Effect of circulation flowrate on the performance of a spiral finned freeze concentrator

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\textbf{Abstract.} Progressive freeze concentration (PFC) has emerged as a viable technology for concentration of liquid solution. In this study, a newly designed spiral finned crystallizer to improve productivity of PFC process was proposed. The spiral fin is presented based on the advantage of additional surface area to the spiral finned crystallizer. The performance of spiral finned crystallizer was analysed by the system efficiency and the effect of circulation flowrate. It was found that the efficiency of the system has significantly improved in terms of a lower effective partition constant and a higher recovered solute. An effective partition constant of 0.35 and a recovered solute of approximately 0.96 g of glucose per 1 g of initial glucose were obtained. Thus, spiral finned crystallizer for PFC system is evidently an effective system to concentrate solution and to produce pure ice crystal.

\textbf{Introduction}

Freeze concentration (FC) is the process of concentrating a solution by freezing the water content and thus producing ice crystals from the system [1]. The aim of FC is to form very pure ice crystal where there is only water without any solids retained in the ice crystal [2]. Two techniques are used for growth of ice crystals including suspension freeze concentration (SFC) and progressive freeze concentration (PFC) [3]. A conventional SFC steps consist of crystallization, growth and separation of ice crystals, involving a scraped-surface heat exchanger (SSHE) and a recrystallizer [4]. This method needs very complicated system which makes the SFC process the most expensive method among other concentration methods.

Nowadays, many developments of FC have shifted towards PFC because of the simpler separation step. In PFC, the solution to be concentrated is in contact with a cooled surface. The ice crystal is progressively produced layer by layer on the cooled surface until it forms a large and single crystal block. Since there is only a single block of ice crystal, it would be much easier to separate the ice crystal from the mother solution and result in low maintenance cost.

In the development of a better PFC, many PFC systems have been studied and built such as vertical freezing system [5], bubble-flow circulator [6], radial freezing device [7], tubular ice system [8], coil crystallizer [9] and shaking type of FC [10].

In order to improve the efficiency of PFC process, a new crystallizer namely spiral finned crystallizer was designed and constructed in this research. The improvement of concentration efficiency in PFC assisted with the additional spiral fin has been experimentally examined. By providing increased contact surface area by the additional spiral fin, this crystallizer attempted to improve the concentration performance by increasing the heat transfer between solution and coolant. Although the theory and practice of fin has been widely studied by many researchers for different applications of heat exchangers, the efficiency of fin in a crystallizer has not been studied.

In the present paper, the newly designed spiral finned crystallizer was investigated in PFC with the effect of circulation flowrate. The effect of circulation flowrate was experimentally evaluated from the viewpoint of both effective partition constant (K) and recovered solute (Y).
Materials and Methods

Materials. Solutions of glucose (QRec, Selangor, Malaysia) with concentrations of 6 %Brix was prepared with distilled water. A 50% (v/v) ethylene glycol solution (QRec, Selangor, Malaysia) was used for the coolant.

Experimental Procedure. As shown in Fig. 1, the major apparatus employed for this study consisted of the spiral finned crystallizer, a waterbath, a feed tank and a temperature display unit. Glucose solution was prepared according to the desired concentration. Two parts of glucose solution were prepared. The first part was cooled in the refrigerator where it was cooled to a temperature close to the freezing point of water (2 °C). Another part of glucose solution was frozen into solid form.

Before starting the ice crystallization process, the coolant was filled in the cooling jacket when the temperature of coolant has reached its desired temperature. The temperature of coolant was controlled by the Scientz waterbath (DC-2030, Ningbo, China). Both the solidified and cooled glucose solutions were mixed in the feed tank. Then, the glucose solution was pumped to the crystallizer by a peristaltic pump through a silicone tube. The solution was flown upwards over the surfaces of the spiral fin and was collected in the feed tank, from which the cycle starts again. When the glucose solution has filled the entire pipe and crystallizer, the feed tank valve was closed. As the solution was circulated in the crystallizer, ice layer was formed at the cooling surface of the crystallizer leaving behind a more concentrated solution.

