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Pilot-scale investigation of effectiveness of evaporation of skim milk compared to water

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Abstract As evaporation is an energy-intensive process, it is important that evaporators operate efficiently at their maximum capacity. The aim of this study was to compare the effectiveness of a pilot-scale, single-stage falling-film evaporator in the evaporation of water and skim milk. The solutions were fed at a boiling temperature of 60 °C, and a mass flow rate of $50.0 \pm 0.7 \text{ kg}\cdot\text{h}^{-1}$. There was no significant variation ($p < 0.05$) in the evaporation rate or in the energy efficiency for the experiments with skim milk at two different initial concentrations, but these values were higher than those obtained with the experiments with water. The heat transfer coefficient did not differ according to the product, and this result does not explain why the evaporation of skim milk was more effective than that of water. Flow behavior was modified according to the product: a thicker and slower film was obtained at the end of the skim milk concentration process compared to water. Increasing the concentration of a product would lead to an increase in residence time, which would modify the evaporation rate. The behavior of a product during the evaporation process cannot be predicted by the overall heat transfer coefficient alone, and a wide range of information is required to understand the evaporation process, such as residence time distribution, product viscosity, and surface tension.

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Keywords Evaporator · Skim milk · Enthalpy balance · Vacuum concentration · Overall heat transfer coefficient

Nomenclature

A	Heating surface (m^2)
D	Tube diameter (m)
EE	Energy efficiency ($\% \cdot \text{w} \cdot \text{w}^{-1}$)
H	Enthalpy ($\text{kJ} \cdot \text{kg}^{-1}$)
h	Height (m)
ΔH_v	Latent heat of vaporization ($\text{kJ} \cdot \text{kg}^{-1}$)
\dot{m}	Mass flow rate ($\text{kg} \cdot \text{h}^{-1}$)
P	Pressure (MPa)
\dot{Q}	Heating power (kW)
\dot{q}_p	Heat loss ($\text{kJ} \cdot \text{h}^{-1}$)
SEC	Specific energy consumption ($\text{kJ} \cdot \text{kg}^{-1}$)
TS	Total solids ($\% \text{ w} \cdot \text{w}^{-1}$)
U	Overall heat transfer coefficient ($\text{kW} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$)

Greek symbols

η	Viscosity ($\text{mPa} \cdot \text{s}^{-1}$)
θ	Temperature ($^\circ\text{C}$)
Φ	Heat flux ($\text{kW} \cdot \text{m}^{-2}$)

Subscript

abs	Absolute
cc	Product concentrate
cd	Product condensate
cw_{in}	Inlet cooling water
cw_{out}	Outlet cooling water
ev	Evaporation
p_{in}	Inlet product
v_{-1}	Steam
v_1	Steam condensate

1 Introduction

Evaporation is a process through which a liquid is brought to its boiling point by external heating, transforming the solvent into vapor that escapes from the surface of the liquid. Such thermal concentration is commonly used for liquid foods (i.e., milk, fruit juice, and sugar solutions) to manufacture products such as sweet condensed milk (Gänzle et al. 2008), “dulce de leche” (Hentges et al. 2010), beet or cane sugar, fruit juice (Tonelli et al. 1990), and tomato sauce concentrates (Runyon et al. 1991). Above all, it is an intermediate process in the production of milk, buttermilk and whey powders (Schuck 2002), infant formula (Zhu et al. 2011), protein isolates (Onwulata et al. 2006), etc.

In order to reduce energy consumption and environmental impact, it is important that evaporators operate at their maximum capacity, which is strongly dependent on

the overall heat transfer coefficient. This parameter cannot be considered as an intrinsic characteristic of the evaporator since it also depends on the nature of the product and on their flow conditions (Mafart 1991). The factors that control heat transfer in the evaporator tubes are important for close monitoring of the evaporation process and for calculating the dimensions of evaporators (Bouman et al. 1993; Jebson and Iyer 1991).

