Development of a modular thermal storage system for industrial waste heat

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In the „ModulHeatStore" research project, a consortium of companies and research institutions has developed a modular heat storage system for the efficient and economical storage of industrial waste heat at high temperatures of up to 1,200 °C. The system is based on a combination of sensible and reliable heat storage systems. What is new about it is the combination of sensitive and latent heat storage modules, taking into account the specific properties and advantages, such as charging and discharging characteristics, temperature stability, costs, etc., as well as an interconnection concept for coupling the individual modules and an intelligent thermal process control system for integrating the storage unit into existing and new processes. Although heat storage systems for industrial applications are already available on the market, flexible standard solutions for storing process heat in high-temperature applications are hardly commercially available.

By 2030, CO_2 emissions in Germany are to be reduced by at least 65 % compared to 1990 levels in order to limit climate change. This poses particular challenges for the manufacturing sector with its energy-intensive operations in Germany. In 2019, German industry consumed 519 TWh of thermal energy. Of this, 46 TWh was used for low-temperature (less than 130 °C), 169 TWh for medium-temperature (between 130 and 500 °C), and 303 TWh for high-temperature (more than 500 °C) applications. [1] To achieve the climate target, a switch to alternative climate-friendly energy sources such as renewable electricity, biomass, and climate-neutral gases is obvious. However, there is also still great potential for savings in energy efficiency. A 2015 study concluded that there is a rough and theoretical waste heat potential of 225 TWh/a available in the manufacturing sector (reference year 2008). [2]

Since many industrial processes are operated in batches, the resulting waste heat often accumulates discontinuously. The recycling of waste heat into the production process is often practiced, but in many cases there is a time mismatch between the availability of waste heat and the heat demand. This means that only part of the waste heat can be used. In systems for the utilization of surplus energy, such as steam power plants based on the organic Rankine cycle (ORC) for the conversion of thermal energy into electrical energy, it is necessary to adapt the operation of the ORC plant to the availability of heat. As a consequence, the operation of the ORC plant is not possible in the optimal process window and the electrical efficiency is reduced compared to the design condition.

This results in the need to be able to store all or part of the energy from the waste heat over defined periods of time and to be able to release it as required in order to feed it back into the processes or to make it available to the downstream processes in the form of heat or electricity. Although heat storage systems for industrial applications are already available on the market, flexible standard solutions for storing process heat for high-temperature applications up to 1,200 °C are hardly commercially available.

THE CONCEPT OF THE MODULAR HEAT STORAGE SYSTEM

The idea behind the "ModulHeatStore" research and development project was therefore to develop a modular heat storage system (**Fig. 1**) for high-temperature systems such as industrial furnaces, including intelligent thermal process control for the energetic utilization of industrial waste heat. The storage system must allow waste heat to be decoupled from its utilization over time. This can increase the energy efficiency of existing and new processes of

Fig. 1: The modular heat accumulator in the laboratory with a high-temperature and a low-temperature module. A connection of the storage tank to an industrial firing system enabled near-operational tests. (Source: OWI)

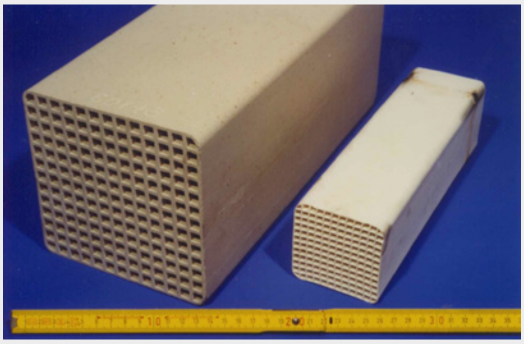

Fig. 2: Ceramic honeycombs for the storage of high-temperature heat. (Source: Hülsenbusch)

