



Research Note

Determining convective heat transfer coefficient during sterilisation of canned evaporated whole milk

Raúl L. Garrote*, Enrique R. Silva, Rubén D. Roa, Marisel Ayala

Instituto de Tecnología de Alimentos, Facultad de Ingeniería Química, Universidad Nacional del Litoral, Primero de Mayo 3250, 3000 Santa Fe, Argentina

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ABSTRACT

The effect of retort temperature, rotation speed, headspace and radius of rotation on mean convective heat transfer coefficient during sterilisation of canned evaporated whole milk was studied. The mean total solids content of evaporated milk obtained in a pilot plant installation was 25.25 g/100 g. Processing variables used ranged as follows: retort temperature: 117–123 °C; speed of rotation: 10–20 rpm; headspace: 4–12 mm; radius of rotation: 3.5–16.5 cm. The model developed for heat transfer coefficient was adequate, showing no significant lack of fit and satisfactory coefficient of determination. Retort temperature, speed of rotation, headspace and radius of rotation have a significant effect. Dimensional correlations were developed for convective heat transfer coefficient, in terms of Nusselt number as a function of Reynolds number, Prandtl number and relative headspace; the best agreement was obtained using the diameter of rotation as the characteristic dimension.

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1. Introduction

Autoclave rotation during processing, either axial or end-over-end, offers significant advantages when compared to still retorts: less sterilisation time at a constant sterilising value and a higher quality as a result of the improvement in heat transfer rate (Deniston, Hassan, & Merson, 1987; Fernández, Rao, Rajavasireddi, & Sastry, 1988; Lenz & Lund, 1978; Stoforos & Merson, 1990). The factors expected to influence heat transfer to cans in an agitating retort include the amount of headspace, viscosity of the product, the presence of particulate matter, container dimensions and the initial temperature of the product (Anantheswaran & Rao, 1985; Rao & Anantheswaran, 1988).

When there are no particles, heat transfer occurs mainly by forced convection, heat penetration increased, making the temperature distribution within the can more uniform. In end-over-end rotation the headspace bubble moves along the length of the can and brings about agitation of the can's contents (Anantheswaran & Rao, 1985). These authors studied the end-over-end rotation on heat transfer rate to canned Newtonian liquids over the range 0–38.6 rpm and radius of rotation 0–149 mm, finding that the internal heat transfer coefficient was independent of radius of rotation and the ratio of length to diameter of can; they also

established that headspace between 3 and 9% did not affect the heat transfer coefficient. They developed a dimensionless correlation to predict the heat transfer coefficient: $Nu = 2.9 Re^{0.436} Pr^{0.287}$. Sablani, Ramaswamy, and Mujumdar (1997) found the following equation for the overall heat transfer coefficient during the end-over-end thermal processing of water and oil: $Nu = 0.93 Re^{0.51} Pr^{0.36} (h_s/H_c)^{0.21}$. Naveh and Kopelman (1980) evaluated the heat transfer coefficients for a 84° Brix glucose syrup within cans and being rotated by end-over-end method; end-over-end rotation was found to result in a 2–3 times higher heating rate than with axial rotation. End-over-end rotation with an off-center axis of rotation resulted in a higher heat transfer coefficient than end-over-end agitation with the axis at the center of the can. An increase in rotational speed increased the heat transfer coefficient continuously during heating, and it approached an asymptotic value at about 40 rpm for cooling. The presence of a 2% headspace markedly increased the heat transfer coefficient vs that with no headspace. Further increase on headspace volume up to 10%, improved the heat transfer coefficient only slightly. Garrote, Silva, Roa, and Bertone (2006) developed the following dimensional correlation to predict the overall heat transfer coefficient during the end-over-end thermal processing of a solution of 2 g/100 g NaCl and 1.5 g/100 g of sucrose: $Nu = 1.866 Re^{0.379} Pr^{0.28}$.