As boiling and concentration take place inside the falling-film evaporator, the study of the mechanisms is complex because both occur simultaneously (Li et al. 2011; Pehlivan and Özdemir 2012). Some studies of the evaporation process reported in the literature were carried out on industrial evaporators. In this case, operating conditions such as the configuration of the equipment and the quality of the raw materials were not controlled (Jebson and Iyer 1991; Jebson and Chen 1997). In contrast, other studies on laboratory and pilot scales were carried out using model solutions (water, sucrose solutions, etc.) (Herbert and Sterns 1968; Luo et al. 2011; Prost et al. 2006) and evaporation systems whose design had been modified from industrial evaporators in order to separate phenomena and facilitate their understanding (Adib et al. 2009; Bouman et al. 1993). There is, therefore, only limited information on evaporator performance, i.e., the performance of real evaporators working with real products over real concentration steps.

The aim of this study was to compare heat and mass balance using a pilot-scale, single-stage vacuum falling-film evaporator composed of three tubes in series, for the evaporation of skim milk and water. This equipment was designed to study both phenomena (boiling and concentration) occurring during the evaporation of dairy products. The experimental effectiveness of evaporation was compared to theoretical effectiveness with no energy loss. The investigation also involved calculation of the energy used by the evaporator, the overall heat transfer coefficient for each run, and study of the factors influencing the evaporation rate of skim milk compared to water.

2 Materials and methods

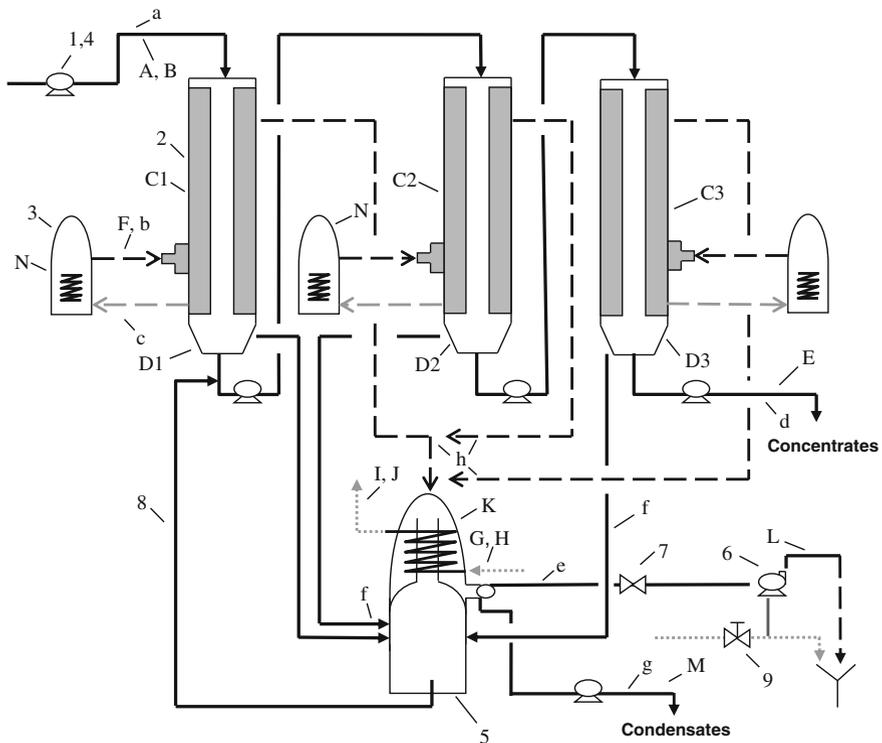
2.1 Pilot vacuum evaporator and experiments

The equipment used in these experiments consisted of a pilot-scale, single-stage falling-film evaporator (GEA Process Engineering, St Quentin-en-Yvelines, France; Fig. 1). The dimensions of the three tubes of the falling-film evaporator are shown in Table 1.

Each tube has an independent electrical heating system (no. 3 in Fig. 1) that provides the vaporization energy. As the vapor emitted by the product (secondary vapor) is not used for heating the product in the next tube, this pilot is a single-stage evaporator.

