A HYBRID ENERGY STORAGE CONCEPT FOR FUTURE APPLICATION IN INDUSTRIAL PROCESSES

by

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The efficiency of many industrial processes, applying steam as heat transfer medium, can be increased by integrating Ruths steam accumulator. This component makes it possible to store surplus steam for consumption at later time, whereby high loading and unloading rates can be realized with this storage type. For improving this storage type in terms of storage capacity and application range a hybrid storage approach is presented. The concept combines a Ruths steam storage with phase change material and electrical heating elements. For a first analysis of the interaction between the Ruths steam accumulator and the phase change material, which surrounds the steam storage vessel, a dynamic model was created. Also, an example which consist of a charging, storing, and discharging phase is presented. The simulation results show a positive impact in terms of storage capacity. Therefore, the hybrid storage concept is a promising approach for integration in industrial processes.

Key words: *hybrid storage, Ruths steam accumulator, phase change material, thermal energy storage, dynamic model, storage capacity, electrical heating element, power to heat*

Introduction

For decoupling energy production and consumption and to increase the efficiency of an industrial process or energy supply system (power plant) storages, can be applied. The Ruths steam accumulator contains liquid water and steam and is an attractive storage component for processes in which steam plays a major role, because of the possibility to store steam directly, without heat exchangers. During charging, the incoming steam partly condenses and the pressure inside the storage tank increases. During discharging saturated steam, the pressure decreases and the liquid water partially evaporates [1-6].

The possibility to integrate steam storages as buffer storage in solar thermal systems, because of their fast reaction time and high discharging rates was presented by Steinmann and Eck [2]. Fabrizio *et al.* [3] mentioned the integration of steam storages in industrial food processes and the possibility to cover short-term peak loads with a steam accumulator, so that the steam boiler has to provide only the mean load.

One part of the hybrid storage concept presented in this paper is the addition of phase change material (PCM), which has a high specific energy density, to the outer shell of a Ruths steam accumulator to increase the storage capacity per volume. Steinmann and Eck [2]

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presented different methods for improving Ruths steam accumulators. A presented method uses an additional storage type for superheating the discharging steam of the Ruths steam accumulator. The possibility to integrate encapsulated PCM inside the liquid phase of the Ruths steam accumulator to provide steam with constant pressure during discharging is mentioned. Another presented option to provide steam with constant pressure is the application of an external flash evaporator.

Buschle *et al.* [4] compared the integration of PCM at the internal side and outer side of Ruths steam accumulators. The outside arrangement consists of a tube register surrounded with PCM. For discharging water evaporates while for charging, steam condenses in the tube register.

There are a lot of PCM available for the application in latent thermal energy storages. Some of them and their properties are presented by Agyenim *et al.* [7] and Gil *et al.* [8]. A problem using PCM is the low thermal conductivity and the limited heat transfer between the heat transfer fluid (HTF) and the PCM [7, 9].

For improving the performance of latent thermal energy storages, several methods for increasing the heat transfer between HTF and PCM have been investigated. Some of them are summarized by Ibrahim [9]. They mentioned for example the possibility to arrange different PCM for realizing an approximately constant temperature difference between the HTF and the PCM. Laing *et al.* [10] presented a concept with aluminum or graphite fins for increasing the heat transfer area. Rudonja *et al.* [11] studied the improvement of heat transfer by adding copper fins. Xu *et al.* [12] and Liu *et al.* [13] numerically analyzed the application of porous media. The combination of paraffin wax and alumina nanoparticles in terms of thermal conductivity was studied by Valan Arasu *et al.* [14]. Pincemin *et al.* [15] studied the thermal conductivity improvement of composite materials made of inorganic PCM and graphite.

In this paper a dynamic model of a Ruths steam accumulator and a surrounding PCM layer is presented. The model for the Ruths steam accumulator or liquid water/steam part is based on energy and mass balance equations and the assumption that the two-phase fluid is in thermodynamic equilibrium at any time, as for example presented by Fabrizio *et al.* [3] and Hofmann *et al.* [5].

The model for the PCM part presented in this paper is based on energy balance equation and was modeled similarly to the Stefan-model presented by Zauner *et al.* [16], where the simulation results of the model were compared to experimental measurements.

In scientific literature different model approaches for latent heat storages can be found. Verma *et al.* [17] summarized some approaches by dividing them in models based on the First and on the Second law of thermodynamic. Also, approaches to describe the heat transfer inside of PCM are presented by Mehling and Cabeza [18].

