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Process optimization of freeze desalination of brine using HybridICE^{TM} pilot plant

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ABSTRACT

Freeze desalination of synthetic brines prepared from sodium chloride was investigated. Brine solutions of levels between 2.3% to 10% sodium chloride were used as feed to the plant operated in a batch and continuous mode. The effects of pump, gear motor speed, and differential temperatures on ice formation and purity were investigated. The HybridICE process produced ice of quality levels between 80–96% purity. It was observed that the pump speed was directly proportional to the effluent flow rate coming out of the heat exchangers. Generally, it was observed that the quality of product ice was higher at low to medium flow rates of feed. The gear motor speed variation was inversely proportional to effluent flow rate from the heat exchangers. The HybridICE was found to be a viable desalination technology in terms of quality of water produced, energy consumption, and its easiness to be incorporated into existing refrigeration systems.

Keywords: Desalination; Ice slurry; Heat exchanger; R404A; Brine; Impurity

1. Introduction

A significant amount of saline wastewater (brine) in South Africa originating from a number of industrial processes are stored in earth dams, lined ponds, and/or mine shafts. Usually this saline water is finally disposed into specially made evaporation ponds, where most of the water is removed through evaporation and a salt pan is left on the pond surface.

Brine waste is produced in large quantities but the industry lacks viable technologies to process this brine waste. Brine is a major threat to groundwater resources and agricultural farmland. There is more pressure on industry to find a solution to brine pollution as its threat to human health and the environment is ever increasing.

Most of the industrial wastewater can be treated by desalination processes. In South Africa, desalination is widely used as a means of treating brine waste produced by industry. The process of desalination involves the removal of excess salts from saline water commonly known as brine [1,2]. In industry, brine is a by-product from desalination processes such as

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reverse osmosis (RO) and electrodialysis (ED). Highly concentrated solutions with high salt load (brine) and relatively clean water are produced from these processes. Brine is produced as waste by industries such as pulp and paper, mining, and nuclear energy. Currently, brine is treated by distillation or evaporation in large ponds. The cost associated with distillation is ZAR214 m^{-3} at a power cost of ZAR0.30 kWh^{-1} compared to ZAR36 m^{-3} in the case of freeze desalination [3,4]. Hence, freeze desalination is a more energy efficient technology than evaporation. The use of evaporation ponds to treat brines is not favored by the environmentalists due to the real possibility of soluble substances being returned to the environment.

The quantity of heat required to produce one kg of clean water from ice is about one-seventh of that required to produce an equivalent amount of water from the condensed vapor of a distillation process. This is because the latent heat of fusion of ice (335 kJ kg^{-1}) is less than that of vaporization of water (2,500 kJ kg^{-1}) [5]. In the case of evaporation, the temperature of the brine has to be increased from about 25˚C to above 100˚C (owing to the elevation of the boiling point of water in the presence of salts), which indicates a temperature rise of more than 75˚C. In contrast, freeze desalination requires a change in temperature from about 25˚C to below 0˚C, which indicates a temperature drop of more than 25˚C. Clearly, the energy required for the evaporation processes is far greater than that required for freeze desalination. Apart from energy economics, freezing has minimal corrosion potential and little scaling/precipitation to the process equipment [6].

The HybridICE technology utilizes refrigeration energy by freezing out water in a contaminated fluid without adding chemicals. During freezing of a salt solution, salts are excluded by the growing ice crystals by partitioning of the salts between the ice phase and the liquid phase. The ice crystals formed can then be separated from the concentrated solution by filtration, where the ice and the concentrate are continuously separated.

The HybridICE plant is essentially a conventional compressor-driven refrigeration cycle with a condenser to cool the refrigerant and scrapped-surface heat exchangers to provide an efficient heat transfer surface between the refrigerant and brine. The advantage of this approach is that the compressor operates over a smaller temperature range and therefore performs less work per unit of freshwater produced [4]. This process is economically feasible in most brine treatment applications due to the possibility of designing the process to near thermodynamic reversibility (energy recovery). This is because, in mining sectors, the ice formed from freeze desalination moves down a pulley system and gravity connected kinetic energy can be converted to electrical energy and stored. This property can also be harnessed in industrial and domestic cooling systems because of the high energy density of the product ice [7]. In the case of mines, ice instead of water, is sent underground (with the help of gravity) resulting in an increased cooling effect due to the stored latent heat of melting of ice [8]. In this way, a part of the input energy is recovered which translates into cost savings. In addition to ice formation inside the heat exchangers in the HybridICE process, a considerable amount of ice forms on the outer shells (shell ice), which can be scrapped off. This makes the HybridICE technology an appropriate and probably the most cost-effective process for the treatment of brines from mines.

