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SIMULATION OF WATER EVAPORATION ON ULTIMONITORED THERMOMIX®: POTENTIAL APPROACH FOR STUDIES ON MILK EVAPORATION

Simulação da evaporação da água em Termomix® multi-monitorado: abordagem potencial de estudos sobre evaporação de leite

Rodrigo Stephani[1], Júlia d'Almeida Francisquini[2], Igor Lima de Paula[1], Antônio Fernandes de Carvalho[2], Luiz Fernando Cappa de Oliveira[1], Ítalo Tuler Perrone[3]*

ABSTRACT

It was simulated the industrial evaporation process using a multi-monitored Thermomix®. To validate the hypothesis that this equipment could act as a laboratory-scale evaporator, we evaporated water from milk to produce *dulce de leche*. Using this equipment, we were able to precisely determine mass changes throughout the process, observe the effect of the exhaust system on the evaporation, obtain *dulce de leche* with market composition, and determine the effect of sugar addition on water evaporation. The error between the observed boiling point temperature and that predicted by theory was ~ 2%; as a consequence, the equipment could be used to establish Dühring curves. It was found that the Thermomix® multi-monitored configuration was a simple and inexpensive equipment for simulate evaporation in industrial *dulce de leche* production.

Keywords: laboratory scale; concentration; *dulce de leche*; boiling point.

RESUMO

Foi simulado o processo de evaporação industrial usando um Thermomix® multi-monitorado. Para validar a hipótese de que este equipamento poderia funcionar como um evaporador em escala laboratorial, evaporou-se água do leite para

1 Federal University of Juiz de Fora (UFJF), Department of Chemistry, Juiz de Fora, MG, Brazil.
2 Federal University of Viçosa (UFV), Department of Food Technology, Viçosa, MG, Brazil.
3 Federal University of Juiz de Fora (UFJF), Department of Pharmaceutical Sciences, Juiz de Fora, MG, Brazil. E-mail: italotulerperrone@gmail.com
* Autor para correspondência.

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produzir doce de leite. Usando este equipamento, pôde-se determinar com precisão as mudanças de massa ao longo do processo, observar o efeito do sistema de escape na evaporação, obter o doce de leite com a composição do mercado e determinar o efeito da adição de açúcar na evaporação da água. O erro entre a temperatura do ponto de ebulição observado e o previsto pela teoria foi de ~ 2 %; Como consequência, o equipamento poderia ser usado para estabelecer curvas de Dühring. Descobriu-se que a configuração multi-monitorada Thermomix® foi um meio simples e barato de simular a evaporação na produção industrial de *doce de leite*.

Palavras-chave: escala laboratorial; concentração; doce de leite; ponto de ebulição.

INTRODUCTION

Evaporation of dairy liquids is an important step in the dairy industry. Sweetened condensed milk, *dulce de leche*, evaporated milk, and dairy powder products are the main dairy products obtained by evaporation (SILVEIRA et al., 2013; SILVA et al., 2015; SILVEIRA et al., 2015; SCHUCK et al., 2016).

The energy expenditure is a problem involving this technique due to the removal of water by its phase change. For example, to concentrate atmospheric pressure 1 kg of 10 % sucrose solution to 20 % sucrose requires a total of 1439 kJ eliminating a total of 0.5 kg of water. Therefore, industries explore ways to reduce energy consumption and consequently lower costs.

It is admitted that this operation of concentration induces strong modifications of the physicochemical conditions not only impacting negatively the concentrates but also the process (TANGUY et al., 2016). Upon milk evaporation, lactose crystallization, Maillard reaction and an increase in viscosity are consequences of the heating and the concentration of the solids (SILVA et al., 2015; SOUZA et al., 2015; STEPHANI et al., 2015).

Many studies have concerned flow properties of concentrates, and heat transfer and industrial performance during evaporation of food, but relatively few studies address evaporation of dairy products at laboratory scale (KIM et al., 1983; DODEJA et al., 1990; TEJINDER, 2000; RIBEIRO; ANDRADE, 2003; SILVEIRA et al., 2013; SOROUR et al., 2013; SILVEIRA et al., 2015).

In view of the above, Thermomix, which corresponds to a process simulator, appears as a tool to study the manufacture of dairy products such as *dulce de leche*. This equipment has the advantage of less time of manufacture, besides its ease of handling, with use of smaller amount of ingredients, resulting in less waste. Although it has as a disadvantage the high value and need for thorough washing.

