CHEMICAL ENGINEERING TRANSACTIONS

VOL. 76, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976131

Robust Control of Heat Exchangers in Stratified Storage Systems – Simulation and Experimental Validation

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Since many industrial processes are not operated continuously, large shares of the heat recovery potential in those processes can only be achieved indirectly. While conceptual design methods to integrate stratified thermal energy storage systems are being developed, the control of the resulting systems is addressed in this paper. The main challenge of the control of heat exchangers in stratified storage systems is the fact that both outlet temperatures of the heat exchanger need to be maintained at their setpoint. A simulation model describing plate heat exchangers and based on this a control strategy are presented. The simulation model is experimentally validated and represents the real heat exchanger with a steady state error within the bounds of ± 0.31 K. The control strategy contains a feed forward path using measured disturbances and a lookup table to set the intermediate loop-sided mass flow rate. Furthermore, one feedback PI controller is used to control one outlet temperature by adjusting the intermediate loop-sided inlet temperature with a mixing valve. As the lookup table is based on a sufficiently accurate description of the heat exchanger characteristics, the second outlet temperature (process-side) is maintained within bounds of ± 0.5 K. For further development, the measurement effort is recommended to be reduced by means of state and disturbance estimation. The rather rigid control algorithm might be replaced with a multivariable control approach such as model predictive control in order to increase the versatility of the system.

1. Introduction

Industrial processes can be broadly classified into either continuous, semi-continuous or pure batch processes. Due to the time dependent behavior of semi-continuous and batch processes, indirect heat recovery (HR) using stratified thermal energy storage (TES) systems with intermediate loops (IL) is often used. Different approaches exist to develop conceptual designs for such TES systems based on either graphical or mathematical methods. Krummenacher and Favrat (2002) introduced a graphical methodology for the heat integration of batch-processes based on the time average model (Kemp and Deakin, 1989). Walmsley et al. (2014) proposed an extension of this methodology by shifting streams according to their HR potential. Olsen et al. (2016) extended these two approaches to a conceptual method to design TES for batch and semi-continuous processes.
Following such conceptual design, an important design consideration is to ensure a stable and robust control strategy. However, this is a challenge as the heat exchangers (HEXs) associated with the TES have to be typically operated at various operating points. For example, it was often observed in industry that common HEX control strategies fail when they are used for strongly varying process streams because they focused only on the process side of the HEX, without considering the characteristics of the HEX leading to a strongly varying IL outlet temperature and therefore reduced and/or destroyed storage stratification. The main disturbance in these observed cases were the variation of the mass flow rate. Similarly, Atkins et al. (2012) analyzed transient data of the dairy industry to develop HR loops for indirect HR in non-continuous processes. It was concluded that HR can be increased significantly, but due to the dynamic nature of such systems good control is necessary to achieve this increase. Walmsley et al. (2015) suggested that the simulation of HEXs in HR loops has to incorporate the changing heat transfer capabilities of the HEX. Other research has focused on how to improve the control quality of the desired outlet temperature. For example, Vasičkaninová et al. (2018) presented a gain-scheduled controller for a serial connection of shell and tube HEXs within a kerosene plant. Oravec et al. (2018)

Paper Received: 16/03/2019; Revised: 23/04/2019; Accepted: 06/05/2019
Please cite this article as: Agner R., Lucas E.J., Olsen D.G., Gruber P., Wellig B., 2019, Robust Control of Heat Exchangers in Stratified Storage Systems – Simulation and Experimental Validation, Chemical Engineering Transactions, 76, 781-786 DOI:10.3303/CET1976131

applied robust model predictive control on a plate HEX. Both significantly improved the aimed target: the control of one outlet temperature under certain constraints and minimal use of utility.
This present work aims to establish a control strategy that enables the continuous operation of constant temperature stratified TES systems by controlling the HEX in the intermediate loop so that both outlet temperatures of the HEX are kept at their setpoint. Contrary to the existing control strategies this work tackles the multivariable control problem of the HEX in the IL. The main goal is to maintain the desired temperatures of the stratified layers of the TES, which is the key requirement to enable stable operation of the constant temperature TES. If the layer temperatures are not kept at their setpoints, HR potential of the TES system would be destroyed due to thermocline degradation.

