Proceedings of the ASME 2018 International Mechanical Engineering Congress and Exposition
IMECE2018
November 9-15, 2018, Pittsburgh, PA, USA

IMECE2018-86281

DESIGN AND INTEGRATION OF HIGH TEMPERATURE LATENT HEAT THERMAL ENERGY STORAGE FOR HIGH POWER LEVELS

Maike Johnson
German Aerospace Center
Stuttgart, Germany

Bernd Hachmann
F.W. Brökelmann GmbH & Co. KG
Ense-Höingen, Germany

Andreas J. Dengel
Steag New Energies GmbH
Saarbrücken, Germany

Michael Fiß
German Aerospace Center
Stuttgart, Germany

Matthias Hempel
German Aerospace Center
Stuttgart, Germany

Dan Bauer
German Aerospace Center
Stuttgart, Germany

ABSTRACT

A latent heat thermal energy storage unit is being integrated into a heat- and power cogeneration plant in Saarland, Germany. This storage unit system will act as an intermediate backup to a heat recovery steam generator and gas turbine and is therefore situated in parallel to this unit, also between the feedwater pumps and the steam main. The steam required is superheated, with a nominal thermal power of 6 MW. The storage unit needs to provide steam for at least 15 minutes, resulting in a minimum capacity of 1.5 MWh. Integration of this storage unit will increase efficiency and decrease fossil fuel use by reducing the use of a conventional backup boiler, while maintaining the steam supply to the customer.

The detailed design and a partial build of the storage unit has to-date been successfully concluded, as well as system design and build. Hot and cold commissioning of the storage unit, including filling of the storage unit, will commence following the completion of the storage unit. With the integration of this storage unit, fossil fuel use will be reduced in this power plant. Additionally, the production of superheated steam at a high power level in a latent heat storage unit and a comparison with simulation tools will be possible. This project includes the design, build, commissioning and testing of the storage unit. The paper discusses the detailed design of the storage and system, including the simulations of the system integration.

1 INTRODUCTION

The storage unit system, comprising of a latent heat thermal energy storage unit, piping, valves, a foundation, control systems and thermal insulation is being integrated into a heat- and power cogeneration plant in Saarland, Germany. This system will act as an intermediate backup to a heat recovery steam generator (HRSG) and gas turbine and is therefore situated in parallel to this unit and the existing backup boilers, as shown in Figure 1. The steam required is evaporated and superheated from feedwater, and has a nominal thermal power of 6 MW. The storage unit is required to provide steam for at least 15 minutes at a minimum flow rate of 8 t/h. These parameters result in a minimum storage capacity of 1.5 MWh.

In the current system, a conventional backup boiler is kept at a minimal load, so that it can assume full steam production within two minutes if the gas turbine trips. It produces the necessary steam until the gas turbine and HRSG are back in operation.

With the integration of the thermal energy storage unit, the conventional backup boiler is held at a warm load, from which it needs 15 minutes to reach full operational load and production. Depending on how often the storage unit is needed as well as the demand for steam from the other steam customers, the load reduction of the backup boiler could amount to energy savings of approximately 5000 MWh/a.

For this ramp-up time, the storage unit will provide the minimum steam load. Thereafter, the conventional backup boiler produces steam until the cause for the gas turbine tripping has been alleviated.

Once the gas turbine and HRSG are operating again, the storage unit is charged using steam from this HRSG. Using a bypass and a control valve, the steam exiting the storage system during charging also meets the requirements of the industrial customer.

The storage unit uses extended finned tubes in a tube-and-shell latent heat storage concept with sodium nitrate as the phase change material (PCM), storing the energy both in a combination of sensible and latent heat. The detailed simulations and thermodynamic design are described in (1) and the integration of the storage unit into the system in (2).

