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Optimal adaptive scheduling and control of beer membrane filtration

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ABSTRACT

An adaptive optimal scheduling and controller design is presented that attempts to improve the performance of beer membrane filtration over the ones currently obtained by operators. The research was performed as part of a large European research project called EU Cafe with the aim to investigate the potential of advanced modelling and control to improve the production and quality of food. Significant improvements are demonstrated in this paper through simulation experiments. Optimal scheduling and control comprises a mixed integer non-linear programming problem (MINLP). By making some suitable assumptions that are approximately satisfied in practice, we manage to significantly simplify the problem by turning it into an ordinary non-linear programming problem (NLP) for which solution methods are readily available. The adaptive part of our scheduler and controller performs model parameter adaptations. These are also obtained by solving associated NLP problems. During cleaning stages in between membrane filtrations enough time is available to solve the NLP problems. This allows for real-time implementation.

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1. Introduction

Large industrial process designs are generally separated into parts to simplify and manage the designs. The separation is generally obtained from a hierarchical decomposition (Antelo, Banga, & Alonso, 2008). When scheduling and control are both involved these are usually separated by the hierarchy. But in general, separation leads to loss of performance especially if the scheduling and control heavily interact. Beer membrane filtration is an example of an industrial process with significant interaction between scheduling and control. This is because different long and short term phenomena and goals exist. Fouling concentrations of beer change very slowly whereas beer flow inside the membrane changes very rapidly. In between are the fouling phenomena of the membrane. The long term goal is to filter enough beer in time while the short term goal is to prolong the filtration stages as much as possible because membrane cleaning is costly. The filtration stage is prolonged through removal of parts of the fouling cake layer on the membrane. They are flushed back into the beer.

Currently beer membrane filtration is performed by supplying default set-points for flows in the filtration system. Sometimes these set-points are adjusted from their default values by operators, based on experience and measured values of the pressure over the membrane (transmembrane pressure). This happens mainly when the amount of filtered beer is too low or when membrane fouling occurs too fast. By adjusting these set-point also the scheduling of different phases occurring during beer membrane filtration, is affected. Fig. 1 shows the block diagram of beer membrane filtration (BMF). The set points concern the flow of beer into the membrane filter F^i and the flow out of filtered beer F^o. These together determine the cross flow F^c because $F^i - F^o = F^c$. F^i, F^o and F^c should always be nonnegative. To ensure this our adaptive optimal scheduling and control system design considers F^o and F^c to be the control variables which are taken to be non-negative. Then $F^i = F^o + F^c$ is also non-negative.

Fig. 2 shows the phases which make up the schedule associated with beer membrane filtration. In it backflushes (BF) occur. These are stages where beer filtration is suspended and water is flushed backwards through the membrane to clean it. This type of cleaning fully removes cake fouling on top of the membrane but only partially removes membrane pore fouling by aggregates. Another thorough way of cleaning the membrane is by chemicals. This is more costly but fully removes membrane cake and pore fouling at the expense of deterioration of the quality and strength of the membrane. Chemical cleaning stages are denoted by (C) in Fig. 2. The cheapest way of removing fouling is by manipulating the beer flow during filtration. In this way part of the cake layer fouling on top of the membrane can be removed. The associated costs relate to pumping costs during filtration stages (F). These are very small compared to the costs of backflushes (BF) and chemical cleaning stages (C).

The scheduling and control problem can be briefly stated as follows. Besides the set-point values for flow during each filtration

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stage (F), in the schedule represented by Fig. 2 the number of filtration cycles (FC) within a single chemical cleaning cycle (CC) needs to be optimised. In Fig. 2 this number is two, but in general it must be higher. Also the duration of each single filtration stage (F) needs optimisation. Backflushes (BF) have a fixed duration. Finally the filtration of beer consists of several chemical cleaning cycles (CC). Their number also needs optimisation. So a complicated scheduling and control problem results. Scheduling and control problems of a similar nature have been reviewed, classified and unified in (Wang, Gao, & Doyle, 2009). But, as opposed to (Wang et al., 2009), in this paper the process model used for adaptive scheduling and control is a non-linear first principles model, instead of a series of linear models. Also, instead of tracking *a-priori* fixed trajectories, the trajectories and associated controls are adjusted by minimising a cost function reflecting the overall control goal while at the same time satisfying state and control constraints. The latter aspects are similar to what is called non-linear model predictive control that also uses a non-linear systems model and a cost function (Camacho & Bordons, 2007). But non-linear model predictive control excludes scheduling. Estimation of model parameters is generally excluded as well. To the best our knowledge this is the first time an adaptive optimal scheduling and control system for this type of process is proposed that is implementable in real-time.

