HybridICE® HIF filter: principle and operation

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Abstract

The HybridICE technology operates on the principle that growing ice crystals reject impurities during freezing and is a "zero liquid discharge" process, whereby the water is completely isolated from the dissolved waste species. The technology recovers water from waste waters for re uses for all purposes. The process allows the utilisation of both surplus process heat and cooling energy. The waste heat from the refrigeration cycle is, moreover, utilised for vacuum evaporation to recover a fraction of the water as condensate. The predominant water fraction is recovered by isolating the ice from a concentrated process brine stream. The process takes place in a static concentrator, known as the HybridICE Filter module (HIF) that separates the suspended ice crystals from the concentrated brine slurry to recover ice crystals as pure water. The recovered ice from the freeze crystallisation does not require rinsing with fresh water. Basic factors influence the quality and yield of recovered water. These include but are not limited to: TDS of the waste water stream; first ice point; ice content of the process waste water; mass-flow. The slurry ice feed stream was generated using the HybridICE freeze crystallisation plant. The objective was to establish the comparative behaviour of a low and high sodium chloride feed using 2% and 8% (m/m) NaCl feed brine streams.
Keywords: HybridICE, filter, ice, slurry, yield, salt removal.

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1 Introduction

Water which is the basic substance of life on earth is increasingly in short supply. Water shortages affect 88 developing countries that are home to half of the world's population [1]. There are water supply issues in the world and in many countries, demands for water exceeds local water supply. Water is not necessarily destroyed or lost through use. It often passes on to other users though sometimes in a degraded form [2]. Sources of water pollution include Urbanisation, Deforestation, and Damming of rivers; others include destruction of Wetlands, Industries, Mining, Agriculture, Energy use and accidental pollution. There is need for development of technologies to recover water from waste water for re uses. Hence, HybridICE freeze crystallization Technology is a freeze desalination process developed to recover water from waste waters. The technology is a viable option to make water available for all purposes. Freeze desalination works on the principle that growing ice crystals reject impurities during freezing. Advantages over other methods of desalination include minimization of inevitable thermodynamic losses in heat exchange as a result of progressive freeze [3]. The HybridICE freeze crystallization technology is a freeze desalination process which in principle isolates the liquid part from the dissolved solid part. Unlike other processes used for freeze desalination, the HybridICE process generates a slurry of brine ice.

An integral part of the process is isolating the suspension of ice crystals from the process waste water in a static filter. This filtering process requires no fresh water to wash the ice which represents a feasible treatment of saline waste waters. Previous work on the principles of freeze crystallisation [4] shows the potential of cost effectiveness in terms of low energy demand, low pollution from by-products, process flexibility, simplicity and the possibility to further utilize the cold energy as a process by-product.

The HybridICE HIF filter is a crucial process component in the HybridICE technology. In principle the slurry of brine ice is pumped into a vertical column which creates a piston ice extrusion. The filtering process undergoes three basic steps, namely a zone to allow the ice to settle due to the buoyancy force, a filtering zone which isolates a substantial amount of process concentrate, and a purification zone which allows the separation of the remaining concentrate by gravity. Limited research work has been done on the separation of ice from a brine slurry. Most literature reports have been on the use of wash columns [5, 6]. Dickey *et al.* [7] patented work in 1998 on horizontal cross filtration and rinsing of ice from saline slurries. All of these involved washing of ice with water.

The HybridICE HIF filter is a concept which filters the ice particles as pure water in a continuous process without requiring washing with water. This characteristic reinforces the economic feasibility of this freeze crystallization technology.

2 Theory

Figure 1 shows the operation of the filter.

The slurry brine ice enters the filter column at the bottom (1) and moves through various zones (3) in a continuous process. The ice column builds up continuously until it reaches the height where it is harvested and recovered with the aid of the scraper (6) as clean process water (7). The concentrated brine goes through the filtering medium (4) and is pumped out through (5). The filter casing is labelled (2).

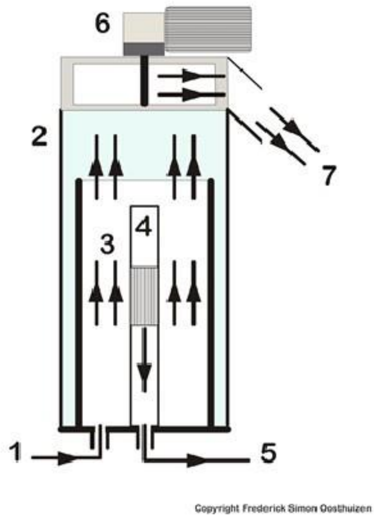


Figure 1: Schematic diagram of the HybridICE HIF filter.