The aim of the hybrid storage concept, which is described below, is to extend the range of application for classical Ruths steam accumulators in industrial processes. In the following chapters the hybrid storage concept and an idealized model for a first analysis will be presented.

Hybrid storage concept and modelling

Concept

The hybrid storage concept consists of a Ruths steam accumulator surrounded by chambers filled with PCM. Thus, the PCM is located outside of the pressure vessel. The chambers can be filled with PCM with different phase change temperatures to increase the adaptability of the hybrid storage component to the process requirements. Another part of the

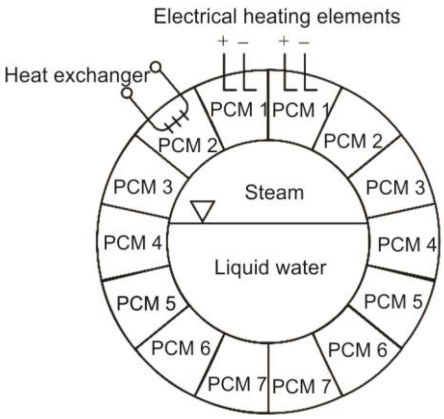

Figure 1. Hybrid storage approach

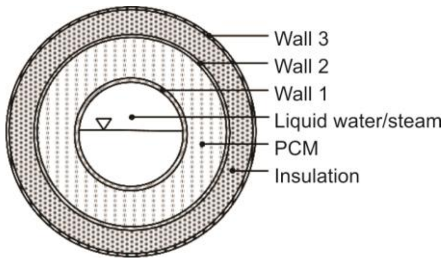

Figure 2. Different parts of the hybrid storage model

hybrid storage concept is the integration of electrical heating elements at the inner side of some PCM chambers. This measure makes it possible to store electrical energy in form of thermal energy and thus opens up new application possibilities. Also, the integration of heat exchangers at the internal side of the PCM chambers to reuse waste heat of other process media is conceivable. A schematic illustration of this hybrid storage concept is shown in fig. 1.

For a first analysis of the presented hybrid storage concept a dynamic model of a Ruths steam accumulator surrounded by a cylinder filled with a single continuous PCM was developed. This model is presented in the following section.

Modelling

The hybrid storage model was realized in Dymola 2015 FD01 [19] with the TIL-Library 3.3 [20]. This model consists of different submodels which are connected to each other. In fig. 2 the different parts of the hybrid storage model are shown. In the wall volume submodels heat capacities are considered. The whole hybrid storage is modelled as a cylinder, whereby the walls at the end faces are neglected and the end surfaces are regarded as adiabatic.

For modelling the liquid water/steam or Ruths steam accumulator part, it was assumed that the liquid water and steam phase are at thermodynamic equilibrium at any time. The current state at the internal side of the volume can be calculated by the mass balance eq. (1) and energy balance eq. (2):

$$V\frac{\mathrm{d}\rho}{\mathrm{d}t} = \dot{m}_{\mathrm{in}} + \dot{m}_{\mathrm{out}} \tag{1}$$

$$m\frac{\mathrm{d}h}{\mathrm{d}t} = \dot{m}_{\mathrm{in}}(h_{\mathrm{in}} - h) + \dot{m}_{\mathrm{out}}(h_{\mathrm{out}} - h) + \dot{Q} + V\frac{\mathrm{d}p}{\mathrm{d}t} \tag{2}$$

In eq. (2), the heat flow $\dot{Q}$ results from temperature difference between the connected parts. The specific enthalpy h_{out} of the discharge mass-flow corresponds to the specific enthalpy of the vapor phase at the internal side of the volume. For determining the properties of the two-phase fluid, a TILMedia 3.3 [20] *VLEFluid_ph* component with pressure and specific enthalpy as input variables was used.

For modelling the PCM part of the hybrid storage the following assumptions are made:

– the thermodynamic properties are constant and equal for the solid and liquid phase,
– the phase change takes place at a certain temperature and the phase change temperature is equal for the solid and the liquid phase,
– heat transfer in solid and liquid PCM is solely by conduction, and
– heat transfer is assumed as 1-D.

The model of the PCM storage is based on energy balance equations. In fig. 3 the heat flow inside the PCM part is shown. The heat flow $\dot{Q}_1$, which is transferred between *wall 1*, fig. 2, and the PCM part, is used to differentiate between charging and discharging of the PCM part. If the heat flow $\dot{Q}_1$ is positive, the PCM cylinder is charged. In case of negative heat flow $\dot{Q}_1$ the PCM cylinder is discharged.

