Supplementary Material

Net zero roadmap modelling for sustainable dairy manufacturing and distribution

Authors: Maria Ioanna Malliaroudaki[1], Nicholas J. Watson[1], Zachary J. Glover[2], Luanga N. Nchari[3], Rachel Louise Gomes[1]

[1] Food Water Waste Research Group, Faculty of Engineering, University of Nottingham, Nottingham, NG7 2RD, UK

[2]Arla Foods Ltd, Arla House, Leeds, LS10 1AB, UK

[3] NIZO, Kernhemseweg 2, Ede, 6718 ZB, The Netherlands

A: Material properties estimation models

Table A.1 Empirical models for the estimation of density, dynamic viscosity and specific heat capacity for milk, skimmed milk, and cream. The composition of whole milk, skimmed milk and cream were obtained from (Bandler, 2021).

	Milk/ Skimmed milk/ Cream properties	**Reference**
Density (ρ) **model**	$$\rho = 1003.073 - 0.179T - 0.368\,F\% + 3.79(C\% + A\%) \quad \left[\frac{kg}{m^3}\right]$$ T: Temperature in °C $F\%$: w/w% fat content $C\%$: w/w% carbohydrate content $A\%$: w/w% ash content	[1]
Viscosity (μ) **model**	For temperatures between 0-30 °C : $$\ln(\mu) = \left(\frac{2721.5}{273.15 + T}\right) + 0.1\,F\% - 8.9 \quad [\frac{kg}{ms}]$$ For Temperatures between 40-80 °C: $$\log(\mu) = \left(1.2876 + \frac{11.07\,T}{10000}\right)\left(\frac{F\%}{100} + \frac{F\%^{\frac{5}{3}}}{100}\right) + 0.7687\left(\frac{1000}{273.15 + T}\right) - 2.437\left[\frac{kg}{ms}\right]$$ T: Temperature in °C $F\%$: w/w% fat content	For temperatures between 0-30 °C [2]. For Temperatures between 40-80 °C [3].

<table>
<tr><td>Specific heat capacity (C_p) model</td><td>

$$C_p = \sum_i \gamma_i \, C_{p_i}$$

Where,

$$C_{p_i} = A_i + B_i \, T + C_i \, T^2 [KJ/kg \; K]$$

T: Temperature in °C

γ_i: content of milk component i (where i is fat, protein, carbohydrate, ash and water).

C_{p_i}: Specific heat capacity of milk component i.

<table>
<tr><th>Coefficient</th><th>Fat</th><th>Protein</th><th>Carbohydrate</th><th>Ash</th><th>Water above freezing point (0-150 ^{0}C)</th></tr>
<tr><td>A_i</td><td>1.9842</td><td>2.0082</td><td>1.5488</td><td>1.0926</td><td>4.1762</td></tr>
<tr><td>B_i</td><td>0.001473</td><td>0.0012089</td><td>0.0019625</td><td>0.0018896</td><td>-9.0864 10^{-5}</td></tr>
<tr><td>C_i</td><td>4.8 10^{-6}</td><td>-1.3129 10^{-6}</td><td>-5.9399 10^{-6}</td><td>-3.6817 10^{-6}</td><td>5.4731 10^{-6}</td></tr>
</table>

</td><td>[4]</td></tr>
</table>

Table A.2 Empirical models for the estimation of density, dynamic viscosity and specific heat capacity of water.

	Water/ chilled water properties	**Reference**
Density (ρ) model	$$\rho = \frac{A + B\,T + C\,T^2 + D\,T^3 + E\,T^4 + F\,T^5}{1 + G\,T}$$	[5]

Constant	value
A	999.83952
B	16.945176
C	-0.00798704
D	-4.61705E-05
E	1.05563E-07
F	-2.80543E-10
G	0.01689785

Viscosity (μ) model	$$\mu = \mu_0 \exp\left[\frac{E}{R(T - \theta)}\right]\left[\frac{kg}{ms}\right]$$	[6]

E	4.7428	$[\frac{kJ}{mol}]$
θ	-139.86	K
μ_0	0.000024152	$[\frac{kg}{ms}]$
R	8.3144626	$[\frac{kJ}{mol}]$

Specific heat capacity (C_p) model	$$C_p = A_i + B_i\,T + C_i\,T^2 [KJ/kg\ K]$$	[4]

		Coefficient	**Water above freezing point (0-150 ^{0}C)**	
		A_i	4.1762	
		B_i	-9.0864 10^{-5}	
		C_i	5.4731 10^{-6}	

Table A.3 Values used for the density and viscosity of steam and empirical model for the estimation the specific heat capacity of steam.

