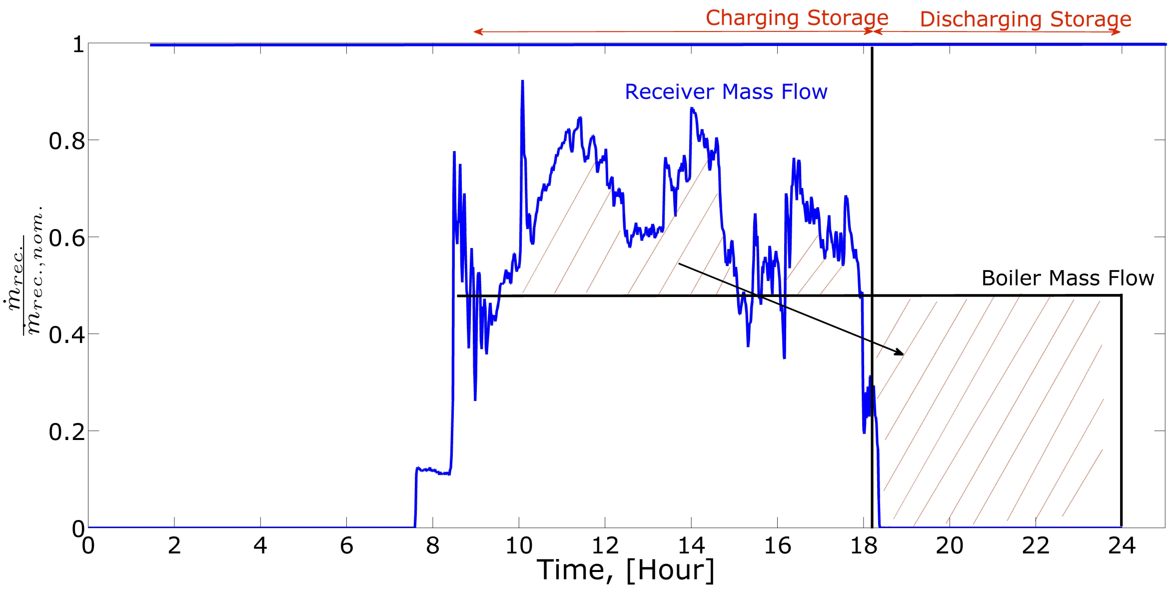


Fig. 3: Receiver mass flow and mass flow at the boiler - Strategy 2

Results for the storage with a homogeneous storage material, i.e. the first storage concept, are presented in Figure 4.

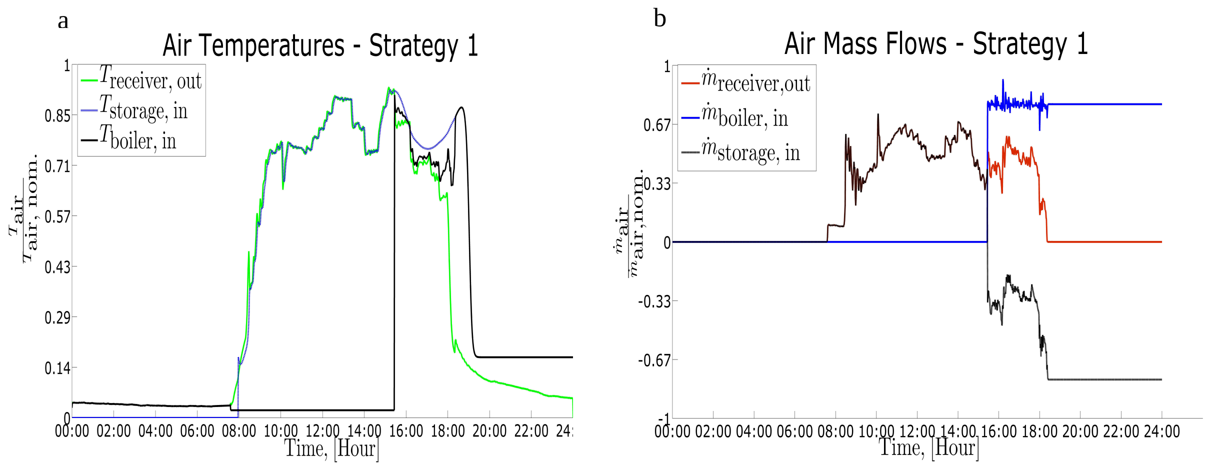


Fig. 4: (a) air temperature; (b) mass flow in the boiler - strategy 1 for storage concept 1

It can be seen that the entire receiver mass flow was sent to the storage until around 15:00 (3:00 p.m.) which is the time when the storage became fully charged. Then, storage discharging started. After 18:00 (6:00 p.m.) thermal power is no longer provided directly from the receiver, and the boiler is operated entirely with the thermal power provided by the storage. At around 19:00 (7:00 p.m.) the inlet temperature in the boiler drops sharply leading to a shutdown of the steam turbine and a stop of electricity production. In this case, the thermal storage provides thermal power for about 4 hours for continuous operation of the steam turbine at nominal power.