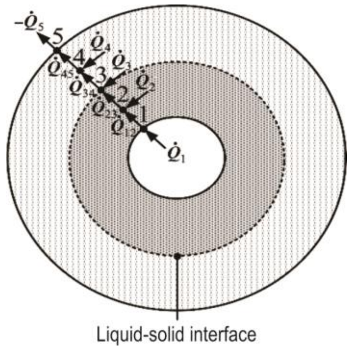

Figure 3. Heat-flow in the PCM volume

The sensible heat per unit time of each PCM phase can be calculated according to eqs. (3) and (4). For charging, in *node 2* the liquid PCM mass and in *node 4* the solid PCM mass are considered. For discharging it is the other way around:

$$\dot{Q}_2 = \frac{\mathrm{d}m_2}{\mathrm{d}t} c_p (T_{\mathrm{pc}} - T_2) - m_2 c_p \frac{\mathrm{d}T_2}{\mathrm{d}t} \tag{3}$$

$$\dot{Q}_4 = \frac{\mathrm{d}m_4}{\mathrm{d}t} c_p (T_{\mathrm{pc}} - T_4) - m_4 c_p \frac{\mathrm{d}T_4}{\mathrm{d}t} \tag{4}$$

If the temperature in *node 1* reaches the phase change temperature during charging or discharging, latent heat is absorbed or emitted by *node 3*. The latent heat absorbed during melting or emitted during solidification is calculated with eq. (5):

$$\dot{Q}_3 = \pm 2r \frac{\mathrm{d}r}{\mathrm{d}t} \pi L \rho h_{\mathrm{pc}} \tag{5}$$

For charging, the latent heat-flow is defined as negative and for discharging as positive. In eq. (5), the radius, r, describes the position of the solid-liquid interface. During melting and solidifying, the solid-liquid interface is moving from the inner diameter to the outer diameter of the PCM cylinder. If the heat flow $\dot{Q}_1$ changes its sign after melting, the position of the solid-liquid interface is reinitialized at the inner wall of the PCM cylinder.

For every node presented in fig. 3 the energy balance equation has to be fulfilled. The energy balance equation for the whole PCM part is summarized in eq. (6):

$$\sum_{i=1}^{5} \dot{Q}_i = 0 \tag{6}$$

The heat transfer between the different nodes presented in fig. 3 is described by conduction as shown in eq. (7):

$$\dot{Q}_{ij} = -\frac{2\pi L \lambda (T_j - T_i)}{\ln\left(\dfrac{D_j}{D_i}\right)} \quad \text{with} \quad \begin{pmatrix} i \in [1,4] \\ j = i+1 \end{pmatrix} \tag{7}$$

Simulation results and discussion

The simulation results of the thermal hybrid storage model are compared with the results of a Ruths steam storage model by means of an example. The Ruths steam storage model corresponds to a simplified hybrid storage model without the PCM cylinder and the wall, located in the hybrid storage between the liquid water/steam and the PCM part. The models were simulated using the *Dassl* solver provided in Dymola 2015 FD01 [19].

Table 1. Geometric data of the compared storage types

	Layer thickness [mm]	
	Ruths steam storage	Hybrid storage
Wall 1	20	20
Wall 2	–	2
Wall 3	1	1
PCM	–	27
Insulation	100	100

Table 2. Material properties [21, 22]

Name	Value	Unit
Wall (steel)		
Specific heat capacity	490	$Jkg^{-1}K^{-1}$
Density	7800	kgm^{-3}
Thermal conductivity	46.5	$Wm^{-1}K^{-1}$
Insulation (mineral wool)		
Thermal conductivity	0.035	$Wm^{-1}K^{-1}$
PCM ($NaNO_3/KNO_3$)		
Melting temperature	220	°C
Latent heat	108.67	$kJkg^{-1}$
Specific heat capacity	1500 (mean value)	$Jkg^{-1}K^{-1}$
Density	1750 (mean value)	kgm^{-3}

In this example, a total storage volume of 29 m³ is considered, with a storage length of 8.4 m and an outer diameter of 2.1 m. In tab. 1, the geometric data of the compared storage types is presented. The descriptions correspond to the designations used in fig. 2. For this example, *wall 3*, fig. 2, is regarded as adiabatic, thus, heat losses are neglected.