The experiments were performed at a total heating power of 25.20 ± 0.05 kW (Table 1), corresponding to the maximum heating power of the equipment, and producing steam (primary vapor) at a temperature of 75 °C. The heating power (8.40 ± 0.02 kW for each tube) was determined by measuring the current and the voltage with a clamp meter and a voltmeter (Fluke Co. Ltd., Everett, USA), respectively.

The product concentrate and the secondary vapor are separated in an indirect condenser (coil-type heat exchanger) that is integrated vertically in the separator (no. 5 in Fig. 1). As the secondary vapor (product vapor) is condensed in the condenser, the



- 1 – Feed pump
- 2 – Heat exchanger falling tube
- 3 – Boilers
- 4 – Centrifugal pump
- 5 – Separator and indirect condenser
- 6 – Vacuum pump
- 7 – Vacuum control valve
- 8 – Separated product
- 9 – Vacuum breaker valve
- a – Product inlet
- b – Steam inlet
- c – Steam condensate
- d – Product concentrate
- e – Non-condensable gas
- f – Mix of secondary vapor and product
- g – Product condensate
- h – Outlet non-condensable gas or steam
- A – Inlet mass flow rate of product (\dot{m}_{pin})
- B – Inlet product temperature (θ_{pin})
- C – Temperature of steam (θ_{v-1})
- D – Temperature of product (θ_p)
- E – Outlet mass flow rate of product concentrate (\dot{m}_{cc})
- F – Mass flow of primary vapor (\dot{m}_{v-1})
- G – Inlet mass flow rate of cooling water ($\dot{m}_{cw,in}$)
- H – Temperature of inlet cooling water ($\theta_{cw,in}$)
- I – Outlet mass flow rate of cooling water ($\dot{m}_{cw,out}$)
- J – Temperature of outlet cooling water ($\theta_{cw,out}$)
- K – Temperature of condenser
- L – Vacuum pressure (P)
- M – Outlet mass flow rate of product condensate (\dot{m}_{cd})
- N – Heating power (Q)

— → Steam circuit; — → Product circuit; → water process circuit

Fig. 1 Single-effect falling-film evaporator. 1 → 9: equipment components; a → f: circulation of product, condensate, and steam in the equipment; A → N: plain text—measurement parameters, *italic text*—calculated parameters

boiling temperature on the product side of the tubes is reduced ($P_{\text{total}} < 0.1$ MPa). All experiments were performed at an absolute pressure (P_{abs}) of 0.02 MPa, and thus the evaporation temperature (θ_{ev}) was maintained at 60 °C throughout the three tubes. The temperature was controlled by the mass flow rate of the cooling water (maximum temperature 20 °C) (point G—Fig. 1). A vacuum pump (point 6—Fig. 1) (liquid ring type, 1.1 kW power consumption) connected to the condenser is required for the starting phase and to extract the non-condensable gases, which would otherwise accumulate in the condenser.

The product, concentrate, and condensate are circulated by means of four circulation pumps (point 4—Fig. 1) (Pompes AB, Maurepas, France), with the same characteristics (centrifuge type, 0.7 kW). All experiments were performed at an inlet mass flow rate of 50.0 ± 0.7 kg·h⁻¹.

The evaporator is equipped with probes to record the temperatures of the product and the secondary vapor in each tube (points B, C1, C2, C3, D1, D2, D3, H, J, and K—Fig. 1). Product feed, cooling water, concentrate, and condensate flow rates were measured with flow meters at different points (points A, E, G, and M—Fig. 1). These measurements were taken in triplicate at ambient temperature.

2.2 Experimental runs

Experimental runs were carried out with water (maximum hardness of 80 mg CaCO₃·kg⁻¹) and skim milk at two different initial concentrations.

Skim milk was prepared at 10% (w·w⁻¹) total solids (TS) from dairy powder (Société Mayenne, Mayenne, France). It was heated to 60 °C before evaporation. After the first run through the evaporator, skim milk was concentrated from 10% TS to 24% TS. This product, still at 60 °C, was reintroduced into the evaporator where it was re-concentrated (second run) from 24% TS to 52% TS (Table 2).