If treated brine was to be used in the mines for cooling purposes, it will be more advantageous to use freeze desalination because its products are at a lower temperature than the products from the distillation technique [9]. Since all nonfreezing desalination processes add energy to saline water and increase its temperature, with the result that additional refrigeration capacity is required to produce chilled water or ice, this requires more energy input into the process which makes it costly.

Freeze desalination removes energy from water, thereby reducing its temperature and consequently eliminating the need for refrigeration of the product water. HybridICE produces ice in slurry form, which makes it a very efficient process since it is of ease to pump slurries through pipes. Ice slurry systems have the ability to cope with rapid fluctuation of the cooling load because of large heat-transfer surface provided by numerous ice crystals. If the system does not cope with rapid fluctuation of the cooling load, the heat exchangers will seize to function and the system will shut down [10]. At ice-fractions below 20%, ice slurries usually show Newtonian behavior, in which case, centrifugal pumping becomes easier [11,12]. One of the first industrial sectors to introduce ice slurries to satisfy cooling needs was the mining sector. The continuously increasing depth of mines, the larger machines, and the larger rock surfaces, resulted in higher temperatures in the tunnels and the pumping costs of chilled water increased significantly [13,14]. Nowadays, mines operate in depths of more than 3,000 m, where temperatures exceed 50˚C. Ice slurries, having much greater cooling capacity than chilled water, can effectively provide the same cooling load with much lower flow rate, offering significant savings in pumping cost and size of equipment [15].

The HybridICE system comes with a unique flexibility that allows it to be integrated into an existing refrigeration plant, the cooling system, and the heat exchangers. Retrofitting of existing plants could be a cost-effective alternative to upgrading an existing system, harnessing the efficiency of the HybridICE process. For the treatment of industrial brines, the HybridICE^{TM} pilot plant process parameters require optimization in order to get usable water from industrial brines.

2. Experimental

2.1. *Chemical reagents and equipment*

Major feed stocks for this study were sodium chloride (simulated brine), and silver nitrate and potassium dichromate (reagents for chloride determination).

The HybridICE^{TM} plant is essentially a conventional compressor (Fig. 1) driven refrigeration cycle with a condenser to cool the refrigerant (R404a) and scraped-surface heat exchangers (Fig. 2) to provide an efficient heat transfer between the refrigerant and the brine. The HybridICE consists of a filter (Fig. 3), where the ice and a concentrate are continuously separated. The process flow block diagram is shown in Fig. 4.

The piping and instrumentation diagram of the HybridICE^{TM} plant used in this study is shown in Fig. 5.

2.2. *Experimental description*

Synthetic sodium chloride brine solutions tested were between 2.5–5% wt. The synthetic sodium chloride brine was prepared in volumes in range of 1 m^3 to 10 m^3 for batch and continuous processes. The prepared solution was stored in a 1 m^3 storage tank for the batch studies and in a 10 m^3 storage tank for the continuous studies.

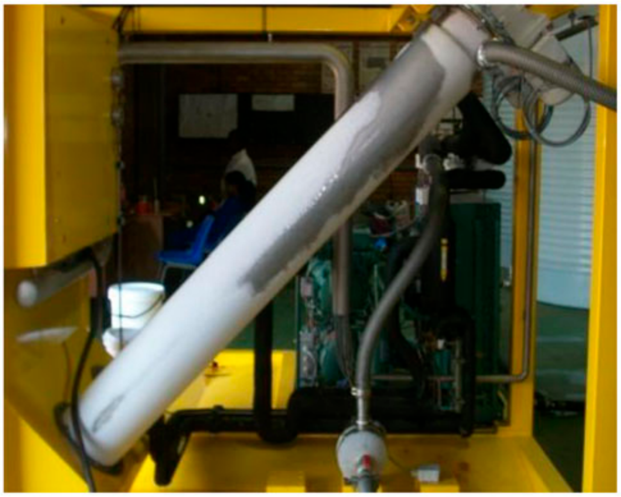
Fig. 2. Heat exchangers (heat transfer between the brine and refrigerant).


Fig. 1. Refrigeration unit (source of cooling energy).

