HybridICE™ filter design in freeze desalination of mine water

A. Adeniyi[1,3], J. P. Maree[2], R. K. K. Mbaya[1], A. P. I. Popoola[1]

[1]*Dept. of Chemical & Metallurgical Engineering;* [2]*Dept. of Environmental, Water and Earth Sciences,*
Tshwane University of Technology, Private Bag X680, Pretoria, 0001, South Africa
[3]*corresponding author: adeniyia@tut.ac.za*

Abstract The design theory of dimensional analysis combined with mathematical analysis was used on the model to establish design equations which can be used to specify critical dimensions for a HybridICE filter when the flow-rate is specified. The model is the present construction of the HybridICE filter which was found experimentally to have maximum yield at brine flow-rate of 25 L/min.

Keywords Freeze, desalination, HybridICE™, filter, design

Introduction

The purpose of this work was to propose a method for designing an efficient HybridICE filter. This is a relatively inexpensive technology that can be used for separation of ice slurry in freeze desalination of mine wastewater. Experiments were carried out to establish the model found to have the highest yield at a flow-rate of 25 L/min. Salt removal was also found to be dependent on the refrigerant temperature. Effective desalination of mine water is required in order to reduce pollution of land and water, meet environmental regulations, provide water for reuse as potable water and even water powered hydraulic machinery. Desalination also removes scaling and corrosion potential in mine waste waters.

Well established desalination methods are evaporative processes which include multistage distillation, multi-effect distillation and vapour compression distillation, and membrane processes which include reverse osmosis and electro-dialysis. Freezing is an alternative process of desalination and has also been seen as one of the more interesting methods of desalination (Cerci *et al.* 2003). One reason for this is the energy advantage of freezing processes over evaporative processes. The latent heat of fusion of ice is only 334 kJ/kg but the latent heat evaporation of water is 2 340 kJ/kg (Qin *et al.* 2008). However, one important difference between freezing processes and distillation processes is that the former require mechanical power while the latter require heat (Brian 1968). Freezing processes are also established methods in the food, pharmaceutical and dairy industries (Dickey *et al.* 1995; Petzold & Aguilera 2009).

HybridICE technology is potentially suitable for freeze desalination applied to mine water treatment. HybridICE freeze crystallization utilizes both the cooling and waste heat energy to achieve zero liquid discharge. The technology generates ice slurry in heat-exchangers which is separated into pure ice and concentrated solution in the HybridICE filter, a significant component of the technology. Most literature describes the use of wash columns for separation of ice from the slurry. Unlike wash columns, the HybridICE filter is economical, easier to operate and there is no need to wash the ice produced. Other components of the technology include a heat pump and vacuum evaporator. Design methods exist for all these components, except for the HybridICE filter. The objective of this study was to show how critical dimensions of the filter can be calculated when the required flow-rate is known.

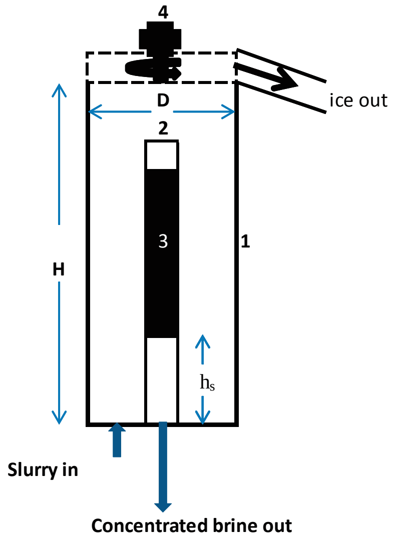

Fig. 1 *Sketch of the HybridICE filter*

Theory

Fig. 1 shows a sketch of the HybridICE filter. The brine slurry is fed from the bottom of the filter (1). The slurry flows into the filter until it reaches the perforation (3) on the filtering medium (2) where the concentrated brine is removed from the filter and the ice build-up begins. The ice level grows continually until it reaches the point where it can be harvested by scraper (4) and emerges from the top orifice of the filter.

Separation is achieved through buoyancy force. Ice being less dense than water, will begin to float at the beginning of the perforation, creating an ice-brine interface. The movement of the ice bed in the filter is sustained by the pressure drive generated by the flow of the slurry into the filter. Critical dimensions that needed to be determined were the height of the filter H, the diameter D and the height of the perforation h_S.

