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A comparison of control techniques for dairy falling film evaporators

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Abstract: **Falling film evaporators (FFE) are widely used in the dairy industry to pre-concentrate milk for powder production. FFE control is, however, not performed well, with many plants still under operator or proportional and integral (PI) control. Several authors have created fundamental models to use for controller development, yet these models have various differences in structure and span feed flow rates ranging from laboratory scale (2 500kg/h) to industrial scale (27 000kg/h). This paper used a single semi-empirical model developed by Haasbroek (2013) to offer a sensible comparison of the most often seen dairy FFE controllers. Disturbance rejection was tested by introducing a feed dry mass fraction (W_F) step and then comparing the product dry mass fraction (W_P) increase as a percentage ($\Delta W_P/\Delta W_F$x100). It was found, as shown in figure 7, that linear quadratic (LQR) control (Haasbroek et al., 2013) and fuzzy predictive controllers showed the best performance (70% and 69% respectively), followed by cascade control (77%) and lastly PI control (123%). The fuzzy controller does, however, struggle with disturbances it has not been tuned for, while cascade and LQR controllers still perform well, as seen in figure 8. Taking into account the involved design required for LQR control, cascade control offers a well balanced approach to FFE disturbance rejection.**

Keywords: **Falling-film evaporator, advanced control, dairy control**

1. INTRODUCTION

Food processing plays an increasingly vital role in modern day society. Food needs to be collected, shipped and stored before reaching the end consumer – each action requiring time which allows for bacterial growth and eventual product spoiling. Effective and well controlled food processing can prevent, or even eliminate, most bacterial growth which in turn increases shelf-life before spoiling is observed.

1.1. Dairy food processing

The dairy industry perfectly showcases the importance of food processing: as an example, raw milk may spoil within a day or two if left in a cupboard, while pasteurised milk may last for many months in the same circumstances. Powdered milk provides even greater resistance to spoiling and offers compact storage possibilities. The reduction of milk from liquid to powder is performed in dryer, requiring large amounts of energy. An intermediate evaporation stage is usually introduced to remove a large portion of water from milk before it is sent to the spray dryers. If these evaporators are correctly controlled, they may offer a ten-fold reduction in energy requirements compared to spray dryers (Paramalingam, 2004). Falling film evaporators (FFE) are the most widely used evaporator setup in the European dairy industry (Ramırez et al., 2006).

1.2. Industrial FFE operation

FFEs are large complex engineering processes, which need to constantly adhere to certain product quality and safety standards (O'Callaghan & Cunningham, 2005). The most important of these product requirements is the final solid dry mass fraction (DMF), i.e. fraction solids of the product, and the level of milk protein denaturisation. DMF directly influences downstream spray drying efficiency and final product quality, while protein denaturisation causes excessive fouling and occurs when milk is kept above 70°C.

Various process disturbances are present, complicating the adherence to the above specifications. Firstly, the feed milk DMF, W_F, may differ greatly from one raw milk source to another. These differences are amplified during evaporation and, therefore, lead to large deviations in product DMF. Secondly, varying steam pressure (used to heat milk) and changing milk properties (e.g. heat capacity) directly influence the temperature of the milk inside the evaporator resulting in a complex temperature management.

1.3. FFE modeling

An attractive alternative to online controller development is offered by offline FFE models. These models range from simple input to output relationships identified from process data (Cunnigham et al., 2006; Russel et al., 2000) to in-depth semi-empirical models developed from fundamental equations (Paramalingam, 2004; Quaak et al., 1994; Quaak & Gerritsen, 1990; Haasbroek, 2013). The semi-empirical models have been proven by several of the above authors to adequately explain FFE dynamics by comparing simulation results to validation data (Haasbroek, 2013).

One complication that arises from the multitude of models used for controller development and simulation is the difficulty in directly comparing simulation results. As an example, the model employed by Van Wijck (1999) was configured for a laboratory scale setup while that of Bakker (2004) was for the Fonterra industrial FFE, which processed ±7500*l/h* of raw milk (see in Table 1 for a comparison of FFE models and associated capacities). Another example of model diversity concerns vapour recycle: the Haasbroek (2013) model uses thermal vapour recompression (TVR), while the Winchester (1999) model uses mechanical vapour recompression (MVR). Therefore, the major evaporative driving variable, steam, is delivered differently.

