Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Food Engineering 73 (2006) 320–326
JOURNAL OF FOOD ENGINEERING
www.elsevier.com/locate/jfoodeng

Determination and correlation of heat transfer coefficients in a falling film evaporator

J.S. Prost [a], M.T. González [a,b], M.J. Urbicain [a,b,*]

[a] *Planta Piloto de Ingeniería Química (PLAPIQUI), Camino La Carrindanga Km 7, (8000) Bahía Blanca, Argentina*
[b] *Departamento de Ingeniería Química, Universidad Nacional del Sur (UNS), Alem 1253, (8000) Bahía Blanca, Argentina*

Received 23 July 2004; accepted 22 January 2005
Available online 23 March 2005

Abstract

The aim of the work was to determine the heat transfer parameters of a single effect evaporator under different operating conditions, in order to extrapolate them to a multiple effect unit. The falling film evaporator consisted of 12 stainless steel vertical tubes, 1″ OD and 3 m long, having an evaporation capacity of 240 kg/h. In this unit the conditions of each effect of a multiple effect evaporator were simulated, varying the feed concentration and the pressure, setting in this way the saturation temperature and the transfer regime. Obtained values were correlated by means of an equation that links the heat transfer coefficient with the fluid properties, geometric parameters and flow conditions. Comparison with existing correlations was carried out.

Keywords: Heat transfer; Evaporator; Falling film; Coefficient

1. Introduction

The concentration of a fruit juice is a widely used practice in the fruit juice manufacturing industry, and it has two main purposes: (1) to reduce the volume and weight of the product, with the subsequent lowering of storage, packaging and distribution costs, and (2) to increase the stability of the juice by reducing its water activity, which is a predominant factor in the majority of the mechanisms of deterioration.

Although other methods of concentration such as freezing concentration and reverse osmosis are used nowadays, evaporation is still the most popular due to operational and economic reasons.

Evaporation is a unit operation that eliminates water from a liquid food. If the liquid contains dissolved solids, the concentrated solution can become saturated or oversaturated, with solid crystals deposition.

As fruit juices contain many substances that can be damaged if submitted to high temperatures during relatively long periods, evaporation under vacuum seems to be the logical answer to this problem. When vacuum evaporation is carried out, the boiling point is lowered, and so thermal degradation is minimized.

A falling film evaporator is essentially a shell and tube heat exchanger. Steam condensing on the shell side provides the latent heat that allows the evaporation of a mass of water from the solution flowing in the tube side. Water vapor and concentrated juice, in thermodynamic equilibrium, are then separated. This process can be accomplished in one evaporation body, so the boiling concentrated solution is withdrawn from the unit for further processing and the vapor is condensed in a separated condenser. Such equipment is named "single effect evaporator".

* Corresponding author. Tel.: +54 291 4861700x201; fax: +54 291 4861600.
E-mail addresses: jprost@criba.edu.ar (J.S. Prost), mtgonzal@criba.edu.ar (M.T. González), urbicain@criba.edu.ar (M.J. Urbicain).

0260-8774/$ - see front matter
doi:10.1016/j.jfoodeng.2005.01.032

Nomenclature

A	heat transfer area, m^2
C	condensed steam mass flow rate, kg/s
F	cold stream mass flow rate, kg/s
g	acceleration of gravity, m/s^2
$\hat{h}$	enthalpy per unit mass, J/kg
h	film coefficient, W/(m^2 °C)
h^+	dimensionless heat transfer coefficient, defined by Eq. (8)
k	thermal conductivity, W/(m °C)
L	liquid mass flow rate, kg/s
Pr	Prandtl number, dimensionless
Re	Reynolds number, dimensionless
Q	heat exchanged, W
r	evaporator tube radius, m
R_F	fouling resistance, m^2 °C/W
S	steam mass flow rate, kg/s
U	overall heat transfer coefficient, W/(m^2 °C)
V	vapor mass flow rate, kg/s
x	fractional weight of sucrose, kg sucrose/kg solution
ΔT	temperature difference between hot and cold fluid, °C
ρ	density, kg/m^3
μ	viscosity, Pa s

Subscripts

C	condensate
F	feed
i	inner surface
L	liquid
m	logarithmic mean
o	outer surface
S	steam
V	vapor
w	wall

However, if a high degree of concentration is needed, it is advisable to use more than one smaller unit in series instead of a large one. Under these conditions, the vapor and the solution leaving the first unit are, respectively, the heating medium and the process stream for the second one. For a suitable driving force to exist in the second unit, the solution boiling point has to be reduced, and this is accomplished by reducing the pressure in the evaporation chamber. In this way, a train of evaporators of decreasing pressure in the direction of the heating vapor is obtained.

This type of arrangement is defined as "multiple effect evaporator", and equipments of 3, 4 and 5 effects in series are common in the food industry.

The equations governing the processes occurring at each evaporator are the well known mass and energy balances, and heat transfer rate equation from the hot to the cold stream. Referring to Fig. 1, they can be stated as follows:

Mass balances, steady state:

Cold stream (process, or juice side), overall:

$$F = V + L \tag{1}$$

Cold stream (process, or juice side), dissolved solids:

$$x_F F = x_V V + x_L L \tag{2}$$

Thermodynamic equilibrium relationships state that $x_V \to 0$.

Hot stream (condensing steam): $S = C$ (3)

Energy balances, steady state:

Cold stream (process, or juice side):

$$F\hat{h}_F + Q = V\hat{h}_V + L\hat{h}_L \tag{4}$$

Hot stream (condensing steam): $S\hat{h}_S = Q + C\hat{h}_C$ (5)

Transfer equation:

$$Q = UA\Delta T \tag{6}$$

The inverse of the overall heat transfer coefficient can be written as the addition of all the resistances to heat transfer posed by both fluids boundary layers (convective), and the tube wall and fouling (conductive):

$$\frac{1}{U} = \left(\frac{1}{h_i} + R_{F,i}\right)\frac{A}{A_i} + \frac{\Delta r}{k_w}\frac{A}{A_m} + R_{F,o} + \frac{1}{h_o} \tag{7}$$

Since resistance due to the wall and fouling is considerable lower than that imposed by the liquid films, and of these, the film heat transfer coefficient of the condensing steam is much higher than the other one, the controlling resistance in this system is that imposed by the inner liquid film. Hence, the design of a unit is strongly dependent on the predicted value of this variable, as the calculated area is directly proportional to the overall resistance, and this is controlled by the inner heat transfer coefficient.

The aim of this work was to obtain experimental values of the film coefficient for the evaporating stream under different conditions, and to fit these values to an equation. It is expected that, if a good correlation is