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MODELLING THE PARTIAL DEMINERALIZATION PROCESS OF COW MILK BY SUPERPRO DESIGNER

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Milk and dairy products contain a number of biologically active compounds (proteins, lipids, vitamins and minerals) that are essential for human nutrition. The most common procedures for demineralization are based on ion exchange-, nanofiltration- and electrodialysis-based technologies. In this study, the application of membrane filtration-based partial demineralization of cow milk was investigated and the process modelled. Using design equations, the partial demineralization process was designed and the economy of the process calculated. The modelling and simulation of the partial demineralization process was carried out by the SuperPro Designer programme. As the first step the unit operations of the demineralization technology were defined using the tools of the programme. The SuperPro Designer possesses industrial tools with reactor models, chemical components, a database of mixtures, and price estimations. By analysing the influence of the operation parameters, the feasibility of the proposed process was investigated. From the results of the modelling it can be concluded that the partial demineralization process can be successfully implemented, achieving the expected demineralization rates with a relatively good payback time of two years.

Keywords: partial demineralization, SuperPro Designer, modelling, economic analysis

1. Introduction

Dairy products play an important role in the health of humans as milk contains a number of biologically active compounds (proteins, lipids, vitamins and minerals). Therefore, the consumption of milk and dairy products is highly recommended [1-2]. Milk is the main raw material in the cheese and casein industry. The disposal of whey creates a major environmental problem for the cheese industry due to the high amount of organic compounds it contains. In the cheese industry to manufacture 1 kg of cheese, 9 kg of whey is produced as a by-product. Whey possesses a large 'biochemical oxygen demand' (BOD) value, therefore, treatment is required before it is released into the environment or recycled. Suárez [3] observed that the nanofiltration membrane is an effective medium for the demineralization of whey. The demineralization efficiency depends on the transmembrane pressure and the volume concentration ratio (VCR). Experimentally, monovalent ions exhibit the highest degree of permeation. [3]

Whey is a watery, dilute liquid, which generally contains 0.8-1.0% total protein, 4.5-5.0% lactose, 0.5-0.7% minerals and 93-94% water. Whey can be divided into two different compositions, namely sweet and acid whey [4]. Another process as part of the treatment of whey is demineralization. Upon demineralization, whey can be used for manufacturing drinks, desserts or ice-cream products. A novel alternative process for demineralization is nanofiltration. Nanofiltration is a membrane separation method that lies between ultrafiltration and reverse osmosis. Nanofiltration membranes can maintain monovalent ions (NaCl) and also organic compounds between 300 and 100 in the Dalton range. Nanofiltration is an effective technique to remove salts, while preserving valuable components [5].

In order to examine the feasibility of the process, technological and economic experiments were carried out by the SuperPro Designer software [6]. This programme is widely used in the pharmaceutical, biotechnology and food industries. The SuperPro Designer is capable of preparing technological and economic documentations and reports about the modelled process. The programme possesses an industrial tool, where the unit operations (reactions, solid/liquid separation, tanks) can be prepared [7]. The purpose of this study is to model the demineralization process using the SuperPro Designer programme and by analyzing the influence of the operation parameters, the feasibility of the proposed process was investigated.

2. Experimental

2.1. Materials and Methods

In this study, one ultrafiltration (UF) and two nanofiltration (NF) membranes were used. The first step was the pre-concentration of milk using the UF

