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Nanofiltration of UHT flash cooler condensates from a dairy factory: Characterisation and water reuse potential

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HIGHLIGHTS

► Flash cooler condensates were characterised to evaluate their potential reuse.
► A 200 Da nanofiltration unit was used to reduce the pollutant load of wastewater.
► The influence of operating conditions on permeate flux and quality was studied.
► The volume concentration ratio was a limiting factor on the final design proposed.
► An economic estimation, based on costs and savings, was carried out.

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ABSTRACT

The large consumption of water in the dairy industry makes water reuse a crucial issue. Flash Cooler (FC) condensates from direct ultra high temperature (UHT) treatments were characterised and nanofiltered in order to obtain potentially reusable water depending on the limitations of its end uses. A nanofiltration (NF) pilot plant (1.6 m^2 membrane area) with a SelRO MPS-34 2540 B2X (Koch Membrane Systems) was used for these purposes. The influence of operating conditions (transmembrane pressure (TMP), temperature, time and water recovery) on permeate flow rate (J) and quality (conductivity, chemical oxygen demand (COD), total organic carbon (TOC) and Ca^{2+}) was studied. Heating (taking into account the thermal potential of condensates) and other miscellaneous objectives were achieved, a volume concentration ratio (VCR) of 8 being set as a design parameter. The experimental data was used to design a NF plant with 20 m^3/h feed capacity whose savings and operating costs were estimated at 2.807 and 0.777 €/m^3, respectively.

1. Introduction

Milk industries consume large amounts of water in different parts of their facilities (washing, rinsing, cleaning-in-place steps (CIPs), pasteurising, UHT processes, chilling, cooling, steam production, etc.). Water consumption varies between 1.5 and 5 L per litre of treated milk [1,2] depending on the type of industry.

Increasing water prices advise look for techniques not only to reduce water consumption, but also to reuse it in the plant. Industries with lower water/milk ratios correspond to those which recover different condensates, mainly from evaporation and drying. Spent cleaning CIP solutions are recommended for partial reuse since they represent one third of the total milk wastewater. Several techniques have been assayed to reduce the pollutant load of wastewaters generated by food industries in general, and dairy industries in particular: flocculation, deep filtration, coagulation, etc. Membrane technologies (MTs), ranging from microfiltration (MF) to reverse osmosis (RO), are among the most promising techniques due to their consideration as "clean technologies". Single MT steps have been used in many published research studies to produce water of different qualities [2,3]. One-step ultrafiltration (UF) experiments were performed by Sarkar et al. [4] and Chollangi and Hossain [5], but obtained permeates did not fulfil the quality levels to reuse the water. UF processes only reject proteins, passing lactose and other small molecules through the membrane, which leads to high values of COD in dairy wastewater permeates [6]. In other cases, a combination of different technologies has been adopted to obtain higher quality water [1,6–11]: pretreatment with cartridge filtration followed by ultraviolet (UV) disinfection and NF [1], an UF operation prior to a NF step [6], single NF or two-pass RO [10], pretreatment followed by nanofiltration (step 1) and nanofiltration or reverse osmosis (step 2) and ending with UV disinfection [12], NF followed by RO [13,14], etc. Vourch et al. [2] studied 11 dairy plants using RO as a technique to recover water. They reported the heterogeneity in composition and studied the negative effect of condensate storage on the final pollutant charge. In that study, RO allowed the reuse of permeates in the plant as cooling–heating waters. Water recoveries of 95% were possible with constant

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Nomenclature

Abbreviations

FC	Flash cooler
UHT	Ultra high temperature
NF	Nanofiltration
COD	Chemical oxygen demand
TOC	Total organic carbon
VCR	Volume concentration rate
CIP	Cleaning in place
MT	Membrane technology
MF	Microfiltration
RO	Reverse osmosis
UF	Ultrafiltration
UV	Ultraviolet
BOD_5	Biological oxygen demand (five days)
NTU	Nephelometric turbidity unit
TSS	Total suspended solids
MWCO	Molecular weight cut-off
TS	Total solids
SDI	Silt density index
ASTM	American Society for Testing and Materials
I.C.	Intermediate cleaning
F.C.	Final cleaning
CFU	Colony forming unit
P.R.	Permeability reduction
R	Rejection
st	Short time
lt	Long time
NPV	Net present value
IRR	Internal rate of return

Symbols

TMP	Transmembrane pressure (bar)
J	permeate flow rate (L/h m^2)
V_f	Feed volume (m^3 or m^3/h)
V_r	Retentate volume (m^3 or m^3/h)
V_p	Permeate volume (m^3 or m^3/h)
R	Rejection (%)
C_f	Feed concentration (mg/L)
C_p	Permeate concentration (mg/L)
h	Hours

permeate flow rates of 11 L/h m^2. Baskaran et al. [15] studied several Australian wastewaters from milk powder industries in order to reduce valuable organic products and reuse permeates after treatment with MTs.

