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# A FOULING PREDICTIVE MODEL-BASED SOLUTION FOR SUSTAINABLE DAIRY HEAT TREATMENT AND CLEANING-IN-PLACE (CIP) PROCESSES

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## ABSTRACT

The heat treatment process and cleaning-in-place (CIP) in liquid dairy manufacturing, consume significant amounts of energy. In an effort to reduce the environmental impact of both of these processes, a fouling predictive model has been developed and used to identify the most sustainable operating conditions. The fouling layer growth and removal predictive model was developed using kinetic models from the literature to simulate fouling behaviour during both processes. Recorded data from a pilot-scale heat treatment unit were used to evaluate an unknown proportionality constant of the fouling predictive model. The model offered representative results for industrial processing conditions. When aiming to investigate more sustainable operating conditions, hygienic-associated risks must be taken into consideration. Therefore, the model also assesses the risk of ineffective cleaning at the end of processing by performing uncertainty analysis. Results demonstrate opportunities for 8.7% carbon emission reduction versus conventional processing conditions with a ~2% risk of ineffective cleaning. The degree of risk acceptability is to be defined by the decision maker.

## INTRODUCTION

On the road towards the net-zero carbon target by 2050, the industrial sector needs to become environmentally sustainable [1]. Research has increasingly focused on practices for process decarbonisation. In fact, substantial savings in energy and resources use can be achieved by adjusting the operating conditions in existing conventional industrial processes. The development of models able to simulate energy and wider resource use consumption in processing, can substantially contribute towards that goal [2].

Milk and other liquid dairy products are in high demand worldwide. As a matter of fact, over 6 billion people worldwide consume dairy products [3], while in 2023, 257.4 billion litres of milk and other dairy drinks were consumed worldwide [4]. Therefore, any improvement in the environmental impact of their manufacturing can have a significant global positive effect [5]. Among the processes undertaken in milk manufacturing, (i.e. reception, heat treatment, cooling, CIP, packaging and cold storing etc.) the heat treatment and CIP processes are the most energy demanding [6–8]. A significant issue that affects the performance of the heat treatment process in liquid dairy processing and its energy consumption is fouling [9]. During heat treatment, dairy components, mainly β-lactoglobulin (β-lg) whey proteins, deposit on the interior surface of the processing equipment and heat exchangers leading to the formation of fouling. Fouling acts as a thermal insulator affecting processes energy consumption while it can impact product quality and equipment longevity. Thus, during processing, heating energy needs to be supplied at an increasing rate to ensure adequate pasteurization. To remove fouling and ensure hygiene, CIP is applied, usually every 8-10 hours of processing [10] which is considerably more frequent when comparing with the oil industry where the cleaning of heat exchangers at least annually. In fact, about 40-50% of energy consumption is attributed to heat treatment, and about 10-25% of energy consumption in milk processing is attributed to the cleaning process [8,11] while the CIP process is highly water intensive, requiring about 0.3 L of water for every L of milk processed, leading to significant amounts of wastewater [12].

To assess the environmental impact of the heat treatment and CIP processes of liquid dairy manufacturing, both processes need to be modelled together due to their interdependence [13,14]. Fouling dynamics need to be taken into account due to their effect on energy consumption during processing and for assessing successful fouling removal after the CIP process. Although the high impact of fouling in dairy liquid processing is well known, there is limited work in the literature that aims to quantify the impact of fouling on heat exchange, energy and water use. Therefore, this study presents a dynamic fouling predictive model

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for the heat treatment and CIP processes, that is used to assess their environmental performance under a range of CIP operating conditions. The model was programmed in MATLAB and regression and ordinary differential equations (ODE) solver MATLAB embedded functions were used.

## MATERIALS AND METHODS

The fouling and cleaning of a plate heat exchanger (PHE) during liquid dairy processing were modelled following a mechanistic approach. Specifically, a thermal model for the PHE has been combined with a fouling predictive model for fouling growth during processing and removal during cleaning. The benefit of following a mechanistic modelling approach is that it offers simulation flexibility under a range of processing conditions [15].