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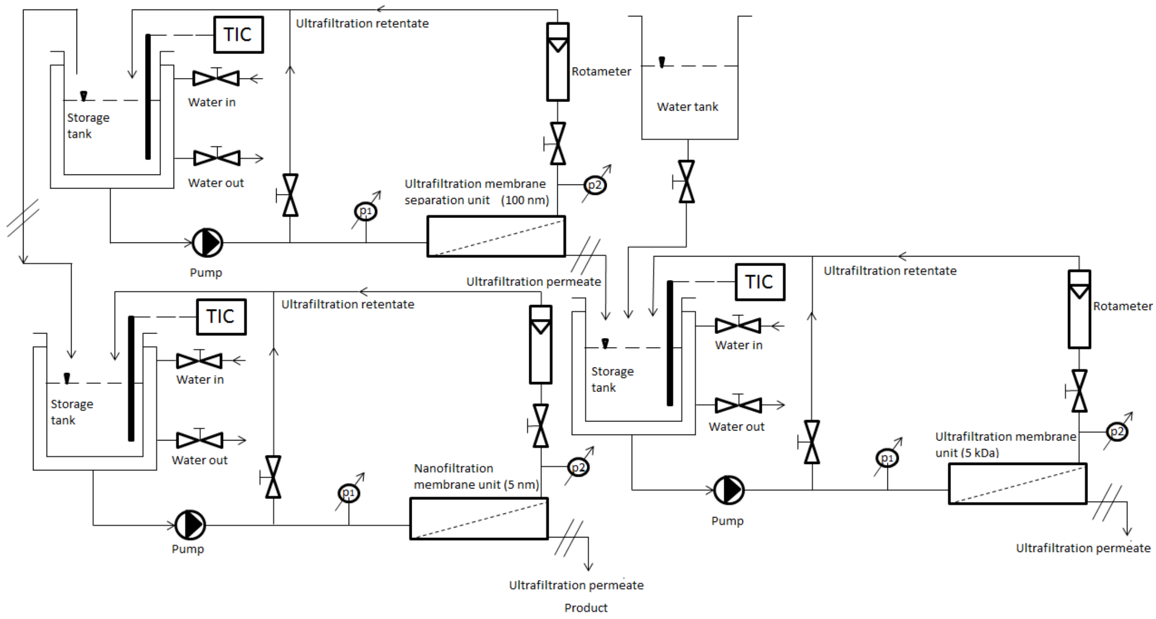

Figure 1. Process flow diagram of the demineralization of cow milk.

membrane. A Schumasiv type 100 nm pore size membrane was used for the pre-concentration phase, a Schumasiv type 5 nm pore size membrane for nanofiltration of the ultrafiltration retentate, and a Membralox type 5 kDa membrane for nanofiltration of the ultrafiltration permeate. The experiments were carried out using ultra- and nanofiltration units in a laboratory unit designed by the Department of Food Engineering. The effective area of the membranes was 0.005 m^2. The milk sample was circulated at a constant temperature (21±1 ºC) maintained by a thermostat. The optimal working parameters were measured during an experimental design in both the UF and NF processes. During the UF process the transmembrane pressure was 1.5 bars and the recirculation flow rate was 150 $dm^3\ h^{-1}$. In both NF processes, the transmembrane pressure was 2 bars and the recirculation flow rate was 200 $dm^3\ h^{-1}$. The transmembrane pressure and the recirculation flow rate were controlled by regulating valves.

2.2. Process simulation

The partial demineralization process was modelled using SuperPro Designer software version 8.5 by Intelligen, Inc. The main target task was partial demineralization. The SuperPro Designer software possesses an industrial tools section, where models of reactors, chemical components, a database of mixtures, price estimations and economic evaluations can be used.

Table 1. The characteristics of the membranes used.

Membrane type	Process parameters	
	Pressure, bar	Flow rate, $dm^3\ h^{-1}$
UF (100 nm)	1.5	150
NF (5 kDa)	2.0	200
NF (5 nm)	2.0	200

The parameters used were calculated from laboratory experiments as shown in *Table 1*.

Firstly, The SuperPro Designer tool was used to install the unit operations. The first unit is the ultrafiltration system. The raw milk enters the system and is separated into its permeate and retentate. In the next step, the two fractions are transferred to each diafiltration unit. Another major step is the definition of essential material streams for milk, the addition of distilled water to the diafiltration unit and the provision of electricity. The diafiltrated, partially demineralized milk and whey components are then sent to the storage tank. The last part of the process is the packaging system, where the products are completed. The demineralized whey is finally loaded into a truck. The mass of the filled entity is 40 metric tons (MT). The basic process flow diagram of the combined partial demineralization of cow milk is shown in *Fig. 1*. The composition of the milk was defined as illustrated in *Table 2.*

In the next step, the transmembrane pressure, flow rate and flux as operating parameters were set and the cost of purchase assigned to each operating unit. The annual operating time is 300 days for this process. The cost of purchase of the ultrafiltration system was set at \$100k, the two diafiltration units at \$75k, the storage

Table 2. The composition of the cow milk considered

Ingredient's name	Mass (%)
Casein	3.4
Fats	3.4
Lactose	5.2
Sodium Chloride	1.0
Water	87

