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A General Dynamic Model of a Complete Milk Pasteuriser Unit Subject to Fouling

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Abstract

Heat treatment of milk for hygiene and preservation is carried out in energy integrated pasteurisers units which include several plate heat exchangers (PHEs), a holding tube and ancillary piping. Fouling reduces energy efficiency and cleanings generate downtime and wastes. No detailed dynamic models are currently available of full heating-cleaning cycles for an overall unit. Using a first principle modelling approach, a 2D dynamic thermal model, coupled with semi-mechanistic fouling and cleaning in place (CIP) models, is developed for the whole pasteurisation process, and used to test various heating-cleaning cycles. The model generality and flexibility are demonstrated for high temperature short time (HTST) and ultra-high temperature (UHT) treatments. The whole unit thermal model is validated against experimental data for a HTST process, with excellent agreement. Fouling evolution, distribution and impact are assessed for both processes. A UHT heating-cleaning cycle simulation enables quantifying the amounts of cleaning agent and waste water produced. The new model is suitable for control, optimisation of heating and cleaning strategies, and waste reduction studies.

Keywords: food processing, pasteurisation, plate heat exchanger, milk fouling, dynamic modelling.

1. Introduction and background

Heat treatments eliminate pathogenic microorganisms in raw milk for safety and extended shelf life. A typical pasteuriser unit (Figure 1) includes a preheater (regenerator), a main heater, a cooler, using plate heat exchangers (PHEs), as well as a holding tube, and ancillary pipework (Wang, et al., 2007). Fouling leads to economic (e.g. energy use, downtime for cleaning) and environmental problems (e.g. cleaning water and chemicals use, waste treatment). Fouling mitigation treatments (Müller-Steinhagen, et al., 2011), mostly focus on a qualitative analysis. Experimentation is time-consuming and costly, and results are often difficult to extrapolate to other conditions. In spite of much modelling research over many years (e.g. Georgiadis et al. 1998a, 1998b), no current model can comprehensively and accurately (1) capture the main thermal and hydraulic behaviours of fluids within the PHEs; (2) reflect the interactions among different sections of the pasteuriser; (3) predict deposit severity, location and composition during heating and cleaning; (4) optimize the overall operation of a full pasteuriser. Here we present a general model for the whole pasteuriser with all these features, and demonstrate it for high temperature short time (HTST) and ultra-high temperature (UHT) milk treatments. The thermal model of the whole unit is validated vs. experimental data for a HTST process. The evolution and impact of fouling are then assessed for both HTST & UHT.

Finally, a UHT full heating-cleaning cycle simulation calculates the amount of cleaning agent and rinsing water required, as well as the cleaning time needed and cycle time.

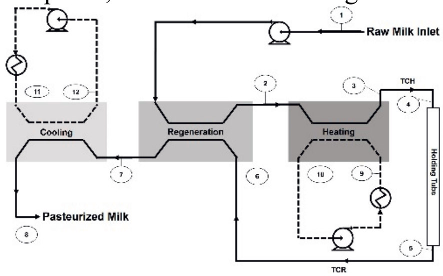

Figure 1. Schematic diagram of a pasteuriser unit (reproduced from Gutierrez et al *(2014)*).

2. Pasteurisation system modelling

The structure of the overall pasteuriser model and sub-models involved (Figure 2) includes heating, regeneration and cooling PHEs, a non-isothermal holding tube and two non-isothermal tubular connections (TCH & TCR). Initial conditions, equipment data and configurations are specified in the main unit model, and passed to the section models for PHEs and tubes, enabling continuity of fluid and temperature among sections. The thermal model in each section (PHE or tube) is coupled with fouling and CIP models.

