Waste Heat recovery in industrial batch processes: analysis of combined heat storage and heat pump application.

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Waste Heat recovery in industrial batch processes: analysis of combined heat storage and heat pump application.

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Abstract

Heat is an important energy source for the chemical industry to drive their processes. Waste heat recovery and re-use therefor provides attractive energy saving and cost saving opportunities. However, in batch processes the availability of waste heat and the demand for heat are shifted in time and storage of thermal energy is needed to overcome this mismatch.
This study looks into the feasibility of a collective waste heat recovery system for a series of batch reactors. An exothermal reaction is carried out in these reactors and the surplus heat is in the current configuration removed by cooling water. In the studied configuration for waste heat recovery, the heat from the batch reactors is collected in a thermal storage system, which is used as heat source for a heat pump system. This heat pump can lift the temperature of the waste heat to the level that it can be fed to the on-site steam supply system.
A dynamic model is developed that incorporates the waste heat supply from the reactors, the thermal storage system and the heat pump. The model is used to study the impacts of thermal storage capacity and heat pump capacity on the waste heat recovery potential and amount of steam produced by the heat pump. The thermal storage system levels out the fluctuations in heat supply, enabling a more constant operation of the heat pump and a reduction in need for any backup steam supply. The analysis indicates that the heat storage system can be economically feasible, achieving pay back times of less than 5 years. The price of electricity is an important factor on the economic analysis.

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Keywords: thermal energy storage, batch process, heat pump , system integration

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1. Introduction

Improving the security of energy supply and reducing greenhouse gas (GHG) emissions are priority concerns for the Energy Union. Given that it helps to moderate energy demand and mitigate climate change, energy efficiency is one of the five pillars in the EU quest for greater energy security, sustainability and competitiveness [1] .

In the process industry a large share of the energy is needed for heating purposes. About 2/3 of the Dutch industrial energy demand is needed for heating purposes. This can be direct gas fired heating of reactants, production of steam and hot water. At the same time, waste heat at lower temperatures is released to the ambient through cooling towers and cooling water circuits. Re-using this waste heat within the processes can be a good solution to increase the industrial energy efficiency, and reduce the CO_2 emissions. The application of heat pump technology to upgrade the temperature level of industrial waste heat to allow re-use is considered as a strong building block for industrial energy efficiency [2].

In the chemical and food industry a significant share of the processes is operated in batch mode. These processes have a discontinuous character, which limits the possibilities for heat integration and direct re-use of waste heat [3]. Thermal energy storage uncouples in time the supply and demand of thermal energy and thus allows to enlarge the potential for re-use of waste heat.

The current study is looking into the contribution of a thermal storage system in improving the recovery and re-use of waste heat in industrial batch processes. A case study is done to analyse the feasibility of waste heat recovery system consisting of a mechanical steam recompression system combined with a thermal storage unit to smooth the variations in waste heat supply from the batch process.

2. System description

The industrial process considered in the current study, consists of a series of batch reactors that are operated independent from each other. The batch reactors are used for a polymerization process, that requires initial heat input to initiate the reaction, followed by heat removal to keep the exothermic polymerization process within its temperature boundaries. When the batch is ready the product is cooled down before emptying the batch. The heating and cooling operation is applied to a pressurized intermediate water loop that transfers the heat to and from the reactor product, as is schematically drawn in figure 1. The intermediate water loop operates in the range of 20 to 140°C. The heat supply to the reactors is done by the steam from a centralized steam utility, the heat removal from the reactors is done by the cooling water circuit.