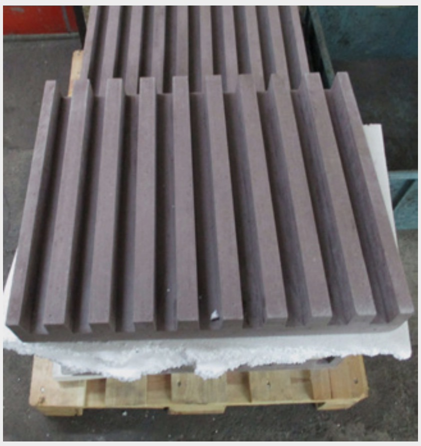

Fig. 3: Concrete storage tank for intermediate storage of residual heat. (Source: Hülsenbusch)

manufacturing companies and achieve higher profitability. The storage materials must be suitable for a temperature range of up to 1,200 °C. The heat storage concept aims to achieve high efficiency and flexible use even with fluctuating temperatures and volume flows. By using standard components and low-cost storage materials, the investment costs and ultimately also the maintenance costs should remain low.

Two different concepts for integrating the accumulator were developed for investigating the general conditions at the industrial users, which differ primarily in the location of the heat extraction from the exhaust gas train. Depending on the type of thermoprocessing plant, such as batch furnaces or continuous furnaces, exhaust gases are available at different temperature levels. To reduce the energy consumption of the furnace system, the combustion air is usually heated by the heat of the exhaust gas. In order not to influence the operating sequence and the energy efficiency of the actual production process, the exhaust gas for the heat accumulator can therefore be taken either upstream or downstream of the recuperator of the air preheater, depending on the exhaust gas temperature and efficiency of the air preheater.

MODULAR DESIGN FOR DIFFERENT TEMPERATURE LEVELS

The combination of different storage materials in the individual modules makes it possible to direct waste heat flows at different temperature levels to the corresponding heat storage module and store them at a suitable temperature that is as high as possible. Since thermoprocess plants run with high variance in temperature and power, the modular heat storage system requires intelligent control of the thermoprocesses, which adjusts fully automatically to the processes (**Fig. 4**). The modular storage system covers two temperature levels and temperature constancy:

High temperature (HT) module: A ceramic accumulator made of honeycombs or molded bricks (**Fig. 2**) is used to store high-temperature heat (temperature between 400 and 1,400 °C). They have a large specific heating surface and can therefore absorb and release large heat flows.

Low-temperature (NT) module: In the lower temperature range, a stone/concrete accumulator is used for intermediate storage of the residual heat at temperatures between 200 and 600 °C (**Fig. 3**). The concrete elements made of special concrete are relatively inexpensive. The stored heat of the stone/concrete storage can be used for further applications, such as feeding into district and local heating networks and the provision of cooling via absorption refrigeration plants. It is also possible to use heat at temperatures below, for example, the evaporation temperature of the working medium in a downstream ORC process.

PCM module with high temperature constancy: This module reproduces a temperature level up to about 400 °C on the basis of a phase change material (PCM). By utilizing the latent heat during the phase change of the PCM, in this case with the solid-liquid phase change, a great amount of heat can be stored even in a small temperature range, in contrast to a sensible heat accumulator. As a result, heat is also released at an almost constant solidification temperature, which is advantageous for subsequent processes (e.g. ORC processes, generation of process steam).

DEVELOPMENT AND DESIGN OF THE PCM MODULE

Various challenges had to be overcome in the development and design of the PCM module. A metallic heat-conducting structure in the form of a fiber structure is used to improve heat conduction in the PCM. The thermal connection of the fiber structures to the heat transfer medium via tubes also plays a decisive role. A thermally conductive bond is created by mechanical whitening (**Fig. 5**). The composite is placed in a container and the cavity in the structure can be filled with the PCM. The large number of parallel channels allows the media flow to be distributed in the storage module and the heat conduction paths in the PCM to be limited. Different design approaches are available for gaseous and liquid heat transfer media (**Fig. 6**, **Fig. 7**).

SELECTION OF THE PCM

A literature research conducted in the project on relevant salts & salt mixtures in the range 300 - 500 °C served as a basis for the selection of a suitable PCM. The initial focus was primarily on chlorides. The advantages of chlorides over nitrates lie in their comparatively high storage capacity, low material costs, good availability and higher temperature resistance. Due to its high latent heat, a promising mixture for heat storage application is a eutectic of MgCl2-KCl-NaCl (melting temperature ~ 380 °C, phase change enthakpy ~ 180.5 kWh/m^3). These are toxicologically harmless and pose minimal disposal requirements with regard to subsequent use. A major challenge, however, was the corrosion of the storage tank and the metallic fiber structures in conjunction with the chlorides.