The fouling predictive model for the processing stage applied in this study, is based on the one presented by Alhuthali et al. (2022) [16] using the fouling kinetic model developed by De Jong (1996) [9] which capture the dynamics of unfolding, aggregation and deposition of beta-lactoglobulin, the main protein in milk that triggers fouling formation. The unknown proportionality constant of the fouling predictive model by Alhuthali et al. (2022) [16] which represents operational, and equipment characteristics of the heat exchange system modelled, was determined using recorded data from a pilot-scale processing unit for high temperature short time (HTST) treatment offering representative results under industrial processing conditions. Specifically, the trials used for parameter estimation had a product flow rate of 125 L/h, and applied an 85℃ heat treatment temperature to the product, while the total processing time was 5 hours.

To model fouling dynamics during the CIP stage, a fouling predictive model from the literature for fouling removal was applied. The fouling removal model used was the one developed by Bird and Fryer (1991) [17] presented in [18]. The model can predict the fouling removal dynamics and assess the cleaning performance at the end of the CIP process. The fouling removal model was developed using the experimental data developed in the thesis of Bird (1993) [19]. In their experiments they used an alkali-solution wash (1% w/v NaOH) at different temperatures, and shear conditions to remove uniform proteinaceous milk deposits [19]. The model takes as input the fouling layer thickness after processing, and considers two stages for cleaning; the swelling of fouling due to chemical reaction with the alkali solution, and the fouling removal due to shear.

For each simulated operating condition for heat treatment and CIP, the energy consumption, water use, and carbon emissions were evaluated per L of product processed. The energy use for heat supply during milk processing has been calculated by evaluating the heating demand during processing with consideration to the additional heat required due to fouling growth, and the heating demand for the CIP process by accounting for the energy required to heat up the cleaning fluids [10]. Then the energy required by the burning fuel is calculated from the estimated heating demand given the efficiencies of the fuel burning engine used. The burning fuel simulated for providing the heating energy was natural gas. This type of fuel was selected since it is the most commonly used fuel in the food industry today. The water consumption was evaluated by accounting for the water demand for the CIP process performed under the respective CIP operating conditions of the simulation [10]. Finally, the carbon emissions due to energy and water use were evaluated given the carbon factor of each resource used.

Processing parameters do not always have a fixed value but might vary around the set value. A small shift in the set processing conditions such as in the processing temperatures, flow rate or product composition, may lead to ineffective fouling removal at the end of the CIP process. Aiming to use the model for investigating operating conditions for improved sustainability for both product processing and CIP, it is important to also assess the associated hygienic risk. If cleaning is ineffective, any remaining fouling within the processing line will accelerate fouling formation in the next running cycle, and this may trigger the formation of biofilm that gives rise to food safety risks [20]. Therefore, uncertainty analysis was performed to calculate the risk of ineffective cleaning at the end of the processing-cleaning cycle. Uncertainty analysis was performed following the Monte-Carlo simulation method [21], where uncertainty is assessed by using random samples from all known distributions of the model parameters, and inputs. These distributions inputs were produced by applying a 5-10% variability in the model input parameters that have and important impact on fouling formation. These were the process operational conditions (i.e. inlet and outlet temperatures and flow rates) and the product composition (i.e. concentration of β-lg protein). The risk of ineffective cleaning was calculated by running 5,000 Monte Carlo. simulations and identifying the number of cases where cleaning was ineffective. The number of simulations was chosen accordingly to provide a sufficient number of significant figures in the evaluated risk for the purpose of the study.

## RESULTS AND DISCUSSION

From the fouling predictive model, the evaluated fouling layer thickness was estimated to be 30.9 μm after 5 hours of processing at 85℃.Given, this estimation, the model was used to evaluate the performance of more sustainable operating conditions by exploring a range of CIP cycles of reduce cleaning time and temperature for the alkali detergent wash step compared to the conventional ones (30 min, 75℃ [10]). . Model simulations were undertaken to evaluate the carbon emissions from energy and water use per L of liquid dairy product processed, for the heat treatment and CIP processes. Specifically, as presented in the heatmap of Figure 1 the carbon footprint per L of product was evaluated under a range of cleaning medium temperatures and durations of the alkali wash step of the CIP process [10].

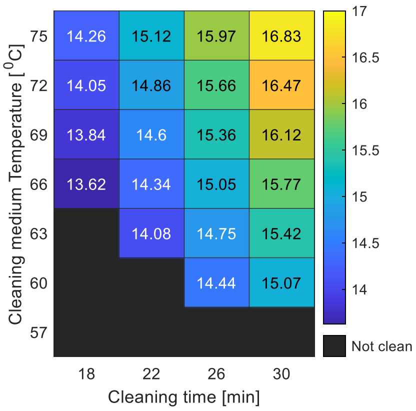

Fig. 1. Heatmap representation, showing the evaluated carbon emissions per L of product processed under a range of different cleaning time durations and cleaning medium temperatures. The black cells indicate operating conditions where cleaning was considered ineffective at the end of the CIP process and therefore, they cannot be considered as potential operating conditions.