Mass balance around the filter at steady state:

$$Q_s = Q_b + Q_i \tag{1}$$

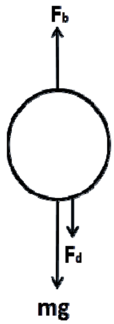
Ice balance gives:

$$I_{cs}Q_s = x_bQ_b + x_iQ_i \tag{2}$$

where Q_s is the flow rate of the slurry brine ice; Q_b is the flow rate of the concentrated process brine; Q_i is the flow rate of the process ice; I_{cs} is the ice fraction or ice concentration of the binary fluid; x_b is the ice fraction in the concentrated brine; and x_i is the ice fraction in the ice. The slurry flow rate Q_s and ice fraction I_{cs} are principal factors in the operation of the static filter.

2.1 Separation

The slurry brine ice is pumped into the filter, causing a continuous formation of an ice column. Principally, three forces are acting on it, the buoyancy force F_b due to density of the ice which has to overcome the drag force F_d and gravity (mg) for the upward movement of the ice crystals. The higher buoyancy force of the ice will reach a point of equilibrium where the buoyancy force is equal to that of gravity.



$$F_b > mg + F_d \tag{3}$$

At ice-brine interface $F_b = mg + F_d$; but $F_d = 0$;

$$F_b = mg \quad \text{(Archimedes' principle)} \tag{4}$$

2.2 Driving forces

2.2.1 Mass flux

The buoyancy force is not the only driving force in the filtering process. The pressure from the pump drives the ice harvesting process. The ice forms a piston which is driven by the pumping force. The mass flux is directly proportional to the mass flow rates of the slurry brine ice for a given ice fraction in the slurry brine ice. Higher flow rates create more output. Therefore, throughput rates are proportional to flow rates. Higher output results in less residence time which affects the quality of recovered process water for a given NaCl concentration. The NaCl concentration is a critical point for quality water recovery. In a low NaCl concentration brine the ice crystals are larger in diameter. High NaCl concentration produces finer ice crystals which adversely affect the process. However, this parameter can be compensated for by increased residence time. The longer the residence times in the filter column, the higher the quality of water recovery and the lower the output. Residency time is reduced by low NaCl concentrations allowing higher output rates.

2.2.2 Compressive force

The rotating scraper harvests the ice in the HybridICE filter. The rotation speed of the scraper needs to be adjusted according to the rate of harvesting. Too slow rotation speeds will cause a counter force on the rising ice column. This will result in the ice column being forced downwards, referred to here as the compressive force. This adversely affects the process and causes poor water quality recovery.

3 Experimental

3.1 Apparatus

The HybridICE demonstration plant used for the trials at the Soshanguve Campus had a 12m³/day treatment capacity.

Instruments used: conductivity meter and a weighing scale.

Figure 2: HybridICE HIF filter in operation.

3.2 Brine samples

Two brine samples were prepared for the trials. For practical reasons, low and high concentration brines were prepared. The low concentration brine was a 2% NaCl solution (by mass) and the high concentration brine was 8% NaCl (by mass).

3.3 Methods

The saline solutions were processed in the HybridICE demonstration plant at flow rates of 25 litres/min, 30litres/min and 35 litres/min. The HybridICE demonstration plant had a 30kW refrigeration capacity with *R404a* as primary refrigerant. For the low NaCl solution the evaporating temperature was set at -10ºC on the HybridICE freeze crystallisers for generating the slurry brine ice. The solution was also processed at flow rates of 25 litres/min when evaporating temperatures in the heat exchangers were varied. Samples of ice were collected at the chute after harvesting with the scraper ejector mechanism. These samples were weighed and the conductivities were measured. The NaCl removal was calculated based on the electrical conductivity of the prepared feed brine and the residual NaCl in the recovered process ice sample.

$$\text{Salt removal (\%)} = (C_f - C_i)/C_f \times 100\ \% \qquad (5)$$

where C_f = Electrical conductivity of feed

C_i = Electrical conductivity of ice

Yield = Mass of ice (kg) produced per minute (kg/min).

4 Results and discussion

When the HybridICE demonstration plant is operational, the slurry brine ice flowing into and out of the filter, through the filtering medium perforation, achieves a steady state before ice starts forming. As the ice starts forming it rises through the brine to float at about the perforation in the filtering medium. Three sections are eventually created in the filter. These are the ice bed sections, the brine section and the stagnant section. The stagnant section forms as a result of differences in the flow-rate of the brine into the filter and out of the filtering medium. Some ice is lost across the filtering medium from the stagnant section and the ice also carries some of the brine into the ice bed section.

