Reduction of energy demand during ultrafiltration of goat's milk

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Abstract. This experimental investigation aimed to establish the energy demand depending on the working pressure (0,2 MPa and 0,5 MPa), the feed flow rate (190 dm^3/h and 330 dm^3/h) and the volume reduction ratio (2 and 4) during ultrafiltration of goat's milk by membrane with molecular weight cut-off 10 kDa. The energy demand increased with the rise of all three factors investigated. The most significant effect had the pressure followed by the volume reduction ratio and the feed flow rate. The lowest value of energy demand (12,29 kWh/m^3) was obtained at low levels of all factors (pressure of 0,2 MPa, feed flow rate of 190 dm^3/h, volume reduction ratio of 2).

1 Introduction

The increase in the energy consumption is due to the increase world's population, global economic development, prosperity and industrial productivity. The problem with the environmental protection, ecology and energy efficiency is very acute [1]. The dairy industry is characterized as the largest electricity consumer in the world, which can however be reduced to a considerable extent by introducing relatively simple but effective energy-saving methods and processes [2, 3].

A traditional method for milk concentration is evaporation [4]. It is the second energy intensive process for concentration of milk after drying [5, 6]. The application of evaporation can reduce the product quality due to the adverse impact of heat on thermolabile milk components. The scientific interest is focused on the foundation of low energy alternative processes which can successfully substitute the energy intensive one [7]. Ultrafiltration can be used instead evaporation due to its advantages – low energy costs, novel non thermal environmentally friendly technology that minimizes the adverse effect of temperature rise such as change in phase, denaturation of proteins and alteration of sensory characteristics [8-11]. The knowledge of the main factors and management of energy demand during ultrafiltration is necessary for the successful application of the membrane process in the dairy industry.

The aim of the present experimental investigation was to evaluate the effect of working pressure, feed flow rate and volume reduction ratio on the energy demand during ultrafiltration of goat's milk in order to reduce it.

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2 Materials and Methods

2.1. Materials

2.1.1. Milk

The experimental investigations were performed with a whole goat's milk with trademark „Olympus". The fat content of milk was 3,5 %.

2.1.2. Membrane

Membrane with molecular weight cut-off 10 kDa made from polyacrylonitrile was used for the experiments. A dry-wet phase-inversion method of polymer solutions with a solvent of dimethyl sulfoxide (Sigma Aldrich, Germany) was used for the membrane preparation. After this operation the membrane was heat-treated in an aqueous medium for 10 min at 60 °C.

2.2. Methods

2.2.1. Equipment

The scheme of the laboratory ultrafiltration equipment is shown in Fig. 1. The initial milk was fed from the tank for feed solution (position 10 in Fig. 1) to the replaceable plate and frame membrane module (position 4) using a pump (position 6), where the ultrafiltration was performed. The retentate obtained was moved to the tank (position 10) for recirculation. The permeate was collected in the tank (position 8). The working pressure was changed by the pressure regulator (position 1). The manometers were used for measuring of the pressure before and after the membrane module.

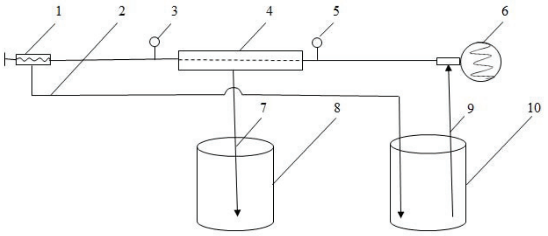

Fig. 1. Scheme of laboratory equipment

1 – pressure regulator; 2 – pipeline for retentate; 3 - manometer (0 MPa to 1 MPa); 4 - replaceable plate and frame membrane module; 5 – manometer (0 MPa to 1 MPa); 6 – 3-frame piston pump; 7 – pipeline for permeate; 8 - tank for permeate; 9 – pipeline for feed solution/retentate; 10 - tank for feed solution/retentate.

