Progressive freeze concentration of coconut water: Effect of coolant temperature on process efficiency and heat transfer

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Abstract. In this research, coconut water was concentrated by applying progressive freeze concentration (PFC) using coil crystallizer. Overall heat transfer coefficient (U) was analyzed from the process by varying different coolant temperature values since both of them are closely related. In this case, heat transfer efficiency depends strongly on ice crystal formed on the inner cooled surface and is explained theoretically from that angle. At optimum flowrate, operation time and initial concentration best results were observed at -10ºC of coolant temperature where the concentration efficiency and effective partition constant (K) obtained were 48% and 0.2 respectively. Meanwhile, U obtained at the first and second stages were 183.0046 W/m^2ºC but dropped at lower value at later stage at 154.9625 W/m^2ºC due to ice fouling.

Introduction

Coconut water (CW) is largely consumed worldwide, not only as a refreshing drink but also because of its various therapeutic qualities [1]. At present, CW is widely marketed as a natural energy drink and sports drink. It has garnered attention because of its low content in fat, carbohydrate, calories, and sodium but high in potassium and minerals [2].

Freeze concentration (FC) is a separation process of solution by freezing concept. The process involves lowering the solution temperature to below its freezing point in a controlled manner so that only the water component is solidified. In spite of the initial high equipment investment, this method considerably use less energy compared to evaporation [3]. FC process efficiency is mainly influenced by purity of ice and separation of ice crystal from concentrate [4]. One of the favourable method in FC is progressive freeze concentration (PFC).

Continuous heat extraction is very important in FC process. Stages of heat transfer in FC were discovered previously by Qin et al. [5], who have characterized it into three stages: chilling, nucleation, and crystallization. Stage 1 consists of initial solution cooling to the temperature below the freezing point. Meanwhile, in stage 2, particle nucleation starts to occur and it is shown by a discrete jump of the solution temperature. In stage 3, ice crystals are form continuously as the concentration of solution increases. Solution temperature changes slowly as the result of freezing point depression [6]. Fouling refers to the formation of unwanted deposit layers on heat transfer surface which increases the thermal resistance. In crystallization process, freezing fouling describes the phenomenon where the ice layer is formed on the cooled surface.

The principal aim of this paper is to focus on the experimental measurement of heat transfer of PFC before and after ice formation. Overall heat transfer coefficients (U) in stage 1 and stage 3 during the process have been determined and the observed trends were interpreted based on the ice fouling. Since the heat transfer is closely related to the coolant temperature, effect of the coolant temperature has been analyzed to determine performance of the PFC process based on concentration efficiency (%) and Effective Partition Constant (K).

Materials and methods

Materials. Fresh young coconuts were obtained from local market in Johor, Malaysia. The coconuts were peeled and the water was then collected and filtered to be used as sample solutions.

Experimental Equipments. Fig. 1 shows the schematic diagram of the experimental apparatus of the PFC process. The experimental set up comprises of a coil crystallizer (CC) unit as shown in Fig. 2, a water bath (Cole-Parmer, Canada), a peristaltic pump (Cole-Parmer, Canada), and a data acquisition tool, Picolog TC-08 (Pico-Technology Ltd., Hardwick, UK) for temperature display which is connected to a computer. CC is made of stainless steel (2.54 cm in diameter and 237 cm long), consisting of three cycles that lay out horizontally with the inlet and outlet of the crystallizer are facing upward. The CC unit is an indirect contact cooled surface and acts as a freezer where energy for refrigeration is transferred through its wall. Consequently, ice layer is produced on the cooled inner surface in cylindrical shape. The water bath cools down the temperature of coolant solution below 0 ºC. After ice crystal is formed, the ice is separated by means of defrosting the crystallizer after flushing out the concentrate.

