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Evaluation of a Stratified Tank based Heat Recovery Loop via Dynamic Simulation

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Prerequisite for hot water recovery in the dairy and beverage industry is the use of heat storage, such as stratified tanks. Total Site Heat Integration enables the targeting of heat recovery potential, the concrete identification of suitable sinks and source profiles and the dimensioning of intermediate circuits and storages. For a cost and energy efficient storage, the aim to maintain stratification by suitable thermocline control management. Dynamic simulation enables a reliable estimation of energy savings and correct storage/control design considering the changing operation times, source and sink loads as well as thermal inertias. This poses two challenges: model accuracy and acceptable simulation time. A stratified tank model with Variable Layer Height (VLH) is evolved reducing numeric diffusion effects. A sensitive analysis shows the increased accuracy with acceptable simulation time. As part of a case study, thermocline growth due to numeric diffusion is reduced up to approximately 35 % by a VLH model. The model is simulated for a case study in the dairy industry. It is shown that up to 94 % of the total heat recovery target can be achieved by the modelled heat recovery loop based on a stratified tank and the applied system control.

1. Introduction

In Europe, the food and beverage industry is the fifth largest energy consumer (Eurostat, 2017). Relatively, the food industry has even the highest share of low-temperature heat demand of the total process heat demand (Chan Y. and Kantamaneni R., 2015). Using renewable energies and increasing energy efficiency are ways to reduce the Greenhouse Gas emissions (Philipp et al., 2018). First, potential to reduce process energy demand has to be identified using Process Integration methods (Klemeš, 2013). If the possibilities of increasing the energy efficiency at process level and the direct heat recovery are exhausted, further energy savings are possible by Total Site Heat Integration (Klemeš et al., 1997) with specific focus on low-temperature processes (Schumm et al., 2017) and heat recovery loops (HRL) (Walmsley et al., 2015).

In many industries, such as the dairy and beverage industry, the individual processes are operated non-continuously for recipe and cleaning reasons. This poses additional challenges to heat recovery and often requires the use of energy storage. In terms of batch processes, the Time Average Model (TAM) indicates heat recovery potential, which can be achieved by indirect heat transfer and storage based on HRL. The method Indirect Source and Sink Profile (ISSP) enables the concrete identification of suitable sinks and source profiles and the dimensioning of intermediate circuits and storages (Krummenacher, 2002). Due to the integration of multiple sink and source streams, the utilization of the storage capacity increases the overall availability and performance of sources and sinks. For sensible heat storage, there are closed stratified tanks (ST) or variable mass and fixed temperature (FTVM) open storage tanks. FTVM tanks require a larger storage volume than ST, but they are easier to operate and are suitable for very large circulating volumes and small temperature differences, whereas ST needs half the volume and can operate at temperatures above 100 °C when placed under pressure. Due to different densities of a fluid at different temperatures, higher temperature liquid (lower

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density) forms a hot zone at the top of the tank while lower temperature liquid forms one at the bottom. These zones are separated by a narrow transition area - the thermocline. For varying source and sink streams the respective temperature zone increases or decreases, and the thermocline grows or moves vertically in the storage tank (for example Figure 4). This leads to a loss of stratification and in the end to shut down of the HRL (Atkins et al., 2010).

Due to the arbitrary production and logistic, the changing operation time of process states, thermal inertias as well as dynamic interaction a dynamic simulation is necessary to evaluate and prove the performance of an HRL system in any scenario. Past models have focused on either the heat recovery side of the HRL (Walmsley et al., 2014) or the ST (Walmsley et al., 2009). Walmsley et al. (2009) used an experimental scale model of an industrial ST. This study presents a simulation model to investigate the dynamic operation and performance of HRL including the time-dependent variability of multiple sink and source profiles as well as the stratified heat storage system. For numerical simulation methods, sensitivity analyses show the numeric influence of simulation time step and number of layers on the thermocline growth. The growth and movement of the thermocline accelerate the loss of stratification and reduces the effective heat recovery capacity of the tank.

The aim of this study is to identify the fundamental effects on the HRL system by discontinuous source and sink profiles and to reduce numeric diffusion effects. For evaluating the thermocline control, the verified model is applied to a case study with real process data from the dairy industry. The influence of different design parameters and loading strategies on operation and heat recovery potential are evaluated.