Brine stored in the 1–10 m^3 tanks was pumped into heat exchangers, which were connected in series and providing an efficient heat transfer surface between the refrigerant and brine. A compressor-driven refrigeration cycle with a condenser was used to cool the refrigerant. In the heat exchangers, the temperature of the brine was dropped to the level, where ice crystals form. The ice was then scrapped and pumped as slurry through the pipe to the filter. In the filter, the slurry that came from heat exchangers passed through

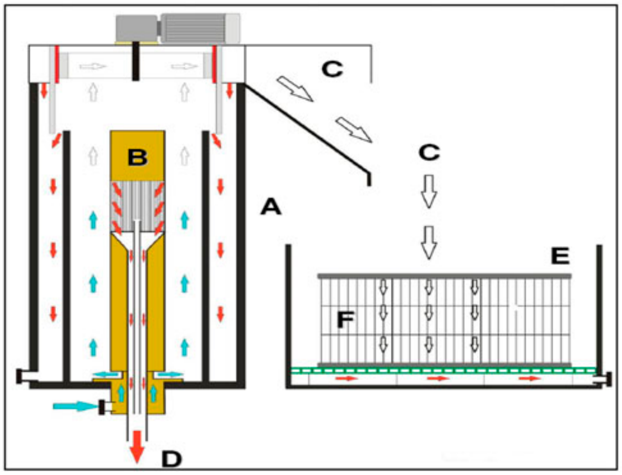

Fig. 3. Schematic filter systems (A: cylindrical vessel, B: filter element, C: outlet ice, D: outlet solute, E: water reservoir, and F: heat exchanger).

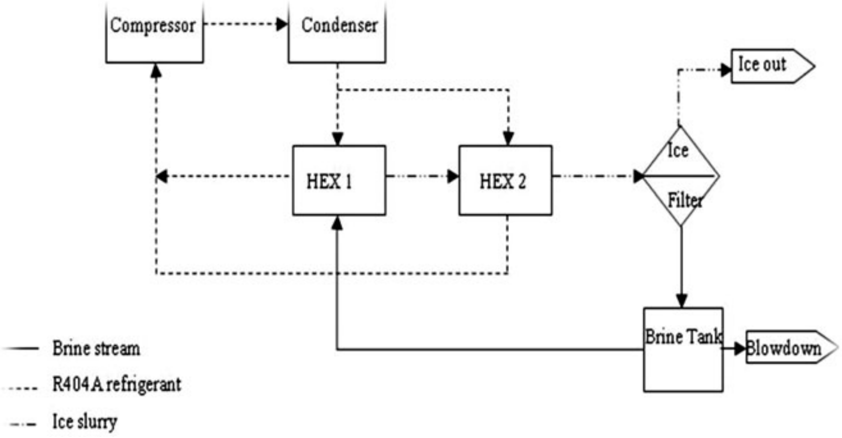

Fig. 4. HybridICE™ pilot plant process flow block diagram.

the filter element for filtration (solid–liquid separation) and drainage by gravity aided by suction. The ice was pushed up the filter and scraped off and kept in the water reservoir, while the contaminated concentrate was pumped back to the storage tank to precool the brine.

The batch experiments were run in order to investigate ice purity under the same operational parameters of the HybridICE plant. The pump speed was at 30 Hz, the gear motor speed was at 60 Hz, while the compressor differential temperature was kept constant at −6˚C. The NaCl simulating industrial brine was 5% wt. Two batches under each experiment were taken into consideration, the first batch at 5% wt with brine concentration of 11,040 mg L^{-1} of chloride. When the first-treated pure ice was produced, the brine became more concentrated, while the concentrate of the first batch became the feed to batch 2. Samples of the brine fed to the system as well as the product ice were collected at their different outlets and analyzed using the calorimetric, titration, and conductometric method. The purity of ice was calculated and the graphs were drawn.

2.3. Measurements techniques

For the determination of ice purity, the experiment was carried out using the HybridICE, whereby 5% wt