Nickel-based alloys and high-alloy stainless steels generally exhibit comparatively low corrosion rates, but are generally very cost-intensive. Low-alloy stainless steels and simple steels also show low corrosion rates in some cases, depending on the PCM used and the atmosphere present (air, nitrogen, inert gas).

On the basis of existing experience and accompanying corrosion tests and material science investigations, the decision in the construction of the demonstrator was ultimately made in favor of a nitrate salt as the PCM, which was also available in the temperature range. This initially represented a more promising variant for late industrial

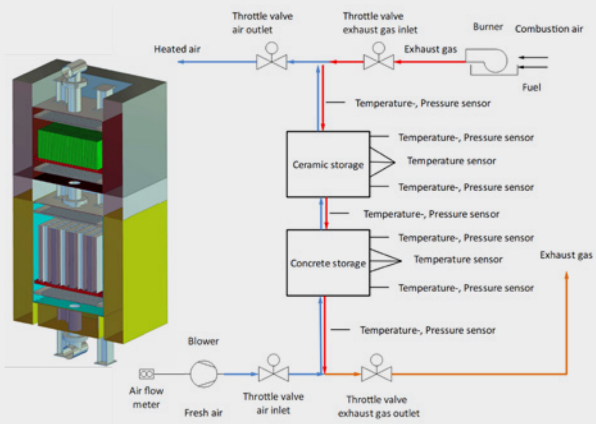

Fig. 4: Test setup of the modular heat storage system with the high- and low-temperature modules. (Source: OWI)

Fig. 5: Composite of tube and fiber structure. The distributed cavity in the structure is filled with the PCM. (Source: Fraunhofer IFAM)

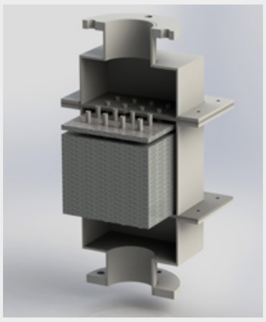

Fig. 6: Construction concept for gaseous heat transfer media. (Source: Fraunhofer IFAM)

Fig. 7: Demonstrator for liquid heat transfer media. (Source: Fraunhofer IFAM)

implementation. Such investigations had not previously been carried out with the combination of nitrate salt and porous fiber structure. The cycle tests carried out for this purpose with corresponding steel fiber samples and PCMs did not reveal any significant material changes during the test period, quite in contrast to the chloride salt PCMs. Within the project budget, the researchers limited themselves to the most promising PCM candidate (NaNO3) and steel-based fiber structures for the demonstrator.

FLOW CONTROL IN THE HEAT ACCUMULATOR

An important point for a high efficiency of the heat storage system is a uniform flow through the storage masses. The basic aim was to avoid irregularities in the inflow and outflow and, in particular, different profiles in the charging and discharging phases. The inflow into the storage modules usually takes place through centrally arranged pipes. For structural reasons, the distance between the inflow and the storage mass is as short as possible, i.e. the flow cannot be distributed over the entire surface of the storage mass. Good distribution and flow through the storage mass is achieved by installing perforated plates on both sides of the storage mass.

THERMAL INSULATION

The heat accumulators will later be used at numerous plants with different operating conditions. These plants also have different time sequences, which accordingly require loading and unloading times ranging from a few minutes to several hours. At high temperatures and long charging times, large heat loss flows can occur, which greatly reduce the energy efficiency of the thermal storage units. Equipping the heat accumulators with thermal insulation reduces these heat losses. Depending on the conditions of use, different thermal insulation materials are suitable:

- Conventional thermal insulation (Al-Si- or Al-O-wool)
- Microporous thermal insulation materials
- Aerogels (still under development)

These thermal insulation materials differ in thermal conductivity and cost by up to a factor of 10, and the processing requirements are also different. Aerogels are not yet ready for industrial use, but they promise considerable advantages for operational use.