Table 3. Cost estimates for energy supplies

Energy supplies	Price
Steam (High P) [242 ℃]	$10/MT
Steam [152 ℃]	$6/MT
Chilled Water [5 ℃ - 10 ℃]	$0.4/MT
Cooling Water [25 ℃ - 30 ℃]	$0.05/MT
Std. Power	$0.1/kWh

tanks at $75k, and the packaging unit at $50k. In addition, the cost of raw materials was set at $1/kg, of packaging material at $0.1/piece (100g), and of water at $0.1/kg. The product must be sold at a price that is in line with the market conditions (est. $2.2/kg). Each unit operation needs a minimum of one operator, thus the cost of labour was set at a basic rate of $10 per hour. The electricity, cooling and heating energy demands were estimated by the programme (*Table 3*).

3. Results and Analysis

Upon the establishment of costs, technological and economic simulations were executed. The summary of the run simulations for the partial demineralization process yielded the relevant costs, revenue and payback time as shown in *Table 4.* According to the simulation results, the annual total revenue is higher than the operating costs. The production costs are given with and without amortization. *Table 5* summarizes the indices of the project. The 'payback time' or 'return on investment' (ROI) for the partial demineralization process in this case was calculated for four years. The ROI is defined by *Eq. (1)*:

$$\mathrm{ROI}\ (\%) = \frac{\text{annual net profit}}{\text{capital cost}} \cdot 100 \qquad (1)$$

Other important parameters were the 'internal rate of return' (IRR) before and after tax. The IRR is a discount value when the 'net present value' (NPV) is zero. The NPV is determined by calculating the costs and benefits of the technological investment. The NPV is defined by *Eq. (2)*:

$$\mathrm{NPV\ (USD)} = \sum \frac{C_t}{(1+d)^t} - C_0 \qquad (2)$$

Table 4. Summary of economy indices (MP stands for "flow of discrete entity").

total investment	$6,279,438
total annual revenue	$30,315,042
annual operating cost	$28,258,168
annual unit production	$10,800,660
reference rate (MP entity)	
unit product cost (per MP entity)	
including depreciation	$2.62
excluding depreciation	$2.59

Table 5. Summary of project indices (IRR = internal rate of return, NPV = net present value).

gross margin, %	6.78
return on investment, %	24.90
payback time, years	4.02
IRR before tax, %	28.36
IRR after tax, %	18.20
NPV (at 7.00%)	5,381,025

where C_t is the cash flow, t is the lifetime in years, d is the discount rate, and C_0 is the initial investment. If the NPV remains positive, the process will be economically viable [8].

The costs of materials and supplies are shown in *Table 6* with the most expensive item being the raw material (cow milk) while the cost of packaging materials is far less. *Table 7* presents the total cost of the plant for the demineralization process. In addition to purchasing the equipment, other costs were the piping, instrumentation, and electrical, building and construction fees.

According to the simulated revenues of the partial demineralization process, the production of milk and lactose solution cost $2.2 and $0.3 per kg, respectively. Assuming that the demineralized whey is transferred into a truck, it can be sold to food industries for $40 per metric ton. The composition of the demineralised whey in the form of lactose solution is 4.3% lactose, 0.8% NaCl and 95% water, which is suitable for the production of candy, yoghurt and ice cream. It is also important to consider the cost of waste treatment. The SuperPro Designer generated two different costs, namely those of utilities ($25k) and transportation ($874k).

4. Conclusion

This study examined the feasibility of the partial demineralization process which was successfully

Table 6. Summary of the costs of materials (in USD per kg annually).

raw materials	unit	amount	cost
milk	$1.00	21,766,316	21,766,316
water	$0.10	10,879,641	1,087,964
packaging material	$0.20	10,800,661	2,160,132
total	-	-	25,014,412

Table 7. Total cost of the plant (in thousands of USD).

equipment purchase	$563k
installation	$266k
process piping	$197k
instrumentation	$225k
insulation	$17k
electrical	$56k
buildings	$253k
yard improvements	$84k
auxiliary facilities	$225k
engineering	$472k
construction	$66k

modelled by the SuperPro Designer software. According to an economic evaluation, the net present value, return on investment, and internal rate of return were \$5.3Million for four years, 28% and 18%, respectively. The revenues of the products were \$2.2 per unit and \$0.3 per kg (or \$40 per metric ton) for the milk and lactose solution, respectively. Future research will focus on the optimization of costs and exploration of alternative ways of recycling whey.

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