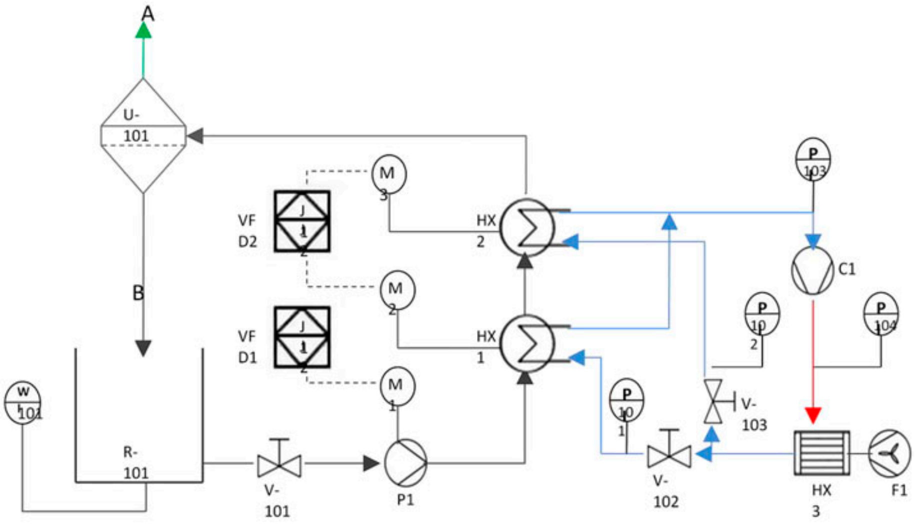

Fig. 5. HybridICE™ piping and instrumentation diagram. (A—ice outlet (ice sampling point), B—concentrate outlet (feed sampling point), C1—compressor, HX1 &2—scrapped surface heat exchangers, HX3—refrigerant condenser (forced air); M1, M2, M3—electrical motors; P1—centrifugal pumps; P1–101, P1–103, P1–104- pressure indicators; R—101—brine storage tank; U—101, V—103—evaporation temperature control valves; VFD1, VFD2—variable frequency drives; W1–101- weight indicator (mass lost = mass of ice)).

of NaCl simulating brine was treated under the following conditions for two batches.

Pump speed was set to 35 Hz for batch 1 and batch 2. Gear motor speed was set to 50 Hz for both the batches, while the evaporation temperatures were kept at −6˚C. Samples of the brine fed to the system as well as the product ice were collected at their different outlets and analyzed using the calorimetric, titration, and conductometric method. The purity of ice was calculated and the graphs were drawn. The energy used was calculated for each batch.

At constant pump speed of 25 Hz and constant gear motor of 80 Hz, the differential temperatures were varied from −2 to −8˚C. Samples of the brine fed into the system and ice produced were collected at their outlets and analyzed using calorimetric, titration, and conductometric method.

The effect of pump speed on flow rate and purity of ice was determined. The pump speed was varied at constant gear motor speed of 80 Hz and the differential temperatures 1 and 2 were kept constant at −5˚C. The pump speed was run at 12, 14, 16, 18, 20, 22, 24, 28, 32, 36, 42, 48, 55, 60, 66, and 80 Hz. Samples of ice produced and feed brine were collected at regular intervals for each set of operating parameters and the samples were taken to the laboratory. Sodium chloride concentration in the product ice and feed brine was analyzed using titrimetric, conductometric, and calorimetric methods.

For this experiment, the differential equations were kept constant at −6˚C and the pump speed was kept constant at 20 Hz. The gear motor speed was run at 0, 30, 40, 50, 60, 70, and 80 Hz. Feed brine samples and the samples of ice produced were collected for each change in gear motor speed. Samples were then analyzed for chloride concentrations.

Energy was monitored constantly for every experiment carried out using a built-in energy meter in kWh.

2.4. Data Measurement

Sodium chloride was used to simulate industrial brine. The concentration of sodium chloride in aqueous solution ranged around 1,000–50,000 g L^{-1}. The amount of residual chloride in the salt was determined by argentometric titration.

The indicator was prepared by dissolving 50 g of K_2CrO_4 in 100 ml distilled water in a volumetric flask. Silver nitrate solution was then added until a definite red precipitate was formed. The solution was left to stand for 12 h. After 12 h, the solution was filtered and diluted with distilled water to 1,000 mL.

Samples of the ice produced and feed brine were collected at regular intervals for each set of operating parameters and the samples were taken to the laboratory. Sodium chloride concentration in the product ice and feed brine was analyzed using calorimetric, titrimetric, and the conductometric method.

The purity of ice produced from freeze desalination of simulated brines was investigated by argentometric method, whereby the presence of sodium chloride still present in the ice was determined by adding silver nitrate as a titrant. When all the sodium has been completed, the solution turns from yellow to a deep red marking the end point of titration.

Ice samples were allowed to melt and equilibrated to 20˚C before their conductivity was measured. The conductivity of the aqueous liquid usually depends on the concentration and nature of impurity present in it.

In the calorimetric procedure, product ice from freeze desalination was mixed with known amount of hot water. Both the temperatures of ice and hot water were determined before the hot water and cold water were mixed. The final temperature after mixing was then determined empirically, using a digital thermometer. The ice fraction was used to determine the purity of ice produced in terms of dryness. The mass of ice in the slurry was then determined using one of the equations developed during this study.