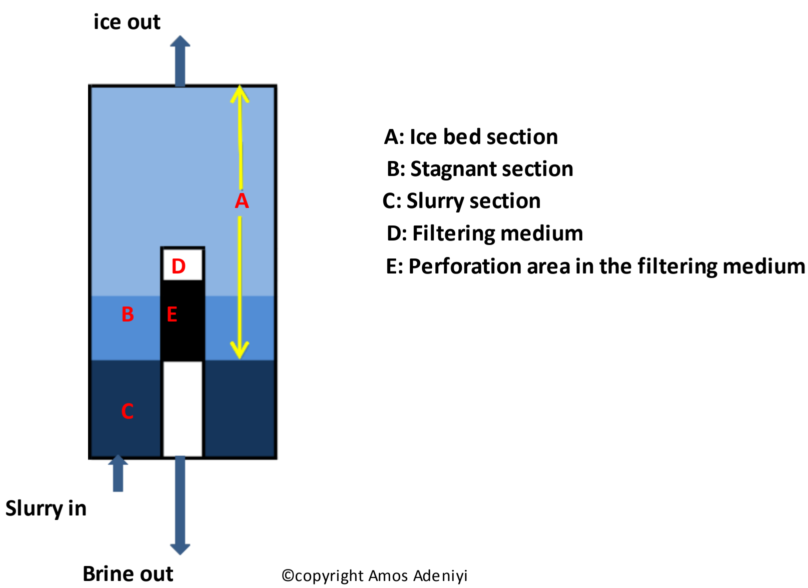


Figure 3: Sections in the HybridICE HIF filter.

Figure 4 shows how the ice yield varies with the flow rate of the feed. The yield decreases as the flow rates increase. This is because of lower ice fraction, because less ice are formed at higher flow rates and constant temperature gradient.

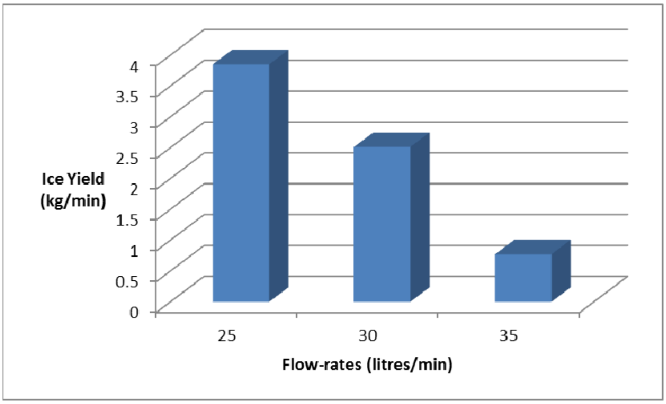


Figure 4: Ice yield plotted as a function of feed flow rates.

Figure 5 shows the variation of salt removal rates with feed flow rates. Salt removal increases with increase in feed flow rates at constant evaporating temperature. It is expected that salt removal should decrease with increase in the flow rates due to reduction in the residence time of the ice bed in the filter. Increase in residence time allows the ice bed to drain in the filter thus making the ice bed free of trapped brine. However, since more heat removal is needed to achieve the same temperature gradient, if mass flow rate increases, less ice formation occurs if the evaporating temperature remains constant. The ice is likely to remain far from the eutectic point and hence be purer. This effect is likely to be stronger because the differences in the flow rates do not result in big differences in the residence time.

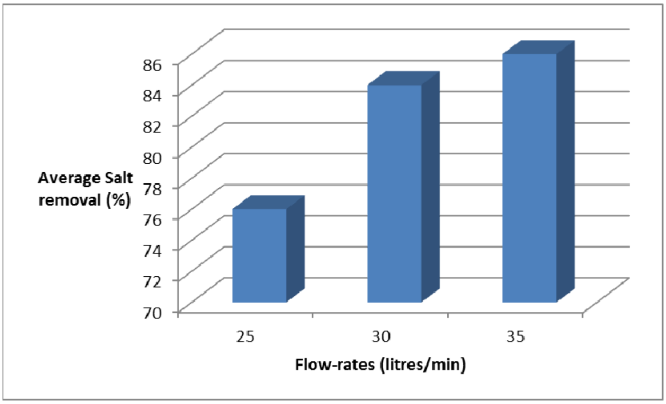


Figure 5: Average salt removal shown as a function of feed flow rate.

Figure 6 shows the variation of salt removal with the concentration of the feed. Average salt removal was higher when the concentration was low. This reflected the concentration of the brine trapped in the ice. The higher the

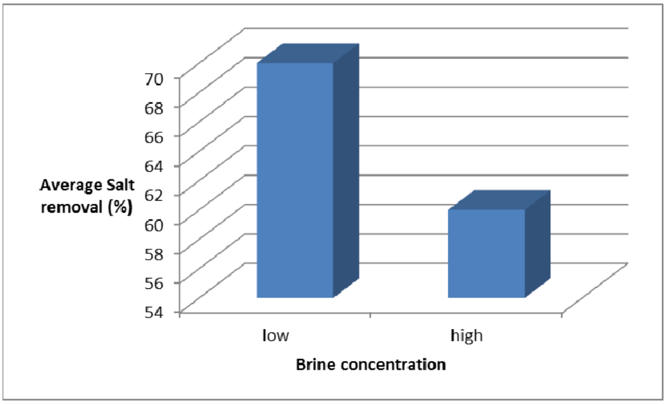


Figure 6: Average salt removal plotted as a function of feed concentration.

concentration of the brine trapped in the ice bed, the lower the purity of the ice yield.