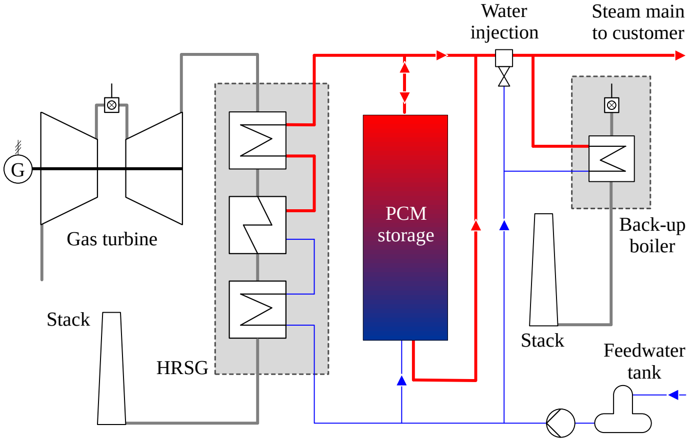


Figure 1: Layout of the cogeneration plant showing the latent heat thermal energy storage integrated in parallel to the HRSG and the backup boiler (2).

Following the basic design of the storage unit and the system, the detailed design of the storage unit system was conducted. The storage unit and system need to accommodate both the charging and discharging of the unit, including switching of operation modes, while consistently providing high quality steam to the industrial customer. Various operating conditions were simulated and the design of the system and the storage planned to meet these requirements, as well as the permitting requirements for operation in a power plant.

2 STORAGE SYSTEM DESIGN AND BUILD

The storage unit design includes 852 extended finned tubes and approx. 32 tons of sodium nitrate ($NaNO_3$) as the storage material mass, with a minimized volume of the headers for fast mode switching between standby and discharging. The build of the storage is, at the time of writing, almost fully completed, with just the mounting pins for the thermal insulation to be clarified and welded. After this, the pressure testing and delivery can occur.

Experiences with the fin assembly, the tight tube spacing, and the dense fin structure can be reported. The system for the integration has been designed and the foundation for the storage built.

2.1 ASSEMBLY METHOD FOR FINNED TUBES

The finned tube design is comprised of a central tube onto which two axial fin segments are clipped using spring steel clips, as shown in Figure 2. The heat transfer material water/steam flows through central tube, which therefore has to withstand pressures up to 26 bar at up to 350 °C. This tube is therefore made of steel. The fin segments transfer heat from the heat transfer fluid and the steel tube to the surrounding storage material. As such, these fins need to have a high thermal conductivity, but do not need to withstand mechanical pressures. The material used in these fins is aluminum.

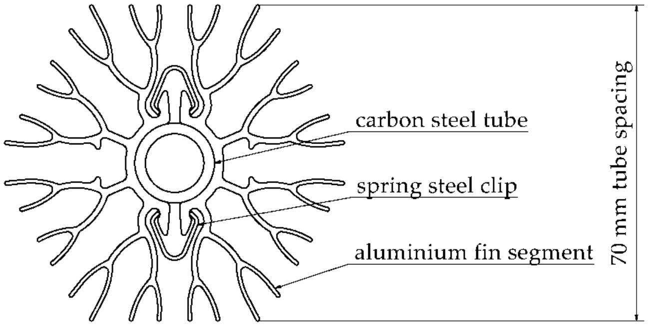


Figure 2: Drawing of fin design showing central steel tube, two fin segments and assembly clips.

The fins are clipped onto the tube with clips that allow for independent thermal expansion of the steel tube and aluminum fins, while ensuring a continuously good thermal contact between the two materials. Spring steel allows for this flexible expansion while maintaining strength at the operating temperatures.

As the specified high power level of 6 MW requires a dense fin structure and small tube spacing, and the storage unit design requires 852 finned tubes to supply the 1.5 MWh capacity, each with a fin length of 5.6 m, a semi-automatic assembly method for the mounting of the fins onto the tubes was developed.

Figure 3 shows the assembly mechanism. During assembly, first, two fin segments are slid onto the assembly mechanism and clips slid at the designed spacing along the assembly. The assembly mechanism then pneumatically pulls the two fin segments apart, which are now joined by the clips. This allows for the central tube to be slid between the aluminum fins. The assembly mechanism is then relaxed, and the mounted finned-tube assembly can be removed. The assembly method was proven as feasible and accurate, and further automation would be possible for an economical production of higher quantities of finned tubes.

Figure 3: Finned-tube assembly mechanism with a fined tube in the mechanism.

The fin segments are shown in Figure 4(a) and the mounted finned tube in (b). Each fin segment is 5.6 m long and the tubes are 6 m, allowing for welding into the headers.