From Figure 1 it can be observed that from the conventional operating conditions for the CIP cycle (where in the CIP program, the alkali solution wash at 75 ℃ is applied for 30 minutes [10]), if the cleaning medium temperature is reduced by 9 ℃ and the cleaning time is reduced by 12 minutes, this can lead to 19.1% carbon emissions reductions per unit of product processed.

The respective evaluated risk of ineffective cleaning for each of the simulated operational conditions is provided in Figure 2. As we move towards the ineffective cleaning zone, the risk of ineffective cleaning increases.

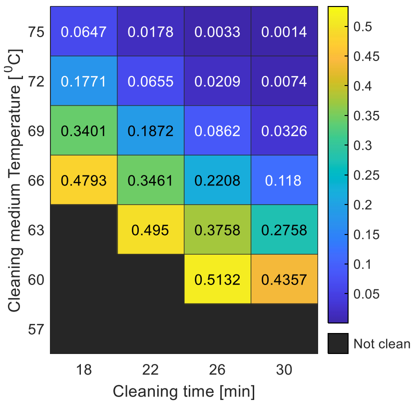

Fig. 2. Heatmap representation, showing the evaluated Risk of ineffective cleaning under a range of different cleaning time durations and cleaning medium temperatures.

As can be seen from both Figure 1 and Figure 2 the least carbon emitting operating conditions for cleaning lead to a significant risk of ineffective cleaning up to ~50%. However, selecting slightly more carbon intensive operating conditions, e.g. 26 minutes of cleaning with a temperature of 72℃ for the cleaning medium, still leads to significant energy savings of 8.7%, but the associated risk of ineffective cleaning could potentially be at a more acceptable range (~2%). At this point, given the evaluated risk of ineffective cleaning and the energy savings that can be achieved, it is upon the client as the decision maker to decide which processing conditions they will apply following the guidelines for that industry and country regulations. It is important to note that upon any decisions undertaken product quality and safety is a priority.

## CONCLUSION

The developed fouling and cleaning model was able to predict the dynamic behavior of fouling and evaluate the carbon emissions due to energy and water use, for the fouling-cleaning cycle under a range of CIP operating conditions. According to model outputs, moving from conventional, to more sustainable processing conditions can save up to 19% of the energy use and carbon emissions in processing and cleaning. However, selecting optimal processing conditions (as determined by the model) may pose a risk of ineffective cleaning due to uncertainty under real operating conditions. The ability to evaluate the risk of ineffective cleaning can help the decision maker to choose the best processing conditions that will lead to energy and water savings, while keeping the risk to an acceptable level.

The uniqueness of this work lies in its ability to merge models for fouling, heat exchange, and cleaning into a simplistic and computationally efficient model. Using a limited amount of data, the hybrid model can effectively capture the underlying mechanics while also providing results that represent a real heat treatment system. Future work suggest the use of industrial scale data, and longer processing runs, as well as to perform model validation, and assessment of feasibility of the more sustainable operating conditions as indicated by the model. In addition, a similar approach can be followed to model other dairy and food processes following the same methodology and model integration approach. The developed model has the potential to improve sustainability in dairy and other liquid product's processing, and at the same time prevent any risk related to ineffective cleaning.

## REFERENCES

[1] C.G.F. Bataille, Physical and policy pathways to net-zero emissions industry, WIREs Climate Change 11 (2020) e633. https://doi.org/10.1002/wcc.633.

[2] M.I. Malliaroudaki, N.J. Watson, R. Ferrari, L.N. Nchari, R.L. Gomes, Energy management for a net zero dairy supply chain under climate change, Trends in Food Science & Technology 126 (2022) 153–167. https://doi.org/10.1016/j.tifs.2022.01.015.

[3] Dairy production and products: Products, (2023). https://www.fao.org/dairy-production-products/products/en/ (accessed April 25, 2023).

[4] Global packed beverages consumption by type 2023, Statista (n.d.). https://www.statista.com/statistics/232924/global-consumption-of-packed-beverages-by-beverage-tpye/ (accessed August 8, 2024).