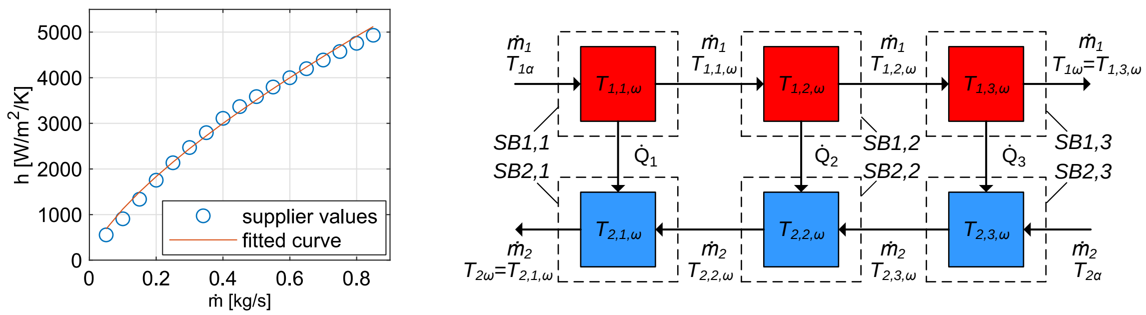
2. Heat exchanger modelling

When a HEX is operated under varying flow conditions, its heat transfer characteristics change. Starting from the Nusselt correlation (Eq(1)) one can derive the change of the film heat transfer coefficient *h* as a function of the mass flow rate of the given HEX (Eq(2)). For this reformulation to hold the same Prandtl number *Pr,* heat conductivity *λ, density ρ* and viscosity *v* are assumed to be constant. For the given case of a HEX in a stratified TES with constant target temperatures, this simplification can be assumed to have little impact since these properties would mainly change with a change in medium temperature. This approach is similar to Walmsley et al. (2015), where they simulated the performance of Heat Recovery Loops with varying production conditions.

$$Nu = \frac{h\,L_{char}}{\lambda} = c\,Re^x\,Pr^y \;\leftrightarrow\; h = \frac{\lambda}{L_{char}}\,c\,Re^x\,Pr^y \tag{1}$$

$$\frac{h}{h_0} = \frac{Re^x}{Re_0^x} \rightarrow h = h_0\left(\frac{Re}{Re_0}\right)^x = h_0\left(\frac{\dot{m}}{\dot{m}_0}\right)^x = c_h\;\dot{m}^x \quad with \quad c_h = \frac{h_0}{\dot{m}_0^x} \tag{2}$$

Eq(2) describes *h* as a function of $\dot{m}$ based on a known pair of $\dot{m}_0$ and h_0 and the exponent *x* of the Nusselt correlation for the given HEX. While the first two parameters could be extracted from the design specification of the HEX, the exponent *x* has to be identified. Using HEX supplier data of the HEX of the experimental setup, Figure 1a shows that the simplified expression fits the supplied data. To fit Eq(2) to the supplier data a Brute Force Algorithm with the root mean squared error as objective function was utilized. The resulting value of *x* = 0.71 is in agreement with the literature (Khan et al., 2010).



(a) (b)

Figure 1: (a) Fit of the film heat transfer coefficient according to Eq(2) with h_0 = 4,001 W/(m²K) x = 0.71 and $\dot{m}_0$ = 0.6 kg/s, *(b) Discretized HEX model into three cells for the hot and the cold side.*

To test the control strategy a simplified model of the HEX has been derived (Agner, 2017). The goal is to represent the nonlinear steady state characteristics of the HEX with a model of minimal complexity, while capturing the relevant system dynamics for this control task. The HEX (counter current plate HEX) is discretized into three ideally mixed cells for the hot and the cold side each, resulting in a 6th order dynamic model as shown in Figure 1b. The heat flow from each hot cell to its corresponding cold cell is calculated using the current overall heat transfer coefficient (OHTC) *U* based on the aforementioned correlation for *h* see Eq(2). To reach a high static accuracy of the model, the logarithmic mean temperature difference (LMTD) is used to calculate the driving force for each pair of hot/cold cells. This, however, reduces the dynamic accuracy of the model which is acceptable for the present work since the main goal is to enable the operation of the HEX in the stratified TES. Using solely the arithmetic temperature difference of the pair of mixed cells would decrease static accuracy, as it would assume a stepwise temperature distribution along the HEX. Eq(3) and Eq(4) describe the transient energy balance of the simplified system for the hot and the cold side respectively (Agner, 2017).