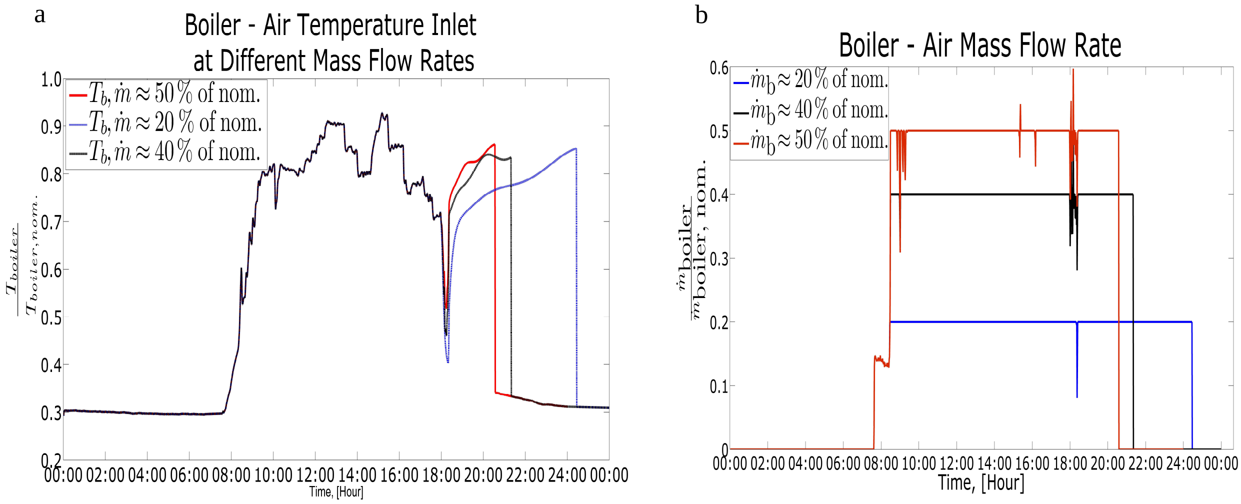
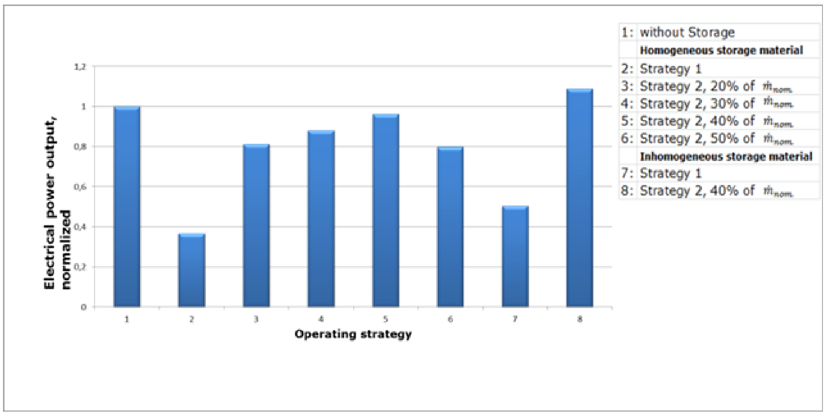


Fig. 5: (a) boiler air temperature; (b) boiler air mass flow – strategy 2 for storage concept 1

Figure 5 summarizes the mass flow and temperature at the boiler inlet when applying the second strategy. For this strategy, three air mass flow rates were chosen for the boiler and held constant throughout the day. It can be seen that at high mass flow rates, the operation time reduces significantly. This is because at higher discharge rates, the minimum operating temperature level of the storage system is reached in a shorter time, and therefore, the mass flow rate cannot be maintained for so long. When applying the minimum mass flow rate, the operation time after receiver shutdown is extended up to 3.5 hours.

The following table shows the simulated electrical power output of the developed operating strategies. In Table 1 it is observed that the lowest power output was obtained for the homogeneous storage with the operating strategy 1. In comparison to strategy 1 for the inhomogeneous storage (column Nr. 7), it is seen than the power generation has slightly increased, reaching a 50 % of the nominal power output. Results of the operating strategy 2 show a higher electrical power generation than for the strategy 1, for all investigated cases.

Table 1: Normalized electricity yield of the simulated concepts



For operation strategy 2 (column Nr. 5 and Nr. 8) the maximum power yield for the concept with homogeneous storage material is slightly below 100 % while the highest output of 110 % is reached with the second storage concept. One reason for this may be the higher thermal capacity of the storage system when different layers of inhomogeneous materials are implemented. In this concept, the middle region of the storage chamber has been replaced with higher density storage material, which brings a higher capacity for the entire system and consequently a higher electrical power yield.

The simulations have shown that an optimized storage system with inhomogeneous storage material can improve the output compared to the standard storage approach and can even achieve a higher output than the reference case with no storage operation.

3. Conclusion

The heat energy of the air receiver is thermal balanced by taking into account the inlet and outlet temperature of the storage system. The outlet air temperature varies as a function of different storage operating conditions; the outlet storage air temperature oscillates generally between 100 °C and 200 °C, although under specific conditions the temperature may be also below to the values.

A concept for optimal operation of the thermal storage system was formulated and developed. Storage concepts include both technical adjustments of the existing storage system as well as the control process of the thermal storage. For simulating the optimized operating strategy of the power plant systems all main power plant components were modeled in MATLAB®/Simulink® and interconnected to form a complete system. The focus of the simulation lies in optimizing the operating strategy of a discretized thermal energy storage model.

The simulation was carried out for days with different solar irradiation profiles. All the cases have shown that the storage capacity is sufficient to bridge periods of insufficient irradiation.

The simulation tool developed at the SIJ can be used for carrying out detailed simulations of solar tower plant with integrated thermal storage concepts for any defined site. Further investigation of the simulation results have to be conducted when integrating new operating strategies.

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