The operating parameters described above were constant for all the experiments with water and skim milk.

2.2.1 Viscosity measurement

Viscosity measurements were obtained at 60 °C with a rheometer Physica MCR 301 (Anton Paar, Graz, Austria) using a coaxial aluminum cylinder (inner radius 23.05 mm; outer radius 25 mm; height of rotor 30 mm; gap 5 mm). Shear rates between 0.1

Table 1 Operating parameters and dimensions of the three tubes in the falling-film evaporator

Tube no.	D (m)	h (m)	A (m ²)	Q (kW)	Φ (kW·m ⁻²)
1	0.036	4.0	0.452	8.40	18.60
2	0.023	4.0	0.289	8.40	29.10
3	0.023	4.0	0.289	8.40	29.10
Total			1.030	25.20	

Wall thickness of each tube is 1 mm

D diameter, h height, A heating surface, Q heating power, Φ heat flux

Table 2 Evaporation rates for skim milk and water, showing inlet and outlet total solids content and viscosities

Product	Inlet/outlet TS (g·100 g ⁻¹)	Inlet/outlet η_{100} (mPa·s)	Evaporation rate ^a (kg·h ⁻¹)	Error of mass balance ^b (%)
Water	–	0.47/0.47	23.5 ± 0.7	1.4
Skim milk first run	10.0 ± 0.5/24.0 ± 0.5	1.08/2.83	30.0 ± 0.7	1.6
Skim milk second run	24.0 ± 0.5/52.0 ± 1.5	2.83/23.81	30.0 ± 0.9	4.6

Average ($n = 3$) ± standard deviation

TS total solids, η_{100} viscosity

$$^a (\dot{m}_{P_{in}} - \dot{m}_{cc})$$

$$^b \left[(\dot{m}_{P_{in}} - (\dot{m}_{cc} + \dot{m}_{cd}) \cdot 100) \right] / \dot{m}_{P_{in}}$$

and 500 s⁻¹ at a temperature of 60 °C were used for rheological determinations. The apparent viscosity at a shear rate of 100 s⁻¹ (η_{100}) was used to make direct comparisons between the different solutions. This shear rate value was chosen because it is applicable to agitation, flow in tubes, and other industrial operations (Steffe 1996).

2.2.2 Total solids

Total solid content (TS) was calculated according to weight loss after drying 5 g of each sample with sand in a forced air oven at 105 °C for 7 h.

2.3 Mass and enthalpy balance

Figure 2 provides a diagram representing the mass flow rate and the physical characteristics of the fluids in the evaporator. Each fluid is characterized by its mass flow rate (\dot{m} , kg·h⁻¹) temperature (θ , °C), pressure (P , MPa), and enthalpy (H , kJ·kg⁻¹).

As seen in Fig. 2, the overall mass balance was calculated as:

$$\dot{m}_{v-1} + \dot{m}_{P_{in}} + \dot{m}_{cw_{in}} = \dot{m}_{cc} + \dot{m}_{cd} + \dot{m}_{v1} + \dot{m}_{cw_{out}} \quad (1)$$

The non-condensable gases from the steam (point h in Fig. 1) were transferred to the condenser where they were removed from the system. The mass flow rate of non-condensable gas was considered as negligible, and therefore it was not taken into account in the calculation of mass and energy balances.

Expressing \dot{q}_p as heat loss, the enthalpy balance (see Appendix for the development of this equation) can be written:

$$\dot{m}_{v-1} \cdot (\Delta H_v) = \dot{m}_{cc} \cdot H_{cc} + \dot{m}_{cd} \cdot H_{cd} - \dot{m}_{P_{in}} \cdot H_{P_{in}} + \dot{m}_{cw} \cdot (H_{cw_{out}} - H_{cw_{in}}) + \dot{q}_p \quad (2)$$

The left term of Eq. 2 corresponds to the heating power Q provided by the steam, i.e., the energy provided by the heating systems of the evaporator.