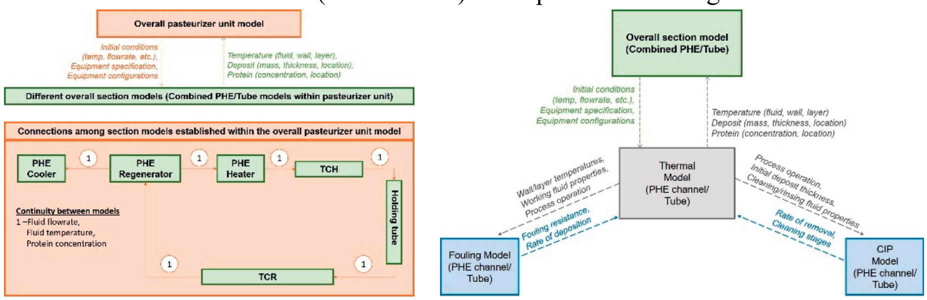

Figure 2. Overall model of the pasteuriser (left) and model components in each section (right).

The PHE dynamic model is modified from those proposed by (Guan & Macchietto, 2018) for single channel and (Sharma & Macchietto, 2019a). Here, each internal PHE channel is delimited by the two side half-plates, the end channels by a half (internal) plate and a full (end) plate. Any desired PHE arrangement is then assembled as a collection of individual channels (Figure 3), using a hierarchal model building design which sets the appropriate boundary conditions. For the two end plates, adiabatic condition is assumed. All models are implemented in gPROMS (PSE, 2018). The holding tube "holds" the heated milk at a desired temperature for a specified time. For skimmed milk, the requirement is to hold milk for at least 15 seconds at or above 72 °C in a HTST process, and for 2 to 5 seconds at 135-140°C in a UHT process (FDA, 2018). The thermo-hydraulic tube model used, adapted from (Diaz-Bejarano, et al., 2016) consists of working fluid, deposit layer, and tube wall domains connected via suitable boundary conditions. Previous holding tube models in milk pasteurisation either assumed isothermal condition or a constant temperature drop based on experimental data (Grijspeerdt, et al., 2004) (Aguiar & Gut, 2014) (Gutierrez, et al., 2014). Here, non-isothermal condition was used, with an average external heat flux determined from experimental data, assuming convective heat transfer to air around uninsulated holding tube and tubular connections. Reaction mechanisms in milk fouling were discussed in Sharma and Macchietto (2019b).

For HTST processes, protein fouling (type A) is the dominant fouling type; while for UHT process, both protein and mineral fouling (type B) are known to occur in different temperature ranges (Khaldi et al., 2015). Only type A fouling was used, so the calculated

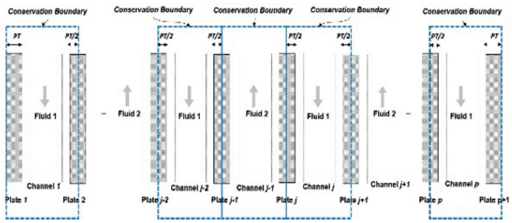

Figure 3. Schematic illustration for PHE channel modelling.

deposit mass is expected to be lower than the experimental one in UHT process. The fouling model of Georgiadis and Macchietto (2000), Sharma and Macchietto (2019a) was adopted with minor modifications. Two β-lg reaction schemes are considered: fouling due to (1) aggregated protein (Dep_A) and (2) unfolded protein (Dep_U) deposition (Figure 4). Here, N, U and A represent the native, unfolded and aggregated β-lg protein, respectively. Reactions of $N \rightarrow U$ and $U \rightarrow A$ occur in both bulk fluid as well as the thermal boundary layer. Fouling can occur anywhere in the pasteuriser unit and its severity is temperature dependent. The fouling model is coupled with the thermal model of both PHE channel and tube (Figure 2). In the combined models, all equations in the thermal and fouling models are solved simultaneously, using a standard DAE solver in gPROMS (PSE, 2018).

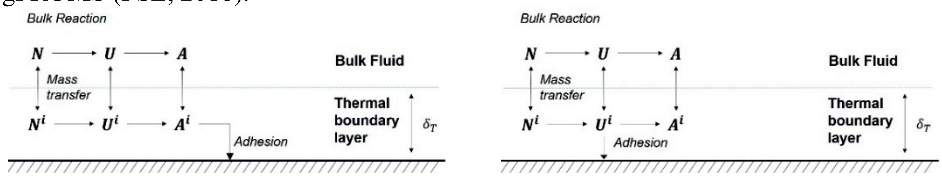

Figure 4. β-lg reaction schemes with fouling due to aggregated protein (Dep_A) and unfolded protein (Dep_u) (adapted from Georgiadis and Macchietto (2000)).

