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Analysis of an Oscillating Two-Stage Evaporator System through Modelling and Simulation: an Industrial Case Study

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With increasing demands on the industry for resource efficiency, processes are often built or retrofitted with recycle streams in order to decrease energy and raw material demands. However, this also increases the complexity of the process as a whole and may bring unexpected effects. In this contribution, such a case, consisting of a two-stage evaporator system, fed with the product stream of an upstream batch system and a continuous recycling stream from downstream separation processes, was analyzed. This evaporator system was subject to potentially performance-limiting oscillating disturbances. The purpose of this study was to, through modelling and simulation, expand the knowledge of the system by analyzing the system dynamics, and to discover any co-oscillations and their extent in the process, as well as their effect on process parameters such as product purity and the energy usage in terms of steam consumption. The investigation was performed by modelling using Aspen Plus Dynamics. Simulation, data-extraction, and analysis was performed via a COM enabled Python interface. The results of the study highlight the full-system propagation of oscillations along with co-oscillation of selected key parameters, and support the conclusion that there is potential for cost-reductions by decreasing steam consumption by 1.1 %, without any investments.

1. Introduction

Evaporator systems are integral parts of many different purification processes, e.g. sugar or kraft pulp production, but exhibit the inherent trait of being energy intense. With globally increasing demands on resource efficiency (Pitarch et al., 2017), recycling of matter and energy may be implemented in order to achieve these demands (Márquez-Rubio et al., 2012). However, even though the multistage evaporator system is common, it is still complex to model and control (Adams et al., 2008), and adding recycling has long been known to risk making the overall system dynamics even more complex – even so if the subsystems are simple (Trierweiler et al., 1998). Thus, understanding the evaporator system dynamics, as well as their interaction with other subsystems in a process is a prerequisite in order to reach the aforementioned demands on resource efficiency.

As such, efforts have been aimed at understanding and improving both the systems, and especially how to improve their degree of process integration (Walmsley et al., 2017). Previous studies have also highlighted the importance of understanding and controlling disturbances in evaporator systems. Adams et al. (2008) designed a new control architecture to solve the suboptimal performance of an evaporator system due to three different cyclic behaviors of the plant, and Pitarch et al. (2017) employed an optimization strategy to improve process control and reduce the effects of disturbances.

The present study was similarly focused on discovering how disturbances propagate and affect an evaporator system, and an industrial case study was performed of a system for polyalcohol purification at Perstorp AB. The investigated system, presented in Figure 1, consists of a two-stage evaporator, including a two-stage mechanical vapor recompression with intercooling, as well as a preceding stripping column. The evaporator system is fed from a balance tank (located between the upstream batch system and the continuous evaporator system) into which a continuous, dilute recycle stream is connected, introduced in order to increase resource-efficiency.

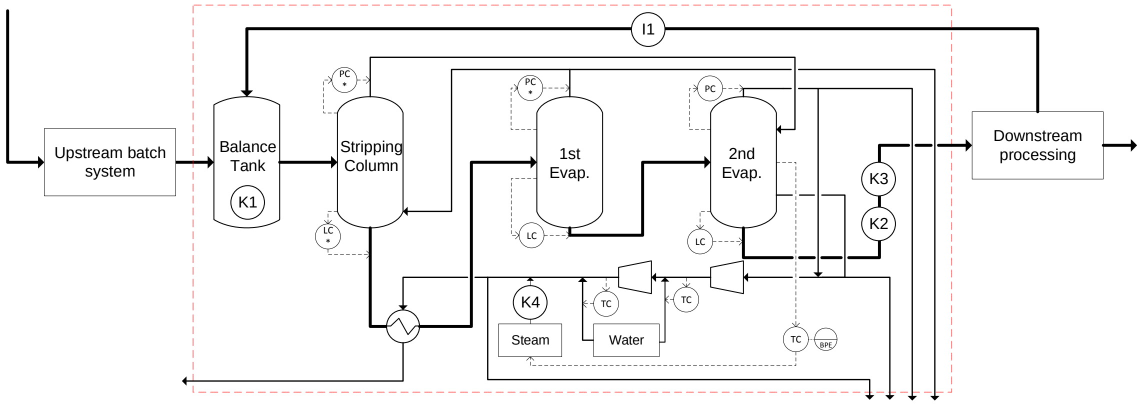

Figure 1: A schematic overview of the studied evaporator system (in dashed box), including mechanical vapor recompression and a stripping column, and its connections to the upstream batch system and downstream processes.