Thermomix is equipment that can be used on a laboratory scale for the purpose of developing new products. By enabling the screening of certain technologies, reducing energy and material costs thus optimizing costs.

The aim of this study was to apply and validate the Thermomix as a laboratory scale evaporator, by optimizing water evaporation and *dulce de leche* production.

MATERIAL AND METHODS

To emulate the industrial evaporation process, we used the Thermomix® TM5 (Vorwerk, Wuppertal, Germany) coupled to a load cell (Ramuza IDR 7.500, Santana de Parnaíba, Brazil) with a precision of 1 g, a PT-100 temperature sensor, and an exhauster (Blower NáuticoSeaflo 3", XIAMEN

HUILIYUAN, Xiamen, China). The process simulator can be visualized in Figure 1.

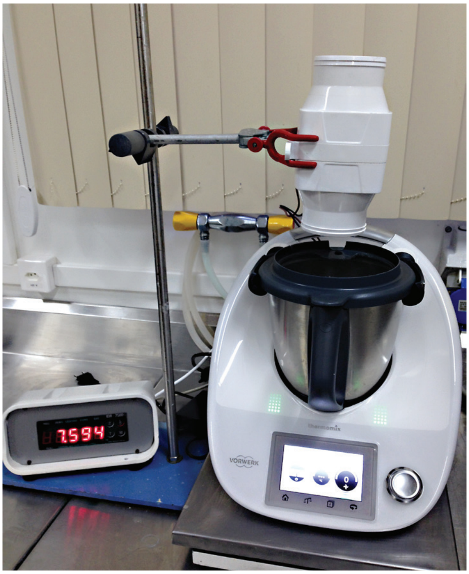

Figure 1 – Process simulator (Thermomix® TM5)

The Sitrad software version 4.13 (Full Gauge Controls, Canoas, Brazil) was used to collect and record data from the load cell and thermometer at 1-s intervals. The supplementary files include a photo of the equipment. To maximize the rate of water evaporation, we analyzed evaporation in light of heating power and the presence or absence of the exhauster. The experimental parameters are described in Table 1.

Table 1 – Design of the experiment for water evaporation (n = 3)

Treatment	Exhaustion ($m^3.h^{-1}$)	Heating control of Thermomix (ºC)
W_{100}	0	100
W_{105}	0	105
W_{110}	0	110
W_{115}	0	115
W_{120}	0	120
W_{varoma}	0	Varoma
W'_{100}	220	100
W'_{105}	220	105
W'_{110}	220	110
W'_{115}	220	115
W'_{120}	220	120
W'_{varoma}	220	Varoma

Note: In all treatments, 900 g of distilled water were evaporated, and the stirrer worked at 100 rotations per minute. Varoma = preset configuration of the Thermomix for maximum heating rate, n = number of repetitions.

Table 2 – Experimental conditions for the dulce de leche productions (n = 3)

Treatment	Exhaustion ($m^3.h^{-1}$)	Dulce de leche formulations		
		Pasteurized milk (g)	Sucrose (g)	Sodium bicarbonate (g)
D_{20}	0	1000	200	1.0
D_{25}	0	1000	250	1.0
D'_{20}	220	1000	200	1.0
D'_{25}	220	1000	250	1.0

Where: D_{20} = formulation with 20% $w.w^{-1}$ of sucrose addition, D_{25} = formulation with 25% $w.w^{-1}$ of sucrose addition, n = number of repetitions.

Aiming to evaluate the Thermomix as an emulator of evaporation in the food industry, we produced *dulce de leche* using two different formulations. Similarly, to maximize the water evaporation rate, the parameters of heating power and the presence or absence of the exhauster were optimized during *dulce de leche* production. The experimental conditions for the *dulce de leche* productions are presented in Table 2. Three repetitions were done for each treatment.

Data were collected according to Figure 2.

The evaluated parameters were: initial boiling temperature, T_i (ºC); final boiling temperature, T_f (ºC); initial time of the evaporation, t_i (min); final time of the evaporation, t_f (min); mass of evaporated water, M_1 (g); mass of total evaporated water, M_2 (min); heating rate, a_h (ºC · min^{-1}); constant evaporation rate, a_e (g · min^{-1}); total evaporation rate, E_r (g · min^{-1}); and air flow rate in the exhauster, V (m^3 · h^{-1}). The total evaporation rate (E_r) can be calculated as

$$E_r = \frac{M_2}{t_f} \qquad \text{(Eq. 1)}$$

where E_r = total evaporation rate (g · min^{-1}), M_2 = mass of total evaporated water (g), and t_f = final time of the evaporation.