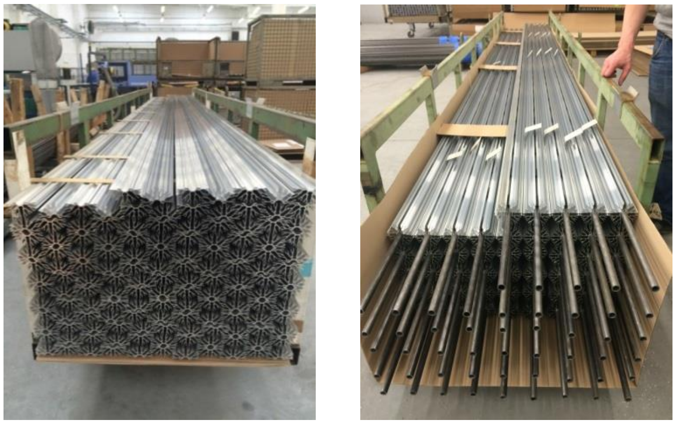

(a) (b)

Figure 4: Finned-tube assembly showing (a) the prepared fin segments and (b) mounted finned tubes.

Figure 5 shows a close-up of a mounted fin, tube and clip assembly.

Figure 5: Assembled finned-tube.

2.2 HEADER DESIGN

The storage unit is designed to be discharged using feedwater that evaporates. It is charged using superheated steam that for most of the charging time remains in the steam phase. Therefore, the upper header is designed for steam and the lower header for either water or steam.

The lower header has to have a very low internal volume to allow for the required fast switch time of two minutes. During these two minutes, feedwater flows into this volume and pushes steam up through the storage unit, while heating and evaporating and thereby expanding.

In order to meet these requirements, the lower header is designed as shown in Figure 6(a) with tapered tubes welded to each of the tubes coming out of the tube plate at the bottom end of the storage. The tapering is for volume reduction. These tapered tubes flow into a semi-header, which is optimized for weldability and internal volume. The single, main header below this is located in the middle of the storage unit. It is slanted, so that any condensate that forms during the beginning of charging and in standby operation flows out of the unit.

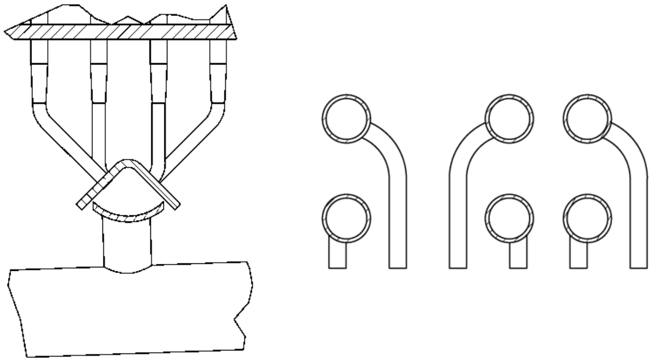

(a) (b)

Figure 6: Detail of the (a) lower header design, showing the narrowing of the individual tubes below the tube plate to minimize the volume in the header. Four rows of tubes connect downwards to one semi-header. This connects to a slanted main header. (b) The upper header design shows the tubes from the tube bundle attaching to stacked semi-header rows.

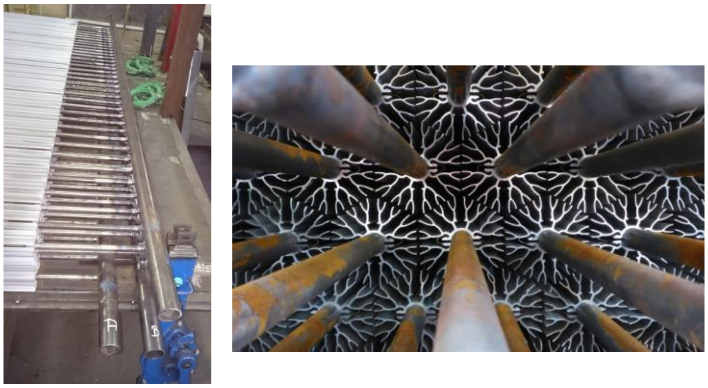
The upper header, as shown in Figure 6(b), is less critical from a thermo-mechanical or operational standpoint, as it is only used for steam and does not experience the temperature gradients that the lower header does. It does need to be designed so that the storage unit can be filled with storage material. To this extent, the semi-header rows are aligned above one another allowing for slits between which the storage material can be filled into the unit.

