CONCRETE STORAGE FOR SOLAR THERMAL POWER PLANTS AND INDUSTRIAL PROCESS HEAT

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ABSTRACT

Economic storage of thermal energy is a technological key issue for solar thermal power plants and industrial waste heat recovery. Systems using single phase heat transfer fluids like thermal oil, pressurized water, air or superheated steam, demand storage systems for sensible heat. A sensible heat storage system using concrete as storage material has been developed by Ed. Züblin AG and DLR. A major focus was the cost reduction of the heat exchanger and the high temperature concrete storage material. For live tests and further improvements a second generation 20 m³ solid media storage test module was built in Stuttgart and is cycled by an electrically heated thermal oil loop. By end of October 2008 the second generation solid media storage test module had accumulated four months of operation in the temperature range between 300 °C and 400 °C and about 50 thermal cycles with a temperature difference of 40 K. The tests will be continued until June 2009. Application fields for the concrete storage technology are parabolic trough solar thermal power plants; industrial waste heat recovery at elevated temperatures; thermal management of decentralized combined heat and power systems for increased flexibility and other high temperature processes. Especially the wide range of possible working temperatures and the modular structure make the heat storage in concrete attractive.

INTRODUCTION

Low temperature storage systems are based almost entirely on sensible heat storage using liquid water. For temperatures exceeding 100 °C, non-pressurized liquid water cannot be used as a storage medium. The use of pressure vessels makes this technology unattractive for higher temperatures. Other liquid storage media with higher evaporation temperature like oil or molten salt could be used, showing other disadvantages like e.g. degradation or high freezing points. An attractive option regarding investment and maintenance costs is the application of solid sensible heat storage media.

The German Aerospace Center successfully tested a first concrete storage on the Plataforma Solar de Almeria in Spain in 2003/2004 within a project funded by the German government [1]. In a follow-up project, Ed. Züblin AG joined the concrete storage development and a major focus was directed on cost reduction [2]. The first test module built in this project was damaged during start-up phase. During heating up of concrete, water evaporates and can build up a critical vapour pressure if the permeability is too low. Analysis of the damage showed that there was still residual water in the core of the concrete storage block, indicating that the exceeding vapor pressure caused the damage of the test module. Intensive effort has been put in the further development of the storage concrete and storage design, to optimize the requirements concerning storage capacity and thermal conductivity on the one side and to achieve sufficient permeability of the vapor on the other side, resulting in a new design, presented in this paper.

DESIGN AND CONSTRUCTION OF THE CONCRETE STORAGE TEST MODULE

Design of the test module

For demonstrating thermal storage in concrete a second test module was designed. In doing so the thermal layout and construction details developed for a full scale storage unit were used. Furthermore methods of construction, the heating-up process and instrumentation were tested. In principle the concrete storage module is composed of a tube register and the storage concrete (Figure 1).

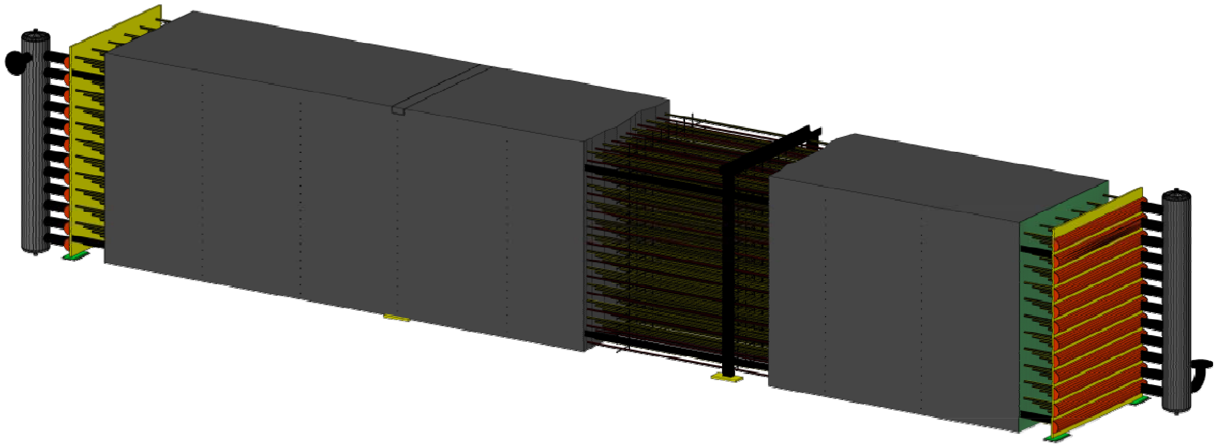

Figure 1: Storage module with laid open tube register

Fabrication of the tube register

The tube register consists of 132 tubes with a length of 9 m and an outer diameter of 18 mm. The tubes are arranged in triangular pitch. Collectors consisting of flat plates and semi-shells are placed at the end of the tubes. The tube register was prefabricated in the workshop, transported on site and lifted onto the previously prepared foundation by crane (Figure 2).

Figure 2: Lifting of the prefabricated tube register

To prevent a contamination of the surrounding soil with the heat transfer oil in case of leaks a steel trough had been placed at the very bottom. Inside the trough a pressure-resistant thermal insulation had been installed (Figure 3).