	Steam properties	**Reference**
Density ($\boldsymbol{\rho}$) database	The density of saturated steam at 7 bar is $3.667\ kg/m^3$	[7]
Viscosity ($\boldsymbol{\mu}$) database	The density of saturated steam at 7 bar is $\approx 0.000012\ Pa \cdot s$	[8]
Specific heat capacity ($\boldsymbol{C_p}$) model	$C_{p_i} = A + B\,T + C\,T^2 + D\,T^3 + E\,T^4\ [KJ/kg\ K]$	[9]

Coefficient	**value**
A	1.563077
B	0.001604
C	2.93E-06
D	3.22E-09
E	-1.2E-12

B: Benchmarking values for steam, chilled water, cold water and steam supplies

Table B.1 Coefficient of performance (COP) values of each of the components of the chilled water supply system (Chiller, Cooling tower, Chilled water pump, Condenser water pump) [10].

Device of chilled water system	Coefficient of performance (COP)	Value
Chiller	$\frac{\dot{Q}_{cooling}}{\dot{W}_{compressor}}$	6.9
Cooling tower	$\frac{\dot{Q}_{cooling}}{\dot{W}_{ct}}$	117
Chilled water pump	$\frac{\dot{Q}_{cooling}}{\dot{W}_{chwp}}$	117
Condenser water pump	$\frac{\dot{Q}_{cooling}}{\dot{W}_{cwp}}$	117

Table B.2 Coefficient of performance (COP) and efficiency of the cooling water system [10].

Cooling Tower System	Coefficient of performance (COP) and efficiency	Value
Specific heat rejection rate by cooling tower	$\frac{\dot{Q}_{cooling}}{\dot{W}_{ct}}$	117
Efficiency of cooling tower water pump system	%	72

Table B.3 Boiler system for steam production efficiency rates for natural gas and oil fuel [10], [11].

Fuel type	**Combustion efficiency %**	**Thermal efficiency %**	**Reference**	**Condensate recovery rate %**
Natural gas	0.79	0.79	[10]	80%
Oil fuel	0.81	0.81	[10]	
Hydrogen	0.90-1	0.9	[11]	

Table B.4 Compressed air system electricity needs for different pressure ratios [10].

Pressure ratio	Compressed air system power per normal cubic meter of compressed air (kWh/ Nm^3)
4	0.050 – 0.073
5	0.058 – 0.083
6	0.067 – 0.097
7	0.073 – 0.107
8	0.080 – 0.117
9	0.087 – 0.127
10	0.092 – 0.135
20	0.133 – 0.192

C: Centrifugal Separator model calculations

Here is presented a data-driven model for the calculation of the absolute pressure drop $|\Delta P_{sep}|$ and the centrifugal separator power $\dot{W}_{cent}$ given the inlet volume flow rate $\dot{V}_{sep}$ of the separator, using data presented in the study of Szepessy and Thorwid, (2018) [12]. Specifically, for each set of data, a second order regression curve is fitted to create a simple mathematical relationship for the absolute pressure drop $|\Delta P_{sep}|$ as a function of the inlet flow rate $\dot{V}_{sep}$ (**Figure C.1, Equation C.1**), and for the centrifugal separator power as a function of the inlet flow rate $\dot{V}_{sep}$ (**Figure C.2, Equation C.2**):

$$|\Delta P_{sep}| = 0.0117\, \dot{V}_{sep}^{\ 2} + 1.3468\, \dot{V}_{sep} \tag{C.1}$$

$$\dot{W}_{cent} = 0.0002\, \dot{V}_{sep}^{\ 2} + 0.0233\, \dot{V}_{sep} + 13.132 \tag{C.2}$$

$|\Delta P_{sep}|$ and $\dot{W}_{cent}$ can be applied to **equations C.1** and **C.2** for the calculation of the energy use of the centrifugal separator. Now, the total power needs, $\dot{W}_{tot,sep}$ can be estimated for flow rates up to 200×10^3 L/h using **Equation 16**.

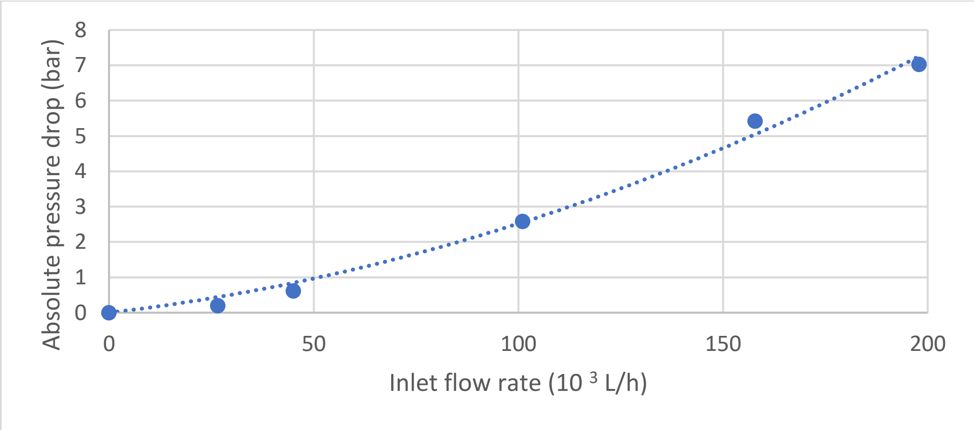

Figure C.1 Second-order regression curves for experimental data of pressure drop $|\Delta P_{sep}|$ as a function of the flow rate $\dot{V}_{sep}$. Data were obtained from the study of Szepessy and Thorwid, (2018) [12].