2.3 STORAGE UNIT BUILD

The storage unit is being built by Seab GmbH and has been built row for row in a horizontal position, with a side and the tube plate welded as a base (Figure 7). Each row of finned tubes was aligned and welded to an upper header row as shown in Figure 8(a), and this assembly then inserted into the tube plate and welded there. Figure 8(b) shows a detail of the assembled finned-tubes and Figure 9 the completed lower header. The green coils of thermocouples visible in some pictures are for analysis of the design as well as operational parameter determination.

Storage unit build will be followed by pressure testing, transport, filling and commissioning of the system, currently planned for autumn 2018.

Figure 7: Storage unit build showing first rows welded into the tube plate assembly and lying on the side wall.



(a) (b)

Figure 8: Storage unit build showing (a) prepared tube rows with upper headers and (b) detail of the assembled finned tubes.

Figure 9: Storage unit build showing complete assembly of the lower header construction.

2.4 SYSTEM DESIGN

The system components, controls and foundations for the integration of the storage unit into the operating cogeneration plant have been designed and partially built.

As shown in Figure 1, the storage will be integrated in parallel to the HRSG and the current standby and backup boiler. The storage unit will be integrated along the back wall of the plant in Saarland, Germany, as shown in the photomontage in Figure 10.

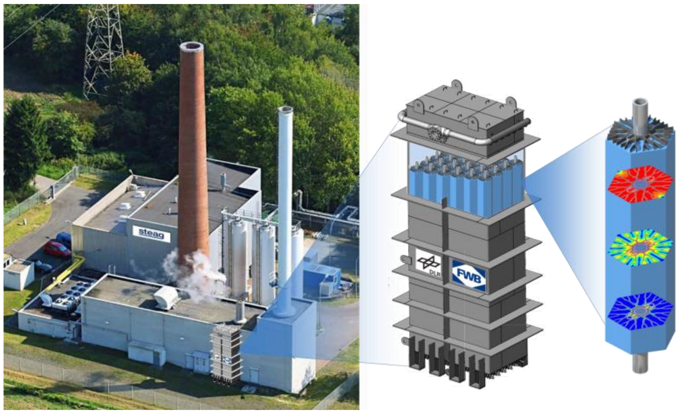


Figure 10: Photomontage of the storage unit erected along the wall of the cogeneration plant in Saarland, Germany.

The foundation needs to carry the weight of the storage unit filled with sodium nitrate (in total ca. 56 t) as well as the insulation and any extra loads such as people during filling of the storage, water weight of heat transfer fluid in the storage unit and piping and snow, as this unit is being erected outside of any buildings. In addition, the foundation needs to be designed to contain the sodium nitrate if there were to be a leak in the unit, and be designed for the pipework of the integration, including feedwater coming into the bottom of the storage unit during discharging and condensate and/or steam coming out of the bottom of the storage unit during charging. The build and plan of this foundation are shown in Figure 11 and Figure 12, respectively.

Figure 11: Foundation for the storage unit prepared for storage erection.

In order to meet these requirements, the foundation is built as a containment well (or pit), into which the molten salt, at temperatures between 306 °C and 350 °C, can flow and be contained if there is a leak. The concrete and rebar have to withstand these temperatures while maintaining static stability. The foundation also allows for the removal of condensate from the system, which is brought around the building to the site at which it can flow into the condensate pool from the plant.