3. Validation of full pasteurisation unit model

A well-documented steady state experimental case for a HTST process was simulated (Gut and Pinto, 2004; Gutierrez, Diniz and Gut, 2014). The heating, regeneration and cooling PHEs consists of 12, 20 and 8 channels, respectively, each with a single-inlet-multiple-pass configuration. Details of experimental apparatus and experimental conditions, at steady-state, for a thermal test with water as both heating/cooling and process fluid are given in the references. The water physical properties, assumed constant within each section at average conditions, estimated from correlations based on the NIST database (Linstrom and Mallard, no date) are detailed in Zhu, 2019. The average external heat flux in the tubes was estimated to be 467 W/m^2 (Zhu, 2019). The key experimental and calculated temperatures in the entire pasteuriser (Figure 5 left.) show excellent agreement. The simulated temperature profiles of the working fluid in different PHE channels within the heating section (Figure 5 right) are very plausible, although no experimental data were available. This validation test confirms that the thermal model of the whole integrated pasteuriser unit matches well the experimental results.

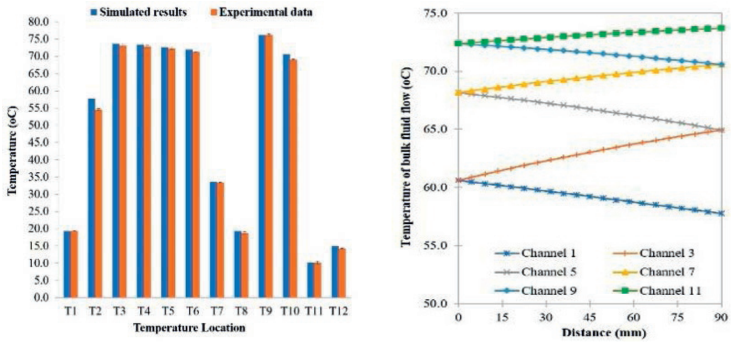

Figure 5. Thermal model validation: Key calculated and experimental temperatures - Exp. Data from Aguiar and Gut *(2014)* – left. Temperature profiles of the working fluid (water) within the heating section - right.

4. Operation and cleaning cycles - full pasteurisation unit

A fouling simulation for the HTST process, with the same experimental conditions used for thermal model validation, shows that fouling is not significant for the first 2.1 days. As a result, a heating-cleaning cycle of the complete pasteuriser unit was studied for the UHT process. As no experimental data on configuration or measured performance of a unit was available in literature, a realistic case was defined based on a typical UHT process (Tetra-Pak, 2015) (FDA, 2018). The PHE plate geometry is adopted from Georgiadis and Macchietto (2000). The heating, regeneration and cooling PHEs, all of single-inlet-multiple-pass configuration, have 12, 8 and 12 channels. The holding, TCH and TCR tubes have lengths of 1.0, 0.42, 1.06 m, internal diameter 40, 30, 30 mm and outer diameter 44, 33 and 33 mm, respectively. Milk, heating water and cooling water enter at 4, 140 and 4 °C. The milk physical properties (Fernández-Martín, 1972; Kessler, 2002; Minim et al., 2002) are detailed in Zhu, 2019. The Dep_U fouling mechanism was used, with $\beta = 15.1$, as estimated for the PHE heating section in previous studies (Zhu, 2019).

The two-stage CIP model of Bird and Fryer (1992), detailed in Sharma and Macchietto (2019b), is used for cleaning, however applied to the whole system, in a CIP procedure with Heating, cleaning and rinsing phases (Figure 6). Heating is terminated when the total deposit mass in any of the sections reaches a certain critical mass. A 3 minutes Rinsing phase follows, where it is assumed that no heat transfer and deposit removal occur. The Cleaning phase then starts, using the above cleaning model. Process-side fluid properties are switched from milk to cleaning solution in both the thermal and fouling models, the latter causing deposit removal. The Cleaning phase stops when the mass left on each plate in any PHE is less than 0.1 g., followed by a final Rinsing phase. Multiple fouling-cleaning cycles can be implemented back to back using this model.