As the upstream batch system intermittently fills the balance tank with material high in product mass fraction, the continuous (dilute) recycle stream has a diluting effect on the contents in the balance tank. Investigating this system is particularly interesting since the disturbance is cyclical (potentially limiting the process to a cyclic steady state at best) and therefore of an oscillating nature, which commonly creates performance-worsening propagations throughout entire systems (Yuan & Qin, 2014).
To examine the process, a dynamic model of the evaporator system was created via Aspen Plus Dynamics, using a COM-enabled Python interface for simulation control, data-extraction, and graphical representation of the data to be analyzed. The analysis employs an approach based on the combination of one-factor-at-a-time (OFAT) sensitivity analysis and phase plane analysis, and is thus able to provide an increased understanding of how process parameters in the system co-oscillate, or co-vary.
The purpose of the present contribution was to analyze the dynamics of the system, to discover and highlight important co-oscillating parameters and their effects on the process, especially regarding the swing-effects on product purity and the energy usage (in terms of steam consumption), thereby improving the understanding of the system's dynamic behavior,. The present study was intended as a precursory study and has the potential of serving as a decision basis for further studies regarding e.g. root cause diagnosis and/or process improvements (e.g. in terms of operations or refurbishments) in order to minimize the oscillation propagation throughout the system.

2. Theory

For the study, an OFAT sensitivity analysis was combined with a phase plane analysis, where different input variables were manipulated in order to analyze their respective impacts on the phase plane of key process parameters, and to explore if and analyze how the key process parameters co-oscillate. An OFAT sensitivity analysis is the practice of changing one variable whilst keeping the others fixed, and is useful for qualitatively identifying input parameter effects on the output of a model (Delgarm et al., 2018). The OFAT approach to sensitivity analysis is simple to implement and functions well in a close proximity to the nominal case, but it carries the risk of deceiving the analyst who could well be tempted to rank input variables' importance based on their impact on the output (Saltelli, 1999). However, in the present study, the aim is not to make a ranking, but rather to illustrate the effects of varying certain input parameters on certain key parameters. As such, the OFAT approach was chosen for this study.
To visualize and analyze the propagation of the oscillations throughout the system, phase planes of the key process parameters were produced and analyzed according to Bequette's (1998) writings. Instead of examining how a process variable changes in the temporal domain, pairing variables in a phase plane facilitates the analysis of the system's stability. It further makes it easier to understand how variables co-vary. This may in turn increase the understanding of the safety margins regarding product quality, and potentially their required quantity. This would serve as an enabler for removing oscillations and/or minimizing swing-effects, which according to Yuan and Qin (2014) would improve operation of the process and lead to financial gains, e.g. through sustaining product quality demands more frequently at a lower cost.