2. Modelling method

In the stratified storage, various heat transfer and transport processes take place. These influence the total energy content of the storage tank as well as on the vertical temperature profile and thus on the characteristics and growth of the thermocline. The most important processes in the storage and the chosen modelling according to Dinçer and Rosen (2011) are forming of temperature stratification by density differences as well as degradation of inversion layers, vertical heat transfer by convection and conduction, mixing by inlet and outlet flows and heat losses through the tank shell.

There is a variety of modelling approaches for the modelling of storage systems. In addition to the empirical models examined by Walmsley et al. (2009), there are some physical modelling approaches, such as Computational Fluid Design, Fully-Mixed models, Moving-Boundary and Plug-Flow models. The chosen modelling approach allows the most accurate mapping of physical processes with acceptable simulation time. This is important if the sensitivity evaluation of HRL-systems requires the simulation of many probable reference years and the application of statistical simulation methods such as Monte-Carlo. The best trade-off is a Multi-Node approach, in which the tank is divided along its height into a fixed number of constant volume cells, for each of which the energy and mass balances are solved, as seen in Figure 1 (Dumont et al., 2016).

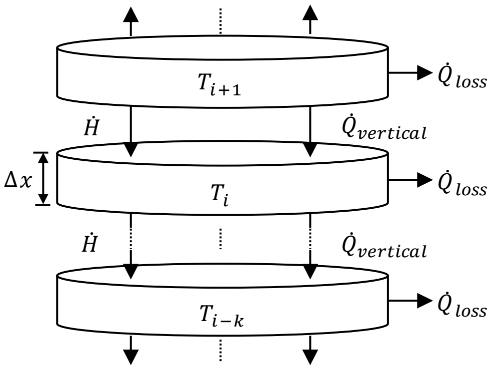

Figure 1: Balance of energy flows in a Multi-Node model

The applied ST model used the Multi-Node model of the Matlab/Simulink® Carnot Blockset. For the calculation of the Multi-Node ST model, the storage volume is divided along its height into n nodes. In each layer, an ideal mixing is assumed, i.e. the temperature is constant in the layer element in both the radial and vertical directions. For each layer and each simulation time step, the balance equation, Eq(1), of the energy transport is solved according to the first law of thermodynamics.

$$\frac{dU}{dt} = \dot{H} + \dot{Q}_{vertical} + \dot{Q}_{loss} \tag{1}$$

The change in the internal energy U describes the change in the temperature T of the individual layers as a function of entering and leaving enthalpy streams $\dot{H}$ caused by the piston flow in the tank and charging mass flows, direct vertical heat conduction effects $\dot{Q}_{vertical}$ through the layers and the heat losses $\dot{Q}_{loss}$ through the container wall. If a layer element has a temperature which is at least 1 Kelvin lower than the underlying layer, both layers are mixed caloric. This happens until all inversion layers have been broken down. Then the next time step is calculated. The number of layers here stands in the field of tension between the computational effort and the spatial resolution of the temperature vector.

2.1 Numerical diffusion

As part of the model validation, a non-physical phenomenon was observed in which, despite ideal tank isolation, neglecting vertical heat transfer, the thermocline has grown through loading and unloading processes. This phenomenon is caused by the discretization of the storage model, also called numerical diffusion (Unrau, 2017). The underlying reason for this is the temperature in the one-dimensional storage model is assumed to be constant over the entire cell height. If a mass element flows at a temperature deviating from the cell temperature over the cell system boundary, a new node temperature for the entire layer is formed at the end of the time step. Figure 2(a) shows exemplarily the process for a thermocline movement in a system with an ideal temperature distribution at the beginning. Every movement of the thermocline, which does not completely fill a cell in a time step, thus leads to a temperature mixture and consequently to the degradation of the temperature stratification. In addition, this problem gains in importance due to permanent thermocline movement in the tank. In a typical HRL with multiple discontinuous source and sink processes, it can be assumed that there is very rarely a sustained balance between hot and cold mass flows (Atkins et al., 2012). Every complete loading or unloading resets the thermocline growth. Depending on tank size, load profile and control strategy, this can happen frequently, rarely or never.