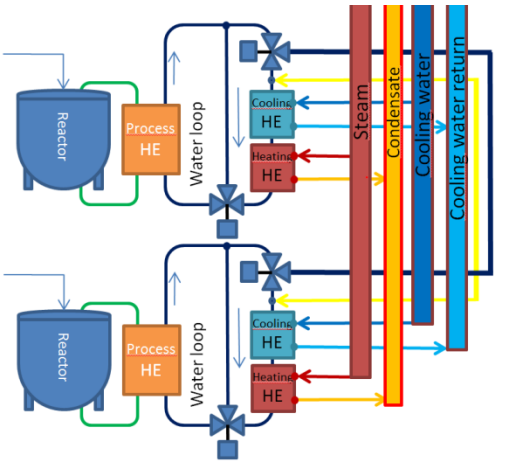

Figure 1: Schematic overview of the batch reactor arrangement in connection with centralised heating and cooling facilities

To recover the waste heat from the batch reactors a new scheme is proposed that allows to use the exothermal heat of the batch reactors as a source for a steam compression heat pump system. (see figure 2) The heat pump, a mechanical vapour recompression (MVR) system, is connected with a flash vessel that provides low pressure steam at the suction side of the MVR. The flash unit receives the pressurized water from the intermediate water loop and the excess heat is removed by flash evaporation. The existing cooling and heating facilities remain operational to assure the required temperature control of the batch reactors.

The proposed MVR operates in the range from atmospheric pressure at the suction side to produce steam at 12barg at the outlet, which can be integrated with the existing steam lines on-site. In order to reach the desired temperature and pressure increase, a 3 stage compression process is introduced with desuperheating by water injection between the stages. The design output of the heat pump is set at 20 tons of steam per hour.

However, the waste heat supply from the batch reactors strongly varies over time, and sometimes equals zero. This leads to large variation in the heat pump operational conditions. For that reason an additional steam supply at 3 bar from the existing steam lines is connected at the inlet of the MVR. This allows the MVR to remain operational in case the waste heat supply would drop below the threshold inlet conditions of the MVR.

Whenever the waste heat supply is higher than the maximum intake of the MVR, the existing cooling system of the batch reactors will remove the surplus heat.

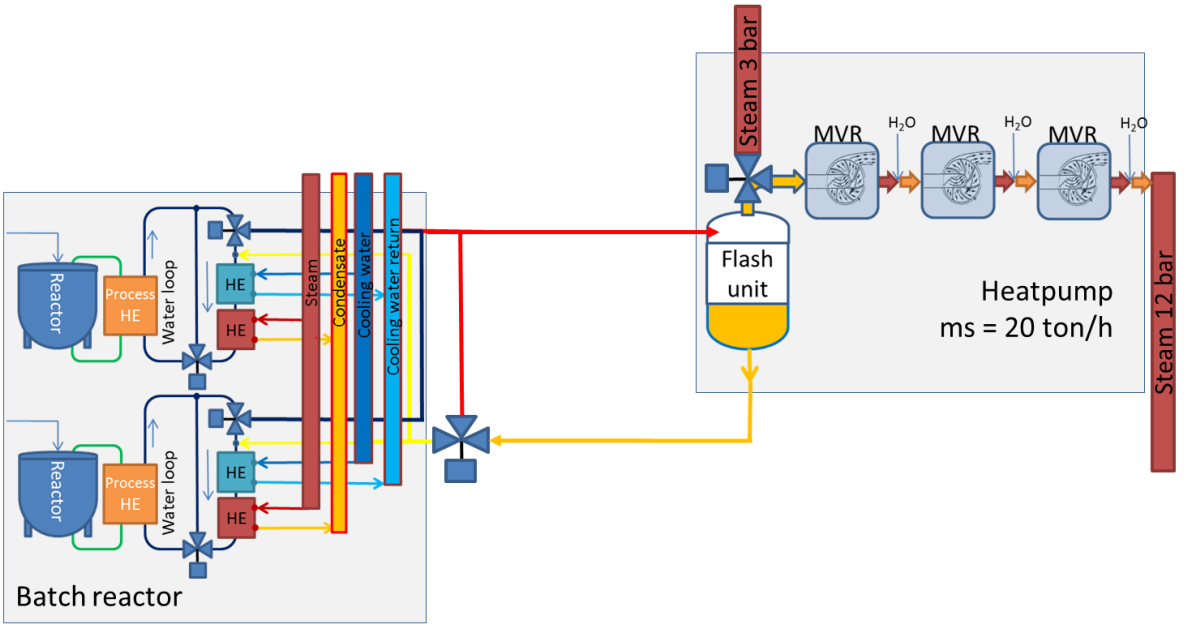

Figure 2: Integration of a mechanical vapour recompression system for waste heat recovery of the batch reactors.