The operating conditions during ultrafiltration were: working pressure of 0,2 MPa and 0,5 MPa, feed flow rate of 190 dm^3/h and 330 dm^3/h, volume reduction ratio (VRR) of 2 and 4. The choice of the levels of the factors was based on the results in similar previous our investigation [12]. The working pressure for ultrafiltration is in the range from 0,2 MPa to 1 MPa It is not suitable to use a pressure higher than 0,5 MPa because it is well known that the increase in the pressure over the above mentioned values lead to a relatively constant flux and that's why we recommended to perform ultrafiltration of milk under these conditions (working pressure from 0,2 MPa to 0,5 MPa). The pump used in the installation can assure a minimum volumetric flow rate of 190 dm^3/h and maximum of 330 dm^3/h. The volume reduction ratio was used in dependence of the subsequent production of yoghurts, where the increase of ultrafiltration concentration (over VRR = 4) led to a drastically higher total solid content and embarrass the production of yoghurts. The temperature during all experiments was 20 °C.

2.2.2. Calculation of volume reduction ratio (VRR) and flux

The volume reduction ratio (VRR) was established as follows:

$$VRR = V_0 / V_R \tag{1}$$

Where: V_0 – was the volume of the initial milk, dm^3;
V_R – was the volume of the retentate obtained during ultrafiltration, dm^3.

The flux (J, $dm^3/(m^2.h)$ was calculated as follows:

$$J = V/(A.\tau) \tag{2}$$

Where: V was the permeate volume, dm^3;

$A = 0{,}125\ m^2$ was the membrane area in the module;
τ was the time, h.

2.2.3. Determination of energy demand

The power required by the pump (W_{pump}, W) was estimated using equation (3) [13-15].

$$W_{pump} = (p_1.Q_{feed})/\eta_{pump} \tag{3}$$

Where: p_1 was the pressure at the inlet of the membrane module without considering the hydraulic resistances because they were negligibly small, Pa;

Q_{feed} was the volumetric flow rate, (m^3/s);

η_{pump} was the pump efficiency, $\eta_{pump} = 0{,}7$ according to [15,16], and type and state of the pump.

The energy demand per m^3 of permeate (E, kWh/m^3) was established [16,18]:

$$E = W_{pump}/(J.A) \tag{4}$$

Where: J was the flux according to equation (2), $m^3/(h.m^2)$;
A was the membrane area, m^2.

2.2.4. Statistics

The effect of the pressure (p, MPa), the feed flow rate (Q, dm^3/h) and the volume reduction ratio (VRR) on the energy demand during ultrafiltration of whole goat's milk was analysed by a full multi-factorial experimental design ($N = 2^3$) with three replications at each point of the design. The natural and the coded values of the factors were presented on Table 1.

Table 1. Experimental design with natural and coded values

№	Natural values			Coded values		
	p, MPa	Q, dm^3/h	VRR	X_1	X_2	X_3
1	0,2	190	2	-1,0	-1,0	-1,0
2	0,5	190	2	1,0	-1,0	-1,0
3	0,2	330	2	-1,0	1,0	-1,0
4	0,5	330	2	1,0	1,0	-1,0
5	0,2	190	4	-1,0	-1,0	1,0
6	0,5	190	4	1,0	-1,0	1,0
7	0,2	330	4	-1,0	1,0	1,0
8	0,5	330	4	1,0	1,0	1,0

Regression model for the energy demand was obtained by StatGraph XIV trial version statistical software.

3 Results and Discussion

Table 2 indicates the values of the energy demand depending on the factors investigated. It could be seen that the energy demand (12,29 kWh/m^3) at p = 0,5 MPa, Q = 330 dm^3/h and VRR = 4 was 5,5 times higher than this (67,31 kWh/m^3) at p = 0,2 MPa, Q = 190 dm^3/h and VRR = 2. The results showed that all factors had positive effect on the energy demand.

Table 2. Energy demand depending on the factors investigated

№	p, MPa	Q, dm^3/h	VRR	Energy demand, kWh/m^3
1	0,2	190	2	12,29 ± 0,11
2	0,5	190	2	28,19 ± 0,37
3	0,2	330	2	20,58 ± 0,18
4	0,5	330	2	37,02 ± 0,49
5	0,2	190	4	21,04 ± 0,55
6	0,5	190	4	48,69 ± 1,50
7	0,2	330	4	35,51 ± 1,64
8	0,5	330	4	67,31 ± 0,71

An adequate model with significant coefficients at confidence level of 0,95 for energy demand was obtained:

$$\textit{Energy demand} = 33{,}8288 + 11{,}4754.X_1 + 6{,}27625.X_2 + 9{,}30792.X_3 + 0{,}58625.X_1.X_2 + 3{,}38792.X_1.X_3 + 1{,}99542.X_2.X_3 \qquad (5)$$

