Contents lists available at ScienceDirect

Food and Bioproducts Processing

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

Effect of thermo-compression on the design and performance of falling-film multi-effect evaporator

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ARTICLE INFO

Article history:
Received 30 July 2014
Received in revised form 18 June 2015
Accepted 2 July 2015
Available online 16 July 2015

Keywords:
Evaporation with thermo-compressor
Falling-film evaporator
Heat transfer area
Economy of the evaporation system
MINLP problem.
Visual C++ Interface.

ABSTRACT

Thermo-compression is used in food evaporators to avoid thermal damage and reduce steam consumption. Thermo-compression has not been analysed in multi-effect food evaporator systems. For this study, an evaporation system for milk using thermo-compression was analysed. The proposed software, FEVAT (falling-film evaporation design), considers the optimization of the cost of the evaporation system and an iterative method to solve the balances of material and energy, design equations and a thermo-compression model. The FEVAT interface introduces thermo-physical properties of the foodstuff in function of composition and temperature. In order to determine the influence of the thermo-compression parameters in the simulation, a series of numerical experiments was proposed whereby the thermodynamic efficiency of the thermo-compressor, source of the steam recycling and the effect percent of recycle were varied, one by one. The results showed that the economy of evaporation is proportional to the percentage of steam recycling and the position of the effect that recycles the steam and inverse to the thermodynamic efficiency of the thermo-compressor. In this study the limiting conditions of the operation of the thermo-compressor were obtained that can be applied to other evaporation systems with different foodstuffs.

1. Introduction

Evaporation is a unit operation that consists of the concentration of solutions by extracting the greatest amount of water possible. Foodstuffs undergo the evaporation process to lengthen their lifespan, reduce storage volume or to obtain a specific consistency. Thermally-sensitive foods are processed in evaporators that do not harm the product using low temperatures and a short residence time (Simpson et al., 2008), as in the case of a falling-film evaporator (Minton, 1986). Evaporation is a process that requires a considerable amount of energy, it is therefore important to consider minimizing steam consumption during the design phase. In this study, evaporation is carried out in multiple effects or stages and includes a thermo-compressor that enables steam to be recycled.

The design of an evaporation system, in a stable state with low energy consumption begins with a determining the operating conditions such as temperature and pressure. Subsequently, the energy consumption must be calculated from the balance of material and energy. This can be numerically complex in two instances, firstly when there are a large number of effects or secondly when the solution to be

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http://dx.doi.org/10.1016/j.fbp.2015.07.004

Nomenclature

A	Heat transfer area of the effect, m^2
C_D'	Cost of the shell of a diameter of tube *j*, \$/tube
C_L	Cost of the length of a diameter of tube *j*, \$/m·tube
Cp	Heat capacity, J/kg °C
EE	Evaporation energy economy ratio
F	Feed flow mass rate, kg/s
g	Gravity acceleration constant (9.81 m/s^2)
H	Specific enthalpy, J/kg
h	Convective coefficient of heat transfer, W/m^2 °C
J	Set of radii to select
K	Set of effects to send recycling steam to thermo-compressor
l	Length of tube, m
M	Flow mass rate of steam exiting the thermo-compressor, kg/s
MM	Disaggregated variable of *M*, kg/s
N	Number of tubes
n	Number of effects
n_R	Number of effects prior to the recycling of steam
P	Pressure of the effect, kPa
P_D	Discharge pressure in thermo-compressor, kPa
P_I	Pressure of supplied vapour from an effect to thermo-compressor, kPa
Pr	Prandtl number
P_S	Pressure of motive steam, kPa
Q	Heat transfer rate, kW
R_S	Steam ratio
Re	Reynolds number
r	Radius of the tube, m
r_C	Value of radius *j*, m
S	Motive steam mass rate, kg/s
SS	Disaggregated variable of S, kg/s
T	Temperature of effect, °C
T^S	Temperature of the heat source, °C
T_M	Temperature of mix in thermo-compressor, °C
U	Global heat transfer coefficient, W/m^2 °C
V	Steam mass rate, kg/s
V_S	Recycle vapour mass rate to thermo-compressor, kg/s
VSS	Disaggregated variable of V_S, kg/s
x	Solids concentration
x_F	Feed solids concentration
x_S	Solids concentration of the product
Y	Boolean variable of disjunction to select the best effect to send vapour to thermo-compressor
YT	Binary variable for disjunction of selection of tube radii
y	Binary variable of disjunction to select the best effect to send vapour to thermo-compressor

Greek letters

Δr	Thickness of tube, m
δ	Fraction of the vapour flow from an effect to thermo-compressor
ε	Convergence criteria
η	Thermo-compressor efficiency
κ	Thermal conductivity, W/m °C
κ_M	Thermal conductivity of the tube metal, W/m °C
λ	Specific condensation enthalpy, J/kg
μ	Viscosity, kg/m s
ρ	Density, kg/m^3

Superscript

in	Inside of tube
out	Outside of tube
L	Liquid phase
u	Iteration number in sub-problem of material and energy balances
V	Vapour phase
v	Iteration number in sub-problem of thermo-compression
w	Iteration number in sub-problem of calculating the heat transfer area

Subscript

i	Effect number
j	Radius to select
k	Effect to select for sending recycling steam to thermo-compressor
m	Effect as heat source
new	Variable computed
old	Variable in change

concentrated has properties that depend on both temperature and composition. Various techniques have been found to avoid these situations, either using conventional numerical strategies (Lambert et al., 1987; Stewart and Beveridge, 1977) or by iterative methods (Khademi et al., 2009). Once energy consumption has been calculated, it is necessary to determine the operating conditions. The generalized cascade algorithm can be used for this (Stewart and Beveridge, 1977) or alternatively, a temperature route design using flash separators (Khanam and Mohanty, 2010, 2011). Overall design should take into account the optimization of the multi-effect evaporator system as well as determining the operating conditions and energy consumption. Studies such as those involving optimal flow patterns (Nishitani and Kunugita, 1979), minimum utility insights (Westerberg and Hillenbrand, 1988) and cascaded heat representation for the calculation of optimal temperatures (Hillenbrand and Westerberg, 1988) have been carried out to achieve this optimization. These studies preceded the use of empirical models to estimate the global heat transfer coefficient, *U* (Higa et al., 2009; Piacentino and Cardona, 2010) and quadratic programming (Amer, 2009). Rigorous models have been applied to the optimization of climbing-falling-film plate (Ribeiro and Andrade, 2002) and falling film evaporators (Díaz-Ovalle et al., 2013a; Sharma et al., 2011). Another possible optimization strategy is to obtain a response surface by changing the entry variables (flow, composition and the number of effects). This alternative was used to determine optimum operating conditions from experimental data (Zeboudj et al., 2005); optimal evaporation sequences with pre-heating systems (Kaya and Ibrahim Sarac, 2007); optimum number of effects using feed-flow variation (Simpson et al., 2008). The response surface has even been combined with genetic algorithms and neural networks to determine the optimization of annual energy costs (Janghorban Esfahani et al., 2012).

Studies reported on evaporation using thermo-compression include desalination of water where the position of the thermo-compressor has been analysed (Kouhikamali et al., 2011) and the operating conditions of a horizontal tube evaporator (Kamali et al., 2008, 2009). For the processing of foodstuffs, a single effect multi-objective optimization has been proposed (Sharma et al., 2011). However, this strategy does not take into consideration food properties such as the function of temperature and composition.