3. Method

To create a dynamic model able to highlight the dynamics of the swings, a steady state model of the evaporator system presented in the dashed box in Figure 1 was first created in Aspen Plus v8.8, using standard blocks. Formaldehyde oligomerization was modeled by applying the Maurer model, which provides high quality representations of the aqueous formaldehyde systems (Ott et al., 2005). Specifically, AspenTech's own implementation of the Maurer model was used, with SYSOP7K as property method with NRTL as base method. This was implemented with small modifications in the same way as in Nolin et al. (2017).
The steady state model was then converted into a flow-driven dynamic model, which made use of PI controllers to reflect the real process, as well as *PtoT* and *Delta* blocks to model boiling point elevation (BPE) control. The controllers denoted by asterisks in Figure 1 were implemented in order to keep the simulation within operationally possible bounds. This functioned as a solution towards qualitatively catching pressure-driven phenomena in a flow-driven simulation, and eliminated issues with unrealistic pressure gains. However, it might have unexpected effects on the simulation results and thus needs to be considered during analysis.
The phase planes were constructed for key process parameters from the sensitivity analysis simulations, for which an input variable had been perturbed individually. The input variables to vary and key process parameters to examine were chosen based on the experience of process engineers working with the process, as well as using the Subset Selection Algorithm (SSA) as applied in Nolin et al. (2017), based on Andersson et al. (2014). Some of the choices and SSA recommendations overlapped, and are presented together with the relative perturbation in table 1 below, with overlapping parameters denoted by *‡*. The shorthand names given to the input variable and key parameters, i.e. I1 and K1 through K4, are also mapped in Figure 1.
To control the simulations, and to gather and present the data, a COM-enabled Python interface was used. This utilized the Python extension win32com, but using other methods, e.g. OPC, should be possible to use as well depending on Python and simulation software support, adding generalizability in terms of software. The perturbation was performed by making a positive and a negative step change to the input variable. Data collection was started after the perturbed simulations had reached a cyclic steady state, as it was desired to investigate how the changes affect the cyclic steady state and its position in the phase planes.

Table 1: Input variables and key process parameters for the sensitivity and phase plane analyses. ‡ denotes overlap between SSA recommendations and process engineer choices.

Input variable	Unit	Relative Perturbation [%]	Key process parameters	Unit
I1: Recycle stream mass flow	[kg/h]	± 2.5	K1: Balance tank product mass fraction	[-]
			K2: 2nd stage liquid product stream mass flow *‡*	[kg/h]
			K3: 2nd stage liquid product stream product mass fraction, i.e. product purity	[-]
			K4: Added steam mass flow, i.e. steam consumption *‡*	[kg/h]

The temporal domain data that was gathered for each parameter during 24 simulation hours was processed in two different ways before presentation in order to visualize the findings according to Bequette (1998), as well as to visualize the relative movements of the cycles in the different phase planes. The first way meant normalization with respect to its own mean value before the phase planes were produced, and the second way was done through scaling with the variable's nominal run mean value, both of which render the results dimensionless. Furthermore, adding an objective function similar to that in Nolin et al. (2017) allowed for analysis of the system's performance during the cycles. The objective is defined in equation 1 as a function of the discrete temporal element t_i, i.e. the i^{th} simulation run sample, where $\overline{K3}_{nom}$ and $\overline{K4}_{nom}$ are the parameters' corresponding mean values for the nominal run, and *w* is a weight set to 0.7 to reflect process economics.

$$F_{obj}(t_i) = -\left((1-w)\cdot\frac{K3(t_i)}{\overline{K3}_{nom}} + w\cdot\frac{-K4(t_i)}{\overline{K4}_{nom}}\right) \quad (1)$$

4. Case study results and discussion

The scaled times series that the analysis is built upon are presented in Figure 2 below. As can be seen, the model response is oscillating for all four parameters, and small changes in I1 may have great effects on steam consumption (K4). However, the way in which the parameters co-oscillate is difficult to discern from Figure 1.