3. Results and discussion

3.1. Batch experiment on desalination of brine

The results obtained from the batch experiments were the pump speed, gear motor speed, and compressor differential parameters were kept at 30 Hz, 60 Hz, and −6˚C, respectively, and are shown in Figs. 6 and 7. These figures show the salt removal achieved using the HybridICE™ pilot plant. The average salt removal based on the average chloride analyses from the two runs was 96% when initial 3.5% feed synthetic

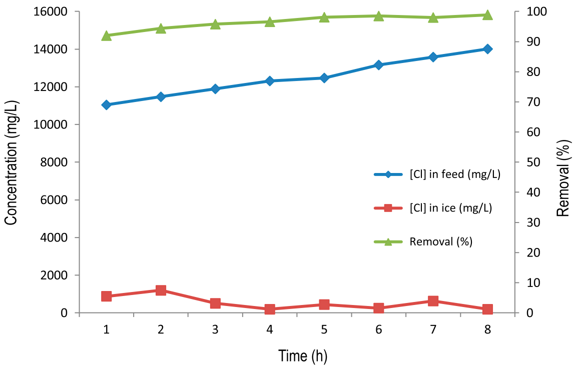

Fig. 6. Ice and feed concentration (mg L^{-1}) and the removal (%).

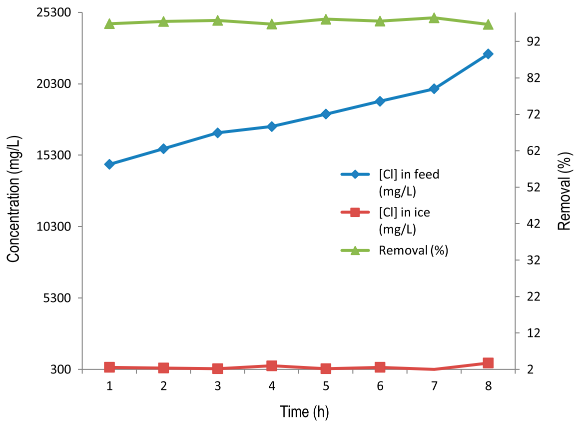

Fig. 7. Ice and feed concentration (mg L^{-1}) and the removal (%).

brine was used. The removal of salt in the product ice is observed when there is an increase in the salt concentration in the residual feed. Several batch studies were carried out and the residual salt in the ice was monitored as various operating parameters were being varied.

In one of the batches, the initial chloride concentration in the feed was 11,040 mg L^{-1} and the final feed after 8 h of recycling was 14,010 mg/L, and the overall salt removal was calculated to be 96.5%.

$$\% \text{ Removal} = \frac{[\text{Cl}]_{\text{feed}} - [\text{Cl}]_{\text{ice}}}{\text{Cl}_{\text{feed}}} \times 100 \qquad (1)$$

Calculation for salt removal based on chloride concentration was performed using Eq. (1).

The variation of chloride concentration in both product ice and recycled feed is shown in Fig. 6. Generally, there was a linear relationship between the partitioning of salt into the liquid phase (brine) and the solid phase (ice). The salt was less soluble in the solid phase.

The process stability can be observed from the production of ice of consistent quality over a period of time. Fig. 7 shows that the ice produced in this batch was of consistent quality. In this experiment, the chloride in the feed was 14,660 mg L^{-1} and the final feed after 8 h of recycling was 22,390 mg L^{-1}, and the overall salt removal was calculated to be 97.5%.

3.2. Continuous experiments on simulated brines to determine purity of ice produced

The results of the purity of the ice generated from the treated simulated brine for the continuous experiment are shown in Figs. 8 and 9. The variation of the concentrations of the recycled feed increased with time as expected (Figs. 8 and 9). The impurities were successfully removed from simulated brine to produce ice of more than 90% purity. The overall impurity removal from the 10 subsamples taken during a period of 10 h was found to be 82.8% using titrimetric method and 82.6% using calorimetric procedure (Eq. (1)). The energy used was monitored during the process and it was observed that 49.7 kW h was needed to produce an average of 300 kg of dry ice based on ice fraction theory. The conductivity of each subsample of recycled feed taken during the process was measured. It was observed that the conductivity increased with an increase in salt concentration (Tables 1 and 2). Calculations of salt removal from product ice from samples with different initial salt concentrations was found be on average of 84.1 and 81.4% based on conductivity measurements.