The PCM volume is 4.6% of the total hybrid storage volume. In tab. 2 the thermal properties of the different materials are presented. As PCM, $NaNO_3/KNO_3$ (60/40 mol.%) with the thermal properties given by Foong *et al.* [21], was chosen. The other thermal properties presented in tab. 2 are taken from [22]. For the PCM a thermal conductivity of 6 W/mK was assumed, for the other properties the pure PCM properties were chosen. The consideration of a suitable heat transfer enhancement method and its impact on the performance will be part of further research.

The initial pressure in the liquid water/steam volume was assumed to be 20 bar_a and the initial liquid water filling level (relation liquid volume to total volume) was 60%. A pressure of 26 bar_a and a temperature of 227 °C were specified for the inlet steam mass-flow. This was realized with a *Boundary* element from TIL-Library [20]. For the heat transfer coefficient between the liquid water/steam part and *wall* 1 4,700 W/m²K were assumed. This value is an estimated mean value of the possibly occurring heat transfer coefficients [23] related to the heat transfer areas.

In the application example the storages are initially charged for 50 min and after a storing phase of 20 min the storages are discharged for 50 min. For charging and discharging the storage vessels an OrificeValve component from the TIL-Library [20] was used and the effective flow area was defined with 5 cm². After the discharging valve a constant pressure of 20 bar_a was specified. In fig. 4 the time-dependent difference between charging and discharging steam mass-flow is presented.

In fig. 5 the pressure gradient is shown. The maximum pressure is set to 26 bar_a. After approximately 6 min, the pressure in the hybrid storage is significantly lower compared to the Ruths steam accumulator due to the amount of energy transferred into the PCM part. During the storing phase of 20 min the pressure inside the liquid water/steam part of the hybrid storage decreases, because there is still a temperature difference between the PCM volume and the liquid water/steam volume.

After charging, the liquid filling level of the hybrid storage is slightly higher compared to the Ruths steam storage. This is shown in fig. 6. This corresponds to the fact that more steam is condensed when the hybrid storage tank is loaded compared to the Ruths steam storage.

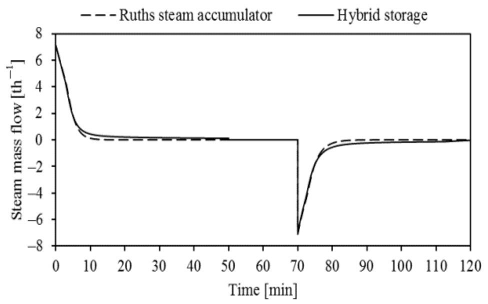

Figure 4. Difference between incoming and outgoing steam mass-flow for hybrid storage and Ruths steam accumulator

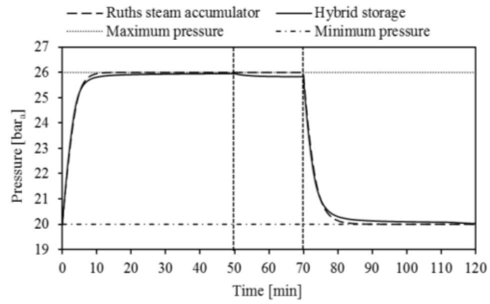

Figure 5. Pressure at the internal side of the hybrid storage and the Ruths steam accumulator

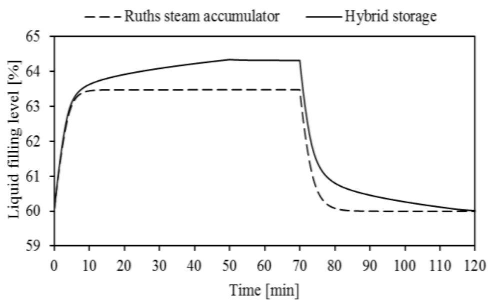

Figure 6. Liquid filling level of the hybrid storage and the Ruths steam accumulator

