Effect of coolant temperature on desalination process via progressive freeze concentration

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Abstract. The world is still suffering from a shortage of clean water supply and the problem is expected to become more serious in the future. Consequently, researchers have been trying to find the best solution to address this problem by introducing new desalination technologies that are able to accommodate the demand for clean water which is increasing from time to time. One of the new technologies introduced is the desalination of seawater through freeze concentration. In this study, progressive freeze concentration (PFC) is implemented to produce pure water in the form of ice crystal block and leave behind a higher concentration solution. The effect of coolant temperature was investigated and the efficiency of the system was reviewed based on the value of effective partition constant, K which is defined by the ratio of solute in ice and liquid phase. The low value of K leads to the best efficiency for the system. Apart from that, the efficiency, E% and salinity reduction were also calculated in order to determine the system performance.

Introduction

Water shortage has become a major issue, particularly in developing countries. The existing water resources are unable to meet the water supply demand based on the latest trend of human population growth which is increasing enormously [1]. The tremendous growth of industrialization and urbanization has also led to higher demand for water supply [2]. After all, researchers have been working in earnest to find the best solution to address the water shortage. According to the latest report, desalination plants have a capacity of 78.4 million m^3/d all over the world, showing 64.7% increment compared to the capacity at the end of 2008 [3].

Desalination technology can be developed to produce fresh water for industry, agriculture and also human consumption. The technology has now been practiced on a large scale for more than 50 years. For many years, thermal technologies were the only viable option, and multi-stage flash (MSF) was established as the baseline technology. With the growth of membrane science, reverse osmosis (RO) has overtaken multi-stage flash as the leading desalination technology, and should be considered as the baseline technology, while others as alternatives. The search for improved desalination method led to the use of freeze concentration method [4].

In freeze concentration, the solution is made concentrated by making pure ice in solution. Meanwhile, impurities are excreted from the formed ice [5]. One of the methods to form a large single ice crystal is by applying progressive freeze concentration process. The ice crystal is formed on the surface of the conducting material where the cooling is supplied. Its separation from the mother liquor is much easier to be handled and at a lower cost as only a single crystal is formed [6].

According to previous reports, one of the main advantages of freeze desalination process is its energy consumption. In this method, only 420 kJ/kg of energy is required to remove salt and produce 1 kg of fresh water which is six times lower than the energy required by MSF [7]. However, one of the difficulties in dealing with this system is ice handling after the process is completed [8].

Previously, a progressive freeze concentration device has been successfully used in concentrating glucose solution. In the same way, this device was employed in this study to apply for desalination process. There are several factors affecting the efficiency of the system and the thawed ice quality [9] including circulation flow rate, initial concentration, coolant temperature and circulation time. However, for this study, the effect of coolant temperature was investigated because itis the most significant factor that influences the ice crystal formed on the inner wall of crystallizer.

Material and Methods

Material and Equipments.A saline solution was used throughout the experimental work to represent seawater. A 50% (v/v) ethylene glycol solution was used for the coolant in the water bath. The crystalliser used is made up of aluminium structured in hollow helical structure. The three layers or stages crystalliser could be split into two and are attached by flanges at five points where the ice formation could be seen. In order to determine the temperature profile of the process, nine thermocouples were used by engaging them on each stage of the crystalliser to detect the temperature of the solution, aluminium wall and coolant temperature which were later displayed by PicoLog recorder software. A pump was used for solution movement. The waterbath acted as a cooling chamber for the process, which function is to maintain the process at the desired temperature. Salinometer was used to determine the salinity of the ice produced and saline concentrate.

Experimental Procedure. The saline solution was first kept in the freezer at 2°C to 3°C as the initial temperature of the sample should be near the water freezing temperature. Cubes of saline solution were mixed with the sample to maintain the temperature during feeding process. Pure water was then pumped into the crystalliser to provide seed ice or form ice lining. This step is necessary to avoid initial super cooling, which could cause serious contamination in ice crystal initially formed [9,10]. The experimental set up is shown in Fig. 1. The saline solution was fed into the crystalliser using a peristaltic pump through a silicone tube until the solution has filled the crystalliser. Each end of the silicone tube was then connected carefully to avoid the presence of any bubble in the tube. In order to allow the crystallisation process to occur, the solution then was immersed into the waterbath at desired temperature and circulation flowrate for about 10 minutes. After that, the circulation was stopped and the crystalliser was taken out to be thawed. Theconcentrated solution in the silicone tube was drained out as concentrate sample. The whole volume of the concentrated solution left in the crystalliser was collected by disassembling the flanges. A sample of the ice layer produced was collected. The salinity of each sample was then measured using salinometer.

