Research Journal of Applied Sciences, Engineering and Technology 10(3): 322-327, 2015
DOI: 10.19026/rjaset.10.2494
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: December 29, 2014 Accepted: January 27, 2015 Published: May 30, 2015

Research Article

Simulation of Sugarcane Juice Evaporation in a Falling Film Evaporator by Variation of Air Flow

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Abstract: In order to concentrate the high viscous solution and prolong the quality, a thin falling film evaporator was used in sugarcane processing. This study was aimed to study the distribution of temperature and concentration along the falling film evaporator. The variable used in this research was liquid flow rate of 0-80 L/h, air flow rate: 1-5 m^3/h and initial juice concentration: 11-14%. The result showed that by increasing air flow rate from 1 to 3 m^3/h and juice flow rate 40 L/h, the juice could be concentrated up to 1.439%. This result was best fit with experimental data with average error of 5.5%.

Keywords: Concentration, distribution, evaporator, falling film, heat, sugarcane juice

INTRODUCTION

The development of concentrated sugar cane mainly has two main purposes:

- To reduce the volume and weight of the sugar cane product, as well as lowering of storage, packaging and distribution costs
- To increase the stability of the sugar cane juice by reducing its water activity, which is a predominant factor in the majority of the mechanisms of deterioration (Prost *et al*., 2006)

The heat evaporation is still considered as favorable process to concentrate sugarcane juice due to its easy operational and economic reasons as compared to freeze drying and reverse osmosis.

Evaporator is a unit operation to reduce water content in the liquid food products. If the liquid contains dissolved solids, the concentrated solution can become saturated or oversaturated, with solid crystals deposition. The sugar cane juices contain many substances that can be damaged if it is submitted to high temperatures during relatively long periods and a falling film evaporator is considered as the best alternative for this juice products. Steam condensing on the shell side provides the latent heat that allows the evaporation of amass 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 This process can be accomplished in one evaporation body, so the boiling concentrated solution is withdrawn from the unit for further processing and the vapor is condensed in a separated condenser (Saravacos *et al*., 1970).

Thin-film evaporation is one of heat and mass exchangers due to movement of molecules from gas phase to liquid phase which caused by condensation (Kern, 1965). The most common thin layer evaporator is vertical thin-layer evaporator which is characterized by small pressure drop and short residence time of the phases in the apparatus, thus contact time of the liquid with hot surface of the evaporator wall is shorter. Therefore, this feature of the evaporator is mostly applied for heat sensitive liquid solutions especially with high viscosity (Palen *et al*., 1994).

There are two main types of the thin-layer evaporator: static type thin-layer evaporator and mechanically agitated thin-layer evaporator. All types are constituted by vertical cylinder heated from the outside, inside which liquid flows off gravitationally on the heated surface. During that flow vaporization of liquid takes place. Two types of thin evaporators are mostly utilized in industries namely static type thin layer evaporator and mechanical thin layer evaporator. These evaporators are distinguished based on their presence of blade for mechanical action or not.

There are few works that deal with heat transfer during the high viscous liquid evaporation process in thin film evaporator. Most of them are devoted to individual heat transfer coefficients determination in case of one component liquid treating (Alhusseini *et al*., 1998). There are mathematical equations that allow determination of individual heat transfer coefficients depending on the conditions of heat transfer.

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Sugarcane is one of important crops in the world especially Indonesia. Most of them are used as the sugar and alcohol production. Due to high content of nutrition, most company use sugarcane as juice. However, the quality of the juice is easily deterioted due to un-optimized in treatment procedures. Mechanism of evaporation of concentrated juice is quite complicated and depends on many factors such as: liquid physical properties, the roughness of the surface (where, vapor bubbles are formed) and heat load (Lonkar *et al*., 1991). Therefore, understanding the heat and mass distribution along the treatment i.e., evaporation is important (Hugot, 1972). This study presents the distribution of temperature and concentration of sugar cane juice during evaporation in a thin film evaporator. These distributions were studied based on the variation of liquid and gas flow rate as well as the initial concentration of sugarcane juice used in the evaporator.