2.4 Overall heat transfer coefficient

The overall heat transfer coefficient for each tube was calculated as:

$$Q = U \cdot A \cdot \Delta\theta \Leftrightarrow \Phi = \frac{Q}{A} = U \cdot \Delta\theta \Leftrightarrow U = \frac{\Phi}{\Delta\theta} \quad (3)$$

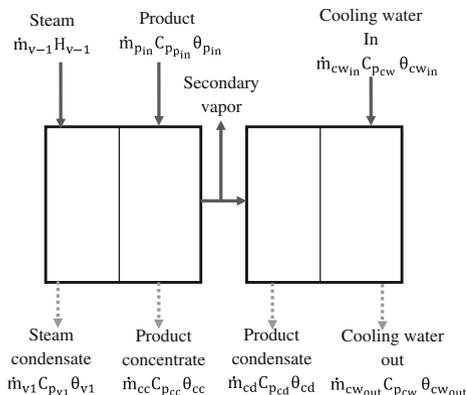
where U is the overall heat transfer coefficient ($\text{kW} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$), Q the heating power (kW), A the heating surface (m^2), $\Delta\theta$ the mean temperature difference between steam and product concentrate ($^\circ\text{C}$), and Φ the heat flux ($\text{kW} \cdot \text{m}^{-2}$).

The overall heat transfer coefficient is an overall resistance resulting from the combination of the resistance to heat transfer on the steam heating side, the tube wall thickness, a fouling layer on the product side, and the interface with the boiling product (Pehlivan and Özdemir 2012; Adib et al. 2009; Adib and Vasseur 2008; Prost et al. 2006; Bouman et al. 1993).

Heat transfer in the literature is expressed in terms of heat flux (Φ , $\text{kW} \cdot \text{m}^{-2}$), and this is convenient for the purpose of comparison with other studies. The technical characteristics of the evaporator studied are provided in Table 1.

2.5 Assessment of process efficiency

The energy consumption for evaporation is a key parameter used to assess the efficiency of a plant. As in drying, it can be evaluated from the Specific Energy Consumption (SEC; $\text{kJ} \cdot \text{kg}^{-1}$ of water evaporated) (Bimbenet et al. 2002) and from the energy efficiency (EE; % $-\text{w} \cdot \text{w}^{-1}$), that is the ratio between the amount of water



Legend:

C_p = sensitive heat [$\text{kJ}/(\text{kg} \cdot ^\circ\text{C}^{-1})$]

H = enthalpy of evaporation ($\text{kJ} \cdot \text{kg}^{-1}$)

θ = temperature ($^\circ\text{C}$)

\dot{m} = mass flow rate ($\text{kg} \cdot \text{h}^{-1}$)

Fig. 2 Thermodynamic diagram of a single-stage vacuum evaporator

evaporated and the amount of steam, expressed as a percentage (Bimbenet et al. 2007). SEC and EE are defined by the following equations:

$$\text{SEC} = \frac{\dot{m}_{v-1} \cdot \Delta H_v}{\dot{m}_{cd}} \quad (4)$$

and

$$\text{EE} = \frac{\dot{m}_{cd}}{\dot{m}_{v-1}} \quad (5)$$

2.6 Statistical analysis

Data were analyzed by regression analysis of variance using SAS (2008) software, at the 0.05 level of significance.

3 Results and discussion

3.1 Mass balance

The initial and final product concentrations before and after the run in the evaporator are presented in Table 2. The viscosity of these solutions was also measured (Table 2). The viscosity of water remained constant during evaporation, whereas the viscosity of skim milk increased from 1.08 mPa·s to 2.83 mPa·s during the first run, and its behavior was Newtonian, i.e., its viscosity remained constant whatever the shear rate. In the second run, the viscosity increased from 2.83 mPa·s at 24% TS to 23.81 mPa·s at 52% TS ($w \cdot w^{-1}$). At this concentration, the product had a shear thinning behavior, i.e., its viscosity decreased with increasing shear rate. This behavior can be explained as a consequence of increasing the shear rate which induces the asymmetric dispersed molecules to align themselves within the shear planes, causing the frictional resistance to diminish (Tung 1978; Vélez-Ruiz and Barbosa-Cánovas 1997). The mass balance of the process was effective for all experiments, with a maximum error of 4.6%, representing the difference between the inlet and outlet mass flow rates (Eq. 1). The evaporation rate was calculated by subtracting the inlet flow rate of the product and the outlet flow rate of the product concentrate. This parameter reflects the amount of water evaporated from the product. There was no significant variation ($p < 0.05$) in the evaporation rate for the two runs carried out with skim milk, and it was higher than that obtained for the experiments carried out with water. To explain these results, the enthalpy balance was calculated and the process efficiency assessed (Table 3).