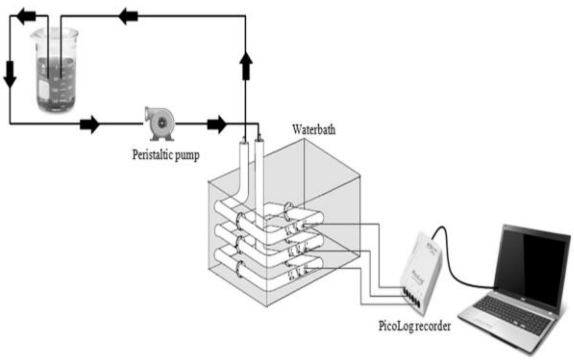

Fig 1: Experimental setup

Result and Discussion

The exclusion of solute molecules from the moving ice front and the interface between the ice and solution phases is the main mechanism of concentration in progressive freeze concentration [11]. For evaluation method, effective partition constant, K, was reviewed to determine the system performance by employing the following equation.

$$(1-K) \log (V_L/V_o) = \log (C_o/C_L) \quad (1)$$

From Eq. 1, V_L is defined as the concentrate volume, $V_o$is the initial volume of solution, C_o is the initial concentration of the solution and C_L is the concentration of concentrate. Eq. 2 was applied for evaluation method in this research. In any condition, lower K value shows higher efficiency of the system. According to Fujioka et al.[2] the effect of desalination increases when the K value is smaller. Apart from that, the purity of ice produced can be determined based on its measured salinity. Lower salinity means higher salinity reduction of ice produced. Thus, the lowest K-value and lowest salinity of ice are considered as the favourable conditions for the system. In addition, according to Petzold et al. [12], the concentration increment in solution relative to the quantity of NaCl remaining in the ice fraction was defined as efficiency (*E %*), which can be calculated by using Eq. 2 as follows:

$$\text{Efficiency (\%)} = [(C_L - C_i)/C_L] \times 100 \quad (2)$$

The coolant temperature is an important parameter that influences the process, because it is closely related to freezing rate [9]. An investigation on coolant temperature effect is crucially needed in order to determine the best temperature for the system. The freezing point of saline water decreases as salt concentration increases. As the freezing point of water of 0°C, pure water will obviously become ice at the studied temperatures, leaving behind saline water which has a lower freezing point. While the coolant temperature varied, the other operating conditions were kept constant. After examining the samples and determination of its salinity, the effect of coolant temperature on K, salinity reduction, and efficiency is illustrated in Fig. 2.

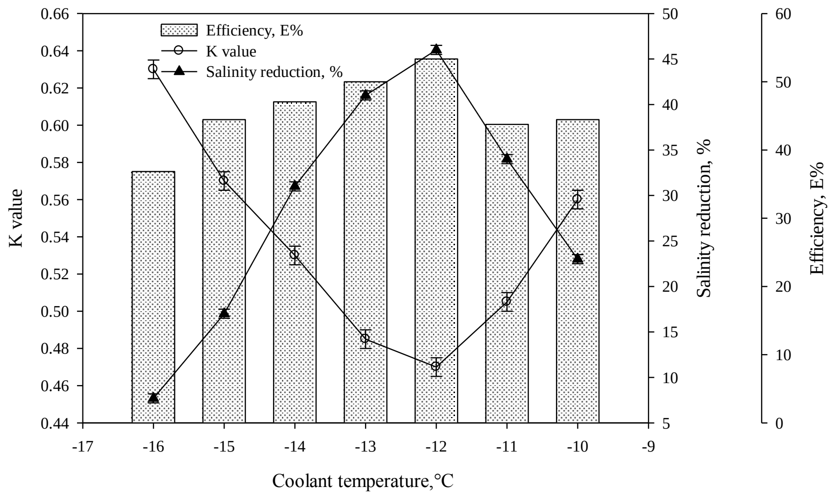

Fig. 2 Effect of coolant temperature on K, salinity reduction and efficiency.

From Fig. 2, coolant temperature of -12°C is considered as the best condition due to its lowest value of K. There are decreasing changes of K-value from -10°C to -12°C showing that lower coolant temperature resulted in lower K, which means higher efficiency for the system [13]. However, as the coolant temperature is decreased to -13°C onwards, the K-value starts increasing. This means that the efficiency of the system would decrease if the coolant temperature is too low. At -13°C, there is a possibility that the saline water would also start to freeze and the salt would get trapped in the pure ice formed, resulting higher value in salinity of ice. Thus, K-value would also get higher, performing low efficiency of the system.

In addition, coolant temperature will influence the ice growth rate and low growth rate will give high purity of ice produced. According to Flesland [14], when the difference between the entering solution and the surface temperature increases, the ice growth rate will increase as well. In the same way, when the coolant temperature is decreased, it will bring a higher growth rate of the ice front. This situation is undesirable to produce a low K for the system. The higher the ice growth rate, the more impurities would be entrained in the ice. For this reason, the solute outward movement will be blocked by the high speed of moving front, resulting promotion of solute inclusion in the ice crystals [15].Therefore, the salinity of ice would increase as the coolant temperature is reduced to -13°C because of the higher amount of ice impurities as it is approaching the freezing state of saline water. It is again showing that the coolant temperature of -12°C is the most optimum condition for producing pure thawed ice with the lowest value of salinity.

Summary

This study has successfully proven thatthe designed progressive freeze concentration system has a splendid potential to be applied for desalination process. The effect of coolant temperature was magnificently investigated by employing three determinant factors which are effective partition constant, K, salinity reduction and efficiency, E%. From the results, the system has achieved its best performance at intermediate coolant temperature which is -12°C. Even though this study is on its way to success, several recommendations should be proposed in order to ameliorate the system. The quality of ice production can be improved by introducing the double PFC process in order to satisfy the standard quality of daily water usage. Moreover, further studies on extended range and other potential parameters are necessary in enhancing the performance of the system.

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