DESIGN OF THE HEAT ACCUMULATOR

Within the project, a tool and optimization procedures for design and operation were developed. Design criteria for thermal storage are the heat capacity in MWh or GJ, the heat output in MW and the loading/unloading temperature level. Basically, two different scenarios can be distinguished for heat storage systems for industrial applications:

Heat accumulators for periods starting from about 1/2 h up to about 48 h. These heat accumulators are planned for interruptions in industrial processes, for night shutdowns and for weekend and holiday shutdowns. Here, the storage capacity is in the foreground, the heat output is largely constant.

Heat accumulators to compensate for operating fluctuations and interruptions in industrial processes. During normal operation, many industrial processes experience fluctuations in temperature and enthalpy flows in the range of 10 to 125 %. The time window for these fluctuations is around 30 s up to 15 min. The large fluctuations are difficult to compensate. To compensate for these fluctuations, much smaller heat accumulators are required compared to long-term accumulators, where heat output is the primary concern. Here, the high heat flows have to be ensured by suitable heat transfer properties.

In this project, the focus was on a heat accumulator for short-term storage, since this task is more demanding, especially with regard to intelligent process control (which reacts directly to the change in the main process), and a solution for these accumulators can also be transferred well to the long-term accumulators. The calculated heat capacity for this storage will be 140 kWh, and the heat output should be up to 250 kW. At thermal process plants, typically 1/4 to 3/4 of the primary energy introduced remains unused and is lost to the process as waste heat. By using a heat accumulator, up to 80 % of the waste heat can be fed back into the process or used for other processes. In large plants, additional energy quantities of up to 100 GWh/a can be utilized in this way. The economic efficiency of the entire plant would thus be considerably increased by the use of waste heat, and CO_2 savings would be achieved through lower primary energy consumption. The storage concept is not in competition with the process optimization of the main process, since only the residual heat is integrated via the storage tanks, which would otherwise remain unused.

PROCESS CONTROL OF THE LABORATORY PLANT

A key objective of the process control is to operate the heat storage system without any repercussions on the waste heat source. The software developed in the project controls the loading and unloading of the heat storage system. This process control was used at the test plant and enables the automated operation of the storage unit on a laboratory scale. From the upstream process (in the project experimental combustion chamber, in industrial practice: furnace plant or other process with hot exhaust gas) the control system receives the temperature of the exhaust gas. In the storage tank itself, the temperatures of the individual modules as well as the damper positions and current flow rate of the discharge blower are recorded and forwarded. In the case of discharge, the amount of exhaust gas passed through the accumulator is controlled on the basis of the exhaust gas temperature in such a way that the maximum permissible temperatures for the accumulator materials are not exceeded. The control damper upstream of the inlet to the accumulator is provided as the control element here. The limit values for the storage materials can be flexibly parameterized here, so that adjustments can also be made here - for example on the basis of changes to the storage material or operating experience - without the need for structural changes to the control system.

In the case of unloading, control of the air quantity enables the unloading temperature to be set variably. The target temperature of the discharge is not set by a parameter, but is an input at the interface to the connected utilization. This allows the utilization process to adjust the withdrawal temperature at any time based on current requirements.

During operation of the storage tank, situations may occur in which there is a supply of hot flue gas, but the storage tank is not ready to accept heat (e.g., because the maximum temperature of individual modules has been exceeded) (**Fig. 8**). In the case of discharge, it is possible that the accumulator cannot supply process heat at the required level due to the current load level. In these cases, the status of the storage tank is reported on the interface to the outside as "Not Available" so that the external systems can react accordingly. If the status of the storage tank is "Not Available", all dampers are closed and the fan is switched off. This avoids unnecessary heat loss and maintains the charge level of the storage tank as good as possible.