In wash columns, ice crystal size is very important for effective separation. Larger and more uniformly sized ice crystals result in higher capacities in the wash column, thus reducing the cost of the washing step (Brian 1968). The size of the crystals formed is very important because fine crystals are difficult to wash (Lu and Xu 2010). However, in the HybridICE filter, it is also important that the ice fraction in the slurry feed into the filter is kept in a temperature region where the ice crystals do not trap impurities. The major contributors to these conditions are the temperature of the refrigerant, the brine flow-rate and the first ice-point of the process solution.

Experimental

Feedstock water

The brine used on the pilot plant was prepared by making up a 2 % by mass solution of common salt (NaCl) in water.

Apparatus

Apparatus used for the experiments included the pilot HybridICE plant situated at the Soshanguve Campus of the Tshwane University of Technology and the laboratory scale "baby" HybridICE unit. The operation of both is the same. The pilot plant handles a higher volume of process water. Fig. 2 shows the HybridICE filter in operation while Fig. 3 shows the "baby" HybridICE unit in operation.

Other instruments used were an electrical conductivity meter and a mass meter. The ice fraction was determined by filtration using a coffee-plunger machine.

Method

The flow-diagram is as shown in Fig. 4. Brine was first passed through heat exchangers where the ice slurry was generated in a continuous process. Ice slurry was then passed through the filter where the separation of the ice takes place. Brine was run on the pilot plant at flow-rates of 25, 30 and 35 L/min when the temperature of the refrigerant was at -10 °C. Samples of ice were collected and weighed. Samples of slurry were also taken from the filter bypass and the ice fraction determined using the coffee-plunger. The temperature of the refrigerant was then varied at flow-rate of 25 L/min. Electrical conductivity (EC) measurements were made on ice samples. Salt removal was calculated based on the initial EC of the

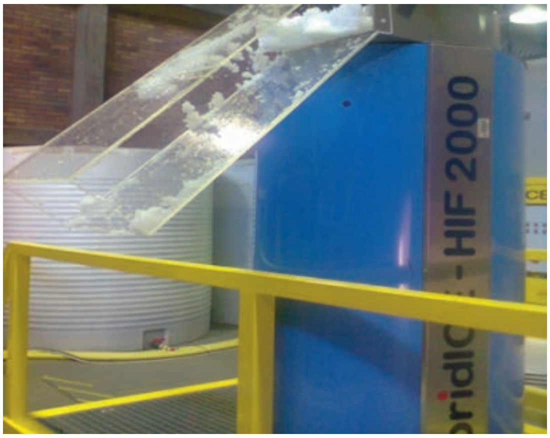

Fig. 2 *HybridICE filter*

Fig. 3 *"Baby" HybridICE unit.*

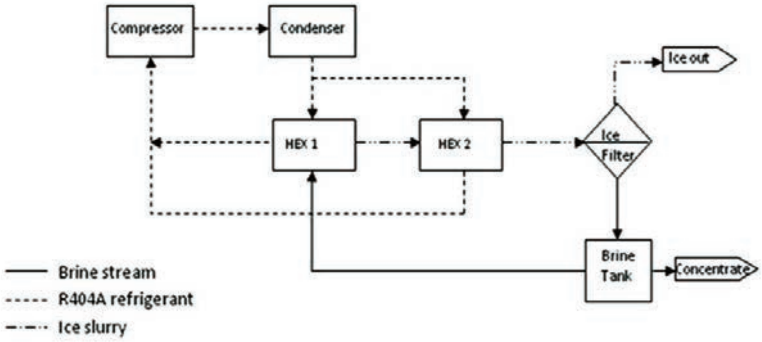

Fig. 4 *Flow diagram of the HybridICE process*

feed sample and the EC of the melted ice sample.

The behaviour of the ice bed was observed in the "baby" HybridICE unit.

Analytical

Actual yield was mass of ice produced, in kg/min.

Salt removal was calculated based on the electrical conductivity of the feed brine C_f and the electrical conductivity of the melted ice sample C_i.

$$\text{Salt removal} = (C_f - C_i)/C_f \qquad (1)$$

Results and Discussion

The aim of the experiments was to establish a model for the filter design. Fig. 5 showed that maximum yield was obtained at flow-rate 25 L/min. The average ice fraction was 11 %. Fig. 6 indicated that salt removal could be improved by control of the temperature of the refrigerant. Ice behaviour was observed on the "baby" HybridICE unit to determine which other parameters to be included in the design. The observed behaviour indicated the need to provide an alternative opening for the excess concentrated brine to leave the filtration section so as to eliminate overflow in the filter.