It is possible to divide Figure 2 in two zones. The first zone relates to the heating of the product or water until the boiling temperature (heating zone). The second part relates to the water evaporation (evaporation zone), begins at t_i (initial time of the evaporation) and T_i (initial boiling temperature), and ends at t_f (final time of the evaporation) and T_f (final boiling temperature). The amount of evaporated water is represented by the difference between M_2 (mass of total evaporated water) and M_1 (mass of evaporated water).

Dulce de leche composition analysis

Moisture, water activity, fat content, and percentage of soluble solids were measured

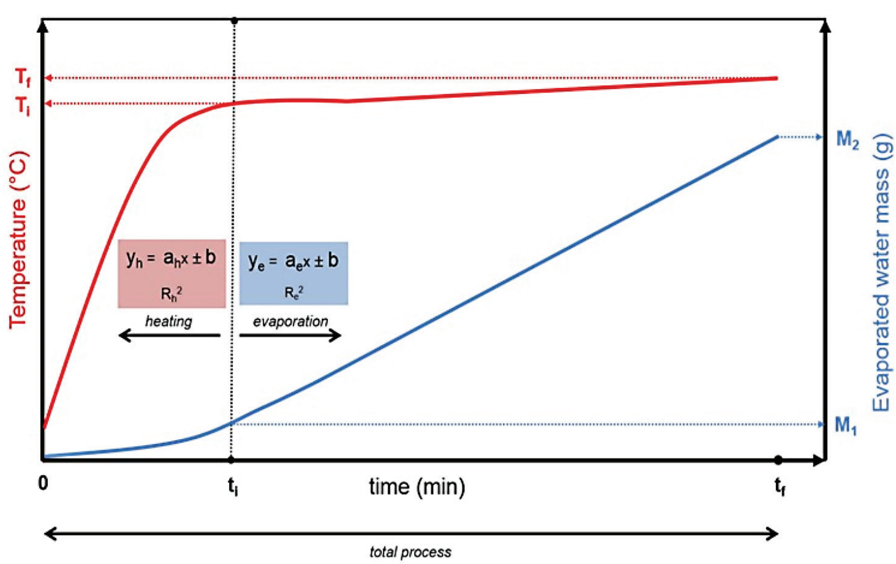

Figure 2 – Collected parameters during evaporation

Table 3 – Results for water evaporation and *dulce de leche* production experiments (n = 3)