Evaporated milk is a dairy product that may be utilized as an intermediate material for sweetened condensed and dried milk production or as final product for the consumer. The evaporation process causes major physicochemical and structural modifications

* Corresponding author. Tel.: +54 342 4571164/2601; fax: +54 342 4571166.
E-mail address: rgarrote@fiq.unl.edu.ar (R.L. Garrote).

to the milk that are reflected in its flow properties (Vélez Ruiz & Barbosa Cánovas, 1998). It is well known that the rheological behaviour of milk products is very complex, depending mainly on temperature and concentration and physical state of their disperse phases (Fernández Martín, 1972).

The purpose of our work was to determine the convective heat transfer coefficient during the sterilisation of canned evaporated whole cow milk, studying the effect of retort temperature, rotation speed, headspace and radius of rotation, and obtaining appropriate dimensional correlations.

2. Materials and methods

In order to obtain the sterilised evaporated whole milk the following steps were performed (see Fig. 1):

2.1. Determination of fresh and evaporated milk composition

Total solids: it was used the reference method of International Dairy Federation standard, 21B: 1987. Results are expressed as g/100 g.

Fat content: the gravimetric reference method of International Dairy Federation standard, 1D: 1996, was used. Results are expressed as g/100 g.

Protein content: it was followed the reference method of International Dairy Federation standard, 20B: 1993. Results are expressed as g/100 g.

Ash content: by incineration of dried matter at 530 °C during 2 h. Results are expressed as g/100 g.

Lactose content: it is obtained by difference; (total solids-fat content-protein content-ash content).

Density was determined by weighing a known volume of fresh or evaporated whole milk. Results are expressed as g/ml.

2.2. Determination of heat transfer coefficients

For fluids, the time-temperature profile is derived by solving the heat balance for a container in which there are no thermal gradients (Lenz & Lund, 1978).

$$hA(T_a - T) = mC_p dT/dt \quad (1)$$

With the boundary condition: at $t = 0$, $T = T_0$; as the heating medium used in the retort was steam, its thermal resistance could be considered negligible, and h instead of U was used in Eq. (1).

If the retort exhibits a thermal lag during heat up, the temperature can be described by the Eq. (2),

$$T_a = T_s - (T_s - T_{s0})\exp(-\tau_s t) \quad (2)$$

where τ_s is the time constant of the retort, which is obtained by nonlinear regression knowing the retort temperature evolution during the come up period.

Under these conditions, Eq. (1) is solved using Laplace transform to give,

$$T = T_0 + (T_s - T_0) \cdot (1 - \exp(-(hA/mC_p) \cdot t)) + (T_s - T_{s0}) \cdot (hA/mC_p) / ((hA/mC_p) - \tau_s) \cdot (\exp(-(hA/mC_p) \cdot t) - \exp(-\tau_s \cdot t)) \quad (3)$$

The procedure involved initially comparing the calculated and measured lethality at the center position in the can based on an assumed h value, and then subsequently changing h until the calculated lethality matched the measured one (Sablani & Ramaswamy, 1996),

$$F_R = \int_0^t 10^{(T - T_R)/z} dt \quad (4)$$

Integral in Eq. (4) was numerically solved using Simpson method, being $\Delta t = 15$ s. In Eq. (4), $10^{(T - T_R)/z}$ is the lethal rate function; graphically, the area under the plot of $10^{(T - T_R)/z}$ vs. time is the sterilising value F_R .

2.3. Experimental methodology

A screening factorial experimental design, $2^4 + 2$ replicates of the central point were chosen. Independent variables with corresponding levels were: retort temperature, 117–123 °C, speed of rotation of cans, 10–20 rpm headspace of cans, 4–12 mm, radius of rotation of cans, 3.5–16.5 cm, while the dependent variable was h , the mean convective heat transfer coefficient.

To determine the heat transfer coefficient, three cans (107 mm high \times 69.8 mm diameter) were placed inside the basket of the rotary retort, at the corresponding radius of rotation, accordingly to the experimental design. These cans contained the evaporated milk and had a thermocouple in their geometric centers. A thermocouple was also used to control steam temperature. Cans of the same dimensions, filled with water, were placed at both sides of the three cans with the thermocouples. The process steam was quickly transferred to the process vessel so that a come up time of approximately 2 min was achieved. All heat penetration studies were carried out in a pilot plant rotary retort designed by the working group and locally constructed. Thermocouples Ellab Type T were used in every case and a Fluke Data Logger, model 2625 A, was used for the recording of temperature–time relationships.