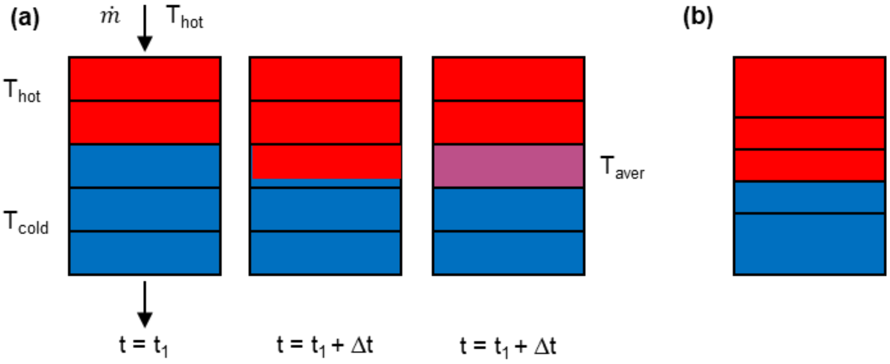

Figure 2: (a)Schematic representation of the temperature distribution at the beginning, during and at the end of a time step. (b) Reduced numerical diffusion effect by Variable Layer Height model

2.2 Development of a Variable Layer Height model

A sensitivity analysis is carried out to investigate the effects of numerical diffusion and possible reduction approaches. The greatest impact on the numerical diffusion, apart from the simulation time step size, is expected from a higher spatial resolution, i.e. a higher number of layers, which is in competition with the simulation duration (Powell and Edgar, 2013). The degree of freedom of the parameters fluid velocity u, simulation time step size Δt and cell height Δx is limited by the so-called Courant condition ($c \leq 1$) following. To prevent instability and physically incorrect discretization behavior, the following condition must be met:

$$c = \frac{u \cdot \Delta t}{\Delta x} \leq 1 \Leftrightarrow \Delta t \leq \left| \frac{\rho \cdot \pi \cdot D^2 \cdot H}{4 \cdot \Delta \dot{m}_{max} \cdot n} \right| \tag{2}$$

The limitation of the simulation time step size Δt results by the maximum difference of the source and sink mass flows $\Delta\dot{m}_{max}$, the tank height H, diameter D and the number of layer elements n. If the Courant condition is met, Δt is coupled to the number of layers. Figure 3(a) shows the ideal temperature distribution (black) over the tank height in comparison to the course resulting for a different number of layers n after periodic loading and unloading depending on numerical diffusion effects.

In a balanced HRL, most of the thermocline movement occurs in medium tank height. There, the number of layers is increased and in the edge, area reduced, as seen in Figure 2(b). Thus, a higher spatial resolution can be generated in the areas of relevance without increasing the total number of layers and consequently the computational effort. The variable distribution of layers and its height is called Variable Layer Height (VLH). Figure 3(b) shows the improvement for smaller number of layers. For increasing number of layers, the influence of the spatially concentrated layers is less.

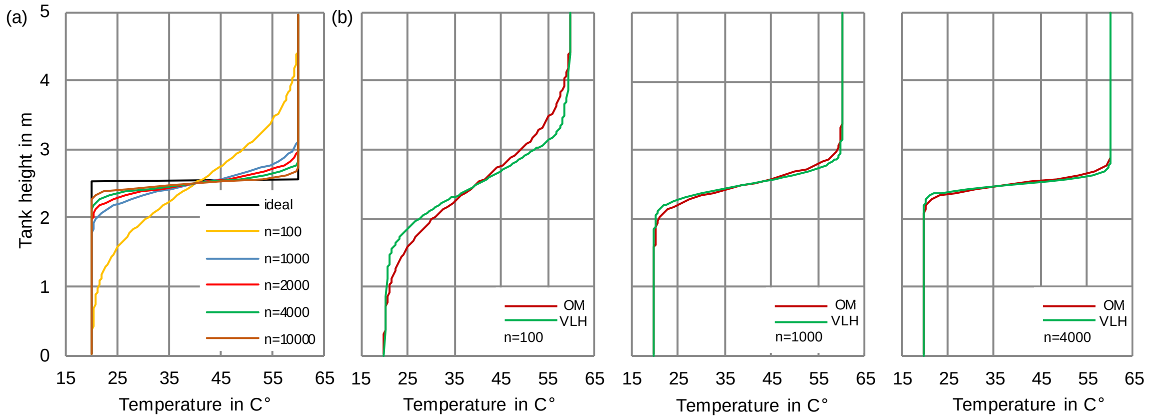

Figure 3: (a) ST temperatures of the original model (OM) over the height for different number of layers n. (b) Comparison of OM to adapted VLH model for 100, 1000 and 4000 layers.