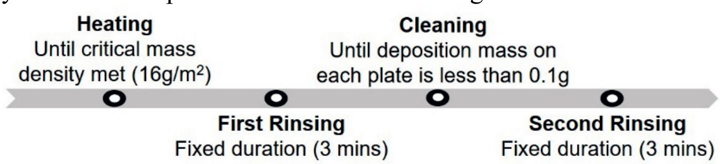

Figure 6. Heating-CIP operation cycle.

The predicted deposit mass over time in the heating PHE and the holding tube are shown in Figure 7. Relative to HTST, much more severe fouling is found in the main PHE heater for the UHT process. The switch from heating to first Rising is triggered by the deposit mass in the main heating PHE. No significant deposit is observed in most of the regeneration PHE channels, although there is deposit in some of them, and the cooling PHE. For numerical reasons, a small initial deposit thickness (1.0E-7 m) was applied to all tubes, while zero initial deposit thickness was set for PHEs. This explains the rapid initial jump of the deposition mass in the holding tube. Cleaning starts before significant drop in the exit milk temperature of the main PHE heater occurs. Considering the overall interactions between the sections of the pasteuriser unit, fouling effects in one section have limited impact on the overall processing temperature. This suggests that a less stringent global stopping criteria could be used for heating phase termination. With the cleaning lasting about 30 minutes, the total cycle time is rather short. The CIP requires 404 Kg of Cleaning fluid (caustic solution) and 85.3kg of wastewater (both circulated at a rate of 0.237 Kg/s).

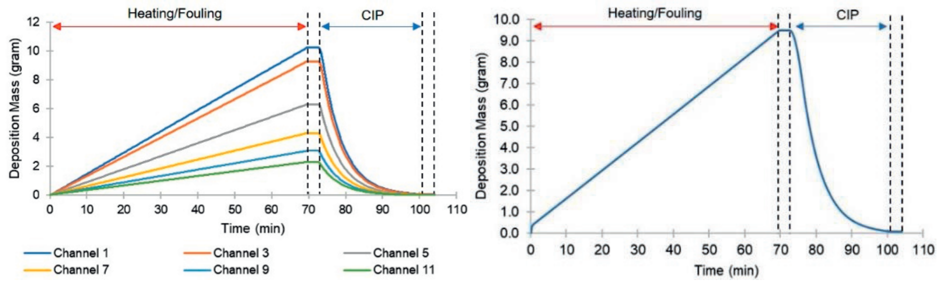

Figure 7. UHT Pasteuriser - Deposit mass during Heating-CIP cycle in the heating PHE (left) and holding tube (right).

5. Conclusions and perspectives

This work extended to a full pasteuriser the 2D distributed model developed by Guan & Macchietto (2018) and Sharma & Macchietto (2019) respectively for a single PHE channel and a PHE. This model is general, modular and versatile. Its predictions have been validated with good agreement against available experimental results. Fouling is considered in all the pasteurisers elements, reflecting configuration and operating conditions. Coupling fouling and cleaning models enables the simulation of heating-cleaning cycles for the whole unit, based on user-defined procedures and phase switching conditions. The model may be used to optimize of the overall operation, considering complex trade-offs between energy for heating, use of cleaning agents and rinsing water for CIP, downtime due to cleaning and cycle length (hence throughput and productivity). It could also be used to optimise continuous and sequential control strategies, and provide diagnostic information. There is scope for further validation of all models, in particular the prediction of local deposit growth/removal and its distribution over time. Only protein fouling was considered here. Further work and validation are also needed to improve the kinetic models, to better link process performance to the inlet milk properties.

References

Aguiar, H. F. & Gut, J. A. W., 2014. Continuous HTST pasteurization of liquid foods with plate heat exchangers: Mathematical modeling and experimental validation using a time-temperature integrator. *Journal of Food Engineering,* 123, 78-86.

Bird, M. R. & Fryer, P. J., 1992. An analytical model for cleaning of food process plant. *Food Engineering in a computer climate. ICHEME Symposium Series,* Issue 126, 325–330.