$$\frac{\mathrm{d}E_{1,i}}{\mathrm{d}t} = M_{1,i}\, c_{p1}\, \frac{\mathrm{d}T_{1,i,\omega}}{\mathrm{d}t} = \dot{m}_1\, c_{p1}\left(T_{1,i,\alpha} - T_{1,i,\omega}\right) - \underbrace{\frac{1}{\frac{1}{c_h\ \dot{m}_1^x} + R_w + \frac{1}{c_h\ \dot{m}_2^x}}}_{U}\, \frac{A}{3}\, \Delta T_{m,i} \qquad \forall\, i = 1..3 \tag{3}$$

$$\frac{\mathrm{d}E_{2,i}}{\mathrm{d}t} = M_{2,i}\, c_{p2}\, \frac{\mathrm{d}T_{2,i,\omega}}{\mathrm{d}t} = \dot{m}_2\, c_{p2}\left(T_{2,i,\alpha} - T_{2,i,\omega}\right) + \underbrace{\frac{1}{\frac{1}{c_h\ \dot{m}_1^x} + R_w + \frac{1}{c_h\ \dot{m}_2^x}}}_{U}\, \frac{A}{3}\ \Delta T_{m,i} \qquad \forall\, i = 1..3 \tag{4}$$

Where $M_{j,i}$ is the mass of the held liquid in each cell and $c_{p,j}$ the specific heat capacity of the liquid, both of which are assumed to be constant. $T_{j,i,\alpha}$ and $T_{i,i,\omega}$ are the inlet and outlet temperature of each cell respectively, and $\dot{m}_i$ represents the mass flow rate of the respective side. $\Delta T_{m,i}$ is the LMTD, whereas R_w describes the heat resistance through the HEX wall. The given model was implemented in MATLAB/Simulink®.

3. Control strategy

3.1 Hydraulic setup

To be able to control both outlet temperatures of the HEX, $T_{1\omega}$ and $T_{2\omega}$, the controlled HEX with its actuators needs two manipulated variables accessible by the controller in order to fulfill the steady-state energy balance of each side (Eq(5)) and the steady state heat transfer equation of the HEX (Eq(6)).

$$\dot{Q} = \dot{m}_1\, c_{p,1}\, (T_{1\alpha} - T_{1\omega}) = \dot{m}_2\, c_{p,2}\, (T_{2\omega} - T_{2\alpha}) \tag{5}$$

$$\dot{Q} = \underbrace{\frac{1}{\frac{1}{c_h\ \dot{m}_1^x} + R_w + \frac{1}{c_h\ \dot{m}_2^x}}}_{U}\, A\, \underbrace{\frac{(T_{1\alpha} - T_{2\omega}) - (T_{1\omega} - T_{2\alpha})}{\ln \frac{(T_{1\alpha} - T_{2\omega})}{(T_{1\omega} - T_{2\alpha})}}}_{\Delta T_m} \tag{6}$$

Using a mixing valve and a variable frequency pump in the IL as illustrated in Figure 2, $\dot{m}_1$ and $T_{1\alpha}$ can be adjusted. This setup allows an adaption of the system to the mass flow-varying process stream. Hence, the process stream piping herby is not impacted by the control system allowing for a constant hydraulic characteristic in the process stream piping.

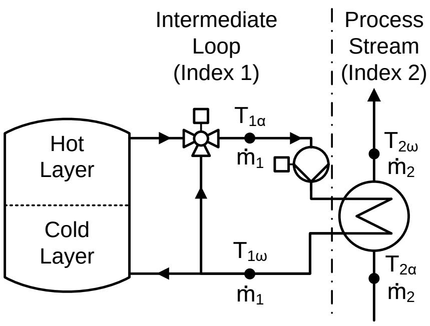


Figure 2: Hydraulic setup of the controlled system with the pump and the mixing valve as manipulated inputs.

3.2 Signal flow description

The goal of the control strategy is to maintain both outlet temperatures of the coupled multiple input multiple output (MIMO) system at their setpoint. Both manipulated inputs of the controlled system ($\dot{m}_1$, $T_{1\alpha}$) are nonlinearly influencing both outputs ($T_{1\omega}$, $T_{2\omega}$). To facilitate the controller design and guarantee the stability of the nonlinear system, the MIMO-system is suggested to be controlled actively with only one controller accessing one input ($T_{1\alpha}$) and setting the other input ($\dot{m}_1$) directly via a feed forward path, using the HEX characteristics and the measured disturbances (Agner, 2017). Figure 3 visualizes the signal flow. The lookup tables represent the inverse nonlinear static model of the HEX. To build the lookup tables Eq(5) and Eq(6) are solved numerically. Since this approach utilizes knowledge about the HEX characteristics and model errors are not assumed to be negligible, a correction of c_h (Eq(2)) is included into the strategy. For this correction the current c_h is calculated