The program Statgraphic (Statistical Graphic System Plus for Windows 3.0) was used for data analysis. The significance of the lack of fit was thus evaluated, and the model competence was verified by the analysis of variance (ANOVA).

2.4. Dimensional correlations

Data obtained for h were used to calculate the Nusselt number using the relationship $Nu = hD_{cd}/k_l$, where D_{cd} and k_l are the characteristic dimension and thermal conductivity of the evaporated milk, respectively. Other dimensionless numbers, like Re, Pr, h_s/H_c were calculated using the physical properties of evaporated milk (at the average bulk temperature), and system (operating) parameters (Heldman & Lund, 1992; Sablani et al., 1997). Viscosity of evaporated milk was obtained using the following correlation (Fernández Martín, 1972):

$$\log \mu = 0.249 - 0.0130^*T + 0.000052^*T^2 + (0.025490 \cdot 0.000098^*T + 0.0000004^*T^2)^*c + (0.000543 - 0.0000139^*T + 0.000000177^*T^2)^*c^2 \quad (5)$$

where T = temperature, °C and c = total solids of evaporated whole milk, g/100 g; this equation is valid for $T = 0$ –80 °C and $c = 0$ –30 g/100 g. A nonlinear regression analysis was performed in order to obtain the values of the constants of the dimensional correlations.

3. Results and discussion

Composition of fresh milk was the following ($P < 0.05$, $n = 11$): total solids = 11.39 ± 0.15 ; fat content = 3.19 ± 0.11 ; protein content = 3.03 ± 0.16 ; ash content = 0.5 ± 0.07 , lactose content = 4.67, while density of FM was 1.030 ± 0.007 ; for evaporated milk the

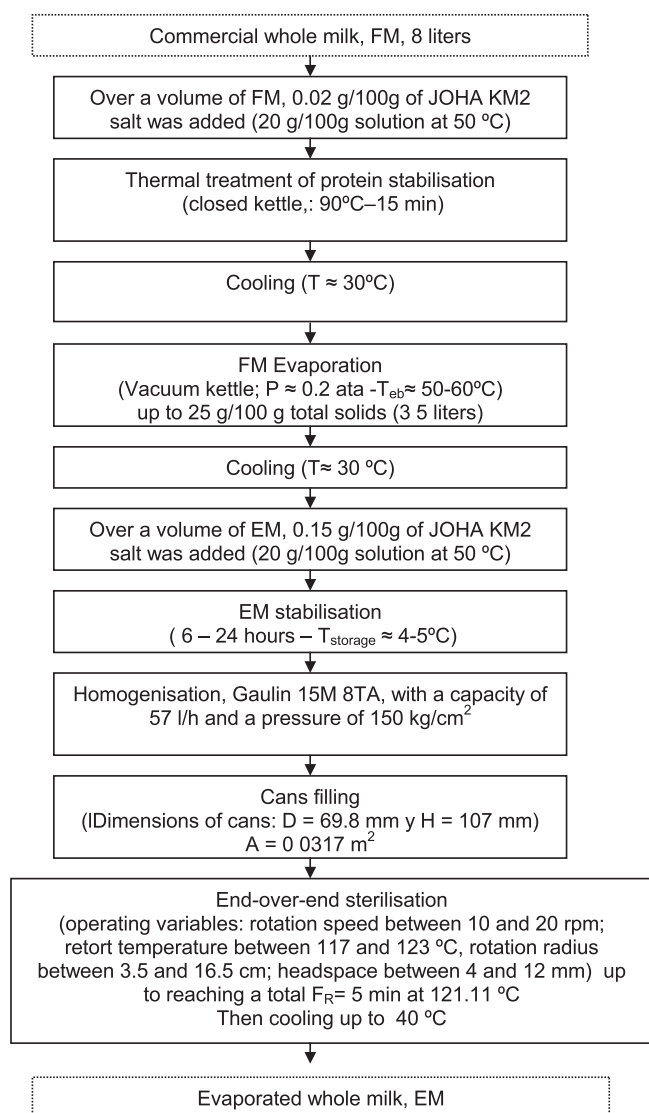


Fig. 1. Steps followed in the processing of sterilised evaporated milk.

composition was the following: total solids = 25.25 ± 0.34 ; fat content = 6.78 ± 0.40 ; protein content = 6.75 ± 0.60 ; ash content = 1.33 ± 0.09 , lactose content = 10.39 while density of EM was 1.06 ± 0.004 .