To improve the effective heat recovery of the proposed concept, a thermal storage system is added to it. The thermal storage system allows to take up any surplus of waste heat from the batches, and release this surplus in times of insufficient waste heat supply form the batches. The system lay out is shown in figure 3. The storage system is based on a pressurized water tank, placed between the batch reactors and the MVR. The thermal storage system is assumed as a stratified water tank that can maintain a temperature gradient inside the tank and that no mixing of hot and cold water is taking place inside the tank.

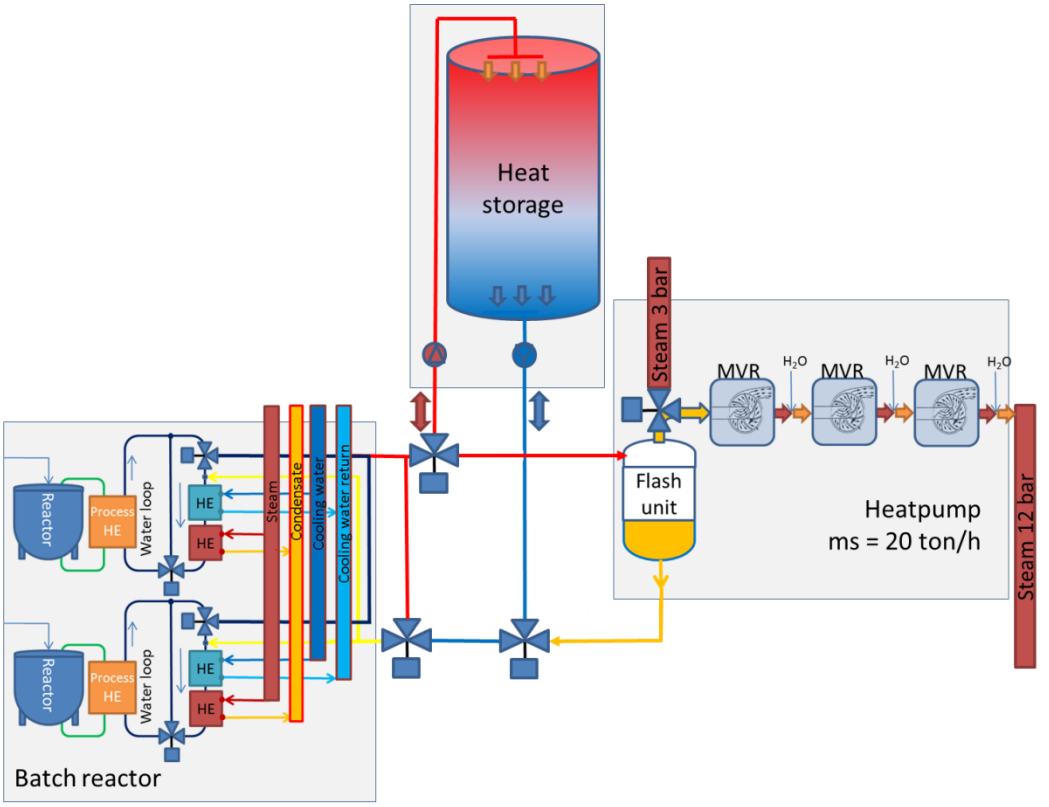

Figure 3 System lay-out for waste heat recovery of the batch process with integrated thermal storage unit

3. System model

A system model was built to simulate the process conditions and to allow analysis of the dynamics of the heat pump operation both with and without a thermal storage systems. MS-Excel is used as modelling tool combined with Refprop that provides the thermodynamic data of the steam to calculate the MVR conditions as well as the flash vessel conditions.