Figure 3: Pressure-resistant thermal insulation

Concreting of test module

As preparatory work a large number of material tests with various kinds of cements, aggregates and admixtures had been carried out. Finally a special concrete mixture using polyethylene fibers was used for the storage. In Figure 4 the finished test module can be seen.

Figure 4: Finished test module (without thermal insulation)

INSTRUMENTATION

To measure thermal performance of the test module and control the start-up process the test module was equipped with a number of temperature, flow and vapour pressure sensors. Temperature and pressure was measured at various locations inside the test module. Special focus was directed to the measurement of vapour pressure, to control the start-up process.

TEST RESULTS

When a concrete storage module is heated from ambient temperature to 400 °C for the first time, most of the water contained in the concrete mixture is expelled. During this process water evaporates and builds up a vapor pressure within the concrete. If the vapor pressure exceeds a critical value, a serious damage may occur.

The storage test module was therefore closely monitored during initial heating-up. As indicated by the sensors, each increase in temperature was followed by an increase in vapor pressure with some delay. The vapor pressure reached a peak and fell back to base level during an extended hold time. When this point was reached, all the water that could be mobilized at the current temperature had been expelled and the next temperature step was taken. This method allowed for a safe start-up operation. After this successful start-up operation the storage test module reached a concrete temperature of 400 °C by mid of May 2008. Subsequently, it was submitted to thermal cycles corresponding to charge/discharge cycles in the storage system of a power plant of ANDASOL type. By end of October 2008 the second generation solid media storage test module had accumulated four months of operation in the temperature range between 300 °C and 400 °C and about 50 thermal cycles with a temperature difference of 40 K. During this time the performance of the storage was absolutely constant.

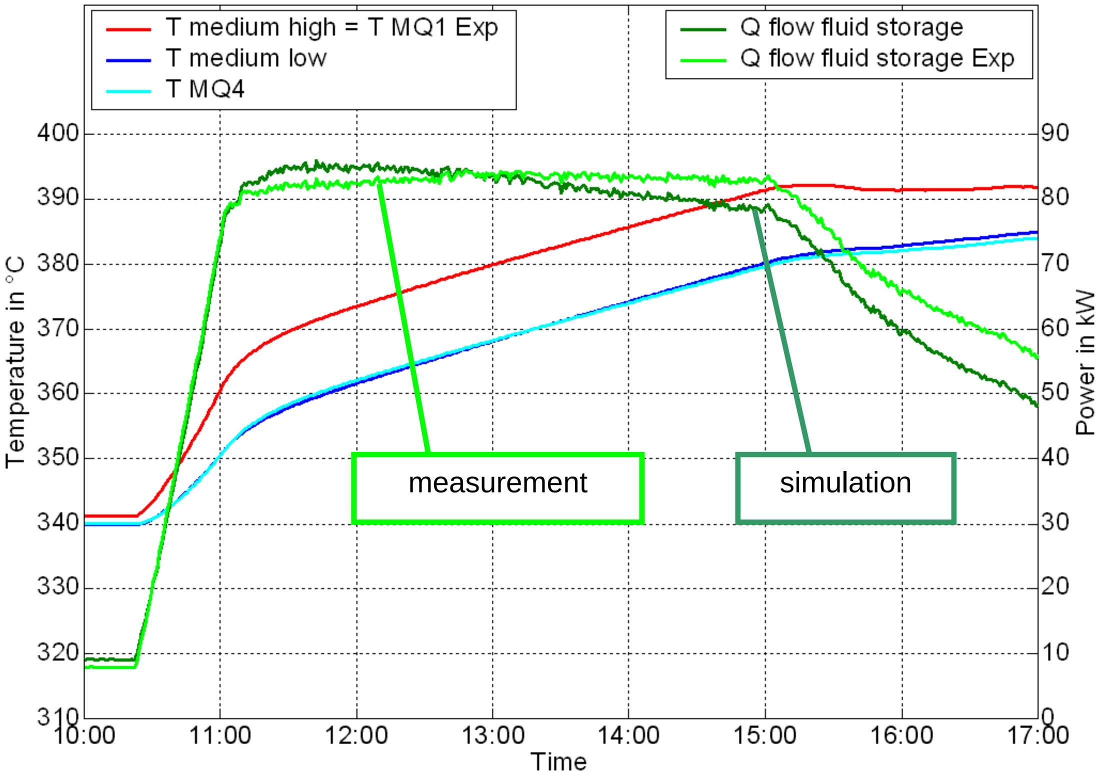

Figure 5: Comparison of simulation and experiment

Preliminary calculations of the theoretical storage capacity for the boundary conditions of six hours charging and discharging and a temperature difference of 40 K resulted in a total capacity of 474 kWh, corresponding to a specific capacity value of 25.6 kWh/m³. These values were confirmed by the measurements very well. The thermal behavior of the storage test module was modeled using the object-oriented modeling language Modelica and the Dymola environment as described by Steinmann and Buschle [3]. Figure 5 compares some of the simulation results to the measured values. To compare model and experiment as closely as possible, the fluid source in the model was supplied with experimental data for the temperature of the thermal oil at the inlet of the storage module and the volume flow. The storage unit in the model was initialized with the temperature measured in the experiment in steady state conditions before switching into charging mode. As can be seen in Figure 5, the simulation correlates very well with the measured values. These results prove that the storage module performs as expected. Furthermore the simulation tool allows us up-scaling of the system and the design of concrete storage systems for commercial applications.