T	T_i (°C)	T_f (°C)	t^{-1} (min)	t_f (min)	M_1 (g)	M_2 (g)	a_h[1] (°C.min^{-1})	a_e[2] (g.min^{-1})	E_r (g.min^{-1})	V (m^3.h^{-1})
W_{100}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	8.5 ± 0.0^{a}	137.0 ± 2.6^{a}	17 ± 5^{a}	900 ± 0^{a}	9.5 ± 0.3^{a}	6.6 ± 0.1^{a}	6.6 ± 0.1^{a}	0.0 ± 0.0^{a}
W_{105}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	9.3 ± 0.6^{abc}	99.7 ± 3.8^{c}	26 ± ^{abc}	900 ± 0^{a}	9.3 ± 0.0^{ab}	9.4 ± 0.4^{b}	9.0 ± 0.3^{b}	0.0 ± 0.0^{a}
W_{110}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	8.8 ± 0.3^{abc}	82.3 ± 2.3^{de}	20 ± 2^{ab}	900 ± 0^{a}	9.3 ± 0.0^{ab}	11.8 ± 0.4^{cd}	10.9 ± 0.3^{c}	0.0 ± 0.0^{a}
W_{115}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	8.7 ± 0.3^{ab}	76.3 ± 2.5^{def}	19 ± 2^{a}	900 ± 0^{a}	9.3 ± 0.3^{ab}	12.8 ± 0.5^{de}	11.8 ± 0.4^{cde}	0.0 ± 0.0^{a}
W_{120}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	8.8 ± 0.3^{abc}	77.0 ± 0.0^{def}	19±4^{a}	900 ± 0^{a}	9.5 ± 0.0^{b}	12.6 ± 0.1^{de}	11.7 ± 0.0^{cd}	0.0 ± 0.0^{a}
W_{Varoma}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	8.7 ± 0.6^{ab}	69.0 ± 0.0^{g}	19±2^{a}	900 ± 0^{a}	9.7 ± 0.1^{b}	14.5 ± 0.1	13.0 ± 0.0^{f}	0.0 ± 0.0^{a}
W'_{100}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	9.7 ± 0.6^{abc}	108.0 ± 2.6^{b}	36 ± 14^{abc}	900 ± 0^{a}	8.9 ± 0.5^{ab}	8.5 ± 0.1^{b}	8.3 ± 0.2^{b}	220.0 ± 0.0^{b}
W'_{105}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	9.8 ± 0.3^{bc}	82.7 ± 4.0^{d}	37 ± 8^{abc}	900 ± 0^{a}	8.7 ± 0.0^{a}	11.4 ± 0.4^{c}	10.9 ± 0.5^{c}	220.0 ± 0.0^{b}
W'_{110}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	10.0 ± 0.0^{c}	75.3 ± 2.0^{efg}	45 ± 5^{c}	900 ± 0^{a}	8.6 ± 0.4^{a}	12.8 ± 0.4^{ef}	12.0 ± 0.3^{de}	220.0 ± 0.0^{b}
W'_{115}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	10.0 ± 0.0^{c}	71.3 ± 2.5^{fg}	43 ± 4^{c}	900 ± 0^{a}	8.6 ± 0.1^{a}	13.8 ± 0.5^{fg}	12.6 ± 0.4^{ef}	220.0 ± 0.0^{b}
W'_{120}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	9.8 ± 0.8^{bc}	69.0 ± 1.0^{g}	42 ± 12^{bc}	900 ± 0^{a}	8.6 ± 0.2^{a}	14.4 ± 0.1^{g}	13.0 ± 0.2^{f}	220.0 ± 0.0^{b}
W'_{Varoma}	98.5 ± 0.0^{a}	98.5 ± 0.0^{a}	9.5 ± 0.5^{abc}	68.7 ± 1.5^{g}	38 ± 9^{abc}	900 ± 0^{a}	8.9 ± 0.4^{ab}	14.1 ± 0.3^{g}	13.1 ± 0.3^{f}	220.0 ± 0.0^{b}
D_{20}	98.5 ± 0.0^{a}	101.5 ± 0.0^{a}	9.2 ± 0.3^{a}	92.7 ± 2.1^{a}	6 ± 2^{a}	748 ± 9^{a}	9.1 ± 0.2^{a}	8.7 ± 0.2^{a}	8.1 ± 0.2^{a}	0.0 ± 0.0^{a}
D_{25}	98.5 ± 0.0^{a}	102.2 ± 0.6^{a}	9.8 ± 0.3^{b}	90.0 ± 1.7^{a}	9 ± 4^{ab}	719 ± 4^{c}	8.6 ± 0.3^{a}	8.8 ± 0.1^{a}	8.0 ± 0.2^{a}	0.0 ± 0.0^{a}
D'_{20}	98.5 ± 0.0^{a}	101.5 ± 0.0^{a}	10.0 ± 0.0^{b}	68.3 ± 0.6^{b}	26 ± 7^{c}	738 ± 6^{ab}	8.4 ± 0.0^{a}	12.4 ± 0.2^{b}	10.8 ± 0.2^{b}	220.0 ± 0.0^{b}
D'_{25}	98.5 ± 0.0^{a}	102.2 ± 0.5^{a}	10.2 ± 0.3^{b}	67.7 ± 0.6^{b}	19 ± 4^{bc}	727 ± 8^{bc}	8.4 ± 0.4^{a}	12.4 ± 0.2^{b}	10.7 ± 0.1^{b}	220.0 ± 0.0^{b}