The MVR system was modeled as a three stage compressor having independent drive-units for the individual stages, in order to have each stage operating at its optimum efficiency. The sizing of the MVR is derived from the average value of waste heat supply, being around 10 MW. The outlet condition of the compressor was fixed at 12 bara pressure. At an inlet pressure below 0,75bara, the MVR can no longer achieve the required pressure increase. At this point the heat supply from the storage or from the 3 bar backup steam supply will be provided, in order to keep the MVR to produce 12 bar steam.

The thermal storage unit was modeled as a pressurized water tank, capable of storing hot water in the range between 140 to 80°C. The water storage volume is taken as a parameter to vary between 500 and 2500m^3. Heat losses were neglected in the simulation.

The supply of waste heat from two of the batch reactors is taken as input to the model with time steps of 1 hour. Five days in a row of the waste heat supply were taken as a representative period for the operational conditions of the batch reactors. The temperature and the thermal power of the waste heat source during the 5 day period are shown below in figure 4.

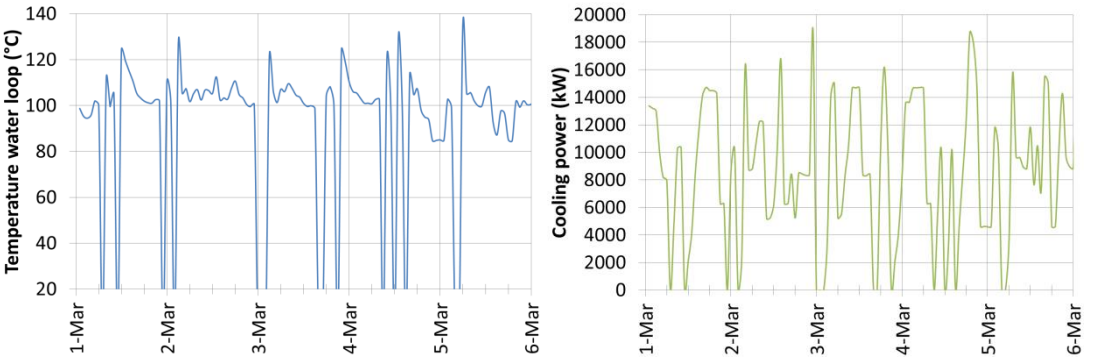

Figure 4 Temperature (left) and thermal power (right) profile for the waste heat of the batch reactors

4. Model results

The results of the calculations for the five day period of production for the system without the thermal storage are plotted in figure 5. The plot shows in green the timing of the steam needs during the five days for those periods where waste heat from the batches is too low. In this configuration the model calculates a back-up steam need during 22 hours with an averaged steam consumption of 87 ton/day