One of the aspects to bear in mind when selecting the type of membrane treatment is that of deciding on the desired quality of the permeate, as this affects both the technology (MF-RO) and the process conditions used (effect of pressure, feed concentration, pH, etc., on membrane selectivity). Different water specifications depending on its end use can be seen in Table 1. The highest possible water quality is required when the aim is to reuse water to produce steam. Its main properties must include a low Ca^{2+} content as well as low conductivity and a low concentration of soluble solids. Water for boilers is only obtained using RO, combining two NF steps or sequences of NF and RO. The characteristics of water that is to be used in cleaning and watering are less restrictive and, in these cases, simple processes can be sufficient to achieve the purpose. Bacteriological control is of paramount importance when the reused water may come into contact with food (heat exchangers, etc.).

Table 1
Water specifications according to end uses.

Parameter	Boiling water[a]	Cooling–heating water[a]	Water for cleaning[a,b]	Process[a,b]	Other uses[a,c]
pH	7–10	6.9–9.0	6.5–9.0	6.5–9.5	6–9
Conductivity (25 °C), μS/cm	<40	1000	<200	2500 (20 °C)	/
COD, mg O_2/L	<10	75	/	<5	43[d]
TOC, mg O_2/L	<4	14[d]	<4	<4	16[d]
BOD_5, mg O_2/L	1–50	25	/	/	30
Ca^{2+}, mg/L	<0.4	240	<1	<400	/
Total suspended solids, mg/L	0.5–10	100	35	/	<20
Turbidity, NTU	/[e]	50	/	<5	<10
Colony count/1 mL	/	/	<100	<100	/
E. coli/100 mL	/	/	ND[f]	ND	<200
Coliform bacteria/100 mL	/	/	ND	ND	<200

[a] Adapted from Mavrov et al. [11], Judd and Jefferson [16], Spanish legislation [17,18] and the US Environmental Protection Agency [19].
[b] Water used in the industry for production processes, equipment cleaning, heat-exchangers, etc., which could be in contact with food (must be drinking quality water).
[c] Watering, fire protection systems, industrial washing of vehicles, etc.
[d] Using the most unfavourable correlation between COD, TOC and BOD_5 (BOD_5/COD = 0.7 and BOD_5/TOC = 1.85).
[e] No limitation found.
[f] Not detected.

The heterogeneity of dairy industry wastewaters is summarised in Table 2, in which values of conductivity, pH, COD, TOC, total suspended solids (TSS) and residual hardness are used as the main properties to define the pollution load of the wastewater and permeates. Condensates from evaporation and drying may be considered low pollutant waters according to Chmiel et al. [1] and Mavrov and Bélières [12], while end pipe wastewaters need intense treatment to obtain clean water.

Segregating wastewater streams or "in situ" wastewater treatment before mixing with other currents can be a wise practice. It has the advantages of optimizing water use and the treatments to reuse the water produced by MT, adapting the water composition to the most suitable technology to obtain a certain water quality. Automatic online monitoring of each stream for pH, conductivity and turbidity is recommended to control and isolate water streams with a similar composition which could be processed using similar technology.

FCs are present in all food industries when direct UHT treatment is used and consist in a vacuum chamber into which the sterilised product is sprayed. The degree of vacuum is regulated to remove the amount of vapour which was previously diluted into the product through direct heat treatment.

Water streams from FCs and condensates from evaporation and drying processes represent an important percentage of the total wastewater generated in the factory (between 20 and 40%) [2]. These streams can be considered as having a low pollutant load [1]. However, their composition fluctuates strongly depending on several factors such as the type of product that is being treated, the stability of the operation and the moment at which the FC is working (cleaning, production, etc.), making it necessary to continuously inspect and monitor condensate quality.

The benefits of water recovery from FCs may be twofold, providing savings in water consumption as well as in the recovery of heat energy. Steam condensates can be reused in numerous areas of the plant such as boiler and cooling tower feed water, CIP systems, reconstitution of powdered products, cheese curd wash water, dryer wet scrubbers, indirect heating (via heat exchange) and pump seal water, depending on the quality of the water. Recovering the steam condensate from boilers and steam distribution systems can significantly reduce operating costs, the use of chemical and the amount of makeup water required by the boiler. A condensate return system also reduces