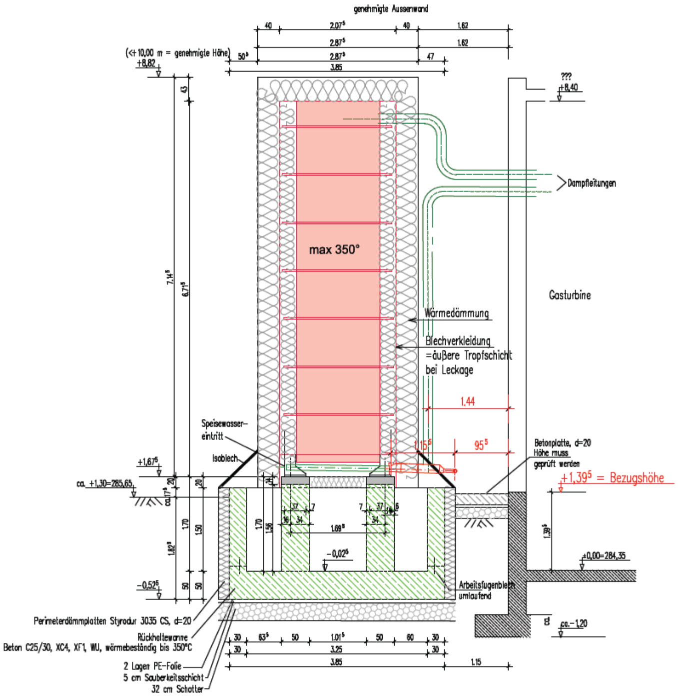


Figure 12: Foundation for the storage unit as a plan.

3 SIMULATION RESULTS

System simulations of discharging and charging, with a bypass operation for charging of the storage unit, have been conducted using the model described in (1). The discharging system requirements are 15 minutes of steam at a minimum of 300 °C and a pressure of at least 21 bar. Steam at temperatures above 300 °C will be temperature controlled down to this temperature using water injection. Figure 13 shows the simulation results from the design of the storage unit. Shown here are the input flow in blue at a constant 103 °C, and a slowly sinking outlet line in red, beginning at 350 °C and ending at 300 °C, at which point the storage unit is considered discharged in this application. This occurs after about 28 minutes, showing that the storage unit has been oversized for increased supply security as well as plant flexibility.

Discharging with these cut-off criteria results in only a portion of the storage material being solidified, as can be interpreted from the green temperature plots in Figure 13. The green lines depict the averaged temperatures of the PCM at cross-sections of the storage at the top, middle and bottom of the unit. The phase change temperature of the PCM is 306 °C, which means that the PCM at the bottom of the storage unit undergoes a phase change very quickly, after less than two minutes of discharging. The PCM in the middle of the storage unit undergoes phase change after approximately 19 minutes and the top of the storage unit is still liquid at the cut-off point at 28 minutes. According to the simulations, approximately 27 % of the PCM remains liquid throughout normal operating conditions.

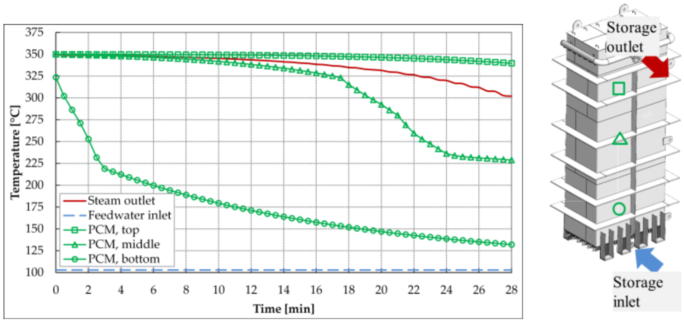


Figure 13: Discharging temperatures of the averaged values in the PCM at the top, middle and bottom as well as the storage outlet and inlet temperatures. The schematic on the right shows approximate calculation locations. (1)

Charging of this storage system requires that the storage system outlet be of a steam quality that the industrial customer can use for as much time as possible. This results in a sensible charging of the storage unit for a large percent of the charging time, and a much longer storage charging time in comparison to the discharging – ca. 800 minutes compared to 28 minutes. As the power plant and customer can use this steam during charging, this long charging time is acceptable.

The temperatures of the averaged values in the PCM at the top, middle and bottom as well as the storage outlet and inlet temperatures are shown in Figure 14. The storage is charged from the top, so that inlet and outlet of the storage switch with the change in operating modes. A new line (purple) is introduced in this figure – the temperature after the bypass and after the storage unit (see Figure 1). This is the mixing temperature of the storage outlet and bypass steam that is sent to the industrial customer, prior to any temperature adjustment by water injection. This temperature adjustment would be necessary after about 600 minutes of charging.