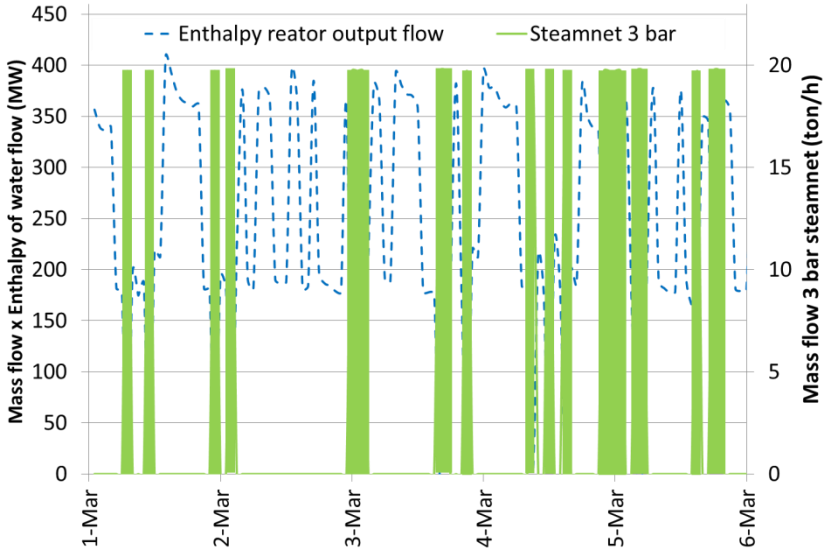

Figure 5:Input flow of waste heat from the batch reactors (dotted line) and back-up steam supply (green bar) for the MVR system, without thermal storage.

When including the thermal storage system the surplus of waste heat can be stored, and during times of too low waste heat supply the stored heat is released from the storage. For the situation of 1000m^3 and 2500m^3 of hot water storage these charge and discharge cycles are analysed. The results of these analyses are shown below in figure 6.