MATHEMATICAL MODEL

The physical model of thin film evaporator used in this study was a vertical tube of height H and a radius R (Fig. 1). The tube wall is subjected to a uniform heat flux. To solve the model, the following assumptions were conducted: the flow is laminar, the temperature is distributed normal in the film, the convection heat transfer is only to axial direction, the physical properties are not temperature dependent and the gas is considered as ideal gas (Liang-Han and Chuan-Hung, 2006).

The governing equation: The momentum equation was derived based on the assumption that the flow was incompressible and axi-symmetric, the solubility of air in the liquid film was negligible, the vapor and liquid phases were in thermodynamic equilibrium at the interface, the addition heat transfer, viscous dissipation and other secondary effects are negligible (Hewit *et al*., 1993).

Momentum equation:

$$\frac{-d(r\tau_{rz})}{dr} + (\rho_L - \rho_G)gr = 0 \quad (1)$$

Energy balance equation for film:

$$V_z \rho_L Cp_L \frac{\partial T_L}{\partial z} = \frac{k_L}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_L}{\partial r}\right) \quad (2)$$

where,

$$V_z = \frac{(\rho_L - \rho_G)g}{4\mu}(R^2 - r^2) - \frac{(\rho_L - \rho_G)g}{2\mu}(R-\delta)^2 \ln\frac{R}{r}) \quad (3)$$

Energy balance for gas:

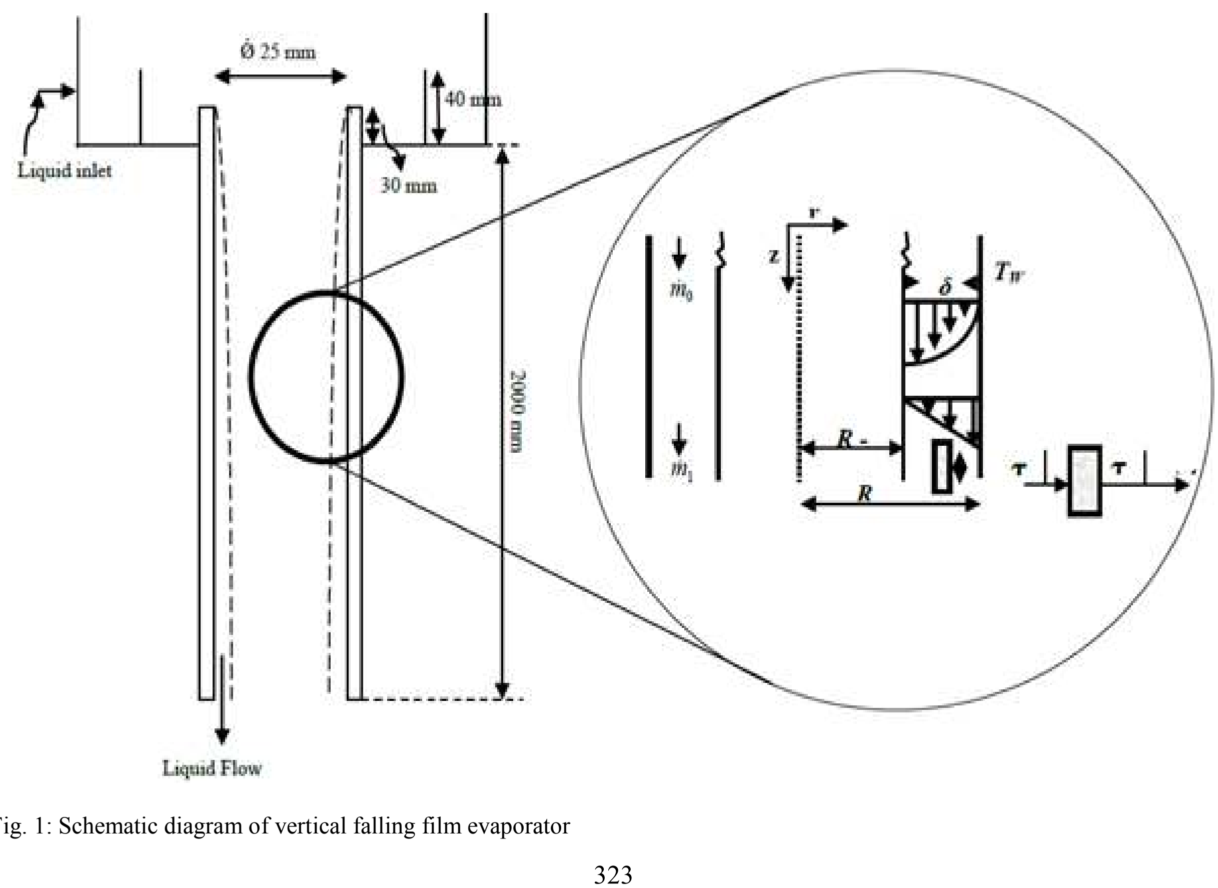

Fig. 1: Schematic diagram of vertical falling film evaporator

$$\rho_G c p_G v_G \frac{\partial T_G}{\partial z} + h_G \left(Ts - T_G\right) = 0 \quad (4)$$

Mass balance total:

$$\frac{\partial F}{\partial z} = -k_y \pi D \left(Y_{AS} - Y_{AG}\right) \quad (5)$$

Gas equation:

$$\frac{\partial y_{AG}}{\partial z} = -k_y \pi D \left(y_{AS} - y_{AG}\right) \quad (6)$$

The boundary condition for these equations is:

$z = 0 \quad T_L = T_{Lin}$ and $z = L \quad T_G = T_{Gin}$

$z = 0 \quad Ca = Ca_{in}$ and $z = L \quad Y_{AG} = Y_{AGin}$

The governing equations for continuity, momentum and energy and species concentration with appropriate boundary conditions are solved by the finite-difference numerical method. A fully implicit numerical scheme in which the axial convection terms are approximated by the backward difference and the radial convection and diffusion terms by the central difference is employed to transform the governing equations into finites differences equations.

RESULTS AND DISCUSSION

Effect of flow rate to temperature distribution: Figure 2 shows the distribution of solution temperature in radial direction.

Figure 2 shows temperature distribution profile in the falling tube from center to the tube side (with diameter of 0.0016 m). Since the heat source is at the surface, therefore the temperature at the tube side is higher than at the center. Figure 2 also confirm that temperature distribution was affected by flow rate of solution. Increasing flow rate of solution, lead to an increase of film thickness and the amount of heating load is greater. This consequently reduces the temperature of the solution.

Figure 3 shows the effect of flow rate to temperature distribution of solution during evaporation in axial direction. In the first 0.25 m, the temperature was drop due to the solution need adaptation to new system in the evaporator before the heat transferring by gas flow rate was exposed to the tube. However, the temperature then gradually increases due to heat accumulation along axial direction. At the interface, there is a phase changes from liquid to vapor due to evaporation.

Figure 4 depicts the temperature of the solution at the column wall at the axial direction increase. This is probably due to the accumulation of heat in the solution. The effect of juice flow rate was evaluated by varying juice flow rate at 40-80 L/h and resulted that increasing juice flow rate will reduce the temperature of solution at the same position. This reduction is caused by film thickness in the axial direction so that the faster propagation of heat which causes the temperature of the solution at the wall increases.

The effect of initial juice concentration to temperature changes has been investigated. Figure 5 shows the temperature profile of different initial juice temperature during evaporation. Increasing concentration of juice will decrease the temperature in the solution. This is due to the fact that the concentration will affect to the viscosity, density and thermal conductivity of the solution. The physical properties are a major influence on the viscosity of the solution. At high concentrated solution, the heat transfer process will be less important, so that the solution temperature changes are also decreases.

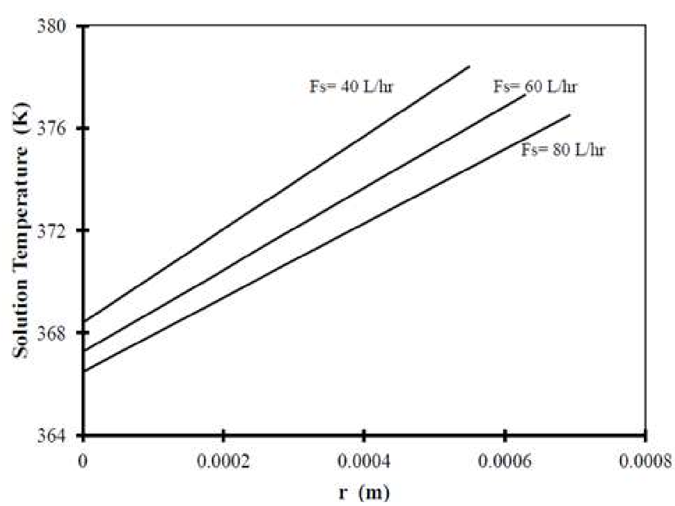

Fig. 2: Temperature distribution of solution with constant gas flow rate of 2 m^3/h and initial concentration of 11%