Calculated specific heat of evaporated milk fluctuated between 3599 and 3611 J/kg °C, thermal conductivity between 0.5518 and 0.5583 W/m °C, while viscosity between 1.476×10^{-3} and 1.619×10^{-3} kg/m s.

Table 1 shows, for the 18 runs performed, the values of T_s , T_{so} , T_o , τ_s and m . Table 2 shows the values of the independent variables used in the experimental design and corresponding mean convective heat transfer coefficients obtained; heating times fluctuated between 6.75 and 17.75 min; for No 7 run Fig. 2 shows the very good agreement obtained for experimental and theoretical time–temperature profiles.

From Table 2 it may be seen that h ranged between 618 and 910 W/m² °C. These values are similar to those obtained by Anantheswaran and Rao (1985) for a 20–30% sucrose solution. The analysis of variance showed that the model developed was adequate showing no significant lack of fit, with a satisfactory $R^2 = 0.9747$. Retort temperature, speed of rotation, headspace and radius of rotation had a significant effect. A significant effect of

Table 1

Values of T_s , T_{so} , T_o , τ_s and m for each experimental run performed between parenthesis is the standard deviation.

Run	T_s °C	T_{so} °C	T_o °C	τ_s s ⁻¹	m kg
1	123.43(0.07)	20.75(2.18)	22.26(0.07)	0.02284(0.001)	0.4162
2	122.97(0.254)	17.80(1.70)	20.05(0.08)	0.03497(0.0007)	0.3839
3	123.59(0.017)	22.13(1.49)	20.16(0.23)	0.03407(0.001)	0.3839
4	117.15(0.041)	21.30(1.20)	20.31(0.95)	0.0467(0.0004)	0.3875
5	117.09(0.042)	22.57(0.44)	21.74(0.25)	0.0388(0.002)	0.4201
6	117.12(0.021)	23.85(0.40)	19.29(1.27)	0.0428(0.003)	0.4170
7	117.27(0.082)	23.85(0.39)	22.20(0.07)	0.0481(0.0001)	0.3846
8	117.19(0.080)	39.00(1.94)	26.53(0.78)	0.0351(0.002)	0.3830
9	117.08(0.014)	28.99(2.86)	23.22(1.05)	0.03826(0.0009)	0.3830
10	117.23(0.136)	31.18(3.46)	33.51(2.49)	0.0364(0.002)	0.4138
11	120.38(0.06)	13.95(0.4)	20.27(1.60)	0.03083(0.0005)	0.3997
12	123.09(0.05)	63.09(0.15)	30.47(0.22)	0.0261(0.0007)	0.3817
13	119.91(0.02)	13.15(0.19)	18.80(0.71)	0.03051(0.0004)	0.3997
14	122.94(0.13)	14.89(0.5)	17.81(0.92)	0.0414(0.006)	0.4127
15	121.64(0.41)	18.51(0.61)	19.69(0.35)	0.0190(0.0007)	0.3806
16	116.91(0.02)	17.35(0.71)	19.04(2.75)	0.0452(0.007)	0.4182
17	122.59(0.09)	27.36(1.33)	18.90(0.18)	0.0448(0.001)	0.4160
18	123.17(0.02)	22.89(0.16)	21.51(0.14)	0.0509(0.002)	0.4160

(Temperature × Radius of Rotation), and (Rotation speed × Radius of rotation) for h was also found. Working with water and oil as fluids Sablani et al. (1997) also found a significant effect of retort temperature, end-over-end rotation speed, headspace and radius of rotation on the values of U obtained; a strong correlation of heat transfer coefficient with the speed of rotation and the fluidity (inverse of viscosity) of the liquid was found by Anantheswaran and Rao (1985), but not with radius of rotation and headspace between 3 and 9%. Naveh and Kopelman (1980) found that moving the rotation can from a central axis to an off-center axis of rotation improved the heat transfer coefficient at speeds of 20–120 rpm.