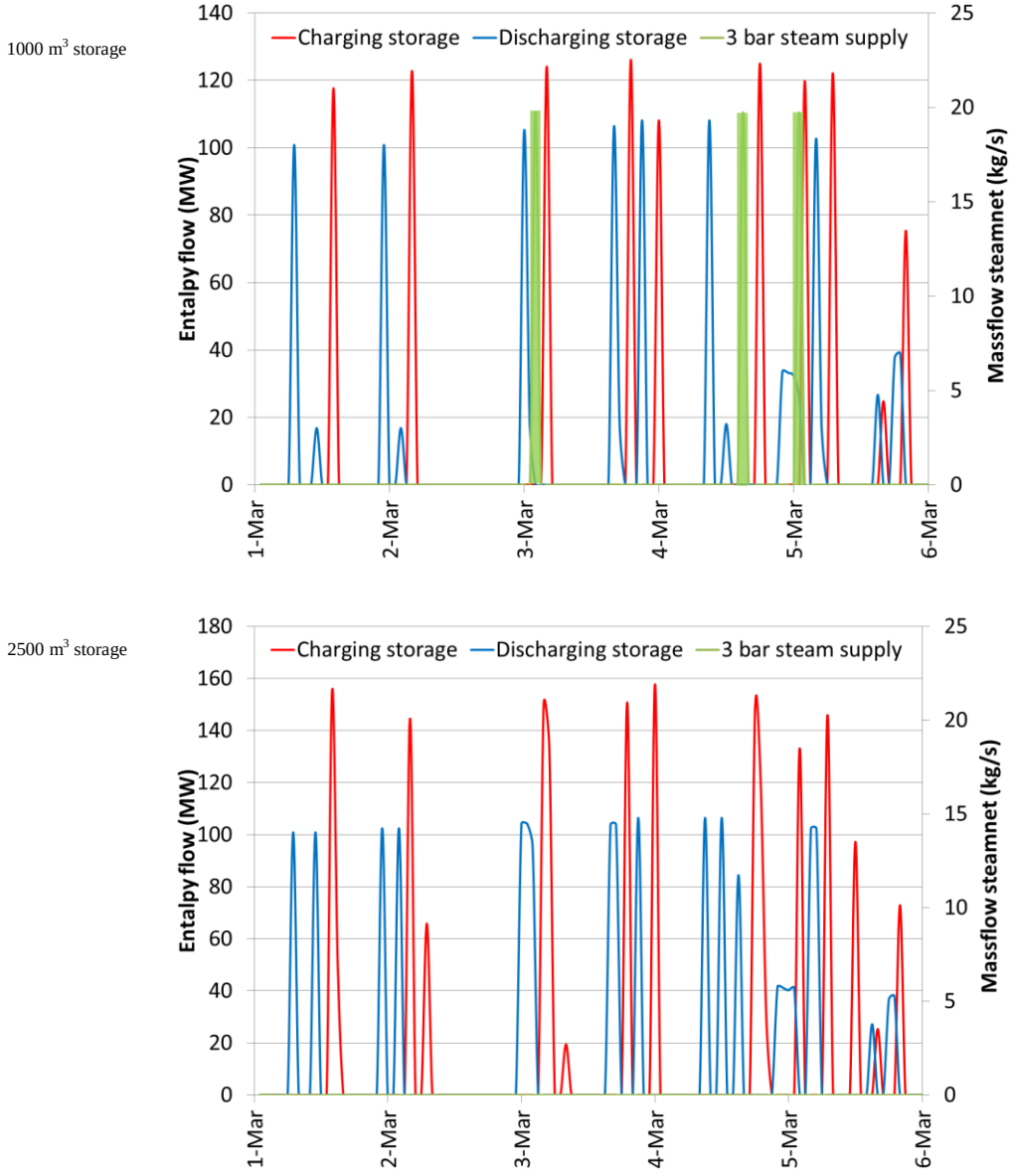

Figure 6: Charge (red) and discharge cycles (blue) of the thermal storage and backup steam supply (green) for the cases of 1000m^3 (top) and 2500m^3 (bottom) thermal storage

The 1000m^3 storage system is already very effective in reducing the backup steam needs by 85%. Only for 3 hours over a period of 5 days, the backup steam is used, resulting in an average steam need of 12 ton per day. On further increasing the storage size to 2500m^3 the need for any backup steam has gone to zero.

The impact of the thermal storage size on the residual steam use was analysed for a range of storage sizes from 0 to 2500m^3. The amount of steam needed decreases sharply with storage sizes increasing to 1000m^3, but on further increasing the reduction in steam consumption is limited. Also the effective use of the thermal storage was calculated based on the amount of heat charged to the storage divided by the storage capacity and expressed as the number of full cycles. The results of both analyses are shown below in figure 7.

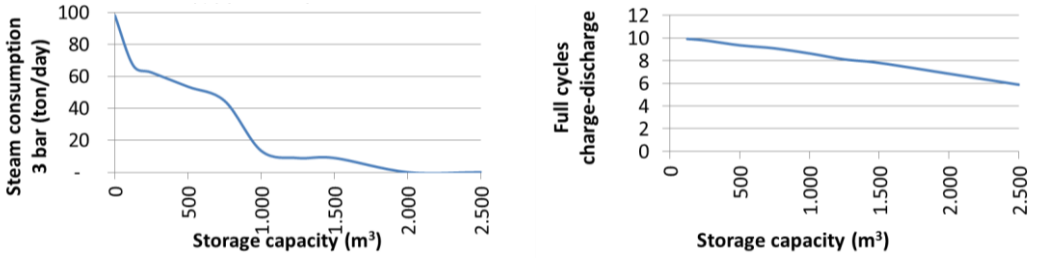

Figure 7: Calculated residual steam needs for the MVR with various thermal storage sizes (left) and the calculated full charge-discharge cycles of the storage for the various storage sizes (right).

The efficiency of the MVR system in terms of COP_heating varies with the capacity of the storage system. Without a thermal storage system the frequent backup steam supply at 3 bar, reduces the needed compression ratio in comparison to using the waste heat directly from the batch reactors or from the thermal storage system. With the 3 bar steam as a source the heat pump can thus run with higher average COP.

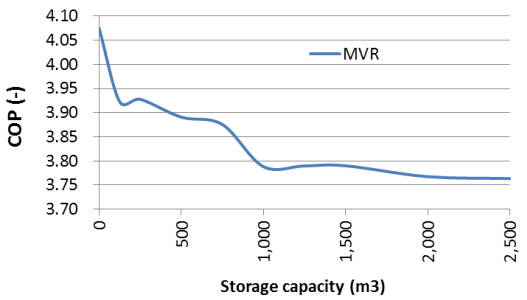

Figure 8: The Coefficient of Performance of the steam compression system as function of the storage capacity.

