Contents lists available at ScienceDirect

Food and Bioproducts Processing

journal homepage: www.elsevier.com/locate/fbp

A mathematical model based parametric sensitivity analysis of an evaporative crystallizer for lactose monohydrate

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ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form 16 September 2015
Accepted 22 September 2015
Available online 9 October 2015

Keywords:
Evaporative crystallizer
Lactose
Mathematical model
Sensitivity analysis
Operation guideline
Simulation

ABSTRACT

Lactose is produced from whey by crystallization after a series of concentration steps. Evaporative crystallization is the process where both concentration and crystallization occur simultaneously. There is no current literature on an industrial scale evaporative crystallizer producing lactose monohydrate. Crystal size is the most important output parameter for the lactose crystallization process. In order to understand the effect of various operational and kinetic parameters on the final crystal size coming out of the crystallizer, a mathematical model was developed to mimic the operation of the industrial unit. The model includes mass and crystal population balances along with mutarotation and nucleation kinetics for lactose. A sensitivity analysis was conducted by simulating the developed model for a range of values for parameters like residence time, evaporation rate, crystallizer temperature and growth and nucleation kinetics. It was found that the secondary nucleation rate was the factor most affecting the crystal size. The crystal size and dissolved lactose data from the industrial unit were collected and fitted to the model predictions to estimate the crystallization kinetics of lactose in the industrial unit. Based on the simulation results, operational and design guidelines for an evaporative crystallizer were laid down.

1. Introduction

The extraction of lactose from whey and milk permeates is achieved using the processes of concentration and crystallization. These occur together during the evaporative crystallization of lactose manufacturing. The use of evaporative crystallization in lactose manufacturing is unique to the New Zealand dairy industry. Despite being in operation for many years, the dynamic operation of the evaporative crystallizers still present challenges, particularly around controlling the crystal size distribution (CSD). Crystal size is important for both edible lactose and refined/pharmaceutical manufacture for two reasons; first, the particle size has a large impact on the final yield, as small crystals are difficult to separate and process in the post-crystallization unit operations and second, size is the defining parameter used to separate the different specifications of lactose.

The industrial unit being studied in this work is an industrial forced circulation (FC) crystallizer which consists of a vessel for evaporation and crystallization, and the circulation

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http://dx.doi.org/10.1016/j.fbp.2015.09.009
0960-3085/

Nomenclature

C_α	dissolved α-lactose concentration [kg (kg of solution)$^{-1}$]
C_β	dissolved β-lactose concentration [kg (kg of solution)$^{-1}$]
$C_{\alpha s}$	equilibrium solubility of α-lactose [kg (kg of water)$^{-1}$]
C_{LS}	equilibrium solubility of lactose [kg (kg of water)$^{-1}$]
C	total dissolved lactose concentration [kg (kg of solution)$^{-1}$]
C_c	crystal content of slurry [kg (kg of slurry)$^{-1}$]
B_s	secondary nucleation rate [# min^{-1} (kg of slurry)$^{-1}$]
B_p	primary nucleation rate [# min^{-1} (kg of slurry)$^{-1}$]
$D[4,3]$	volume weighted mean diameter [μm]
F	correction factor for α-LMH solubility
G	growth rate [μm min^{-1}]
K_m	mutarotation rate constant
L	bin size/crystal size [μm]
M	mass of the slurry present in the crystallizer [kg]
Q	mass flow rate [kg min^{-1}]
T	crystallizer temperature [°C]
b	secondary nucleation rate order
g	growth rate order
j	exponential dependence of secondary nucleation on crystal content
p	primary nucleation rate order
k_{evap}	evaporation rate [kg min^{-1}]
$k_{n,p}$	primary nucleation rate constant [# min^{-1} (kg of slurry)$^{-1}$ ((kg of α-LMH) (kg of water)$^{-1}$)$^{-b}$]
$k_{n,s}$	empirical secondary nucleation rate constant [# min^{-1} (kg of crystal)$^{-1}$ ((kg of α-LMH) (kg of water)$^{-1}$)$^{-b}$]
k_g	growth rate constant [μm min^{-1} ((kg of α-LMH) (kg of water)$^{-1}$)$^{-g}$]
m	mass of single crystal [kg]
m_0	0th moment of CSD [# (kg of slurry)$^{-1}$]
m_1	1st moment of CSD [m (kg of slurry)$^{-1}$]
m_2	2nd moment of CSD [m^2 (kg of slurry)$^{-1}$]
m_3	3rd moment of CSD [m^3 (kg of slurry)$^{-1}$]
m_4	4th moment of CSD [m^4 (kg of slurry)$^{-1}$]
$n(L)$	population density of crystal size L [# (kg of slurry)$^{-1}$ (μm)$^{-1}$]
n_p	primary nucleation rate order
t	time [min^{-1}]

