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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:

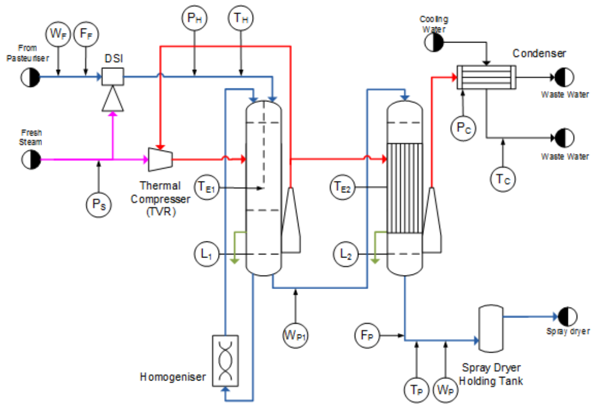


Figure 1: Local FFE layout(Haasbroek et al., 2013)

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 (flash evaporation). The remaining liquid milk flows down the inside of long vertical tubes heated on the shell side by fresh steam and/or recycled vapour. Vapour is recycled using high pressure (P_S) steam that is mixed with low pressure vapour from the effect. The evaporation tubes facilitate most of the evaporation. The concentrated milk is collected in a holding tank (level L_1) and then directed to a second evaporator (which functions in a similar fashion to the first evaporator) to increase heat recovery and drive the final concentration to product DMF of W_P.

The milk then exits the FFE section (at a flow rate of F_P) into a holding tank from where it is fed to a spray dryer which produces the final milk powder product.

2.2. *Semi-empirical model*

Initially,a generic fundamental model was developed using the reported relationships given by Winchester (1999) and Quaak (1990). This model consisted of dynamic heat and mass transfer equations forthe evaporation effects, TVR, and condenser units.After the initial model was created, all the physical aspects of each unit, for example the surface area of the distribution plate, were estimated by comparing literature values and relevant feed flow rates. This was done as only the process data, and not the unit design sheets, were available.

The available historical data was split into training and validation data sets. Training data was used to fine tune the physical parameters, while validation data was used to test the final results. One such set of historical values, where the FFE is under operator control, are compared to the model simulation for the two most important control variables, i.e. W_P and T_{E1}:

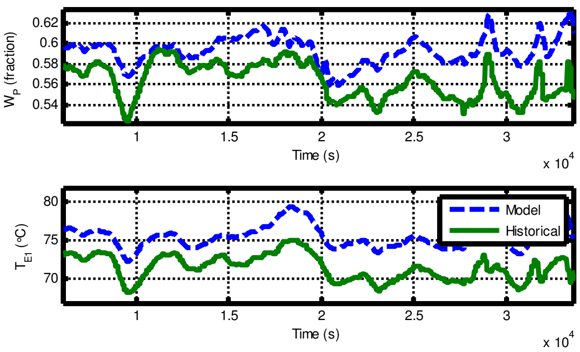


Figure 2: Model comparison to historical data

Note that although a constant bias is present the model clearly captured the process dynamics. This bias was ignored as all controllers are designed with integral action which will negate any long term offset.

3. FALLING FILM EVAPORATOR CONTROL

3.1. *Background and control objectives*

As described in the introduction: the first effect temperature (T_{E1}) and product DMF (W_P) are the most important process variables in terms of product quality. These are then also the two control variables, while motive steam pressure (P_S) and cooling water flow rate (F_{CW}) are the manipulated variables. F_{CW} controls the pressure inside the condenser, which directly affects the pressure inside the second effect (closed system) and thus T_{E2}, as the system is at saturation. In the same way T_{E2} then affects T_{E1}. The $F_{CW} \rightarrow T_{E2}$ interaction is, however, very fast and often T_{E2} is used as the manipulated variable by implementing a PI controller for the $F_{CW} \rightarrow T_{E2}$ sub-process (Karimi et al., 2006; Bakker et al., 2004).

3.2. *Current control strategy*

The local FFE is currently under operator control and experiencing constant poor quality product and heavy fouling. The operators have to balance competing objectives: supply as much heat as possible to the FFE (to increase evaporation rate), while ensuring temperatures below 70°C (to minimise fouling). In addition to these main objectives, operators also have to manage process disturbances and the feed flow rate to ensure a constant W_P, while taking into account process dead times.The poor performance serves as motivation to find a simple, robust and suitable automatic controller.