3.2 Enthalpy balance

To calculate the energy balance, the vacuum evaporation process was considered as a single system (Fig. 2). In other words, we took into account the average temperature of the steam measured in the three tubes (point C—Fig. 1) and the sum of the mass of steam condensed on the three tubes. The temperature of the steam remained constant

Table 3 Data of enthalpy balance for water and skim milk experiments performed at a total heating power of 25.20 ± 0.05 kW

Run	Q_1^a (kW)	Q_{cw}^b (kW)	Energy losses ^c (%)	SEC ^d (kJ·kg ⁻¹ of water)	EE ^e (%)
Water	0.05 ± 0.00	23.64 ± 0.29	6%	$3,243 \pm 102$	70%
Milk first run	0.03 ± 0.00	23.40 ± 0.35	7%	$3,024 \pm 93$	79%
Milk second run	0.05 ± 0.00	23.64 ± 0.11	6%	$2,889 \pm 97$	81%

Average ($n = 3$) \pm standard deviation

SEC specific energy consumption, EE energy efficiency

$$^a Q_1 = (\dot{m}_{cc} \cdot H_{cc} + \dot{m}_{cd} \cdot H_{cd}) - \dot{m}_{Pm} \cdot H_{Pm}$$

$$^b Q_{cw} = \dot{m}_{cw} \cdot (H_{cwout} - H_{cw in})$$

^c Calculated according to Eq. 2

^d Calculated according to Eq. 4

^e Calculated according to Eq. 5

at 75 °C for all experiments. In this case, it was assumed that all energy exchanged between the steam and the product corresponded to latent heat, and consequently the steam temperature measured at point C (Fig. 1) was the same as for the steam condensate (75 °C). The pilot-scale evaporator could thus be considered as a full latent heat exchanger.

The enthalpy balance data for the experiments performed with skim milk and water are given in Table 3. There was no significant variation ($p < 0.05$) in the enthalpy balance error for the experiments. The difference between the inlet and outlet enthalpy values represented the heat loss \dot{q}_p (Eq. 2) by radiation and convection to the surrounding air. Such loss is variable and difficult to measure, depending on factors such as the nature of the steel (state of polish), the temperature difference between the surfaces of the evaporator and ambient air, etc. In industrial single-stage evaporators, an allowance is made for heat loss up to 1% (Jebson and Iyer 1991), but with this pilot-scale evaporator, this energy loss was expected to be greater as the scale was reduced.

As previously explained, SEC (Eq. 4) is a parameter used to evaluate the economic aspects of concentration: the higher the SEC, the greater the cost of the operation. With a single-stage evaporator operating at the evaporating temperature used in this study, an optimal value of SEC of about 2,358 kJ·kg⁻¹ would be expected without energy loss. For the experiments with skim milk, there was no significant variation ($p < 0.05$) in the SEC and this value was lower than the values obtained with water (Table 3), in agreement with the evaporation rate (Table 2). Energy efficiency was calculated to provide a better evaluation of the process yield (Eq. 5). This parameter can be interpreted as the percentage of energy gained from the steam which is used for evaporating 1 kg of product. As expected from the SEC results, there was no significant variation ($p < 0.05$) in the energy efficiency for the experiments with skim milk, and it was higher than the values obtained for the experiments with water. The average values were close to 80% for experiments with skim milk and 70% for experiments with water (Table 3), the difference from 100% (in a theoretical one-stage vacuum evaporator) corresponding to the heat loss and discharge of part of the

steam to drain away. Experiments conducted with water at other heat fluxes showed similar energy efficiency values, demonstrating that the energy from the steam is always produced in excess in this pilot evaporator, thus leading to a lower energy yield.