in steady state operation by solving the heat transfer equation (Eq(6)). This allows a range of model uncertainties to be covered, increasing the robustness of the system.
The mass flow rate $\dot{m}_1$ is set via a subordinated mass flow controller which manipulates the pump frequency. The feedback control path measures the IL-sided outlet temperature $T_{1\omega}$ and adjusts the setpoint for the IL-sided inlet temperature ($T_{1\alpha,\,Ref}$), incorporating a feed forward signal of the static model ($T_{1\alpha,ideal}$) to increase the controller performance. $T_{1\alpha}$ is again set by a subordinated controller accessing the mixing valve.

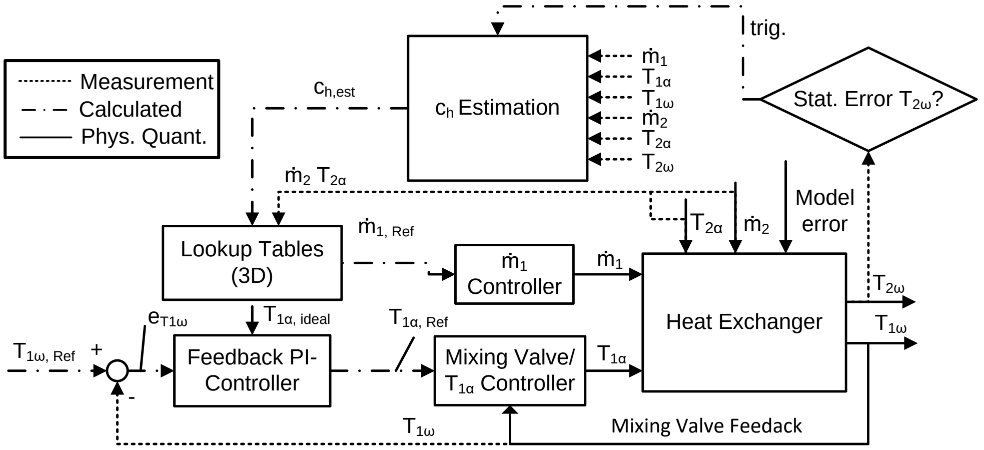


Figure 3: Schematics of the control strategy for the HEX in the stratified TES system.

4. Experimental setup

Since the control strategy relies strongly on the accuracy of the introduced model of the HEX, experimental validation is not only desirable for the closed loop system but also for the open loop model of the HEX. For this purpose, an experimental setup was built. It features small scale commercially available components such as a HEX with A = 4 m^2 and piping in the dimension of DN25. The mass flow range of the circuits is $\dot{m} \approx$ 0.2-0.65 kg/s based on the frequency variable pumps. The experimental setup utilizes the laboratory facility system, which contains two large buffer tanks, holding V = 5 m^3 of a 40 % propylene glycol – water mixture, allowing for a continuous operation for approximately 3 h. This medium is used to simulate the storage tank and the process stream. The (simplified) P&ID diagram of the setup is shown in Figure 4.