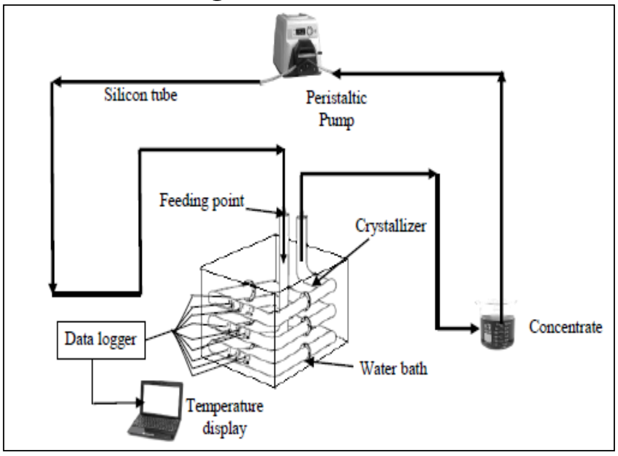

Fig. 1. Basic scheme of PFC system

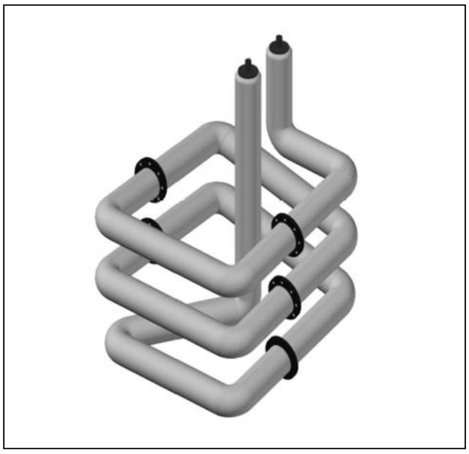

Fig. 2. Coil crystallizer

Results and Discussion

Analytical determination of coconut water. Theoretically, the mechanism of concentration process occurs as a result of the exclusion of solute molecules from the advancing ice front, the interface between the ice and concentrate phases [7]. Effective partition constant (K) acts as an index for separation effectiveness [8]. K is calculated based on Eq. 1.

$$(1 - K) \log (V_L / V_0) = \log (C_0 / C_L) \quad (1)$$

where V_o and C_o are the initial volume of solution and initial solute concentration of solution, respectively. The final volume of solution and final solute concentration of the solution are represented by V_L and C_L, respectively. The value of K varies between 0 and 1 where zero (0) indicates complete freeze concentration process [9]. The efficiency of each concentration process depends on the concentration increment of the concentrate in relation to initial solution concentration. As a rule, decrement solute in ice produce higher solutes remained in concentrate.

Overall heat transfer coefficient. The method used in the present study to determine U is by measuring the variation of solution temperature. The solution and coolant temperature is a function of time, T_m (t), during chilling period which can be determined experimentally by averaging the solution temperature values of inlet, outlet, and middle cycles. If the temperature of the solution in crystallizer decreases from T_{s1} to T_{s2} during the time interval of t_1 to t_2, the heat removed is expressed as $Q_2 = \rho_s c_s V (T_{s1} - T_{s2})$, where ρ_s (1014.42 kg/m³) and c_s (1760 J/kg ºC) are the density and specific heat of the solution; respectively. Thermal insulation with the surrounding would give the heat balance of $Q_1 = Q_2$ and this leads to following equation:

$$U_1 = \rho_s c_s V (T_{s1} - T_{s2}) / A \int (T_{s1} - T_{s2})\, dt \quad (2)$$

where the integral bound is from t_1 to t_2 which are corresponding to the time when the solution temperature is at T_{s1} and T_{s2}, respectively. The latent heat of freezing of the solution is about -0.5 ºC. It occurs in a very short period and facing unsteady heat transfer compared to the stable temperature in stage 3 where it is almost at its freezing point. In stage 3, U values can be determined by measuring the solution concentration increment in a definite time. The initial solution mass and initial solid content are expressed as M_s and C_1 respectively, and C_2 is the final solid content after FC finish. At the end of the process, the mass of water, M_{ice}, that has been frozen to ice is $M_{ice} = M_s [1-(C_1/C_2)]$. The total latent heat liberated by ice formation is $Q_1 = \Delta H_i M_{ice} = \Delta H_i M_s [1-(C_1/C_2)]$. The total heat transferred trough the cooling surface is $Q_2 = AU_3(T_s-T_c)t$. Since Q_1 equals to Q_2, this leads to calculation of overall heat transfer coefficient of stage 3, U_3:

$$U_3 = \Delta H_i M_s [1-(C_1/C_2)] / A(T_s-T_c)t \qquad (3)$$

where ΔH_i is the latent heat of freezing of water (334 kJ/kg) and t is the operation time of crystallization process [5].