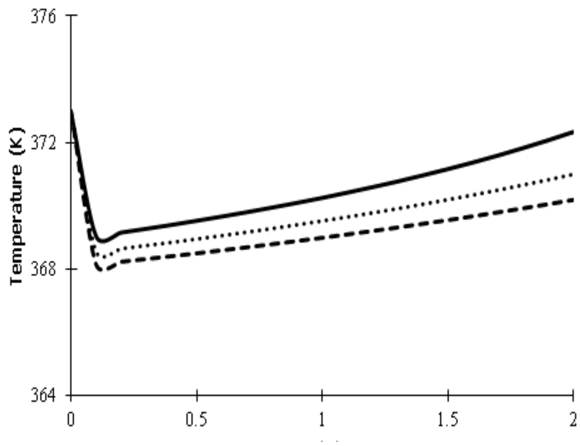

Fig. 3: Temperature profile at the interface for gas flow rate of 1 m^3/h and initial concentration of 12%

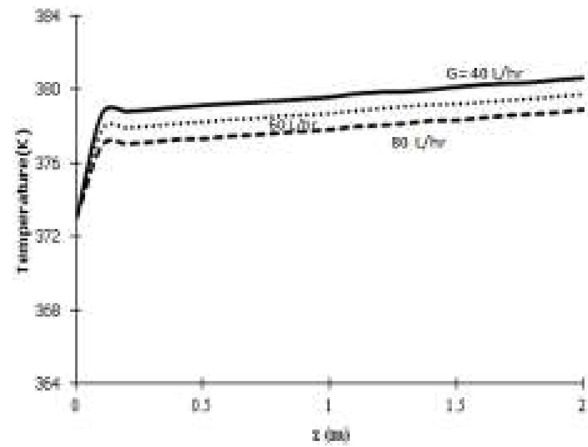

Fig. 4: Temperature profile of solution at the wall with gas flow rate of 1 m^3/jam and initial concentration of 12%

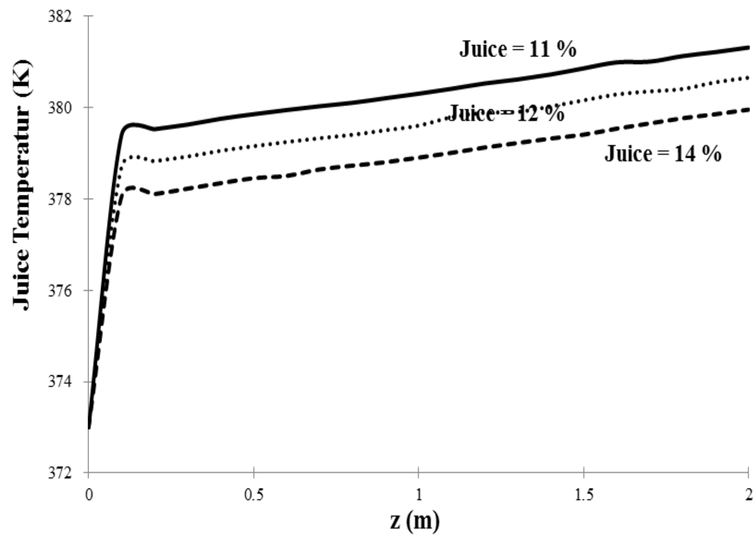

Fig. 5: Temperature profile of juice during evaporation at the axial direction as function of initial juice concentration. The simulation was conducted at juice solution of 40 L/h and gas flow rate of 1 m^3/h