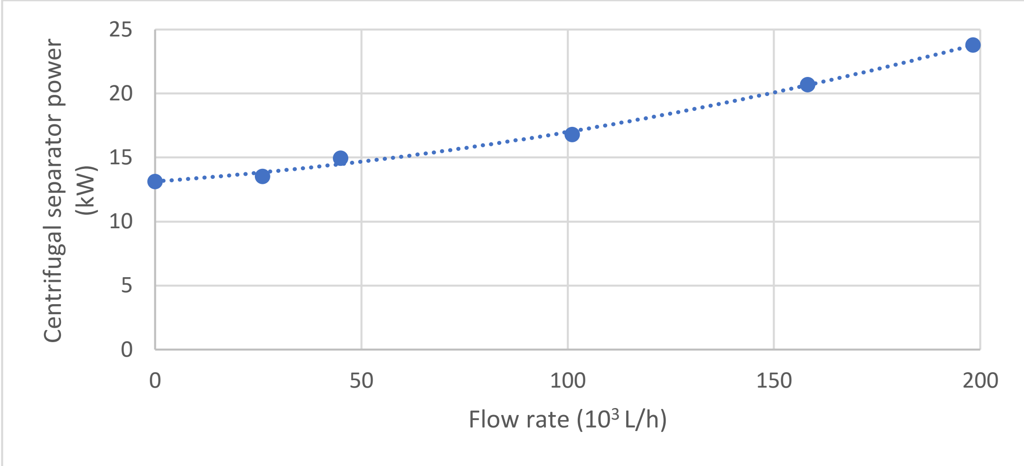

Figure C.2 Second-order regression curves for experimental data of the power needs of the centrifugal separator $\dot{W}_{cent}$ as a function of the flow rate $\dot{V}_{sep}$. Data were obtained from the study of Szepessy and Thorwid, (2018) [12].

References

[1] P. Watson, R. Tittsler, The density of milk at low temperatures. *Journal of dairy science, 44*(3) (1961) 416-424. https://doi.org/10.3168/jds.S0022-0302(61)89758-0.

[2] A. Bakshi, A., D. Smith, Effect of fat content and temperature on viscosity in relation to pumping requirements of fluid milk products. *Journal of dairy science, 67*(6), (1984) 1157-1160. https://doi.org/10.3168/jds.S0022-0302(84)81417-4.

[3] L. Phipps, The interrelationship of the viscosity, fat content and temperature of cream between 40 and 80 C. *Journal of Dairy Research, 36*(3) (1969) 417-426. https://doi.org/10.1017/S0022029900012930.

[4] M.M. Soufiyan, M. Aghbashlo, H. Mobli, Exergetic performance assessment of a long-life milk processing plant: a comprehensive survey. *Journal of Cleaner Production, 140* (2017) 590-607. https://doi.org/10.1016/j.jclepro.2015.11.066.

[5] F.E. Jones, G.L. Harris, ITS-90 density of water formulation for volumetric standards calibration. *Journal of research of the National Institute of Standards and Technology, 97*(3) (1992) 335. https://doi.org/10.6028/jres.097.013.

[6] E. Likhachev, Dependence of Water Viscosity on Temperature and Pressure. *Technical Physics, 48*(4) (2003) 514–515. https://doi.org/10.1134/1.1568496.

[7] Engineering ToolBox, Saturated Steam - Properties for Pressure in Bar. [online] Available at: https://www.engineeringtoolbox.com/saturated-steam-properties-d_457.html, 2003. (accessed 14 June 2021).

[8] Engineering ToolBox, Steam - Viscosity vs. Pressure. [online] Available at: https://www.engineeringtoolbox.com/steam-viscosity-d_770.htm, 2004. (accessed 14 June 2021).

[9] A. Moskalenko, A. Kozhevnikov, Estimation of gas turbine blades cooling efficiency. *Procedia Engineering, 150*(1) (2016) 61-67. https://doi.org/10.1016/j.proeng.2016.06.716.

[10] Lj Energy Pte Ltd, Assessment Framework for Energy Efficiency Benchmarking Study of Food Manufacturing Plants. Singapore: LJ Energy Pte Ltd. https://www.e2singapore.gov.sg/DATA/0/docs/Resources/Industry/FMBS%20Assessment%20Framework%20v1.1.pdf, 2015. (accessed 14 June 2021).

[11] A. Chapman, K. Itaoka, K. Hirose, F. T. Davidson, K. Nagasawa, A. C. Lloyd, ... & Y. Fujii. A review of four case studies assessing the potential for hydrogen penetration of the future energy system. International journal of hydrogen energy, 44(13), (2019) 6371-6382. https://doi.org/10.1016/j.ijhydene.2019.01.168

[12] S. Szepessy, P. Thorwid, Low Energy Consumption of High-Speed Centrifuges. *Chemical engineering & technology, 41*(12) (2018) 2375-2384. https://doi.org/10.1002/ceat.201800292.