[5] FAO & GDP, Climate change and the global dairy cattle sector – The role of the dairy sector in a low-carbon future, Rome, 2018.

[6] M. Compton, S. Willis, B. Rezaie, K. Humes, Food processing industry energy and water consumption in the Pacific northwest, Innovative Food Science & Emerging Technologies 47 (2018) 371–383. https://doi.org/10.1016/j.ifset.2018.04.001.

[7] S.J. Rad, M.J. Lewis, Water utilisation, energy utilisation and waste water management in the dairy industry: A review, International Journal of Dairy Technology 67 (2014) 1–20. https://doi.org/10.1111/1471-0307.12096.

[8] M.I. Malliaroudaki, N.J. Watson, Z.J. Glover, L.N. Nchari, R.L. Gomes, Net zero roadmap modelling for sustainable dairy manufacturing and distribution, Chemical Engineering Journal (2023) 145734. https://doi.org/10.1016/j.cej.2023.145734.

[9] P. De Jong, Modelling and Optimization of Thermal Processes in the Dairy Industry, TU Delft, 1996.

[10] G. Bylund, Dairy Processing Handbook, Dairy Processing Handbook (1995). https://dairyprocessinghandbook.tetrapak.com/ (accessed April 5, 2023).

[11] C.A. Ramírez, M. Patel, K. Blok, From fluid milk to milk powder: Energy use and energy efficiency in the European dairy industry, Energy 31 (2006) 1984–2004. https://doi.org/10.1016/j.energy.2005.10.014.

[12] P.M. Tomasula, N. Datta, W.C. Yee, A.J. McAloon, D.W. Nutter, F. Sampedro, L.M. Bonnaillie, Computer simulation of energy use, greenhouse gas emissions, and costs for alternative methods of processing fluid milk, Journal of Dairy Science (2014). https://www.journalofdairyscience.org/article/S0022-0302(14)00317-8/fulltext (accessed April 5, 2023).

[13] A. Jäsberg, T. Turpeinen, A. Tanaka, A. Ketola, M. Järvinen, U. Ojaniemi, T. Pättikangas, A.I. Koponen, Fouling Dynamics of Simulated Milk Ultrafiltrate on a Plate Heat Exchanger, Heat Transfer Engineering 43 (2022) 1387–1395. https://doi.org/10.1080/01457632.2021.1963550.

[14] A. Sharma, S. Macchietto, Fouling and cleaning of plate heat exchangers: Dairy application, Food and Bioproducts Processing 126 (2021) 32–41. https://doi.org/10.1016/j.fbp.2020.12.005.

[15] D. Solle, B. Hitzmann, C. Herwig, M. Pereira Remelhe, S. Ulonska, L. Wuerth, A. Prata, T. Steckenreiter, Between the Poles of Data-Driven and Mechanistic Modeling for Process Operation, Chemie Ingenieur Technik 89 (2017) 542–561. https://doi.org/10.1002/cite.201600175.

[16] S. Alhuthali, G. Delaplace, S. Macchietto, L. Bouvier, Whey protein fouling prediction in plate heat exchanger by combining dynamic modelling, dimensional analysis, and symbolic regression, Food and Bioproducts Processing 134 (2022) 163–180. https://doi.org/10.1016/j.fbp.2022.05.009.

[17] M. Bird, P.J. Fryer, Experimental study of the cleaning of surfaces fouled by whey proteins, Food and Bioproducts Processing 69 (1991) 13–21.

[18] K.R. Davey, S. Chandrakash, B.K. O'Neill, A new risk analysis of Clean-In-Place milk processing, Food Control 29 (2013) 248–253. https://doi.org/10.1016/j.foodcont.2012.06.014.

[19] M.R. Bird, Cleaning of food process plant., Thesis, University of Cambridge, 1993. https://doi.org/10/251541.

[20] K.R. Goode, K. Asteriadou, P.T. Robbins, P.J. Fryer, Fouling and Cleaning Studies in the Food and Beverage Industry Classified by Cleaning Type, Comprehensive Reviews in Food Science and Food Safety 12 (2013) 121–143. https://doi.org/10.1111/1541-4337.12000.

[21] S. Bhonsale, D. Telen, B. Stokbroekx, J. Van Impe, An Analysis of Uncertainty Propagation Methods Applied to Breakage Population Balance, Processes 6 (2018) 255. https://doi.org/10.3390/pr6120255.