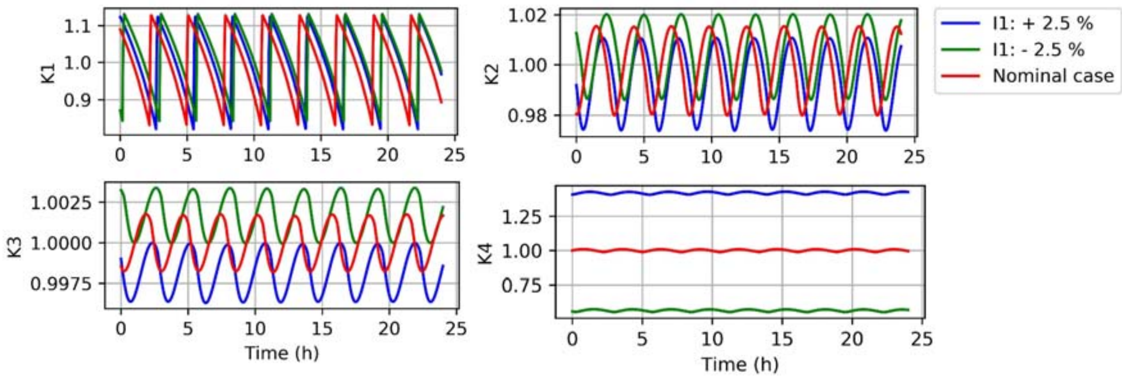

Figure 2: The scaled time series for K1 (upper left), K2 (upper right), K3 (lower left), and K4 (lower right).

This is more easily understood from the phase planes. The scaled and normalized phase planes for the balance tank product mass fraction, K1, and the 2nd stage liquid product stream mass flow, K2, when perturbing the recycle stream mass flow, I1, by ± 2.5 %, are presented in Figure 3a and 3b, respectively. As can be seen in both Figures 2 and 3, the balance tank product mass fraction (K1) varies significantly during the cycles, by roughly ±15 percentage points. In Figure 2, the cycle can be seen to start at the lowest point in each oscillation, when the upstream batch system fills the balance tank, rapidly increasing the product mass fraction in the balance tank (as well as the liquid level), which subsequently is lowered during the rest of the cycle as the evaporator system is being fed, and low-concentrated material is recycled to the balance tank. This means that both the liquid level and the product mass fraction in the balance tank is reduced, until the cycle starts anew. In Figure 3, this cycle starts at the curvature's left-most point, and travels to the right along the horizontal axis. The balance tank disturbance is clearly shown to propagate all the way through the very end of the evaporator system by the ±2 percentage points of variation in the 2nd stage liquid stream mass flow, K2, seen on the vertical axis in Figure 3. Inferred from this is the strain put on the PI controls through the system, that are put in place to keep the process in check and at its set point. Furthermore, it can be seen that only small relative changes are created during the input variable perturbation during the sensitivity analysis, but as shown in Figure 3b, decreasing (green) or increasing (blue) the recycle stream mass flow, I1, will lead to a lower balance tank product mass fraction, but in either end of the cycle. Further indicated in Figure 3a is that increasing the recycle stream mass flow will generally yield lower production rates (and vice versa), which is coupled to a higher dilution factor in this case, i.e. there is comparatively more water in the feed that needs to be evaporated in relation to the desired product.

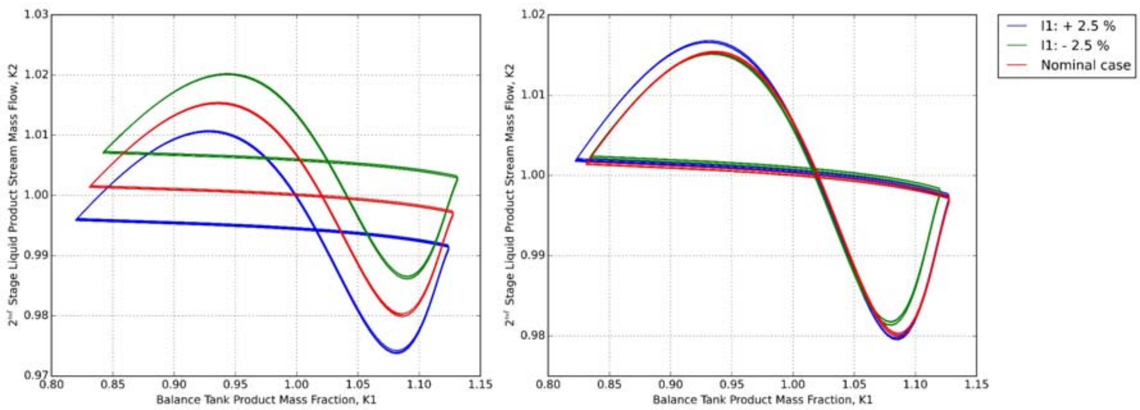

Figure 3: (a) Scaled and (b) normalized phase planes for the balance tank product mass fraction versus the 2nd stage liquid stream mass flow, for the nominal (red), positively (blue), and negatively (green) perturbed case.