STORAGE APPLICATIONS

Concrete storage has so far been designed for parabolic trough solar thermal power plants of the ANDASOL-type, using thermal oil as heat transfer fluid. So for this 50 MWe plant a concrete storage with an overall capacity of approx. 1100 MWh will be build up modularly from 252 basic storage modules with about 400 tons of concrete each [4]. These basic modules will be connected in series and parallel and packed together into four insulated storage units of 63 modules (see Figure 6). A ground surface of approx. 300 m x 100 m is required.

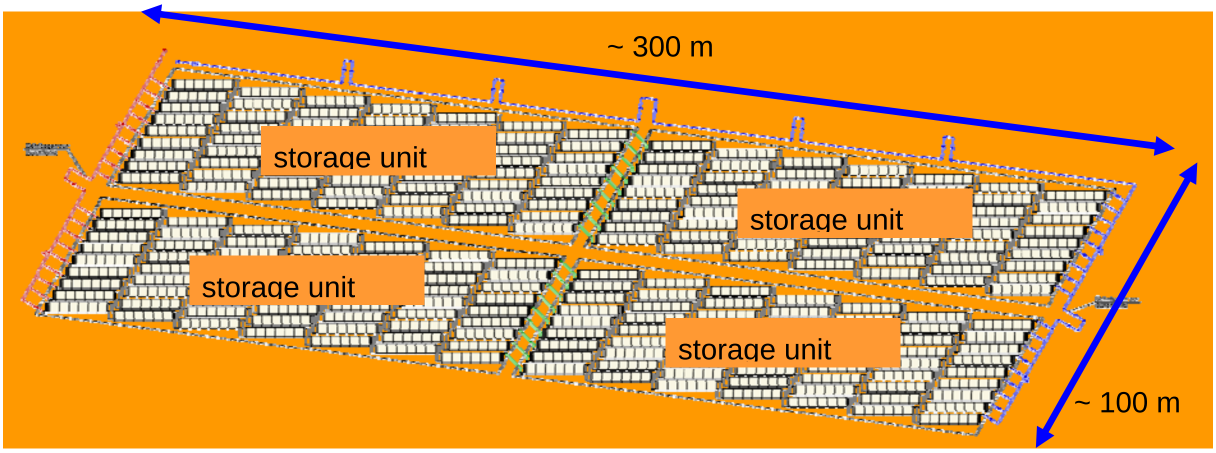

Figure 6: Set-up of a 1100 MWh concrete storage from 252 basic storage modules

Another application in the solar thermal power generation sector is for future parabolic trough plants with direct steam generation. In a storage system for the two phase fluid water/steam, concrete storage will be used for the sensible parts - preheating of water and superheating of steam, while for the two-phase evaporation a phase change material storage will be employed. This technology is currently developed by DLR, Ed. Züblin AG and Siemens AG within the project ITES, funded partly by the German Ministry for the Environment, Nature Conservation and Nuclear Safety [5].

The changing market conditions for energy generation and utilization as well as the legal regulations for climate protection require increasing effort regarding energy efficiency in many industrial sectors and by this increasing effort in the thermal management of heat and power. Hence, efficient and economic energy storage technique will be a key issue to a future sustainable energy supply [6]. So apart from solar thermal power plants there are various application fields for concrete storage in the industrial process heat sector. Regarding all industry sectors, roughly 30 % of process heat requirement is between 100 °C and 400 °C [7], which fits ideally to concrete storage. For remote combined heat and power (CHP) units, heat and power production can be decoupled using heat storage. By this the heat supply is adaptable to a variable power. Surplus heat can be stored and discharged from the storage at a later time when demand is higher than the supply from the CHP unit.

With thermal storage the heat supply is also variable with time and the temperature level can be adapted.

Waste heat recovery is another very important sector, where energy efficiency can be increased using concrete storage, returning heat into the process or to other users in the factory. Also cyclic waste heat from industrial processes can be stored in concrete storage to power continuously or on demand an organic Rankine cycle (ORC) and generate electricity.

CONCLUSIONS

With the successful start-up and thermal cycling operation of the concrete storage test module it was proven that concrete storage technology is a suitable option for storing sensible heat. The technology is applicable for solar trough plants, industrial waste heat and combined heat and power systems. Due to the modular design concrete storage is scalable from the kWh to GWh range. So far, thermal storage in concrete has been tested and proven in the temperature range up to 400 °C. Currently the development is being carried on towards 500 °C. The expected storage capacity has been approved by the experimental results. The developed simulation tool allows up-scaling of the system and the design of concrete storage systems for commercial applications. As reference for future commercial applications a pilot concrete storage with full scale modules is planned.

ACKNOWLEDGEMENTS

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