3.3 Overall heat transfer coefficient

To complement and confirm the results obtained, the overall heat transfer coefficient for each tube and for all three products was calculated. The results are shown in Table 4.

The heating power used in this process was 8.40 ± 0.02 kW for each tube. The diameter of the first tube was greater than the other two (36 mm vs. 23 mm). The heat flux in the first tube, calculated according to Eq. 3, was therefore lower than in the other tubes. The temperature difference between the steam and the product was the same for all the products ($p < 0.05$). This temperature gap was greater than that applied industrially, which is generally less than 10 °C (Adib et al. 2009). In our study, the temperature difference was greater because the heating power used in each tube (8.40 ± 0.02 kW) was higher than needed and steam was produced at 75 °C.

The overall heat transfer coefficient (U), calculated according to Eq. 3, was the same ($p < 0.05$) in the first tube for all products (Table 4), i.e., an average value of 1.24 $\text{kW}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$, whereas it was close to 1.96 $\text{kW}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$ in the other two tubes. Jebson and Chen (1997) obtained values of U between 0.8 $\text{kW}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$ and 3.08 $\text{kW}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$ for whole milk measured from several milk powder factories; Jebson and Iyer (1991) found values of U between 2.00 $\text{kW}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$ and 3.50 $\text{kW}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$ for skim milk concentrated in five-effect evaporators; Prost et al. (2006) reported values of U between

Table 4 Calculated values of heat transfer coefficient and operating parameters for each tube of the vacuum evaporator

Product	Tube no.	Φ ($\text{kW}\cdot\text{m}^{-2}$) ^a	$\Delta\theta$ (°C) ^b	U ($\text{kW}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$) ^c
Water	1	18.6	15.10 ± 0.43	1.23 ± 0.04
	2	29.1	15.30 ± 0.36	1.90 ± 0.03
	3	29.1	15.70 ± 0.44	1.85 ± 0.04
Skim milk—1st run	1	18.6	15.00 ± 0.38	1.24 ± 0.03
	2	29.1	15.00 ± 0.32	1.94 ± 0.02
	3	29.1	15.10 ± 0.34	1.93 ± 0.03
Skim milk—2nd run	1	18.6	14.90 ± 0.31	1.25 ± 0.02
	2	29.1	14.80 ± 0.32	1.96 ± 0.02
	3	29.1	14.60 ± 0.29	2.00 ± 0.02

Average ($n = 3$) \pm standard deviation

Φ heat flux, $\Delta\theta$ temperature difference, U overall heat transfer coefficient

^a Calculated according to Eq. 3

^b $(\theta_{v-1} - \theta_{ev})$

^c Calculated according to Eq. 3

$2.08 \text{ kW}\cdot\text{m}^{-2}\cdot^\circ\text{C}^{-1}$ and $2.40 \text{ kW}\cdot\text{m}^{-2}\cdot^\circ\text{C}^{-1}$ for water evaporated in the first effect of a third-effect evaporator.

In these experiments, the heat transfer coefficient was the same for the same operating conditions (Φ , $\Delta\theta$, P_{abs}) whatever the product. This result does not explain why the evaporation rate of skim milk was greater than that of water (Table 2). It is emphasized that the inverse of U is overall resistance resulting from the addition of four resistance levels in a series, where the limiting resistance is generally the value on the product side between the wall and the evaporated liquid, especially at high concentrations (Jebson 1990; Jebson and Chen 1997). This value depends on several factors:

- Physical properties of the product treated (viscosity η_p , density ρ_p , surface tension σ_p , etc.),
- Process conditions (heat flux Φ , temperature difference $\Delta\theta$, boiling temperature $\theta_{p,\dots}$)
- Nature and geometry of the heating surface (roughness R , etc.).