Techno-economic analysis

In the economic analysis of the thermal storage system the cost savings are obtained by the reduction of the amount of backup steam for the compressor. The results of the analysis for the 5 day period are extrapolated to 365 days obtain the annual figures. The calculated savings are based on steam price of 12.50 €/ton for 3 bar

steam. The capital cost for the storage system is based on literature values for large industrial size systems, that are installed as thermal storage tanks in district heating systems. For a 1000m^3 storage tank the investment costs are assumed to be € 600.000. A plot of the cost savings for the range of storage capacities considered is shown in figure 9, together with investment cost for the various storage sizes. The calculated steam cost saving for the 1000m^3 storage system is around € 350.000.
The integration of the storage unit reduces the COP of the heat pump system, which results in additional consumption of electricity. This additional cost needs to be subtracted from the earnings to calculate the simple payback times. The cost of electricity are calculated for a range of prices from 20 to 50 €/MWh.

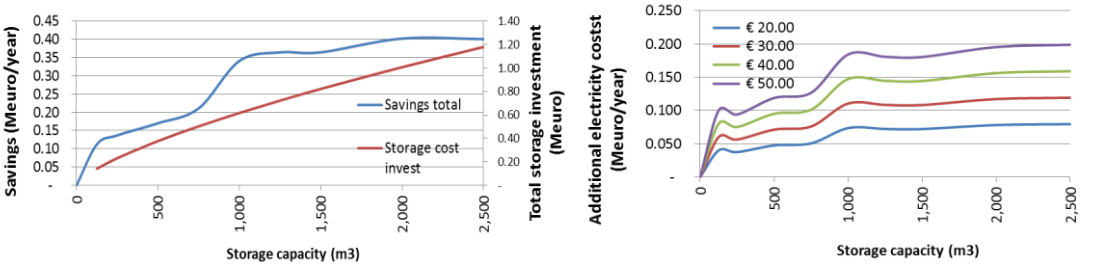

Figure 9: Calculated steam cost savings (left) and additional electricity costs (right) for the various thermal storage capacities

The calculated simple payback times for the thermal storage system for a range of capacities and various electricity prices is shown in figure 10 below.

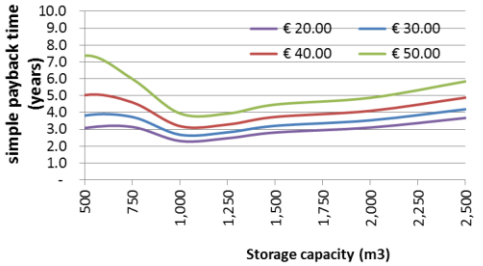

Figure 10: Calculated payback times for the thermal storage system, for a range of electricity prices.

5. Discussion and conclusions

In this study the recovery and re-use of waste heat from batch processes is considered, applying a mechanical vapour recompression combined with a heat storage system. The addition of the heat storage system allows to recover a larger amount of the waste heat from the batch process, and reduces the amount of low pressure backup steam for the MVR. A system model was developed to simulate on hourly basis the dynamics of the heat recovery system, using the dynamic waste heat supply from a real world batch reactor process.

The developed model can quantify the impact of the heat storage system on the annual need for steam backup to the MVR as well as on the COP obtained. These factors, need for backup steam and electricity

demand, determine the payback time of the thermal storage. The electricity price is an important factor in the calculation of the payback time. The model simulation allows to identify an optimal range for the heat storage capacity to be installed, based on the fluctuating pattern of waste supply and selected MVR capacity. The analysis indicates that the heat storage system can be economically feasible, achieving pay back times of less than 5 years.

It is recommended in the further analysis of the business case for waste heat recovery of batch processes, to do calculations using smaller time steps, for example in steps of 5 minutes, to obtain a more detailed view on the compressor dynamics. It is further recommended to include any site specific requirements that will have impact on the cost of installation.

Acknowledgements

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