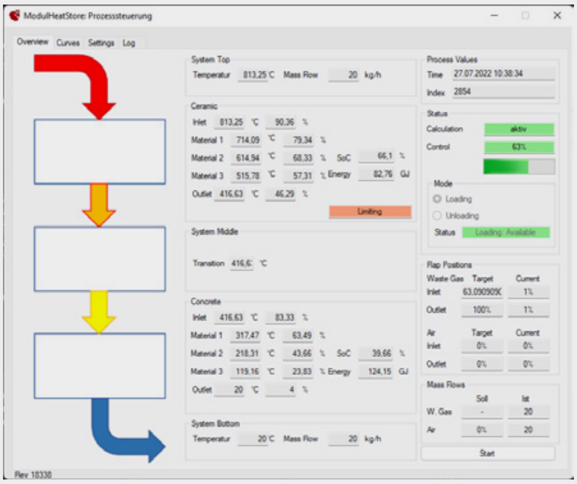

Fig. 8: Control program during a simulated loading of the storage tank. It can be seen that the inlet flap has already been closed to a position of 43 % due to the approach of the permissible maximum temperature (here: 900 °C). (Source: GIWEP)

CONCLUSION

Thanks to its modular design and intelligent thermal process control, the heat accumulator can be optimally and flexibly adjusted to different processes without having to redesign each one. It can be used for processes where waste heat temperatures and mass flows fluctuate or where waste heat is available intermittently due to shutdowns. From an economic point of view, minimal use of the high-quality ceramic honeycomb structures should be aimed for. A phase change material for storing waste heat is particularly suitable for high temperature constancy requirements, since the approximately constant temperature during the phase change allows a continuous heat flow and a high storage density to be realized in a limited temperature range. A new development of the heat transfer structure for the PCM module improves the heat transfer between the heat transfer medium and the PCM. Here, there is still a need for development in the state of the art in the speed and efficiency of heat absorption and release, due to the low thermal conductivity of the PCM. Furthermore, it would be useful to develop a test system for the heat transfer medium that allows the medium to be checked during operation of the storage unit and can thus detect impurities and efficiency losses.

The results and findings obtained in this research and development project form the basis for the industrial implementation of heat storage systems on industrial high-temperature thermal process plants. Due to the flexible modular concept, there is great potential for integrating heat storage systems into complex energy network systems, e.g. for generating electricity, compressed air, cooling or process heat. The mode of operation is to be adapted to the respective concrete system environment. The hardware has been tested with high temperature resistance and flexibility, the calculation program for the design has been verified and the new automation program allows direct and simple connection to the process plants.

The project partners in the ModulHeatStore project were OWI Science for Fuels gGmbH, the Dresden branch of the Fraunhofer Institute for Manufacturing Technology and Applied Materials Research IFAM, Hülsenbusch Apparatebau GmbH & Co. KG and the Gesellschaft für industrielle Wärme, Energie- und Prozeßtechnik mbH.

OVERVIEW OF FUNCTIONS AND UNIQUE FEATURES

- Modular heat storage system for storing industrial waste heat at different temperature levels up to the high-temperature range at 1,200 °C.
- Adaptation to the heat to be stored is not achieved by scaling the storage unit, but by "numbering up" small and highly efficient modules.
- The same design and the possibility of interconnecting modules result in advantages in terms of flexibility and component costs.

- Combination of heat storage materials (ceramic, PCM, stone/concrete) for two relevant temperature levels (high and low temperature) and temperature constancy to achieve higher efficiency and flexibility in the application areas and in the operation mode of the storage. The contained exergy can be optimally and efficiently used and the losses minimized by storing it at the appropriate temperature levels.
- It is possible to minisize the high-quality ceramic storage tank and to expand it with additional modules as required. This allows economically optimized dimensioning of the waste heat storage system for heat recovery.
- Development of optimized heat transfer to the PCM by developing suitable heat transfer structures in the PCM material.
- The PCM storage has the advantage of a largely constant temperature during the phase change, so that heat can be provided for a long time at a fixed temperature level for the subsequent application (e.g. the ORC process), so that an increase in the average efficiency of power generation can be achieved.
- The development of an intelligent thermoprocess control system enables optimal integration of the modular heat storage unit and operation without repercussions on the thermoprocess plant. This makes existing or new processes more efficient and thus more economical with the developed modular heat accumulator.

The research project 16KN061424 was funded by the German Federal Ministry of Economics and Climate Protection as part of the Central Innovation Program for SMEs (ZIM) on the basis of a resolution of the German Bundestag.

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

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