During each run, the temperature of solution and coolant, temperature of solution inlet and outlet of the crystallizer and temperature of coolant inlet and outlet were measured by six type K thermocouples. The temperature measured by the thermocouples was displayed on a computer connected to the PicoLog (PicoLog USB TC-08, United Kingdom).

At the designated time, circulation was stopped. The concentrated glucose was drained out from the crystallizer and the volume of the concentrated glucose was measured. Ice crystal was then detached from the cooling surface of the crystallizer and left at room temperature to melt. Samples from the ice crystal and concentrated glucose was placed on a refractometer (MA871, Romania, Europe) with a precision of ±0.2 %Brix to measure its refractive index (RI).

Evaluation of System Efficiency.

Effective Partition Constant. The effective partition constant, K, is the most important parameter which portrays the effectiveness of the system. The K between ice and liquid phase can be defined by Eq. 1 [11]:

\[
K = 1 - \frac{\log(C_0/C_L)}{\log(V_L/V_O)}.
\]  

(1)
where $V_L$ and $V_O$ are volume (mL) of concentrated and initial solution and $C_L$ and $C_O$ are concentration of glucose (%Brix) in the concentrated and initial solution.

**Recovered Solute.** The recovered solute, $Y$ is defined as a ratio of the glucose concentration in the concentrated solution to that in its initial solution. The equation used to calculate the recovered solute is shown in Eq. 2 [12]:

$$Y = \frac{C_Lm_L}{C_Om_O}$$

where $C_L$ and $C_O$ are the concentration of glucose (%Brix) in the concentrated and initial solution and $m_L$ and $m_O$ are mass (g) in the concentrated and initial solution.

**Results and Discussions**

Glucose solution was freeze concentrated using the newly designed spiral finned crystallizer. The effect of circulation flowrate on the effective partition constant ($K$) and recovered solute ($Y$) was analyzed. Fig. 2 shows the variation in the $K$ and $Y$ value depending on the circulation flowrate of the solution. The result obtained means that with higher circulation flowrate, the more pure ice crystal and high concentration of concentrated solution were produced. The recovered solute increased over the circulation flowrate. As indicated by the line plotted, better outcome can be obtained at 3000 mL/min. At 3000 mL/min, the best value of $K$ and $Y$ have been yielded which are 0.35 and 0.96. This shows that the higher circulation flowrate is preferable for efficient PFC by the spiral finned crystallizer.

![Fig. 2. Effective partition constant (K) and recovered solute (Y) as a function of circulation flowrate](image)

Pure ice crystal with lower solute contents was produced during the higher flowrate. Heat transfer was promoted when the flowrate of solution was increased. Thus, the planar ice growth increased from the cooling wall by rejecting the solutes from the ice-liquid interface. This situation resulted in production of satisfactory ice crystal and concentrated solution, reflecting a good PFC operation. An increase in the circulation flowrate which increased the shear force resulted in a significant increase in the amount of solute recovered. The solutes were not easily caught and were rapidly brought away from the surface of the stagnant ice layer, causing higher amount of solutes remaining in the concentrated solution. This indicates the effectiveness of the circulation flowrate, performed by the peristaltic pump. Therefore, separation performance of the spiral finned crystallizer has been improved by increasing the circulation flowrate.
Summary
This study demonstrated the effectiveness of spiral finned freeze concentrator system, experimentally confirmed through the concentration of glucose solution. The effective partition constant (K) and recovered solute (Y) were found to be dependent on the circulation flowrate. It is important to operate the system with precision in order to form pure ice and to recover the solute. Concentration of glucose solution by using the spiral finned crystallizer was found to be feasible. The K value obtained from this study was 0.35 and Y value was 0.96 g of glucose obtained per 1 g of initial glucose. Circulation flowrate of 3000 mL/min was discovered to result in the lowest K value and highest Y value during the process. In overall, the results show the feasibility of the system and give an excellent idea of the operating conditions that can be used to concentrate glucose solution.

References