3.3. *Investigated control techniques*

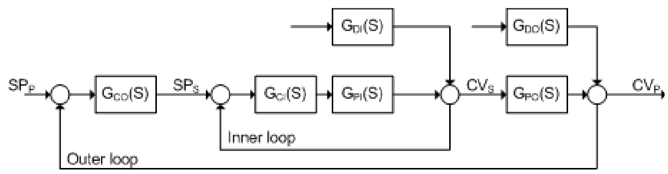
As mentioned in the introduction, this study aims to offer a comparison of control methods for dairy FFEs found in literature. As such PI, cascade, fuzzy logic, and LQR controllers will be investigated. A very brief description given below for the above methods, while a more in-depth description can be found in the relevant sources stated.

PI control

Proportional and integral control offers the simplest solution to quickly counteract a measured error (proportional action) and ensure zero offset (integral action) – both required for the FFE system. Haasbroek et al. (2013) used Ciancone tuning rules (Marlin, 2000), which arerelatively unknown. For this study, internal model control (IMC) (Marlin, 2000) was chosen as an alternative.

Cascade control

Cascade control is a multi-level implementation of PI control, especially useful in systems with process lag. A secondary control variable (CV_S) is sought that responds more rapidly to the same disturbances that influence the primary control variable (CV_P). By then first implementing a so-called inner loop controller on CV_S, one can quickly suppress these disturbances before the error is propagated to CV_P. A generic representation of cascade control is shown below:



Where:	G_{CO}	Outer PI controller	G_{CI}	Inner PI controller
	G_{PO}	Outer process	G_{PI}	Inner process
	G_{DO}	Outer disturbance	G_{DI}	inner disturbance

Figure 3: Cascade structure

The integral action of the inner loop controller can be removed - zero offset following is only required for CV_P. For the local FFE, W_{P1} (the milk dry mass after effect 1) was selected as CV_S as it is influenced in the same manner as W_P by all the main disturbances, but reacts with shorter dead times.

Fuzzy logic controller

PI, LQR and cascade solutions normally require a process model, either for tuning or prediction. These methods neglect additional process knowledge that is freely available in literature or from human operators, in favour of mathematical correlations. Fuzzy logic depends almost solely on expert knowledge by describing the controller actions in colloquial rules, i.e. if the product dry mass decreases, increase the steam pressure to compensate.

For the local FFE these rules were expressed in terms of error (E) and change in error (ΔE) for each CV and a subsequent MV change as shown by the control surfaces below:

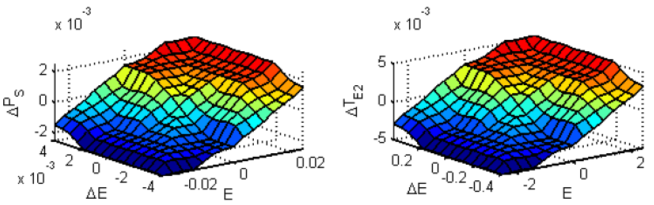


Figure 4: Fuzzy rule surfaces

In this form the fuzzy controller mimics a PI controller, and subsequently also inherits the poor performance for systems with process lag. One solution is to add predictive action by defining fuzzy rules for the main disturbances:

- If W_F increases, decrease P_S
- If F_F increases, increase P_S

Note that, the reverse of the above rules were also implemented. The advantage of fuzzy control lies in the ease with which these fuzzy rules can be created.

Fuzzy feed optimisation

After inspection of historical data for the local process it was determined that frequent and unnecessarily large feed flow rate changes introduced unwanted process disturbances. Process lag and other disturbances make it difficult for operators to correctly balance F_F and other MV changes. Each operator also has a personal preference and bias, which led to further inconsistencies.

A fuzzy feed optimiser (FFO) was created to ensure the FFE always operates close to maximum capacity, i.e. close to maximum available steam usage. This resulted in the simple fuzzy rule set:

- If P_S is below optimal level, increase F_F
- If P_S is above optimal level, decrease F_F

The FFO was set to operate within a limited F_F range ensure no flooding occurred within the FFE. Finally, to prevent interaction withother controllers, the FFO maximum flow rate change was limited to 2070kg/h set point change per hour.

LQR controller

A brief description of the LQR controller is offered below, for the complete design refer to (Haasbroek et al., 2013).