n, number of repetitions; T, treatment; T_i, initial boiling temperature; T_f, final boiling temperature; t_i, initial time of the evaporation; t_f, final time of the evaporation; M_1, partial mass of evaporated water; M_2, mass of total evaporated water; a_h, heating rate; a_e, constant evaporation rate; E_r, total evaporation rate; V, air flow rate in the exhauster. [1]*Coefficients of determination (R^2) for linear relation between heating rate and time: 0.992 (W_{100}), 0.988 (W_{105}), 0.990 (W_{110}), 0.990 (W_{115}), 0.990 (W_{120}), 0.987 (W_{Varoma}), 0.973 (W'_{100}), 0.974 (W'_{105}), 0.973 (W'_{110}), 0.974 (W'_{115}), 0.974 (W'_{120}), 0.987 (W'Varoma);* [2]*(R_2) for linear relation between constant evaporation rate and time: 0.999 (W_{100}), 0.998 (W_{105}), 0.998 (W_{110}), 0.998 (W_{115}), 0.999 (W_{120}), 1.000 (W_{Varoma}), 0.998 (W'_{100}), 0.999 (W'_{105}), 0.998 (W'_{110}), 0.999 (W'_{115}), 0.998 (W'_{120}), 1.000 (W'_{Varoma})*; Statistical analyses of the average attributes, where the same letter does not differ ($P < 0.05$) by Tukey test.

to characterize *dulce de leche*. The determination of the moisture content was performed by the gravimetric method, while the lipid content was obtained by the Gerber method according Pereira et al. (2001) (both in duplicate). Aw analysis was performed in duplicate, and conducted on Aqua Lab 4 ATE equipment (Pullman, USA). The quantification of soluble solids content was obtained in triplicate by refractometry using the Reichert AR200 equipment (Buffalo, USA).

Statistical analysis

The results were evaluated by variance analysis (ANOVA) and Tukey test for comparison of means ($p < 0.05$). Data were analyzed using the statistical program Statistical Analysis System (SAS Institute Inc., 2006) version 9.2, licensed to the Federal University of Viçosa.

Theory/calculation

According to Roos (2007), the increase of the boiling temperature, as a consequence of the concentration of the product, can be calculated as

$$\Delta T_b = \frac{-R * (T_{wb})^2 \ln a_w}{\Delta h_v} \qquad \text{(Eq. 2)}$$

where ΔT_b = boiling point elevation, R = gas constant (8.314 J · mol^{-1} · K^{-1}), T_{wb} = boiling temperature of water (373 · 15 K), a_w = water activity of the product, and Δh_v = molar latent heat of vaporization (J · mol^{-1}).

The Δh_v value can be calculated via equation 3 according to Morison; Hartel (2007).

$$\Delta h_v = 57222 - 44.3 * T_{wb} \qquad \text{(Eq. 3)}$$

RESULTS AND DISCUSSION

Table 3 presents the results of water and *dulce de leche* evaporation experiments.

As expected, the water evaporation occurred at a constant boiling temperature. During evaporation, the exhauster presence was related to the rate of water evaporation, and to the time at which evaporation began. In all tested configurations of the Thermomix, the exhauster delayed the beginning of evaporation; on average the time until evaporation start was 11.4% higher, with the minimum from W_{105} (5.4%) and the maximum from W_{115} (14.9%). However, during the evaporation phase, the exhauster contributed to an increased rate of water evaporation. On average the rate of evaporation was increased by 12.6%, with minimum for W_{varoma} (0.76%) reaching 25.8% for W_{100}. The duration of the evaporation was on average 10.7% lower, reaching 21.2% of reduction for W_{100}. In *dulce de leche* industrial production, the presence of the exhauster is mandatory, primarily because it increases the evaporation rate, consistent with the present results. Simulations of the evaporation process should investigate the exhaust system or pressure reduction (vacuum evaporation), as demonstrated by Silva et al. (2015), Silveira et al. (2013), Rovedo et al. (1991), Martinez et al. (1990), and Pauletti et al. (1990).

Silveira et al. (2015) compared the efficacy of a pilot scale single stage evaporator in the evaporation of water and skim milk. In this study the heat transfer coefficient did not differ according to the product, while the flow behavior was modified. It concluded that the behavior of a product during the evaporation process can not be predicted by the global coefficient of heat transfer alone, requiring a wide range of information to understand the evaporation process, such as residence time distribution, product viscosity, and surface tension.