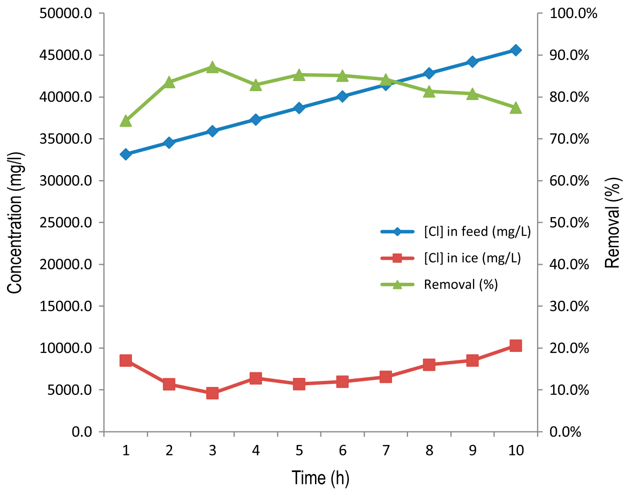

Fig. 8. The amount of chloride in the feed, ice sample with time and % removal (initial brine chloride concentration of 5,000 mg L^{-1}).

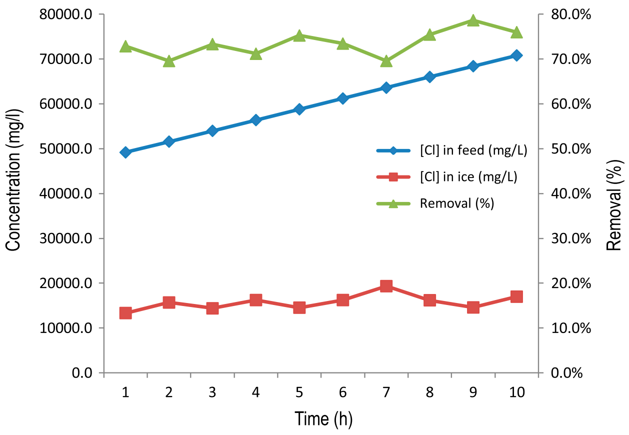

Fig. 9. Amount of chloride in the feed, ice sample with time and % removal. (initial brine chloride concentration of 10,000 mg L^{-1}).

Table 1
Variation of conductivity with residual chloride in the feed subsample (cycle 1)

	Initial		Final	
	Cl^- (mg L^{-1})	Conductivity (mS)	Cl^{-1} (mg L^{-1})	Conductivity (mS)
Feed	33 145.8	72.70	45 889.4	98.44
Ice	8 508.0	15.17	10 280.0	18.74

Table 2
Variation of conductivity with residual chloride in feed subsample (cycle 2)

	Initial		Final	
	Cl^- (mg L^{-1})	Conductivity (mS)	Cl^- (mg L^{-1})	Conductivity (mS)
Feed	49 185	133.7	70 823	490.4
Ice	13 346	32.3	16 995	75.6

3.3. Effect of operational parameters on ice quality

The results of the effect of differential temperature on salt removal are shown in Fig. 10.

Differential temperatures are a very important parameter in the HybridICE technology for the lowering of the brine temperature in order to form ice crystals. It was observed that at high differential temperatures, the rate of ice formation was higher, but the quality of product ice produced was lower, hence increased salt in product ice. This was due to rapid crystallization which leads to the processes of inclusion and occlusion.

The results obtained from the experiment carried out in order to determine the effect of the pump speed on the feed flow rate as well as purity of ice are shown in Fig. 11. This experiment was carried out in order to determine the effect of the pump speed on the feed flow rate as well as on the purity of ice produced. It was observed that the pump speed was directly proportional to the feed flow rate. As the pump speed was increased, more slurry was pumped from the heat exchangers to the filter. However, it was observed that there was a general decrease in product ice purity as the pump speed was increased as shown in Fig. 13.

For the plot Fig. 12 to be obtained, the assumption made was that $F(x) \alpha P^n (t)$ then $F = k P^n$.

The logarithmic values of the pump speed and the flow rate were calculated to plot a graph and find the gradient $\ln F(x) = k + n.\ln P(t)$ was found to be 1, that is, the effect of the pump speed on the flow rate is of direct proportionality. When the pump speed increases, the flow rate will increase.

The relationship between pump speed and ice purity is illustrated in Fig. 13. At lower pump speed, as the pump speed increased the purity increased. As the pump speed was operated at higher speeds, the ice purity decreased. This was due to the fact that at

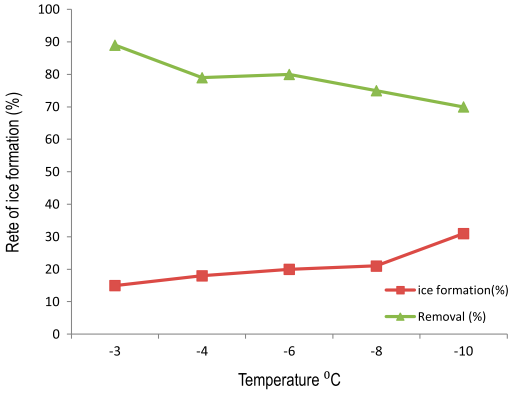

Fig. 10. Effect of compress differential temperature on salt removal.