$R^2 = 99{,}7\ \%\quad F = 2{,}43 < F_T = 4{,}5$

The standardized chart of Pareto (Fig. 2) showed that all factors and factor interactions were significant. The most significant effect had the pressure followed by the volume reduction ratio and the feed flow rate. This was confirmed by the response surfaces shown in Fig. 3. It is well known that in industrial membrane plants, the electricity used by pumps represents a large part of the operating expenses. Fig. 3 showed that the rise of the working pressure led to an increase in the energy demand because the higher pressure led to a higher power required by the pump and energy consumption respectively [17]. Similar was the effect of the feed flow rate [16]. The use of higher level of ultrafiltration concentration increased the operating time and energy consumption of the pump, respectively [17]. In the experimental work of [16] was established that the energy demand decreased with the increase in the temperature and the decrease in the cross-flow velocity. The authors found that the lowest energy requirement of 2,6 kWh/m^3 was obtained at 80 ºC and 1 m/s. The experimental work of [17] showed the effect of the transmembrane pressure (465 kPa, 672 kPa) and dynamic flux on the total energy requirement and found that the pressure had no significant effect, while the temperature (10 ºC and 50 ºC) reduced the energy requirement. According to [18], the rise in the operational pressure from 3 bar to 6 bar led to an increase in the consumed total energy from 51,57 kJ/dm^3 to 62,54 kJ/dm^3.

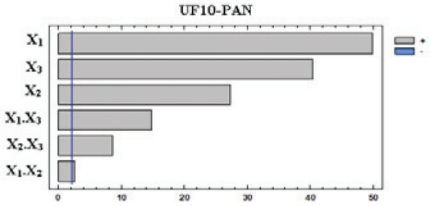

Fig. 2. Standardized chart of Pareto

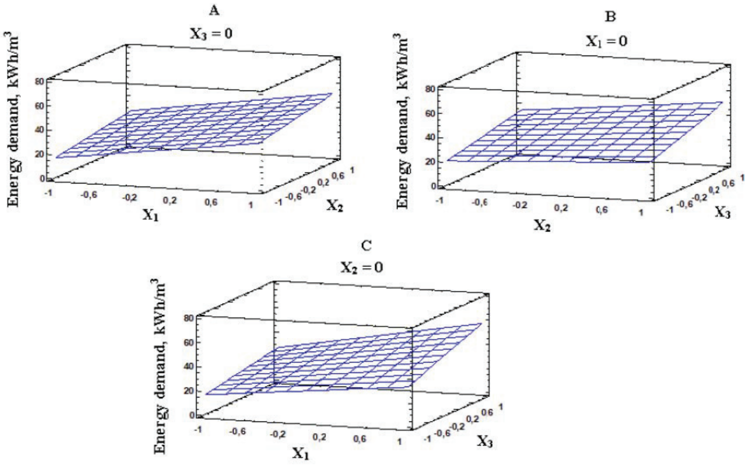

Fig. 3. Response surfaces of the energy demand of UF10-PAN membrane depending on the factors investigated (A – working pressure and feed flow rate; B – feed flow rate and volume reduction ratio; C – working pressure and volume reduction ratio).

The optimization of the process factors (Table 3) showed that the lowest value of the energy demand was 12,29 kWh/m^3 at low levels of all factors investigated. Therefore, we recommend following these levels of the operating factors in order to minimize the values of the energy demand and the operating expenses respectively.

Table 3. Optimization of the levels of the factors investigated

Factor	Low	High	Optimum
Factor X_1	-1,0	1,0	-1,0
Factor X_2	-1,0	1,0	-1,0
Factor X_3	-1,0	1,0	-1,0

Note: The optimum corresponded to the lowest value of energy demand.

Conclusions

The establishment of optimal values of operational factors of each technological process and equipment improves their energy and economic efficiency. The lowest energy demand (12,29 kWh/m^3) in the range of the variation of the factors was achieved at pressure of 0,2 MPa, feed flow rate of 190 dm^3/h and volume reduction ratio of 2. These levels of factors have to be used in order to minimize the energy demand during ultrafiltration of goat’s milk.

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