The suggestion that more water needs to be evaporated when perturbing I1 by +2.5 %, thus requiring more steam, agrees with the results in the scaled phase plane in Figure 4, in which the phase planes are presented for the objective parameters, K3 and K4. In Figure 4a, the positive perturbation of I1 (blue) can be seen to

require more steam than the other two cases. The overall cyclical appearance of these furthermore shows that there is a strong covariation between the two parameters. This variation is most probably primarily caused by the balance tank disturbance visible along the horizontal axis in Figure 3.
The scaled results are shown in Figure 4a, which indicate that even relatively small changes in the recycle stream mass flow may force large adjustments to the added steam mass flow in order to keep the BPE in the second stage at its set point. Whilst the qualitative effect is logical and expected, i.e. an increase in steam consumption with an increase in evaporator feed stream water content and vice versa, the quantity was much greater than expected. This might have been influenced by some unreal behavior the model catches with its use of extra PI controllers for simulation control. Thus, further work will be needed to determine the accuracy, e.g. through big-data analysis or pilot plant experiments. Similarly, the extremely small changes in product purity during a cycle is attributed to the strict control exerted by the model's control of second stage BPE.
Continuing, the model displays a center behavior in the normalized phase plane in Figure 4b, which implies the existence of an equilibrium point. Furthermore, the size increase of the green loop, i.e. for the case of the negative perturbation of -2.5 % to the recycle stream mass flow (I1), shows that the relative difference between peaks and valleys for this run is greater than for the other two. Together with the band widening for the same run, this suggests that this simulation case is relatively difficult to control in a consistent fashion, probably due to other phenomena becoming more pronounced and having a greater effect on the simulation.
The objective score was added to the nominal case phase planes presented above in Figures 3-4 (red), and the results are presented in Figure 5. In Figure 5a, the nominal case 2nd stage liquid stream mass flow (K2) and balance tank product mass fraction (K1) is presented with the objective score.

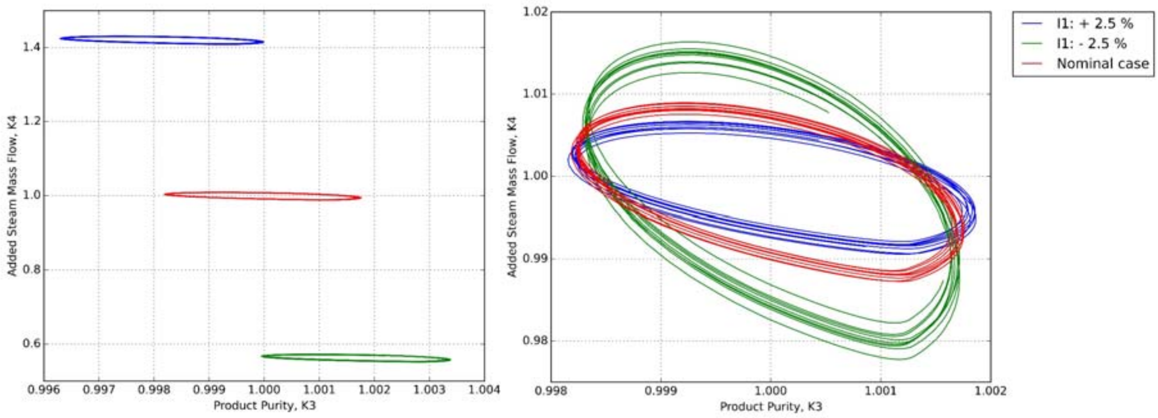

Figure 4: (a) Scaled and (b) normalized phase planes of the objective parameters for the nominal case (red), the positively (blue), and negatively (green) perturbed cases.