These three types of parameter influence the values of the heat transfer coefficient of the product side and therefore the values of U .

Thus, the behavior of a product and the efficiency of the evaporation process (SEC, evaporation rate, etc.) cannot be predicted with only its overall heat transfer coefficient.

It should be remembered that the evaporation rate is related to the operation conditions (e.g., distribution system, heat flux, etc.) (Morison et al. 2006) and product characteristics, such as viscosity and surface tension (Pehlivan and Özdemir 2012; Weise and Scholl 2009; Morison et al. 2006; Paramalingam et al. 2000). Moreover, product viscosity has an impact on the thickness and the residence time distribution of the thin falling film. The flow behavior of the product throughout the evaporator is modified according to its viscosity: a thicker and slower thin film should be formed at the end of the skim milk concentration process compared to water. Therefore, the higher level of viscosity might result in a longer residence time of the product in the evaporator and thus a longer time when the product would receive the evaporation energy, thereby increasing the evaporation rate.

4 Conclusions

The effectiveness of a pilot-scale, single-stage falling-film evaporator in the evaporation of water and skim milk was studied, for which a wide range of information was required: information related to the operating conditions as well as information related to the product. It was demonstrated that the evaporation rate of skim milk was greater than that of water in the same operating conditions.

The heat transfer coefficient alone is not sufficient to explain the vacuum evaporation process. It is therefore necessary to investigate further the residence time distribution in the evaporator and the evolution of viscosity and surface tension of the product in order to improve the working of evaporators at their maximum capacity and efficiency.

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Appendix. Mass and enthalpy balances

At the outlet of the evaporator, the inlet mass flow rate of the product was a combination of the mass flow rate of product concentrate and the mass flow rate of secondary vapor that was finally converted in product condensate (Fig. 2).

$$\dot{m}_{P_{in}} = \dot{m}_{cc} + \dot{m}_{cd} \quad (6)$$

As the condenser was an indirect heat exchanger, there was no mixing of the condensate and cooling water. Therefore:

$$\dot{m}_{cw_{in}} = \dot{m}_{cw_{out}} \quad (7)$$

As the steam entering the evaporator tubes was saturated, it is supposed that its condensation was complete and that all the steam was transformed into the condensate at saturation temperature. Therefore:

$$\dot{m}_{v-1} = \dot{m}_{v1} \quad (8)$$

Thus, only the latent heat of vaporization was exchanged:

$$\Delta H_v = (H_{v-1} - H_{v1}) \quad (9)$$

where H_{v-1} and H_{v1} are the enthalpy of evaporation ($\text{kJ}\cdot\text{kg}^{-1}$) of steam and its condensate, respectively.

The heating power Q (kW) provided to the three tubes originated from the condensation of the steam can be calculated according to:

$$\dot{Q} = \dot{m}_{v-1} \cdot \Delta H_v \quad (10)$$

Equation (10) thus makes it possible to calculate the mass flow rate of the steam, whose pressure and temperature are known, as well as the heating power generated by the boilers. Expressing heat loss as \dot{q}_p , the enthalpy balance can be written:

$$\begin{aligned} \dot{m}_{v-1} \cdot H_{v-1} + \dot{m}_{P_{in}} \cdot H_{P_{in}} + \dot{m}_{cw_{in}} \cdot H_{cw_{in}} = \dot{m}_{cc} \cdot H_{cc} + \dot{m}_{cd} \cdot H_{cd} + \dot{m}_{v1} \cdot H_{v1} \\ + \dot{m}_{cw_{out}} \cdot H_{cw_{out}} + \dot{q}_p \end{aligned} \quad (11)$$

By substituting Eqs. (7), (8), and (9) in Eq. (11):

$$\dot{m}_{v-1} \cdot (\Delta H_v) = \dot{m}_{cc} \cdot H_{cc} + \dot{m}_{cd} \cdot H_{cd} - \dot{m}_{P_{in}} \cdot H_{P_{in}} + \dot{m}_{cw} \cdot (H_{cw_{out}} - H_{cw_{in}}) + \dot{q}_p \quad (12)$$

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