The control objective associated with beer membrane filtration is to minimise the filtration costs per unit filtered beer while satisfying the constraint that a given amount of beer must be filtered in a given amount of time. The costs are determined by costs of chemical cleaning stages (C), costs associated with backflushes (BF) and costs associated with energy needed to realise flows during filtration stages (F) (Zondervan, Betlem, Blankert, & Roffel, 2008a). Besides costs, optimal controller design relies on a dynamic state-space model representing the process behaviour. A first principles model is used in this research because it allows for explicit computation of costs associated with beer membrane filtration. Furthermore first principles models provide insight which is very helpful when searching for errors and improvements. From a scientific perspective the insight provided by first principles models reveal structure and provide understanding and explanation of the process and underlying mechanisms. These enable easy modification and extension of the model and the associated process design. Also operators may benefit from further insight into the process.

A first principles models of membrane filtration has been presented (van der Sman & Vollebregt, 2013). Control system design for

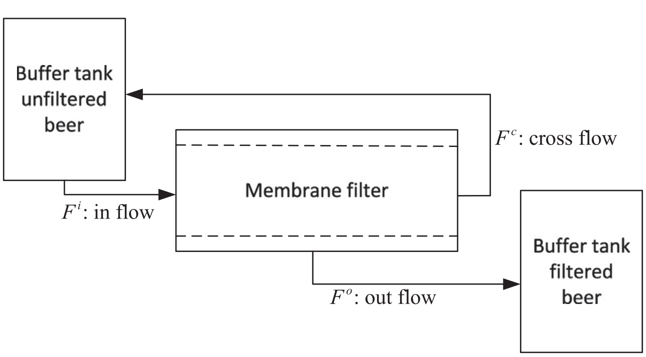

Fig. 1. Block diagram of beer membrane filtration (BMF).

membrane filtration has been performed (Zondervan et al., 2008a). When truly optimising all features of the control and schedule just mentioned, a mixed-integer non-linear programming problem (MINLP) is obtained (Zondervan, Blankert, Betlem, & Roffel, 2008b). These types of problems are most complicated and possibly intractable. When tractable their computation is expensive and therefore generally unsuitable for real-time control purposes (Belottia, Leeb, Libertic, Margotd, & Wächterb, 2009).

By making some dedicated suitable process assumptions that are approximately satisfied, in this paper we manage to reduce the scheduling and control problem to an ordinary non-linear programming problem (NLP). It turns out that our NLP problem suffers from local minima. Therefore a global search algorithm is used to solve it at the expense of loss of computational efficiency. The adaptation of the schedule and control is performed as follows. During each chemical cleaning stage (C) a new schedule and control is computed based on transmembrane pressure measurements of the previous part of this chemical cleaning cycle (CC). These measurements are used to estimate both the initial state of the next chemical cleaning cycle (CC) and some critical model parameters. Next the initial state estimate and the adapted model are used to compute a new optimal schedule and control. Only the control computed for the next chemical cleaning cycle (CC) is applied to the process. The global search algorithm to estimate the initial state and critical model parameters as well as the one to compute the optimal schedule and control is constrained to stop within a fixed amount of time. This ensures their execution not to exceed the time required by a chemical cleaning stage (C) in which they have to be performed.

The first principles model used for the adaptive optimal scheduling and control is presented in Section 2 while the scheduling and control problem is defined in Section 3. To arrive at the adaptive optimal scheduling and control scheme Section 4 first describes open loop optimal control computations. Next Section 5 presents the adaptive optimal scheduler and controller. Results obtained with it in simulation experiments incorporating both parameter and measurement errors are reported. Section 6 presents conclusions an important one being that measurements related to membrane and beer fouling are crucial to the success of adaptive optimal scheduling and control of beer membrane filtration. Although technically feasible they are very much lacking in current industrial practice.

2. Modelling beer membrane flow and fouling

For reasons mentioned in the introduction a first principles model is used to design the adaptive optimal scheduling and control system. The model is developed to describe industrial beer membrane filtration currently in use at different locations. Critical parameters are estimated and experiments are performed on a scaled down pilot plant. The full model is published in (van der Sman & Vollebregt, 2013). Here we only present the most important parts needed to understand the adaptive scheduling and control system design. Also the presentation of the model is quite different from (van der Sman & Vollebregt, 2013) which was inspired by physics. Here a state-space representation is adopted that provides the model structure required for control. The model describes the flow of beer through the membrane and computes the associated

Chemical Cleaning Cycle (CC)				
Filtration Cycle (FC)		Filtration Cycle (FC)		Chemical Cleaning (C)
Filtration (F)	Back Flush (BF)	Filtration (F)	Back Flush (BF)	Chemical Cleaning (C)

Fig. 2. Scheduling and control stages and cycles.

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