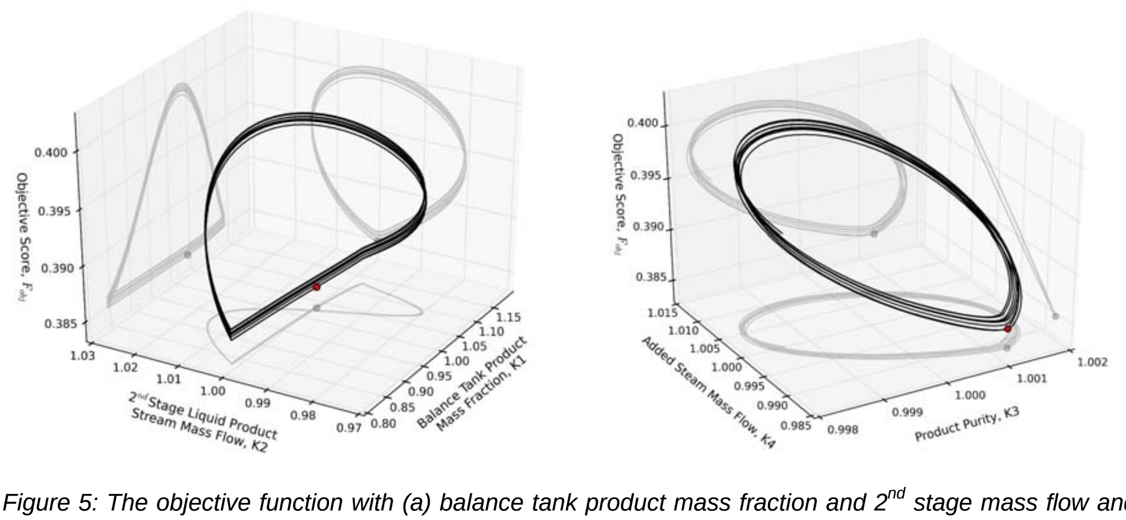

Figure 5: The objective function with (a) balance tank product mass fraction and 2nd stage mass flow and (b) to the objective parameters. The red dot marks the minimum point of the objective during the cycles.

As marked by the red dot, the position with the lowest objective score is along the straight line during the batch system emptying sequence, close to the average value for both parameters. This indicates that minimizing the swing effects would not need grand adjustments since the best operating point during a cycle is close to the mean, and would presumably have a stabilizing effect on downstream separation processes, into which oscillations in the 2nd stage liquid stream mass flow would propagate. In Figure 5b, the addition of the objective score to the nominal case cycle is presented for product purity (K3) and added steam mass flow (K4), with a red, filled circle to mark the minimum of the objective during the cycles. This shows a strong dependability on the added steam mass flow, which exerts a larger influence than the extremely small variation in product purity during the cycle. It can further be seen that the best point for the nominal case needs roughly 1.1 % less steam than the average steam usage during the cycles. This fact, together with the small changes in product purity, means that there is potential for significant financial gain (via a lower steam usage) to be found in the way the process is operated today, even without any drastic adjustments or refurbishments. One way to achieve this could be by fixating the mass flow of added steam to the marked point in Figure 5b, which could also have a minimizing effect on the oscillations in the 2nd stage liquid stream mass flow rate, K2, something that may be confirmed through further simulation.
Finally, an important point to reiterate and highlight is that the oscillations that seemingly start in the balance tank, with parameter K1, further propagate throughout the entire flowsheet, to parameter K2. This indicates that identifying and rectifying the actual root cause of the disturbance may have beneficial effects on the performance of the entire system by removing or reducing the oscillations.

5. Conclusions & Future Work

The results show that swings in steam consumption are present in the nominal case, but that the product purity varies only very little over a cycle, which indicates that by fixating the added steam mass flow to the optimal point in the current way of operation, steam consumption can be decreased by roughly 1.1 %. This translates into significant cost reductions with virtually costless changes to the process. Furthermore, the quantitative effects of the recycle stream mass flow on the steam consumption need to be properly assessed, in order to determine whether there is any real potential for cost reductions of which to take advantage. Finally, the results of the study support the conclusion that there are co-oscillations for the selected key parameters, and that oscillations extend throughout the evaporator system. This means that finding and rectifying the root cause can be a very important next step in improving process performance, and should be performed in follow-up studies.

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