Table 4 – *Dulce de leche* compositions (n = 3)

Treatment	Fat ($m.m^{-1}$)	Water activity	Moisture ($m.m^{-1}$)	Soluble solids (ºBrix)	T_{wbf} (ºC)	ΔT_b (ºC)	Error[1] (%)
D_{20}	6.4 ± 0.8^a	0.834 ± 0.012^a	22.7 ± 2.6^a	71.1 ± 0.5^a	101.5	103.7	2.08
D_{25}	5.3 ± 0.3^a	0.855 ± 0.016^a	23.7 ± 1.3^a	69.0 ± 0.4^{ab}	102.2	102.9	0.72
D'_{20}	6.0 ± 0.5^a	0.842 ± 0.004^a	25.4 ± 2.4^a	67.5 ± 1.9^b	101.5	103.4	1.83
D'_{25}	5.9 ± 0.5^a	0.836 ± 0.008^a	22.8 ± 1.4^a	69.5 ± 0.4^{ab}	102.2	103.6	1.33

n = number of repetitions. Statistical analyses of the average attributes. Where the same letter does not differ ($P < 0.05$) by Tukey test. [1] = error between calculated and obtained boiling temperature at the end of evaporation. where: T_{wbf} = boiling temperature at the end of evaporation, ΔT_b = calculated boiling temperature at the end of evaporation.

For the *dulce de leche* evaporation the exhauster reduced the time of evaporation by 25.5%, increased the evaporation rate by 33.5%, and delay the beginning of boiling by 6.4%.

The rate of water evaporation during the *dulce de leche* production experiments was not affected by the amount of added sugar (treatments D_{20} and D_{25}), and no reduction in evaporation time was detected. The values reported here for the mass of water evaporated were, on average, higher than those found by Silva et al. (2015).

The compositions of the dulce de leche obtained in the experiment are presented in Table 4.

The *dulce de leche* produced using a multi-monitored Thermomix to emulate industrial evaporation of water presented compositions of fat, water activity, moisture, and soluble solids similar to those of industrial products from Brazil, Argentina, and Uruguay (GAZE et al., 2015a; ZARPELON et al., 2016). In a study by Gaze et al. (2015b) was found a variation between 3.56 g / 100 g at 6.99 g / 100 g fat and 17.49 g / 100 g at 29.67 g / 100 g moisture, while Silva et al. (2015) found a mean soluble solids content equivalent to 66.7 ºBrix (± 2.1). These results are in agreement with the present study.

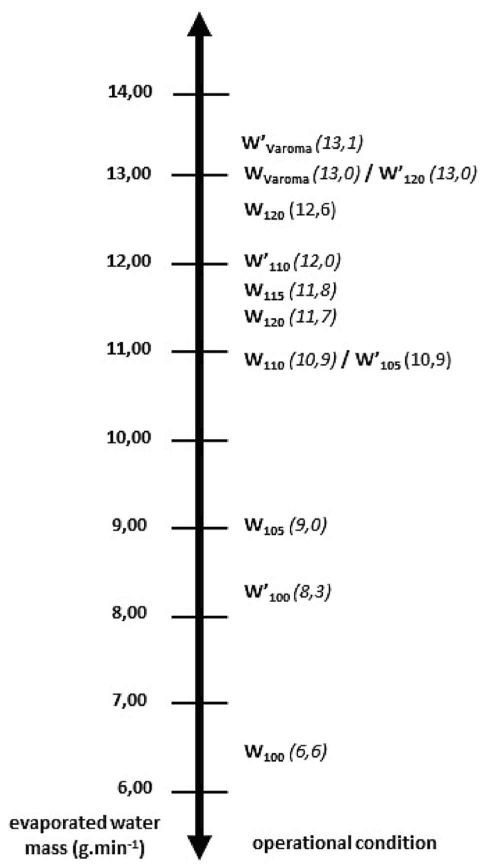

Figure 3 – Comparison of total water evaporation among the treatments.

Table 4 presents the relation between concentration and boiling temperature for *dulce de leche*.

The maximum error between the predicted value for boiling temperature, calculated from equations 2 and 3, and the boiling temperature observed using the multi-monitored Thermomix was of 2.08%. This result implies that the multi-monitored Thermomix can be used to establish Dühring curves for different foods during evaporation.

Figure 3 shows rates of water evaporation for different configurations of the multi-monitored Thermomix.

Among all of the tested treatments, four sets of experimental conditions yielded maximal water evaporation (W'_{varoma}, W_{varoma}, W'_{120}, and W_{120}).