Coolant temperature. Coolant temperature is the crucial factor in FC since the process is closely related to temperature. Fig. 3 shows the variation of coolant temperature with concentration efficiency and K. The coolant temperature range selected varies between -16 and -10 ºC based on the experimental values of coolant temperature used in previous research by Nakagawa et al. [10] and screening tests for coconut water. The figure shows a result for concentration process of solution; as the coolant temperature increases, the concentration efficiency trend increases exponentially from 25.6% up to 48% and K decreases from 0.7 to 0.2. The results seem quite satisfactory in the concentration limit and confirmed its capabilities in high production.

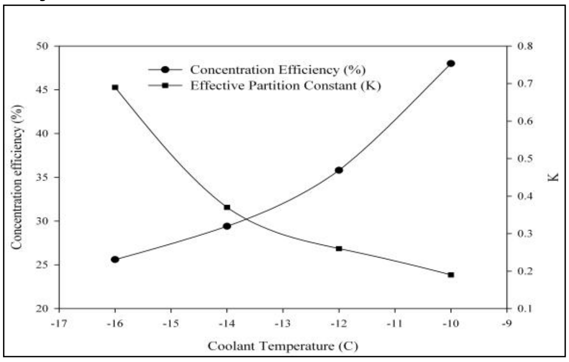

Fig. 3. K and concentration efficiency

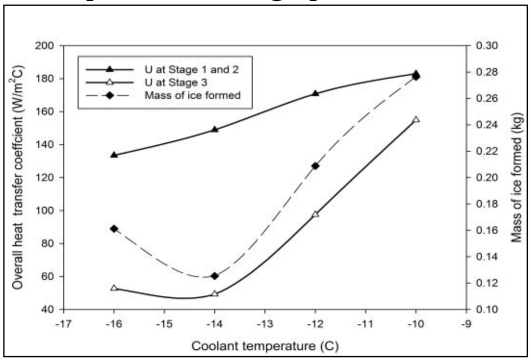

Fig. 4: U and mass of ice formed

From Fig. 3, it can be observed that the separation process is more effective at -10ºC since K value obtained is small and concentration efficiency is high. This implies that more soluble solids remained in the concentrate and higher purity of ice crystals was obtained. Lower K value (0.2) indicates that the ice crystal layer is slow in acquiring the solutes. The higher retention of glucose solution might be due to the fact that its chemical structure facilitates the retention of water by integrating it more easily between the two molecules, thereby facilitating the growth of ice crystals.

Coolant temperature has strong influence on the ice crystal formation rate [10]. As the temperature difference between coolant and solution increases, the ice formation rate increases and larger amount of ice formed. Particularly, the highest rate formation of ice crystal occurs at -16 ºC, it has been noted that the soluble solid trapped in the ice crystal is higher because the speed of moving solids in solution becomes too fast to overtake the solids outward movement and promote solute inclusion in the ice crystals [11]. Concentration efficiency achieved was up to 48% for this parameter and it is quite satisfactory in the concentration process limit.