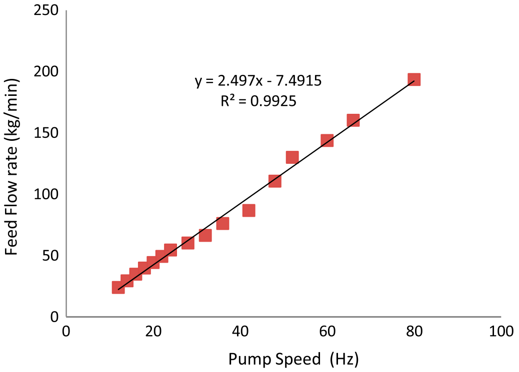

Fig. 11. Effect of pump speed on the feed flow rate.

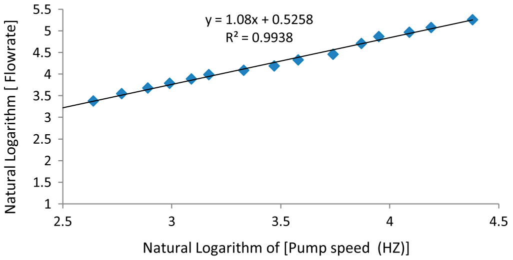

Fig. 12. The logarithmic plot of the effect of pump speed on the flow rate.

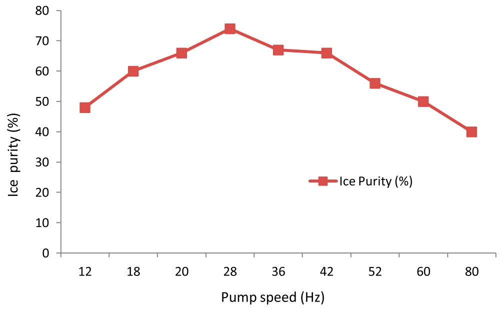

Fig. 13. Effect of pump speed on ice purity.

very high pump speed, the pressure of the liquid was very high resulting in rapid crystallization without enough time for strong crystals to form.

The effect of pump speed, P_s, on the ice purity was deduced to be described by Eq. (2).

Then,

$$I_p^{1/2} = \left(kP_s^{1/2} - \frac{k}{P_s^{1/2}}\right)\frac{P^{1/2}}{P_s^{1/2}} \tag{2}$$

Further simplification of this exponential equation can be reduced to Eq. (3).

$$I_p^{1/2} = kP_s^{-1/2}(P_s - 1) \tag{3}$$

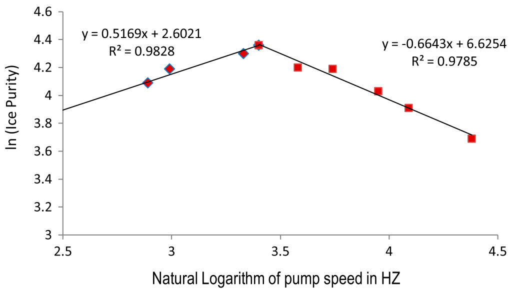

Fig. 14. The effect of pump speed on the ice purity.

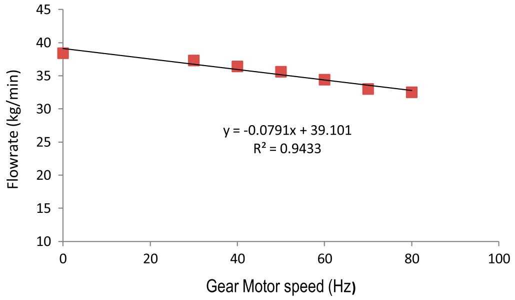

Fig. 15. The effect of gear motor speed on the flow rate.

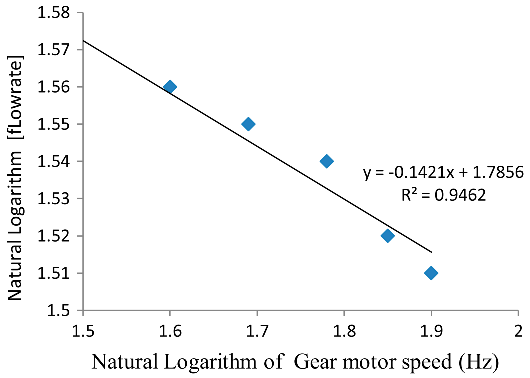

Fig. 16. Gear motor speed vs. ln flow rate.