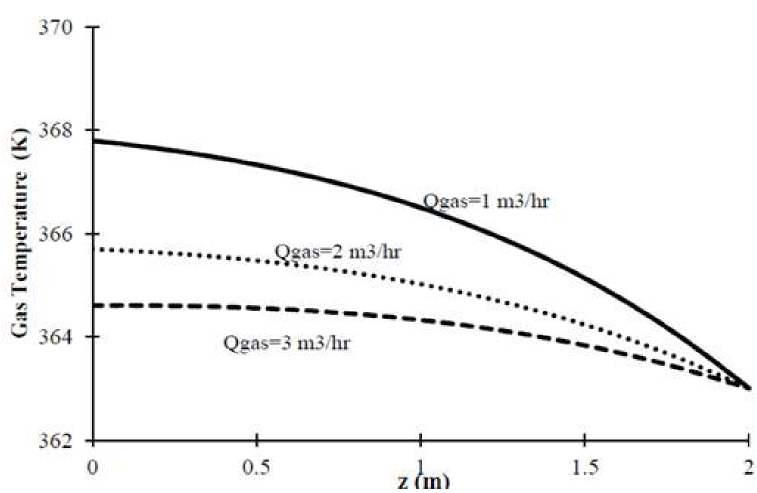

Fig. 6: The temperature profile of gas at the axial direction. The simulation was conducted at juice flow rate of 40 L/h and initial concentration of 12%

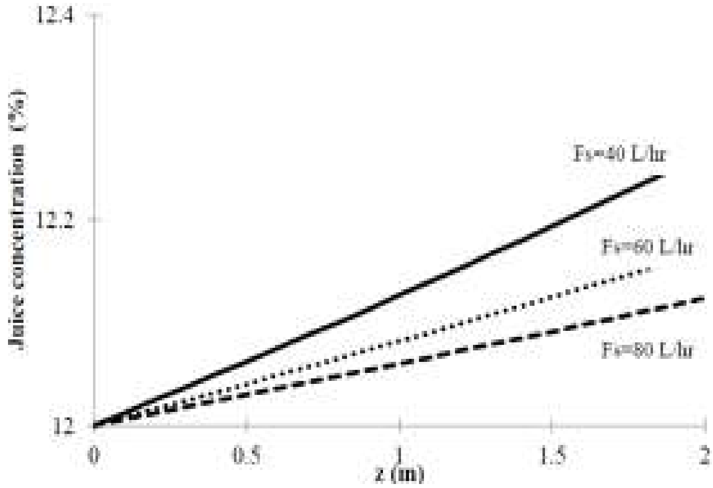

Fig. 7: Profile of juice concentration in tube at axial direction. The simulation was conducted at gas flow rate of 1 m^3/h and initial concentration of 12%

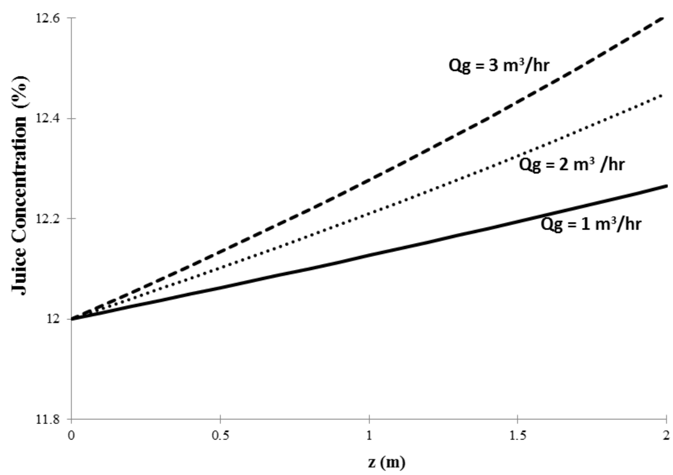

Fig. 8: Effect of gas flow rate to juice concentration. The simulation was done at constant solution flow rate 40 L/jam and initial concentration of 12%