Greek symbols

ρ	density [kg m^{-3}]
φ	voidage [(kg of solution) (kg of slurry)$^{-1}$]
$1-\varphi$	crystal content of slurry [(kg of crystalline lactose) (kg of slurry)$^{-1}$]
τ	residence time [min]

Subscripts

f	feed
o	outlet
c	crystal

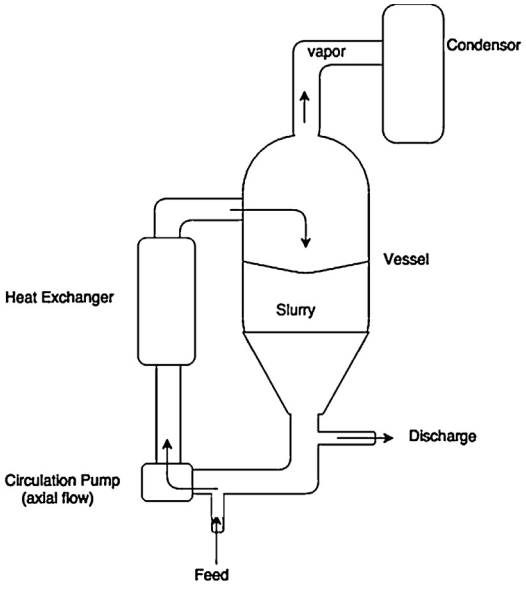

Fig. 1 – A schematic diagram of the forced circulation crystallizer.

circuit consisting of a pump and heat exchanger (Fig. 1). An axial flow pump forces the slurry of crystal and mother liquor through the heat exchanger, where it gains the heat of vaporization before entering the vessel where boiling occurs under vacuum. Residence time in the vessel allows for the crystal to grow. The forced circulation aids in heat transfer, maintaining a homogenous suspension and effective distribution of the generated supersaturation throughout the crystallizer. This helps in keeping the supersaturation within the metastable zone limit, preventing primary nucleation (Mersmann, 2001).

During crystallization, complex feedback interactions occur between the crystals formed and the kinetics that give rise to crystals, namely growth and nucleation rates which in turn depend on the supersaturation and hydrodynamics existing inside the crystallizer. This is shown in Fig. 2. The intent is to model these interactions as occurring in the industrial crystallizer and to perform a parameter sensitivity analysis to determine what factors most affect the crystal size. Based on the analysis results specific design and operation guidelines for evaporative crystallization are suggested. The understanding gained is also used to determine the kinetic parameters of

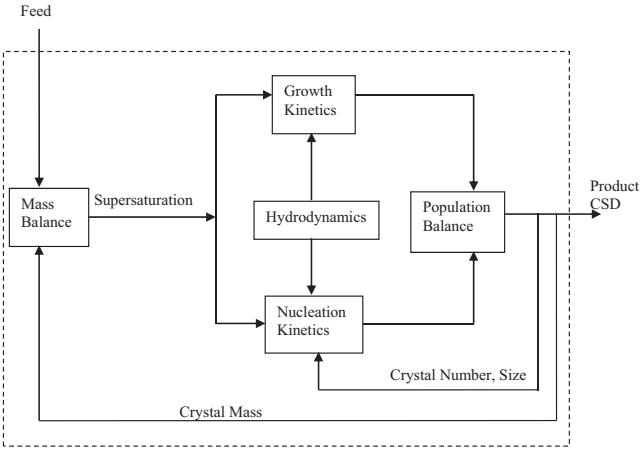

Fig. 2 – Feedback interactions between various factors effecting crystallization [adapted from Randolph and Larson (1988)].