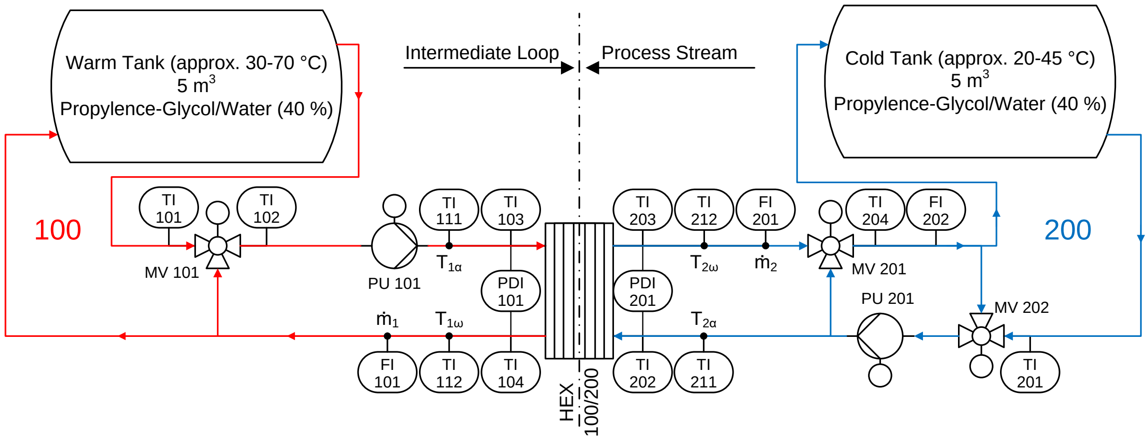


Figure 4: P&ID diagram of the experimental setup to test HEX control strategies. The used variables of the control system ($T_{1\alpha}$, $T_{1\omega}$, $T_{2\alpha}$, $T_{2\omega}$, $\dot{m}_1$, $\dot{m}_2$) are marked beside the respective instrumentation.

4.1 Validation procedure

To validate the open loop model of the HEX, data was recorded from the aforementioned experimental setup. The inlet conditions ($\dot{m}_1$, $\dot{m}_2$, $T_{1\alpha}$, $T_{2\alpha}$) of the HEX were used as inlets in the simulation model. The outlet temperatures of the model were then compared with measurements. In order to test the models' adaption to mass flow changes, both $\dot{m}_1$, $\dot{m}_2$ were step wisely changed across the feasible operating range of the installed

pumps by changing their frequency. The inlet temperatures $T_{1\alpha}$ and $T_{2\alpha}$ were kept constant during the experiment at 40 °C and 20 °C respectively.
For the closed loop validation, the control strategy was implemented on the experimental setups PLC controller and therefore executed in real time. To test the control quality of the strategy across the feasible operating range of the pump a stepwise change of the process-sided mass flow rate $\dot{m}_2$ was simulated. The tests were performed with a process stream that needs to be heated from $T_{2\alpha}$ = 20 °C to $T_{2\omega}$ = 33 °C. The storage temperatures were set as 23 °C and 40 °C for the cold and hot layers respectively.

5. Results

5.1 Open loop validation of the HEX model

In Figure 5 the measured and simulated outlet temperatures are compared. The simulation result is in good agreement with the experiment. As it can be observed in Figure 6, the models maximal steady state error is 0.31 K.

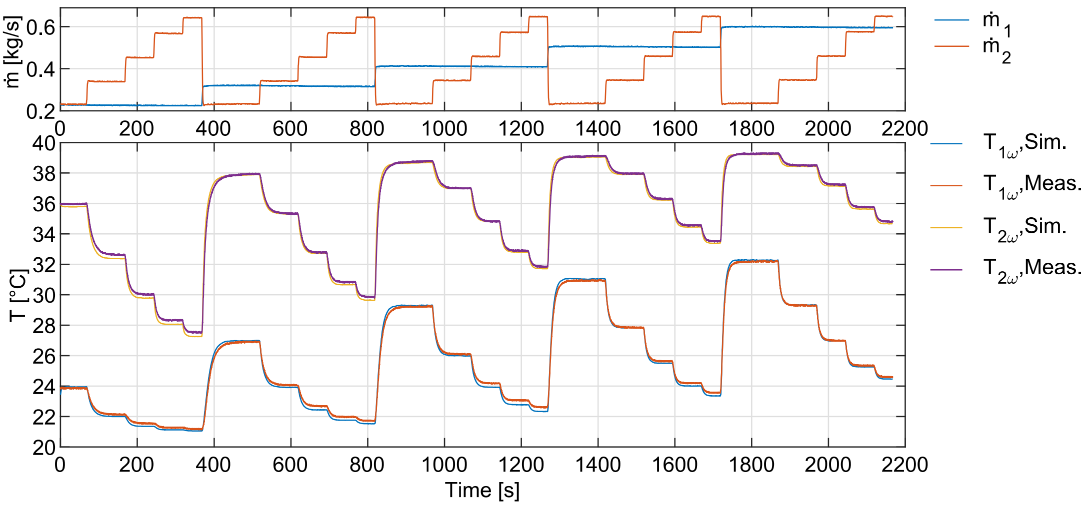


Figure 5: Comparison of the outlet temperatures $T_{1\omega}$ and $T_{2\omega}$ of the measurement and the simulation.