CONCLUSIONS

The food processor brand Thermomix® enabled us to precisely determine the variation of mass during the process, show the effect of the exhaust system on the evaporation, obtain dulce de leche with market composition, and determine the effect of sugar addition on evaporation of water during production. The error between the final boiling point temperature and that predicted by theory was ~ 2%; as a consequence, the equipment could be applied to establishing Dühring curves. The Thermomix® multi-monitored configuration is a potential tool to emulate evaporation in the food industry, as demonstrated by our laboratory-scale production of dulce de leche. Futures studies should apply statistical methods to validate the Thermomix® multi-monitored as an industrial simulator of evaporation.

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REFERENCES

DODEJA, A. K. et al. Heat transfer during evaporation of milk to high solids in thin film scraped surface heat exchanger. **Journal of Food Process Engineering**, v. 12, p. 211-225, 1990.

GAZE, L. V. et al. Preference mapping of dulce de leche commercialized in Brazilian markets. **Journal of Dairy Science**, v. 98, p. 1443-1454, 2015a.

GAZE, L. V. et al. Dulce de Leche, a typical product of Latin America: Characterisation by physicochemical, optical and instrumental methods. **Food chemistry**, v. 169, p. 471-477, 2015b.

KIM, K. H. et al.Factors affecting performance of brine driven evaporators. **Journal of Food Process Engineering**, v. 7, p. 37-62, 1983.

MARTINEZ, E. et al. Sandiness prevention in dulce de leche by seeding with lactose microcrystals. **Journal of Dairy Science**, v. 73, p. 612-616, 1990.

MORISON, K. R.; HARTEL, R. W. Evaporation and freeze concentration. In: Heldman, D. R. & Lund, D. R. (Eds.). **Handbook of Food Engineering**, 2007. Boca Raton: CRC Press. p. 495-552.

PAULETTI, M., et al. Rheological characterization of dulce de leche, a confectionery dairy product. **Journal of Dairy Science**, v. 73, p. 601-603, 1990.

PEREIRA, D. B. C. et al. **Físico-química do leite e derivados – métodos analíticos.** 2ª ed. Juiz de Fora, 2001.

RIBEIRO, C. P.; ANDRADE, M. H. C. Performance analysis of the milk concentrating system from a Brazilian milk powder plant. **Journal of Food Process Engineering**, v. 26, p. 181-205, 2003.

ROOS, Y. H. Phase transitions and transformations in food systems. In Heldman, D. R. & Lund, D. R. (Eds.). **Handbook of Food Engineering**, 2007. Boca Raton: CRC Press. p. 287-532.

ROVEDO, C. O. et al. The effect of pH and temperature on the rheological behavior of Dulce de leche, a typical dairy Argentine product. **Journal of Dairy Science**, v. 74, p. 1497-1502, 1991.

SCHUCK, P. et al. Recent advances in spray drying relevant to the dairy industry: A comprehensive critical review. **Drying Technology**, v. 34, p. 1773-1790, 2016.

SILVA, F. L. et al. Production of dulce de leche: The effect of starch addition. LWT-**Food Science and Technology**, n. 62, p. 417-423, 2015.

SILVEIRA, A. C. P. et al. Pilot-scale investigation of effectiveness of evaporation of skim milk compared to water. **Dairy Science & Technology**, v. 93, p. 537-549, 2013.

SILVEIRA, A. C. P. et al. Flow regime assessment in falling film evaporators using residence time distribution functions. **Journal of Food Engineering**, v. 160, p. 65-76, 2015.

SOROUR, M. A. et al. A case study of orange juice concentration by recompression evaporation techniques. **Journal of Food Process Engineering**, v. 36, p. 337-342, 2013.

STEPHANI, R. et al. Evaluation of the synergistic effects of milk proteins in a rapid viscosity analyzer. **Journal of Dairy Science**, v. 98, p. 8333-8347, 2015.

TANGUY, G. et al. Calcium phosphate precipitation during concentration by vacuum evaporation of milk ultrafiltrate and microfiltrate. **LWT-Food Science and Technology**, v. 69, p. 554-562, 2016.

TEJINDER, S. Flow properties of malt concentrate-sweetened condensed milk mixtures. **Journal of Food Process Engineering**, v. 23, p. 221-235, 2000.

ZARPELON, J. et al. Validation of an automated method for the analysis of fat content of dulce de leche. **Journal of Food Composition and Analysis**, v. 48, p. 1-7, 2016.