Figure 7 shows how the average yield varies with feed concentration. Average yield increases with feed concentration. At higher feed concentrations the brine section was heavier and could sustain the ice bed better resulting in less ice getting lost in the stagnant section through the perforation in the filtering section.

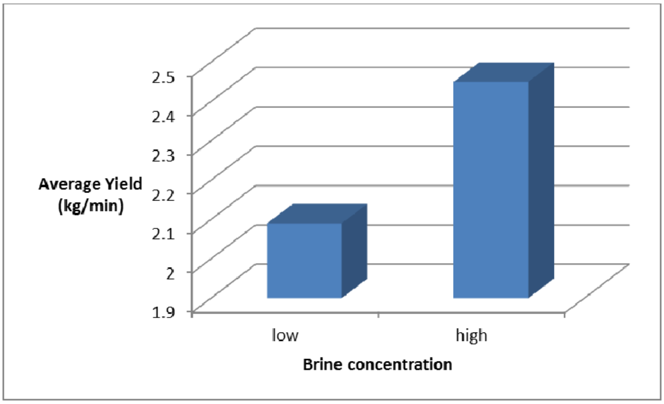


Figure 7: Average yield of ice plotted as a function of feed concentration.

Figures 8 and 9 show the trend for the salt removal when the evaporating temperatures were varied. Salt removal increased with increased evaporating temperature while yield reduced. This was because the closer the evaporating temperature was to the first ice point, the lower was the tendency for the eutectic point to be reached and the lower would be the temperature driving force. More ice crystals were formed rapidly at a higher temperature gradient due to a higher temperature driving force, but more impurities were trapped in the ice. It was also noted that there was no significant difference in salt removal and ice yield at evaporating temperatures of -8ºC and -10ºC. This was because there was no significant difference in the temperature gradient at these evaporating temperatures for the brine treated.

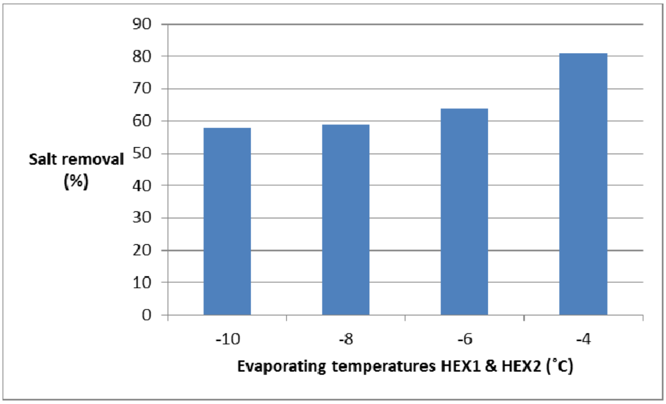


Figure 8: Average salt removal plotted against evaporating temperature (ºC).

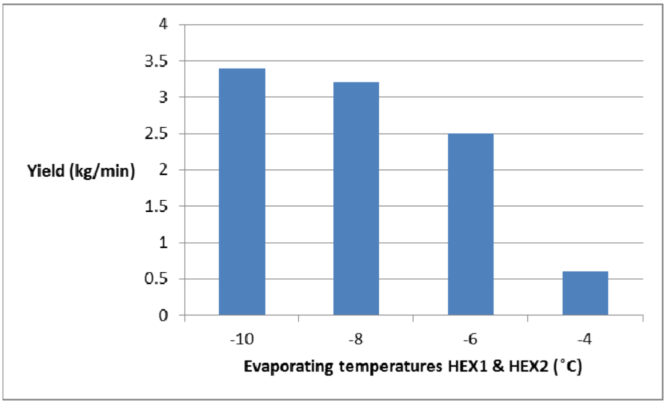


Figure 9: Ice yield plotted as a function of evaporating temperature (ºC).

5 Conclusions

The experimental work led to the following conclusions:

- Ice yield increases with a decrease in feed flow rate at constant evaporating temperatures.
- Ice yield increases with an increase in salt concentration at constant flow rate and evaporating temperature.

- Salt removal increases with an increase in flow rate at constant evaporating temperatures.
- Salt removal increases with decrease in brine concentration at constant flow rate and temperature.
- Salt removal increases with an increase in evaporating temperature.
- Ice yield increases with decrease in evaporating temperature.

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