All the previous control methods described are essentially single-input single-output (SISO) controllers. The local FFE is, however, a multiple-input multiple-output (MIMO) system with 5 inputs (W_F, F_F, T_H, P_S, and F_{CW}) and two outputs (W_P, T_{E1}). If one implements proper step tests (Cunnigham et al., 2006) it is possible to find the relationship between each input-output pair mentioned above. These relationships can then be combined into a state space (MIMO) representation. Once the FFE is represented in state space form it becomes possible to use a multitude of control techniques, including LQR.

LQR allows one to weigh all the process states against each other, and against the manipulated variable usage, and then choose optimal feedback gains to control both control variables simultaneously, without neglecting interaction. Optimal feedback gains are selected by minimising a quadratic cost function:

$$J = \frac{1}{2}\sum_{k=0}^{N}[\boldsymbol{x^T Q_1 x} + \boldsymbol{u^T Q_2 u}] \tag{1}$$

Where, **x** represents the process states, **u** the input variables, and **Q** the weighting matrices used to fine tune the optimisation.

As an enhancement, a state estimator provided states that were not subjected to process delay, thereby allowing the LQR controller to respond to disturbances before an error was seen in the CVs. Additionally, feedback gains for the two main disturbance states (W_F and F_F) were increased.

4. Simulation results and conclusions

Each one of the controllers discussed was designed, tuned and implemented on the local FFE model. Process and measurement noise were added throughout the simulations to check robustness.

The controllers will be evaluated for adequate disturbance rejection, i.e. test whether a step disturbance in W_F (0.01 DMF increase) can be suppressed in W_P (less than a 0.01 DMF increase). This test was proposed by Winchester (1999) and used by Bakker (2004).

4.1. Controller tuning

Special focus will be given to cascade and fuzzy tuning results, as the LQR and PI tuning methods have already been discussed by Haasbroek (2013).

Cascade controller

Two cascade structures were investigated. The first (Cas_{PI}), had PI controllers for the inner and outer loops, while the second (Cas_P) had an outer PI and inner P controller setup. Each controller was tuned using IMC. The difference in W_P

response to a +0.01 DMF W_F step for both cascade controllers is shown in Figure 5 below:

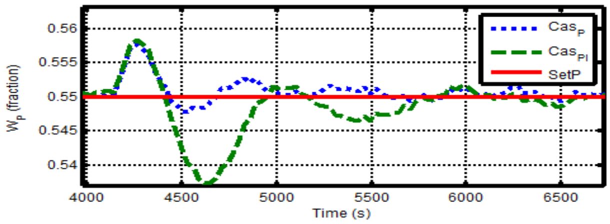


Figure 5: Cascade structure comparison

Both controllers limit the initial deviation in W_P to the same extent, yet Cas_{PI} has an additional downward deviation not seen for Cas_P. This second deviation is due to the integral action on W_{P1}, which introduces a W_P error when zero offset is sought for W_{P1}. As W_{P1} is of little interest to the product (as long as the required W_P specifications are met) the inner loop integral action is not necessary.

Fuzzy predictive controller

As with the cascade control, two fuzzy controller structures were tested. The first, Fuz_{PI}, implemented only the E and ΔE rules shown in Section 2, while the second, Fuz_{Pred}, also included the predictive rules seen in the same section. A comparison between the fuzzy structures and a PI controller for the same W_F step disturbance is shown below:

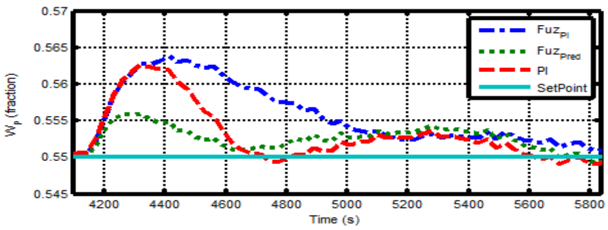


Figure 6: Fuzzy disturbance rejection comparison

Note that, the Fuz_{PI} and PI controller have very similar responses, while Fuz_{Pred} greatly reduces the maximum W_P deviation by estimating a mitigating P_S change as soon as a W_F disturbance is detected. The reduced W_P deviation shows how effective predictive action can be for processes with large dead times.