2.3 Thermocline management control

The regulation of the HRL from Figure 4 (b) is divided into two parts by a single flow and system control. The individual streams are adjusted to the target temperature T_{hot} or T_{cold} by mass flow control. If no process flow is present or the system control overrides, the pump is switched off. The position and the extent of the thermocline allow conclusions about the hot and cold zone capacity and therefore serve as a central control variable in the system control. The system control specifies various operating states (i.e. Normal Operation, Loading, Unloading) depending on the loading state of the ST. If the middle of the thermocline H_G reaches the upper or lower end of the storage, this is considered to be completely loaded or unloaded. The source / sink circuits are then deactivated. The storage potential between upper / lower thermocline edge and the thermocline center can still be used. To prevent a frequent clocking between the deactivation and activation of the sinks for empty tanks, the sinks remain deactivated until the hot zone again occupies 10% of the storage volume. The same applies to the fully loaded storage.

2.4 Case study – diary

For the case study, representative process data of the milk processing industry have been assembled into an exemplary complete system. This results in load profiles of the sources and sinks for a repetitive stream-wise repeat operation period (SROP) of one week, as seen in Figure 4(a).

Table 1: Stream table of Dairy Sources and Sinks (Walmsley et al., 2014)

Process	Type	$\dot{W}_{ave}$ kW/K	T_{supply} °C	T_{target} °C	$\dot{H}_{ave}$ kW	H_{period} kWh
Utility	Hot 1	7.3	45	30	110	18,480
Casein A	Hot 2	26.8	50	22	751	126,168
Casein B	Hot 3	42.4	50	22	1,188	199,584
Milk Treatment	Cold 1	20.8	10	50	-832	-139,776
Whey	Cold 2	17.0	14	45	-527	-88,536
Site Hot Water	Cold 3	45,0	16	60	-1,980	-332,640

For evaluating the quality of the HRL system, an energetic target value for the heat recovery potential is determined according to the TAM method. The design of the HRL for the simulation based on a VLH model is carried out according to the ISSP method. Based on the known load profile from the stream table (Table 1), the heat transfer surfaces can be calculated directly. In addition, it can be determined at what time the storage is charged or discharged with how much energy. With known temperature difference ($T_{hot} – T_{cold}$) between the hot and the cold side of the tank, the storage volume can be calculated.

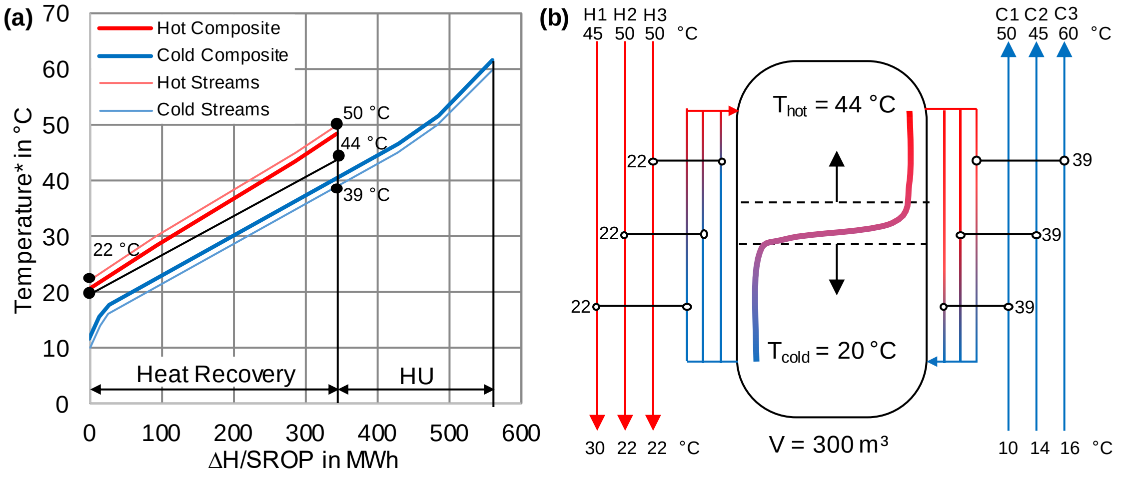

Figure 4: From the Indirect Source and Sink Profile (a) to the storage system (b)