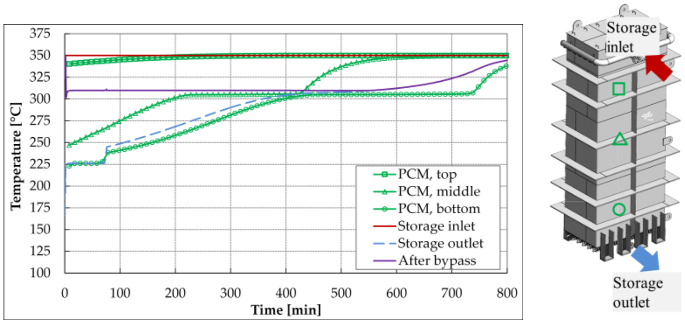


Figure 14: Charging temperatures of the averaged values in the PCM at the top, middle and bottom as well as the storage outlet and inlet temperatures and the temperature after mixing the storage outlet steam with the bypass steam after the bypass. The schematic on the right shows approximate calculation locations.

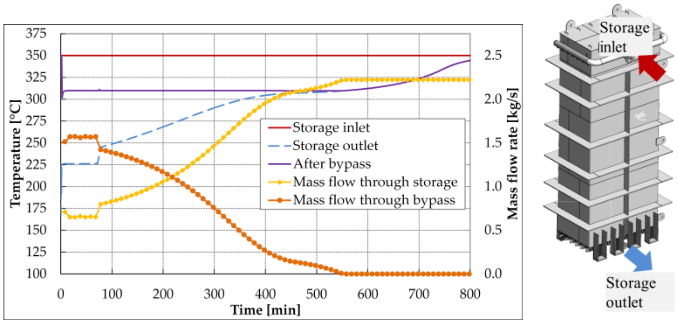


Figure 15: Charging temperatures of the storage inlet and outlet, and mixed bypass temperatures as well as the mass flow rates through and bypassing the storage unit. The schematic on the right shows approximate calculation locations.

In order to attain these mixing temperatures that are above 300 °C for most of the charging time, a regulation of the mass flow going through the storage unit and the bypass is necessary. Figure 15 shows the initially high mass flow rate through the bypass (orange dots) steadily decreasing after about one hour, when the temperature at the storage outlet reaches the evaporation temperature at operating pressure – ca. 226 °C. Only for the last 250 minutes of charging does the entire mass flow rate of 2.2 kg/s flow through the storage unit.

4 CONCLUSIONS AND OUTLOOK

The detailed design and a partial build of the storage unit has to-date been successfully concluded, as well as system design and build. Hot and cold commissioning of the storage unit, including filling of the storage unit, will commence following the completion of the storage unit. The control of the mass flow rates through the bypass and the validation of both this model and the fin model will take place with testing at different flow rates and valve opening rates.

With the integration of this storage unit, fossil fuel use will be reduced in this power plant. Depending on how often the storage unit is needed as well as the demand for steam from the other steam customers, the energy saving could be approximately 5000 MWh/a.

The production of superheated steam at a high power level in a latent heat storage unit and a comparison with simulation tools will be possible. This project includes the design, build, commissioning and testing of the storage unit.

ACKNOWLEDGMENTS

This work has been partially funded by the German Federal Ministry of Economic Affairs and Energy in the framework of the TESIN project (03ESP011). The authors are responsible for the content of this publication.

Present address of Matthias Hempel: QUINTEC Datentechnik GmbH, 90766 Fürth.

REFERENCES

[1] Johnson, M., Vogel, J., Hempel, M., Hachmann, B., Dengel, A. (2017). Design of High Temperature Thermal Energy Storage for High Power Levels, *Sustainable Cities and Society*, 35, 758-763, doi: 10.1016/j.scs.2017.09.007.

[2] Johnson, M., Vogel, J., Hempel, M., Dengel, A., Seitz, M., Hachmann, B. (2015). High Temperature Latent Heat Thermal Energy Storage Integration in a Co-gen Plant, *Energy Procedia*, 73, 281-288. doi:10.1016/j.egypro.2015.07.689.