Design Procedure

The dimensions for the filter at a flow-rate of 25 L/min, were taken as the model for the design procedure based on the results of the experiments.

Ice bed section

Fig. 7 shows the ice bed section in the filter. *D* is the diameter of the filter. *Q* is the flow-rate

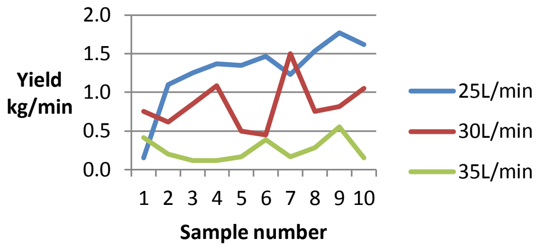

Fig. 5 *Yield of ice at different flow-rates*

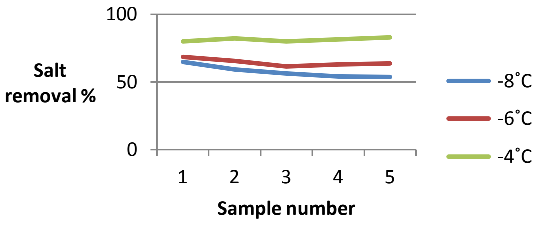

Fig. 6 *Salt removal at different evaporating temperatures; (flow-rate = 25 L/min)*

while X_i is the average ice fraction. Scraping of ice starts at residence time t and height h_i at t=0, h_i =0. Ice balance on the ice section for height dh_i, time dt, gives:

$$X_i Q dt = \left(\frac{\pi D^2}{4}\right) dh_i \tag{2}$$

$$X_i Q \int_0^t dt = \left(\frac{\pi D^2}{4}\right) \int_0^{h_i} dh_i \tag{3}$$

$$X_i Q t = \frac{\pi D^2 h_i}{4} \tag{4}$$

$$t = \frac{\pi D^2 h_i}{4 X_i Q} \tag{5}$$

At Q = 25 L/min = 25,000,000 mm^3/min; h_i = 733 mm, D = 450 mm; substituting these into Equation (5)

$$t = \frac{(\pi \cdot 450^2 \cdot 733)}{(4 \cdot 25000000 \cdot X_i)}$$

Product of Residence time t and ice fraction X_i, $t X_i$ = 4.66

$$4.66 = \frac{\pi D^2 h_i}{4Q} \tag{6}$$

Slurry and ice section weight balance give:

$$h_s = \frac{\rho_i h_i}{\rho_s} \tag{7}$$

Assumption: Density of slurry ρ_s is 1 g/cm^3, and density of ice ρ_i is 0.92 g/cm^3

Equation 7 becomes:

$$h_s = 0.92\, h_i \tag{8}$$

For the height of filter H, $H = h_i + h_s$; substitution of 0.92 h_i for h_s, gives $H = h_i + 0.92\, h_i$ and, clearly

$$H = 1.92\, h_i \tag{9}$$

Slurry section

Flow of slurry in the slurry section (Fig. 7) was similar to the flow in pipes, when based on the Buckingham-π-Theorem. For model and prototype, the dimensionless number, h_s/D is the same (Duncan and Reimer 1998; James & Louis 2009)