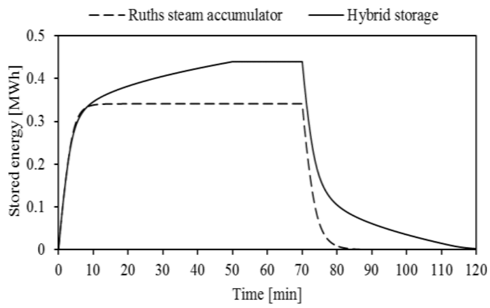

Figure 7. Stored Energy of the hybrid storage and the Ruths steam accumulator

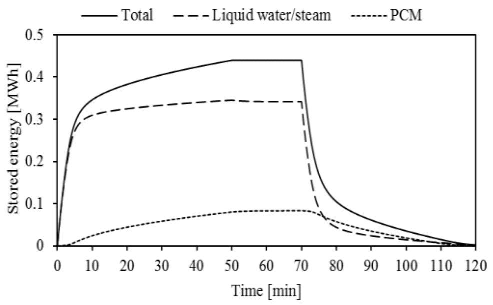

Figure 8. Total stored energy compared to the stored energy in the liquid water/steam volume and the PCM volume of the hybrid storage

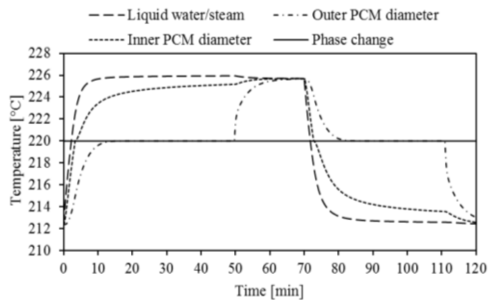

Figure 9. Temperature of different parts of the hybrid storage

The simulation results of the example show that in 50 min approximately 29% more energy is stored in the hybrid storage than in the classical Ruths steam accumulator at the same total volume. Figure 7 presents the time-depending stored energy in both storages. For example, if the thermal conductivity of *wall 1* is reduced to 15 W/mK then the charging time as well as the discharging time can be extended for 15 min to reach nearly the same improvement. There is also more time needed, if a lower heat transfer coefficient occurs between the liquid water/steam volume and *wall 1*.

Figure 8 presents the total stored energy of the hybrid storage unit compared to the energy stored in the liquid water/steam volume and the PCM volume. The sum of the stored

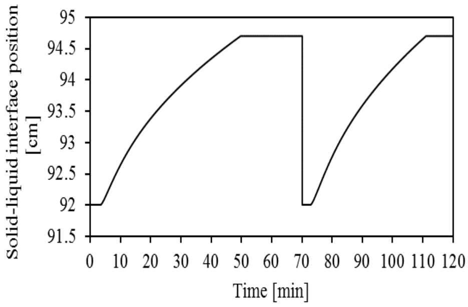

Figure 10. Radial position of the solid-liquid interface

energy in these two different volumes is not exactly equal to the total stored energy, because there is also energy stored in the different wall volumes of the hybrid storage.

As shown in fig. 9 the temperature at the inner diameter of the PCM cylinder reaches the phase change temperature after around 3 min. At that time the PCM starts to melt and the radius of the solid-liquid interface is moving from the inner diameter to the outer diameter of the PCM cylinder. This can be exactly seen in fig. 10. After round 70 min discharging of the PCM volume starts and the radius of the liquid-solid interface is reinitialized at the inner diameter of the PCM cylinder.

Conclusion and outlook

In this paper an investigation of an idealized hybrid storage concept-model was presented. The results show that the performance of the compared storage types is nearly the same for the higher charging rates at the beginning. After round 6 minutes the stored energy in the hybrid storage increases significantly compared to the stored energy of the Ruths steam accumulator. Therefore, the performance of the hybrid storage strongly depends on the heat transfer rate between the liquid water/steam and the PCM part. It shows that the combination of a Ruths steam accumulator can have positive impact on the storage capacity for the same total volume depending on the process requirements.

A more detailed investigation on the heat transfer between the two-phase fluid and the surrounding wall will be part of further studies. Also, the impact of different PCM chambers and electrical heating elements will be studied.

Acknowledgment

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Nomenclature

c_p – specific heat capacity, [Jkg^{-1}K^{-1}]
D – diameter, [m]
h – specific enthalpy, [Jkg^{-1}]
h_{pc} – phase change enthalpy, [Jkg^{-1}]
L – length, [m]
m – mass, [kg]
$\dot{m}$ – mass-flow, [kgs^{-1}]
p – pressure, [Pa]
$\dot{Q}$ – heat-flow, [W]
r – radius of the solid-liquid interface, [m]
T – temperature, [K]
t – time, [s]
V – volume, [m^3]

Greek symbols

λ – thermal conductivity, [Wm^{-1}K^{-1}]
ρ – density, [kgm^{-3}]

Subscripts

in – incoming
out – outgoing
pc – phase change

Acronyms

HTF – heat transfer fluid

PCM – phase change material

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