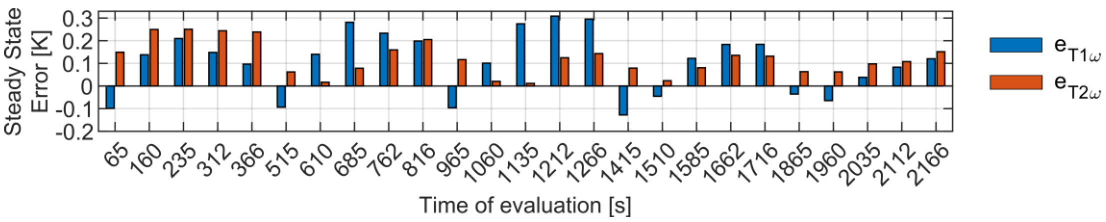


Figure 6: Steady state error of the simulation model evaluated at the end of each step when the system is in steady state operation.

5.2 Closed loop performance of the control strategy

Figure 7 presents the experimental result of the closed loop performance of the control strategy. Step wise change of $\dot{m}_2$, perturbates the system every 200 seconds. The changing dynamic of the system can be observed in the settling time; in high mass flow operating points the temperatures are faster settled than in the low mass flow regions. At t ≈ 380 s a steady state error in $T_{2\omega}$ is detected. The correction of c_h is activated, leading to an adjustment of $\dot{m}_1$. For the following operating points, the control of $T_{1\omega}$ and $T_{2\omega}$ is within the bounds of ± 0.5 K.

6. Conclusion and outlook

The validated HEX model is regarded to be sufficiently accurate to be used for controller design. In a further step, it could be used for development of model based control or to simulate further hydraulic setups. Further Development will be aimed towards the reduction of the measurement effort. Since it is possible to describe the HEX sufficiently accurately with the 6th order dynamic model, this model could be used in a state estimator (e.g. Kalman Filter) to estimate the disturbances ($T_{2\alpha}$, $\dot{m}_2$) and avoid the especially cost-intensive flow measurement.

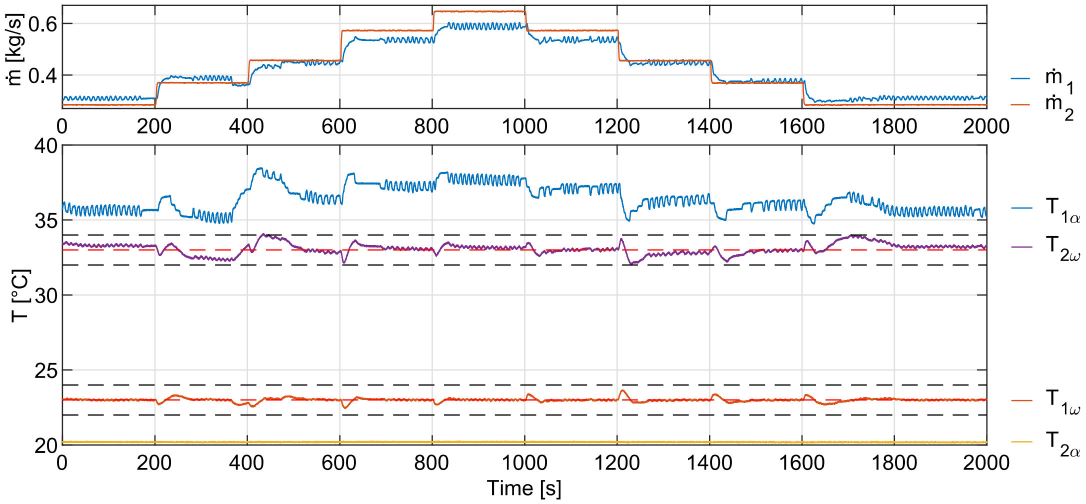


Figure 7: Closed loop performance of the control strategy. Marked orientation-bounds (black dashed lines) are placed at ± 1 K *from the setpoints.*

The control strategy is capable of handling the required variability of the streams. However, it has to be noted that the nonlinear set of equations has to be solved for each HEX individually (during initialization of the controller) which leads to a potentially high implementation effort. Furthermore, accurate flow measurement is needed to allow for adequate control performance. Due to those restrictions it could be advantageous to investigate multivariable control strategies such as model predictive control (MPC) to increase the versatility of the controlled system. MPC could further be interesting in order to include the dynamics and especially the constraints of the actuators in the loop. This could be advantageous since they have non-negligible constraints in rate of change or dead times, as it was observed e.g. with the pumps.

Acknowledgement

This research project is financially supported by the Swiss Innovation Agency Innosuisse and is part of the Swiss Competence Center for Energy Research SCCER EIP.

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