1.4. FFE control solutions

Various control studies have been performed on FFEs, mostly focussing on PID (Winchester & Marsh, 1999) or multi-level (cascade) PID control setups (Bakker et al., 2004; Karimi et al., 2006; Paramalingam, 2004). Limited work has also been performed on fuzzy logic controllers (Foley, 2011; Haasbroek, 2013), with positive results. Finally, recent work by the current authors also investigated linear quadratic regulation (LQR) with enhanced disturbance rejection (Haasbroek et al., 2013).

Table 1: FFE model comparison and controller summary

Author	Plant		Control	
	Size	Feed (kg/hr)	Type	(ΔW_P) / (ΔW_F)
Winchester (1999)	1 Effect MVR	17 000	PI	120%
Bakker (2004)	2 Effects TVR	7 500	Cascade	75%
Karimi (2006)	3 Effects TVR	10 000	Cascade	83%
Van Wijck (1999)	4 Effects	2 500	Supervisory PID	95%
Foley (2011)	4 Effects TVR	26 000	Fuzzy	-
Haasbroek (2013)	2 Effects TVR	10 200	LQR	70%

As with FFE modelling, comparing FFE controller results are problematic due to slight differences in literature controller implementations as well as the large differences in FFE models found upon which the controllers are tested. Therefore, deciding between fuzzy, LQR, PID and cascade control for dairy FFEs is a non-trivial subject. Constructing a single model, and subsequently generic controller implementations on this model, would allow for direct comparison.

1.5. Focus of current study

The current study aims to offer a more comprehensive comparison between the most researched dairy FFE controllers. This will be done by using the semi-empirical FFE model designed and validated (against historical plant data) by the authors in previous work (Haasbroek et al., 2013) as the single model for comparison. This study expands on the previous controllers already designed for the local plant (LQR and PI) by adding fuzzy and cascade controllers.

The model was built using the same rational and principles as that of Quaak (1990), Winchester (1999), and Paramalingam (2004), while the fuzzy and cascade controllers are directly comparable to the work of Foley (2011) and Bakker (2004) respectively, also mentioned in the previous sections.

1.6. Paper organisation

Section 2 will provide a review on the specific FFE modelled. Section 3 briefly reviews the various controller methods. The simulation, results and discussion of the main control comparisons are shown in Section 4. Section 5 offers the final conclusions.

2. LOCAL FALLING FILM EVAPORATOR AND SIMULATION MODEL

2.1. Local FFE description

A local, South African, plant was chosen as base for the FFE model. The local plant consists of two evaporation chambers (referred to as effects), a TVR system for vapour recycling, a condenser to remove heat, and a homogeniser to reduce milk fouling. Figure 1 below, shows the process layout and important measured variables:

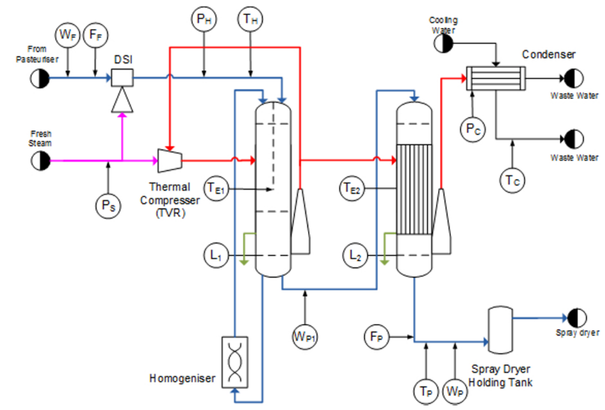

Figure 1: Local FFE layout(Haasbroek et al., 2013)

A brief process description taken from Haasbroek et al. (2013) is given below:

Raw milk with DMF W_F is treated by in-line vitamin enrichment before it is sent to a feed tank. From the feed tank, milk is fed at a flow rate of F_F to a moderate temperature pasteuriser (70°C – 80°C) to deactivate most pathogens. A direct steam injector (DSI) follows the pasteuriser to eradicate the remaining pathogens and pre-heat the milk (T_H of ± 104°C). From the DSI the milk is kept under raised pressures (P_H of 2 – 3 bar) to ensure that it does not vaporise inside the tubing because of the elevated temperatures. The temperature in the evaporator chambers is indicated by T_{E1}.

Once inside the evaporator effect, some milk immediately forms vapour due to rapid exposure to a low pressure system