4.2. Controller comparison

Once all the controllers were designed and fine tuned, an overall disturbance rejection comparison was performed. In the first simulation, a +0.01 W_F step was introduced at 4 000s:

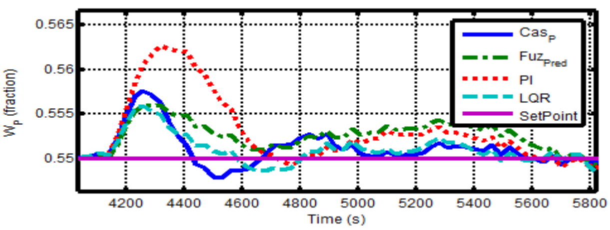


Figure 7: Controller W_F disturbance rejection

Figure 7 shows that the PI controller has the largest W_P deviation, at ±0.012 DMF, while the LQR and Fuz_{Pred} controllers show the smallest W_P deviation, at 0.006 DMF. Although the Cas_P controller was not specifically tuned for a W_F disturbance, it achieves deviation suppression close to that of the LQR controller, while these two controllers also showed the shortest settling time at ±1 000s.

As the LQR and Fuz_{Pred} controllers were enhanced for W_F and F_F disturbances, a feed disturbance (T_H) of 5°C was also introduced to test the controllers on unidentified disturbances:

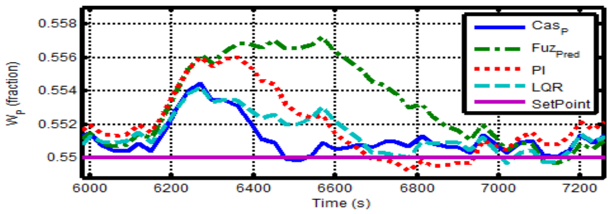


Figure 8: Controller T_H disturbance rejection comparison

From Figure 8 it is clear that the Fuz_{Pred} controller degrades quickly for unknown disturbances, with even PI control showing less pronounced deviations. Cas_P and LQR controllers offer similar maximum W_P deviations, yet Cas_P returns to the desired set point 200s before LQR.

Disturbance rejection conclusions

From Figure 7 it can be seen that only the PI controller does not offer adequate W_F disturbance rejection. Figure 8, however, shows the strength of the cascade controller. It effectively rejects any disturbance that acts on W_{P1} and W_{P2}, while both LQR and Fuz_{Pred} controllers require additional rules or tuning.

4.3. Operator comparison

Historical data were used to compare the controller performance to current operator control of W_P and T_{E1}. The first simulation included W_F, T_H, and F_F disturbance data as well as the manipulated variables inputs. Note that T_{E1} trends were also included for more in-depth comparisons:

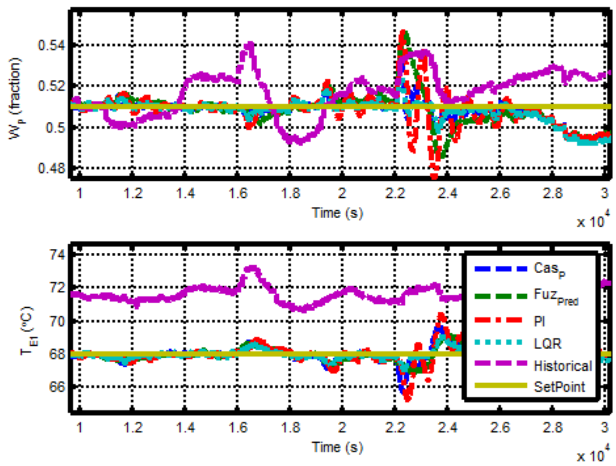


Figure 9: Comparison of operator control to control methods introduced in this work

Figure 9 shows that the controllers perform better than operator based control during the time period 10 000s to 20 000s; yet also show frequent deviations thereafter. The latter poor performance could mainly be attributed to incorrect F_F changes made by the operators. One solution would be to keep F_F constant, as done by Haasbroek et al. (2013), but this would result in sub-optimal FFE operation. The FFO can, however, also improve set point tracking dramatically:

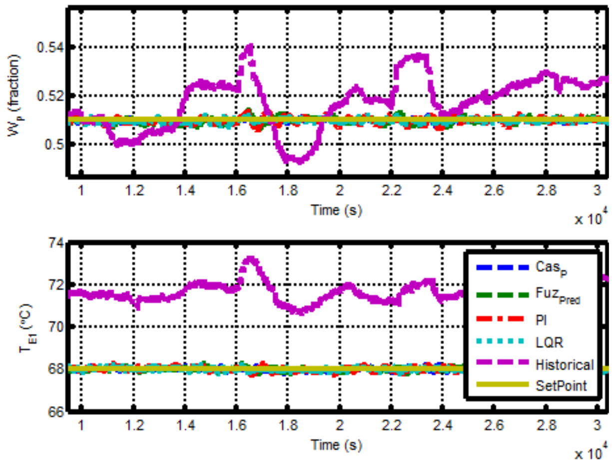


Figure 10: Comparison of operator control to control methods introduced in this work, including FFO

Note that both W_P and T_{E1} trends are kept on the respective set points, while T_{E1} is also kept below 70°C which will greatly reduce fouling inside the FFE.

5. CONCLUSIONS

Various studies in literature have developed controllers for dairy FFEs. There has, however, not been a comprehensive comparison between the most used methods on a single model, thereby making direct performance comparisons difficult. This study applied the model developed and validated by (Haasbroek et al., 2013) to compare controllers developed in accordance with theory from various authors (Bakker et al., 2004) (Karimi et al., 2006) (Winchester & Marsh, 1999) (van Wicjk et al., 1999).

Disturbance rejection was tested by introducing a W_F step and then comparing the W_P increase as percentage ($\Delta W_P/\Delta W_F$x100). It was found, as shown in figure 7, that linear quadratic (LQR) control 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.

In addition, the operator comparisons performed in the previous section clearly show that modern day FFE operation may draw large benefits from automatic control. If one also takes into account the disturbance rejection tests, the cascade controller yields the best performance to development effort ratio. This conclusion was only possible by comparing all the controller methods on a single FFE model.

6. Bibliography

Bakker, H.H.C., Marsh, C., Paramalingam, S. & Chen, H., 2004. Cascade controller design for concentration control in a falling-film evaporator. *Food control*, (17), pp.325-30.

Cunnigham, P. et al., 2006. System identification of a falling film evaporator in the dairy industry. Glasgow, 2006. University of Strathclyde Publishing.

Foley, M., 2011. *The Application of Fuzzy Logic in Determining Linguistic Rules and Associative Membership Functions for the Control of a Manufacturing Process*. Dublin: Dublin Institute of Technology.

Haasbroek, A., 2013. *Advanced control with semi-empirical and data based modelling for falling film evaporators*. M.Sc Thesis. Stellenbosch University.

Haasbroek, A., Auret, L. & Steyn, W.H., 2013. Advanced control with fundamental and data based modelling for falling film evaporators. In *IEEE International conference on industrial technology*. Cape Town, 2013.

Karimi, M., Jahanmiri, A. & Azarmi, M., 2006. Inferential cascade control of multi-effect falling-film evaporator. *Food Control*, 18, pp.1036-42.

Marlin, T.E., 2000. *Process Control: Designing processes and control systems for dynamic performance*. Boston: McGraw Hill.

O'Callaghan, D. & Cunningham, P., 2005. Modern process control techniques in the production of dried milk products - a review. *Lait*, (85), pp.335-42.

Paramalingam, S., 2004. *Modelling, optimisation and control of a falling-film evaporator*. PhD Thesis. Christchurch: Massay University.

Quaak, P. & Gerritsen, J.B.M., 1990. Modelling dynamic behaviour of multiple-effect falling-film evaporators. In *Computer applications in chemical engineering*. Amsterdam, 1990. Elsevier Science Publishers.

Quaak, P., Wijck, v. & van Haren, J., 1994. Comparison of process identification and physical modelling for falling film evaporators. 5(2).

Ramırez, C.A., Patel, M. & Blok, K., 2006. From fluid milk to milk powder: Energy use and energy efficiency in the European dairy industry. *Energy*.

Russel, N.T., Bakker, H.H.C. & Chaplin, R.I., 2000. A comparison of dynamic models for an evaporation process. *IChemE*.

van Wicjk, M., Quaak, P. & van Haren, J., 1999. Multivariable supervisory control of a four effect falling-film evaporator. *Food control*, 5.

Winchester, J. & Marsh, C., 1999. Dynamics and control of falling film evaporators with mechanical vapour recompression. In *Proceedings of the American Control Conference*. California, 1999.