Prior to determining the applicable correlation it was necessary to determine the characteristic length in the dimensional groups (Anantheswaran & Rao, 1985). Different variables as the characteristic length were tried, for example, can diameter, D_c , diameter of rotation, D_r and the sum of diameter of rotation and can diameter ($D_r + D_c$), and evaluating the fit of data in terms of groups Nu, Re, Pr and h_s/H_c using nonlinear regression to obtain the constants of dimensional correlations; in order to obtain the thermal and physical properties it was considered that evaporated milk is a Newtonian liquid; Kowakoshi (1999) found that whole milk up to 30% solids content behave like a Newtonian fluid; Vélez Ruiz and

Table 2

Values of h as a function of processing variables.

Run	Retort temperature °C	Rotation speed rpm	Headspace mm	Radius of rotation cm	h W m ⁻² °C ⁻¹
1	123	20	4	3.5	765
2	123	20	12	3.5	796
3	123	10	12	3.5	698
4	117	20	12	3.5	791
5	117	20	4	3.5	774
6	117	10	4	16.5	630
7	117	10	12	16.5	623
8	117	10	12	3.5	618
9	117	20	12	16.5	832
10	117	10	4	3.5	645
11	120	15	8	10	727
12	123	10	12	16.5	746
13	120	15	8	10	719
14	123	10	4	3.5	645
15	123	20	12	16.5	910
16	117	20	4	16.5	776
17	123	20	4	16.5	874
18	123	10	4	16.5	659

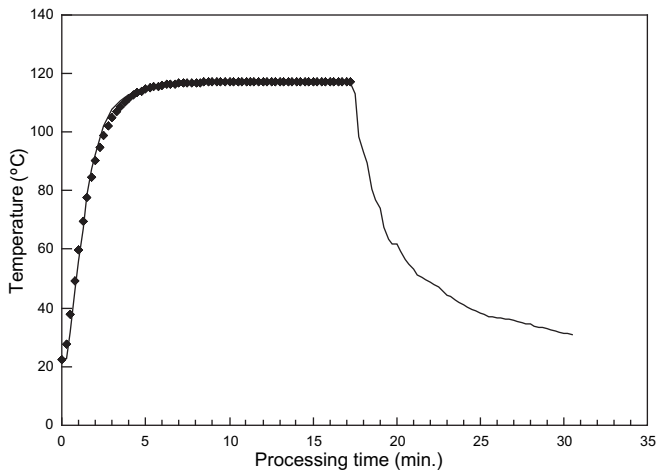


Fig. 2. Theoretical (♦) and experimental (—) time-temperature profiles for run 7. $(F_R)_{\text{heating}} = 5.03$ min at 121.11 °C; average standard deviation = 0.1 °C.

Barbosa Cánovas (1998) found a similar behaviour for solids content up to 22.3%. The best correlation obtained ($R^2 = 0.9827$) was the one in which the Nu and Re numbers were calculated using the diameter of rotation,

$$\text{Nu} = \text{Re}^{0.508} (h_s/H_c)^{0.040} \text{Pr}^{0.281} \quad (6)$$

This dimensional correlation is valid for Reynolds number in the range, 1744–1779,263, Prandtl, 9.54–10.56 and the relative headspace in the range, 3.7×10^{-2} – 11.2×10^{-2} . Sablani et al. (1997) obtained a similar correlation for U, being the fluids used water and oils, using as the characteristic length the sum ($D_r + D_c$); in our case, and for that characteristic length we obtained the following dimensional correlation ($R^2 = 0.9732$):

$$\text{Nu} = \text{Re}^{0.513} (h_s/H_c)^{0.039} \text{Pr}^{0.252} \quad (7)$$

The exponent of Reynolds number appearing in Eq. (6) is slightly higher than that reported by Anantheswaran and Rao (1985), probably, as reported by Sablani et al. (1997), because of the significant influence of diameter of rotation on heat transfer coefficient.