Heat transfer performance. For heat transfer performance, at -10 ºC, U_1 was found to be 183.0046 W/m² ºC and U_3 was found to be 154.9625 W/m² ºC. Compared to another values of U at different coolant temperature, U values at -10 ºC seems to be the highest. The significant decreasing values of U from stage 1 to stage 3 is believed to be due to the ice fouling occurring on the cooled surface as depicted in Fig. 4.U_3 was characterized mostly by ice formation on the cooled surface where the thickness of ice crystal formed varies between 0.35 and 0.45 cm. At the beginning of the ice formation, heterogeneous nucleation that occured on the wall of the crystallizer was not uniform since ice crystals are agglomerated at certain spots. After certain duration of time, the combination of the agglomerated ice crystals formed an ice layer with significant thickness. In order to calculate U in stage 3, mass of ice formed was calculated to know the heat extracted by the coolant for the total freezing process [6]. Ice formation starts when solution temperature decreases to a certain degree of supercooling. Phase transition is triggered by the ice seed and the latent heat increases the solution temperature until it approaches the freezing point (FP). Ice nucleation randomly occurred on the cooled surface resulting in difference of temperature at different points [5].

According to Wakisaka et al. [12] increasing the circulation flow rate of solution promotes heat transfer with ice crystals from its tips; hence, enhancing the planar ice growth from the cooling wall by keeping soluble solids away from the ice-liquid interface. Increased circulation flow rate provides high shear force and enables the fluid flow to carry the solute in the solution. Thus, the soluble solids are brought away from the surface of the stagnant solid ice layer, resulting in improvement of heat transfer efficiency.

Summary

Effect of coolant temperature was studied on PFC. It has been observed that concentration efficiency of 48% and K of 0.2 for the coconut water at -10 ºC of coolant temperature gave a high yield in the process. Ice crystal formed has significant effects towards heat performance in PFC. As the ice thickness increased; it will reduce the heat transfer between coolant and solution and lower the rate of ice formation.

References

[1] A.C.P. Duarte, M.A.Z. Caelho, S.G.F. Leite, Identification of peroxidase and tyrosinase in green coconut water, J. of Food Sci. and Technol. (2002) 266-270.

[2] J.J.R.E. Paull, The Encyplopedia of Fruits and Nuts, (2007) 994.

[3] F.A. Ramos, J.L. Delgado, E. Bautista, A.L. Morales, C. Duque, Changes in volatiles with the application of progressive freeze-concentration to Andes berry (Rubus glaucus Benth), J. Food Eng. 69 (2005) 291-297.

[4] E. Hernández, M. Raventós, J.M. Auleda, A. Ibarz, Freeze concentration of must in a pilot plant falling film cryoconcentrator, Innov. Food Sci. Emerg. Technol. 11 (2010) 130-136.

[5] F.G.F. Qin, X.D. Chen, A.B. Russell, Heat transfer at the subcooled-scraped surface with/without phase change, Journal of American Institute of Chemical Engineers 49 (2003) 1947-1955.

[6] F.G.F. Qin, X.D. Chen, S. Ramachandra, K. Free, Heat transfer and power consumption in a scraped-surface heat exchanger while freezing aqueous solutions, Sep. Purif. Technol. 48 (2006) 150-158.

[7] O. Miyawaki, L. Liu, K. Nakamura, Effective Partition Constant of Solute between Ice and Liquid Phases in Progressive Freeze-Concentration, J. Food Sci. 63 (1998) 1-3.

[8] X. Gu, T. Suzuki, O. Miyawaki, Limiting Partition Coefficient in Progressive Freeze-concentration, J. Food Eng. and Phys. Properties 70 (2005) 546-551.

[9] O. Miyawaki, L. Liu, Y. Shirai, S. Sakashita, K. Kagitani, Tubular ice system for scale-up of progressive freeze-concentration, J. Food Eng. 69 (2005) 107-113.

[10] K. Nakagawa, S. Maebashi, K. Maeda, Freeze-thawing as a path to concentrate aqueous solution, Sep. Purif. Technol. 73 (2010) 403-408.

[11] P. Chen, D.C. Xiao, K.W. Free, Solute Inclusion in Ice Formed From Sucrose Solutions on a Sub-cooled Surface-an Experimental Study, J. Food Eng. 38 (1998) 1-13.

[12] M. Wakisaka, Y. Shirai, S. Sakashita, Ice crystallization in a pilot-scale freeze wastewater treatment system, Chem. Eng. Process: Process Intensif. 40 (2001) 201-208.