At a flow-rate 25 L/min, h_s = 675mm, D = 450 mm; and

$$h_s/D = 1.5 \tag{10}$$

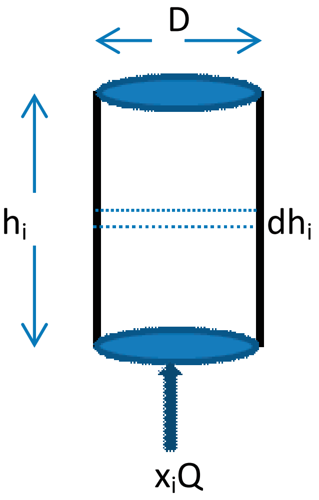

Fig. 7 *Ice bed section*

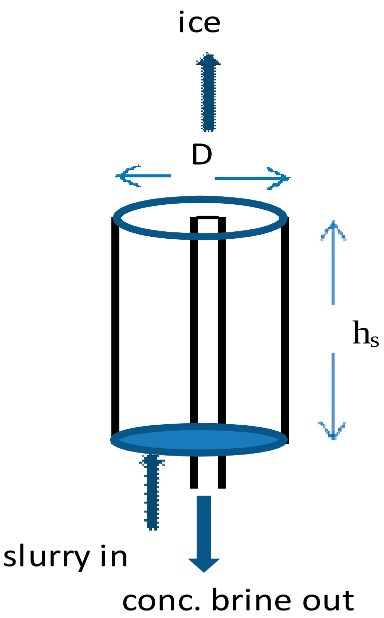

Fig. 8 *Slurry section*

But $h_s = 0.92\,h_i$, therefore $0.92\,h_i = 1.5\,D$; and

$$h_i = 1.63\,D \tag{11}$$

Substituting into equation (6), gives:

$4.66 = \frac{\pi D^2(1.63D)}{4Q}$, which implies that $D^3 = \frac{4.66 \cdot 4 \cdot Q}{1.63\pi}$

$$D = \sqrt[3]{3.64Q} \tag{12}$$

Conclusions

From the results of the experimental work, the following conclusions were reached:

The present construction of the HybridICE filter affords the best yield of ice at a brine flow-rate of 25 L/min.

Salt removal can be improved by adjusting the temperature of the refrigerant.

Overflow can be eliminated by creating alternative perforations for excess brine to flow out of the ice section.

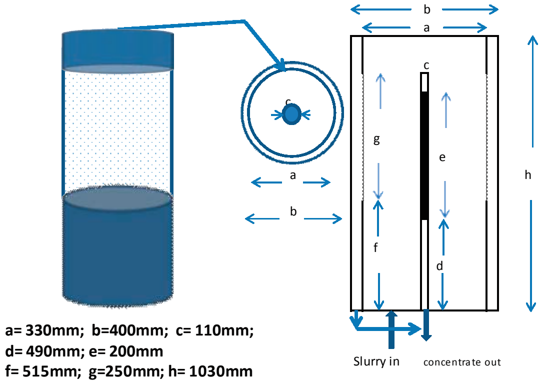

Fig. 9 *Sketch of HybridICE filter at flow-rate of 10 L/min*

Relationships between the flow-rate and the dimensions of the filter were established using mathematical and dimensional analysis.

Fig. 9 shows a sketch of a design of a HybridICE filter using the design equations for a flow-rate of 10 L/min. Sketch does not show scrapper.

Acknowledgements

The authors acknowledge the Tshwane University of Technology for providing research facilities and laboratory equipment and the Technology & Human Resources Program (THRIP) of the South African National Research Foundation for funding the project. Mr Frederick S. Oosthuizen is acknowledged, as the holder of the patent on the HybridICE™ technology, for providing the plant necessary for carrying out the work.

References

Brian PLT (1968) Engineering for pure water Part 2: Freezing. Mechanical Engineering, 90, 42–50.

Cerci Y, Cengel Y, Wood B, Kahraman N, Karakas ES (2003) Improving the thermodynamic and economic efficiencies of desalination plants: Minimum work required for desalination and case studies of four working plants. Agreement No. 99-FC-81-0183. Desalination and Water Purification Research and Development Program, Final Report No. 78, November 2003.

Dickey LC, Craig JC, JR., Radewonuk ER, McAloon AJ, Holsinger VH (1995). Low temperature concentration of skim milk by direct freezing and vacuum evaporation. Journal of Dairy Science 78:1369–1376.

Duncan TM, Reimer JA (1998) Chemical Engineering Design and Analysis An Introduction, Cambridge University Press 1998.

James PA, Louis T (2009) Fluid flow for the practicing chemical engineer. John Wiley & Sons, Inc., New York, p. 14.

Lu Z and Xu L. (2010) Freezing Desalination Process. Thermal Desalination Processes – Vol. II. Encyclopedia of Desalination and Water Resources (DESWARE).

Petzold G, Aguilera JM (2009) Ice Morphology: Fundamentals and Technological Applications in Foods. Food Biophysics 4:378–396.

Qin FGF, Chen XD, Premathilaka S, Free K (2008) Experimental study of wash columns used for separating ice from ice-slurry. Desalination 219: 223–228.