Diaz-Bejarano, E., Coletti, F. & Macchietto, S., 2016. A new dynamic model of crude oil fouling deposits and its application to the simulation of fouling-cleaning cycles. *AIChE Journal,* 62(1), 90-107.
FDA, 2018. *CFR - Code of Federal Regulations Title 21.* https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=1240.61 [Accessed 9 9 2019].
Fernández-Martín, F., 1972. Influence of temperature and composition on some physical properties of milk and milk concentrates. II. Viscosity. *Journal of Dairy Research,* 39(1), 75–82.
Georgiadis, M. C. & Macchietto, S., 2000. Dynamic modelling and simulation of plate heat exchangers under milk fouling. *Chemical Engineering Science,* 55(9), 1605–1619.
Georgiadis, M.C. Rotstein, G.E. Macchietto, S., 1998a. Modelling and simulation of complex plate heat exchanger arrangements under milk fouling. *Computers and Chemical Engineering*, 22 (SUPPL.1), 331-338
Georgiadis, M.C. Rotstein, G.E. Macchietto, S., 1998b. Optimal design and operation of heat exchangers under milk fouling. *AIChE Journal*, 44(9), 2099-2111.
Grijspeerdt, K., Mortier, L., De Block, J. & Van Renterghem, R., 2004. Applications of modelling to optimise ultra high temperature milk heat exchangers with respect to fouling. *Food Control,* 15(2), 117–130.
Guan, S. & Macchietto, S., 2018. A novel dynamic model of Plate Heat Exchangers subject to fouling. Computer-Aided Chemical Engineering Vol. 43 Part B, 1679-1684, Elsevier, Amsterdam.
Gutierrez, C. G. C. C., Diniz, G. N. & Gut, J. A. W., 2014. Dynamic simulation of a plate pasteuriser unit: Mathematical modeling and experimental validation. *J. Food Eng.,* 131, 124-134.
Gut, J. A. W. & Pinto, J. M., 2004. Optimal configuration design for plate heat exchangers. *International Journal of Heat and Mass Transfer,* 47(22), 4833–4848.
Kessler, H. G., 2002. *Food and bio process engineering: dairy technology.* 5th ed. Munich, Germany: Verlag A. Kessler.
Khaldi, M., Blanpain-Avet, P., Guérin, R., Ronse, G., Bouvier, L., André, C., Bornaz, S., Croguennec, T., Jeantet, R., Delaplace, G., 2015. Effect of calcium content and flow regime on whey protein fouling and cleaning in a plate heat exchanger. *J. Food Eng.* 147, 68–78.
Linstrom, W. G. & Mallard, P. J. eds., (no date), *NIST Chemistry WebBook, NIST Standard Reference Database Number 69.* Gaithersburg MD, 20899: National Institute of Standards and Technology.
Minim, L. A., Coimbra, J. S. R., Minim, V. P. R. & Telis-Romero, J., 2002. Influence of Temperature and Water and Fat Contents on the Thermophysical Properties of Milk. *Journal of Chemical & Engineering Data,* 47(6), 1488–1491.
Müller-Steinhagen, H., Malayeri, M. R. & Watkinson, A. P., 2011. Heat exchanger fouling: Mitigation and cleaning strategies. *Heat Transfer Engineering,* 32(3-4), 189–196.
PSE, 2018. *gPROMS,* s.l.: Process System Enterprise Limited.
Sharma, A. & Macchietto, S., 2019a. Fouling and cleaning of Plate Heat Exchangers for Milk Pasteurisation: a moving boundary model. Computer Aided Chemical Engineering 46, Part B, 1483-1488, Elsevier, Amsterdam.
Sharma, A. & Macchietto, S., 2019b. Fouling and cleaning of Plate Heat Exchangers for Milk Pasteurisation: Dairy Application. Heat Exchangers Foulingand Cleaning – XIII, Warsaw, Poland, 2-7 June 2019.
Tetra-Pak, 2015. *Dairy Processing Handbook.* [Online].
Wang, L., Sundén, B. & Manglik, R., 2007. *Plate heat exchangers : design, applications and performance.* s.l.:WIT Press.
Zhu, M., 2019. *A general dynamic model of a complete milk pasteuriser unit subject to fouling,* Imperial College London.