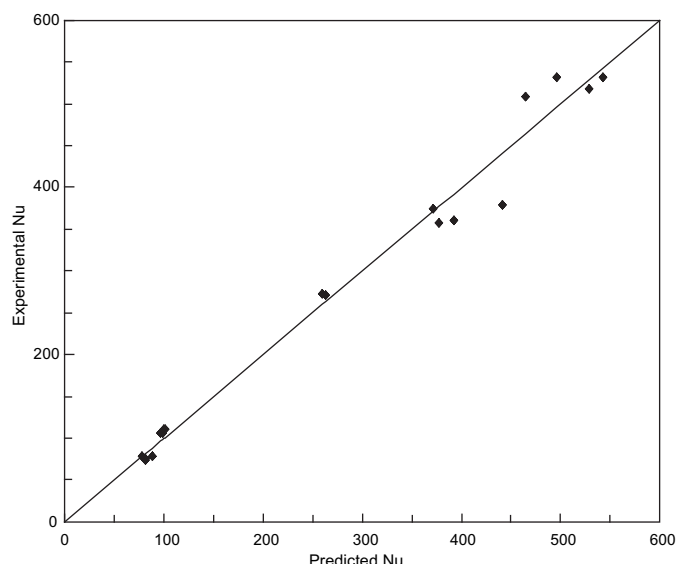


Fig. 3. Predicted (♦) vs. experimental Nu (—).

Fig. 3 shows the plot for Nusselt numbers predicted using Eq. (6) versus experimental values. % deviation, calculated as,

$$\% \text{ deviation} = \sqrt{\frac{\sum ((\text{Nu}_{\text{pred}} - \text{Nu}_{\text{exp}}) / \text{Nu}_{\text{exp}})^2}{n - 1}} \quad (8)$$

being $n = 18$, was 8.18, revealing a very good agreement between predicted and experimental Nu number values; assuming that Eq. (5) used to predict viscosity of evaporated milk may have some error, we recalculated dimensionless parameters supposing that viscosity is greater or lower by five per cent, obtaining a % deviation of 8.13 and 8.41 respectively; so we conclude that Eq. (5) may be used with confidence.

4. Conclusions

The model developed for h during canned evaporated whole milk sterilisation was adequate, showing no significant lack of fit and satisfactory determination coefficient. Retort temperature, speed of rotation, headspace and radius of rotation have a significant effect. Dimensionless correlations were developed for convective heat transfer coefficient, in terms of Nusselt number as a function of Reynolds number, Prandtl number and relative headspace; the best agreement was obtained using the diameter of rotation as the characteristic dimension.

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Nomenclature

A : Surface area of the container, m^2
 C_p : Heat capacity, $\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$
 D_c : Diameter of can, m
 D_{cd} : Characteristic dimension, m
 D_r : Diameter of rotation, m
 EM : Evaporated milk
 FM : Fresh milk
 F_R : Sterilising value at T_R , min
 h : Convective heat transfer coefficient, $\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$
 h_s : Can headspace, mm
 H_c : Can height, mm
 k : Thermal conductivity, $\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$
 m : Mass, kg
 N : Rotational speed, rpm
 t : Heating time, s
 T : Temperature, $^\circ\text{C}$

T_a : Heating medium temperature, $^\circ\text{C}$
 T_o : Initial temperature, $^\circ\text{C}$
 T_R : Reference temperature, 121.11 $^\circ\text{C}$
 T_s : Ultimate heating medium temperature, $^\circ\text{C}$
 T_{so} : Initial retort temperature, $^\circ\text{C}$
 U : Overall heat transfer coefficient, $\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$
 z : Temperature difference required for a ten fold change in the decimal reduction time, $^\circ\text{C}$

Greek symbols

ρ : Density, kg m^{-3}
 μ : Viscosity, $\text{kg m}^{-1} \text{ s}^{-1}$
 τ_s : Retort time constant, s^{-1}

Dimensionless parameters

Nu : Nusselt number, $[h D_{cd}/k]$
 Pr : Prandtl number, $[C_p \mu/k]$
 Re : Reynolds number, $[(\pi D_{cd} N/60) D_{cd} \rho/\mu]$
 h_s/H_c : Relative headspace