It becomes clear that ideally, the waste heat potential of the hot source streams can be fully utilized to heat the sink streams. For the case study, this corresponds to a maximum heat recovery potential of 344 MWh for one SROP. This is already achieved with a minimum driving temperature difference $\Delta T_{min} = 3\,K$ at the pinch point. Further reduction of the minimum temperature difference does not improve the heat integration. For heating the hot streams, an additional minimum hot utility (HU) of 217 MWh is necessary. The use of additional cooling technology can ideally be dispensed with.

3. Results of the simulation study

As part of the simulation study, the identified HRL concept (2.4), the thermocline management control (2.3) and the VLH model (2.2) must be proved for suitability. For evaluation, the returns of the sources and sink circuits are regulated to 40/20 °C, 44/20 °C or variable according to maximum temperature utilization of the single streams (VTS), as described by Walmsley et al. (2014). The 300 m³ tank is modelled using 1,000 layers. The upper 20 % and lower 20 % by volume of the storage tank are represented by 50 layers each while the middle tank area by 900 layers. This distribution of layers provided improved resolution around the thermocline.
The thickness of the thermocline is determined by the distance of the lower boundary layer to the upper layer. The arithmetic means of the relative thermocline thickness over the simulation period based on the VLH-model is 10.7 % of the storage height. The original stratified storage model results in a thermocline thickness of 16.3 % of the storage height. Figure 5 shows the influence of the storage size and temperature control on the heat recovery potential.

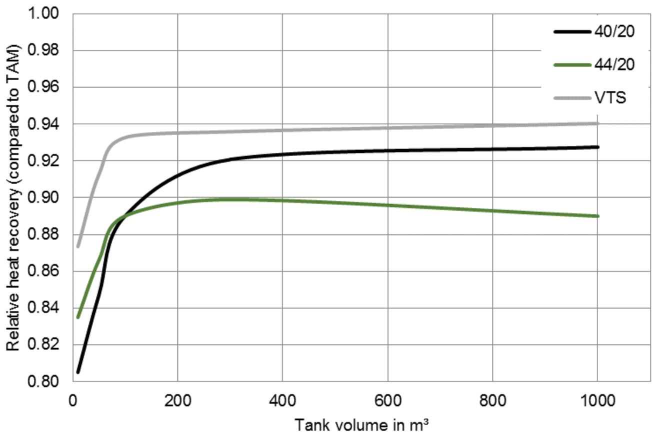

Figure 5: Relative heat recovery compared to the TAM targets for different control temperatures and tank sizes

4. Conclusion

The multi-node approach represented a good compromise between accuracy and simulation time for the sensitive simulation of HRL systems. This is the basis for the dimensioning and selection of the control system for the HRL system as well as for a reliable estimate of energy savings. The results of the sensitivity analysis showed the increase in accuracy by a VLH model reducing numerical diffusion effects. In the case study, the VLH model reduced the thermocline growth by approximately 35 %. The variable temperature control (VTS) of the individual streams achieved the highest energy recovery compared to the TAM method. For the constant temperature control, the choice of target temperature should be thoroughly investigated.

The simulation study included a typical week of production, taking no account of stochastic changes (e.g., order quantity or weather) or deterministic influences such as recipe sequences. Future work will look at the simulation of several years based on synthetic time series with probabilistic influence (e.g. changing temperatures and loads) by Monte Carlo simulation to generate a sensitivity evaluation of the HRL. Prerequisite for this is an accurate and high-performance VLH model. On this basis, the integration of further supply systems such as solar process heat for re-stratifying or thermocline management can be investigated.

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