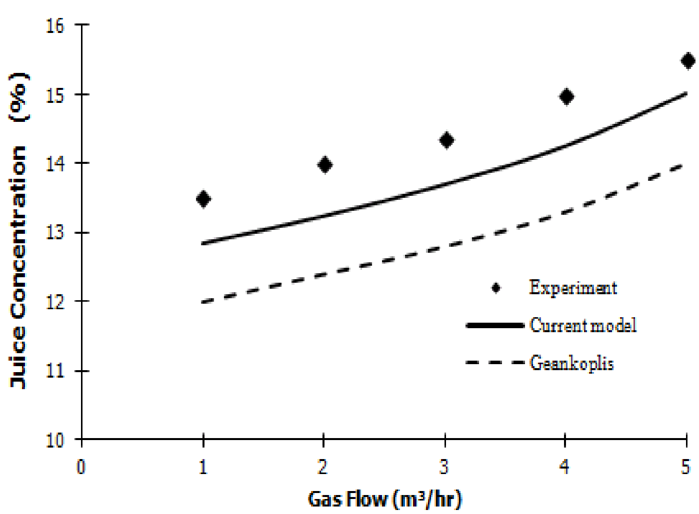

Fig. 9: Experiment and modeling data for falling film evaporation of sugarcane juice. The experiment was done at constant juice flow rate 80 L/h and initial concentration of 12%

Effect of gas flow rate to temperature distribution: Figure 6 reveals that gas temperature at axial direction decreases as the gas flow rate increases. These phenomena occur because the gas flow rate will affect to the partial pressure of the water vapor. A the gas flow rate increases, the partial water vapor will decreases, such that the saturation point of the solution tends to decrease and consequently the air temperature decreases.

The effect of juice flow rate was investigated by varying the flow rate from 40-80 L/h. Figure 7 shows that the greater of flow rate of the incoming solution, the smaller the concentration of the solution at the same position. This is probably due to the formation of falling film at the wall such that the evaporation will be retard at high flow rate.

Figure 8 demonstrates the correlation between concentrations of the juice at axial direction as function of gas flow rate. As the gas flow rate increase, the juice concentration also increases. The presence of gas flowing to the solution will increase the mass transfer of water in the solution into vapor. Therefore, the gas flow rate will enhance the evaporation process.

Experimental validation: In this research, the correlation between gas flow rate and juice concentration has been modeled based on dimensionless number. Geankoplis (2003) has developed mass and heat transfer coefficient with following equations:

$$h_G = C_1\left(\frac{k}{D}\right)\left(N_{\mathrm{Re}}N_{\mathrm{Pr}}\frac{D}{L}\right)^{1/3}\left(\frac{\mu_b}{\mu_w}\right)^{0.14}$$

$$k_c = C_2 N_{\mathrm{Re}}{}^{0.83} N_{Sc}{}^{0.33}\left(\frac{D_{ab}}{D}\right)$$

where, C_1 and C_2 are parameter for heat and mass transfer coefficients, respectively. Geankoplis (2003) proposed the value of C_1 and C_2 are 1.86 and 0.023, respectively.

In this experiment, we evaluated the value of C_1 and C_2 based on our research data and obtained the value of C_1 and C_2 as 1.22 and 0.026, respectively.

The plot between experimental and current model and Geankoplis (2003) is depicted in Fig. 9. As the flow rate of gas was increased to 5 m^3/h the juice concentration increased from 13 to 15.5%. The models showed the same trend with fitting error of 5.5% while Geankoplis model gives 6.9%. This research also shows that our prediction gives better improvement on Geankoplis model.

CONCLUSION

The conclusion of this research can be described as follow:

- The mathematical model of falling film evaporation for sugarcane juice has been developed. The model was successfully predict the temperature distribution of juice in the evaporator, the distribution of the gas temperature and also study the effect of gas flow rate to the concentration of juice during evaporation.
- This research also concluded that the highest concentration of juice out of evaporator was achieved at 12.44%. This was obtained when the evaporation conducted at juice flow rate of 40 L/h and gas flow rate of 3 m^3/h for initial concentration of 11%. Furthermore, when the initial juice was increased as 12%, the exit concentration was 12.43 and 15.76% for initial concentration of 14%.
- The addition of air flow rate will not give any significant influence on the concentration of the product. Increasing air flow rate from 1 to 3 m^3/h, only increase the concentration from 0.692 to 1.439%.
- The validation of the model give low error of 5.47%.

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