A logarithmic form of Eq. (3) was plotted to give Fig. 14. From this plot, it was observed that there was a linear relationship between the pump speed and the ice purity.

The effect of gear motor speed on the feed flow rate is shown in Fig. 15. The results show that the gear motor speed is inversely proportional to the feed flow rate.

In Fig. 16, the relationship between gear motor speed and feed flow rate was found to be inversely

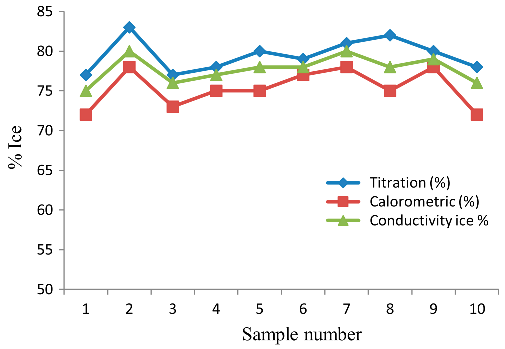

Fig. 17. Titrimetric, conductometric, and calorimetric methods used in purity analyses.

Table 3
Determination of ice slurry quality characteristics using calorimetric procedure

T_s (°C)	−4	−4	−4	−4	−4	−4	−4	−4
m_s (kg)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
T_h (°C)	88	91	91	91.5	91	91	91	87
m_{sh} (kg)	0.395	0.425	0.39	0.44	0.34	0.41	0.41	0.4
T_m (°C)	11	14	22	11	16	16	10	18
m_b (kg)	29.34	33.81	33.15	16.54	44.04	21.02	11.1	20.68
m_h (kg)	0.195	0.225	0.19	0.24	0.14	0.21	0.21	0.2
m_i (kg)	0.16874	0.18908	0.12804	0.21917	0.10841	0.16717	0.19440	0.14191
m_{pi} (kg)	24.7547	31.9641	21.2231	18.1256	23.8725	17.5697	10.7894	14.673
C_i (%)	84	95	64	110	54	84	97	71

Notes: m_i = mass of ice in slurry, m_h = mass of hot water, T_h = temperature of hot water, T_m = temperature of mixture, m_s = mass of slurry, and T_s = temperature of slurry.

proportional. The assumption made was that: $F(x)$ α $G(t)$, then $F = k\ G^n$, where (F) is the feed flow rate and G the gear motor speed.

The logarithmic values of the gear motor speed and the flow rate were calculated to plot a graph and found the gradient n ($\ln F = k + \ln G$). The relationship was found to be inversely proportional.

3.4. Validation of analytical methods

Validation of analytical methods used in the analyses was done. The feed and ice samples were collected and analyzed using the titrimetric, conductometric, and calorimetric method. The results obtained by the titrimetric method showed the amount of chloride present in the brine feed and the produced ice. In calorimetry, known amounts of product ice from freeze desalination were mixed with known amounts of hot water. Both the temperatures of ice and hot water were determined before the hot water and cold water were mixed. The final temperature after mixing was then determined empirically, using a digital thermometer. Glass cylinders were used to weigh and mix the cold water and produced ice, which resulted in loss of heat. Thermo flasks were used for the calorimetric experiment. In the conductometric method of analyses, the conductivity of a sample increased with the increase in concentration of brine. Statistical treatment of the various results from the three methods showed that there was no significant difference between the results of the different methods used. The results from the three methods are graphically presented in Fig. 17.

The mass of ice in the slurry was determined using calorimetric technique based on Eq. (4), which was developed during this study. It was observed that the larger the temperature difference ($\Delta T = T_h - T_m$) with smaller T_m, the higher the percentage of ice in the slurry. The correction factor for the effect of latent heat of melting ($T_m - T_s$) was incorporated to normalize the energetics. Some of the experimental results obtained after applying Eq. (4) are shown in Table 3.

$$m_i = \frac{[4.18\, m_h(T_h - T_m) - 0.85\, m_s(T_m - T_s)]}{[2.1 T_s + 332 + 4.18\, T_m - 0.85(T_m - T_s)]} \tag{4}$$

Table 4 shows the energy that was consumed for each batch for each kilogram of pure ice produced. From the expected energy costs and the results obtained, the conclusion drawn was that the HybridICE technology is indeed a cost-effective technology in terms of energy demand.

Table 4
Energy consumed during batch experiments

Parameter	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Batch 7
Energy used (kW.hr)	41.6	34.4	33.7	42.3	50.4	37.2	43.8
Ice produced (kg)	250	280	300	323	400	308	360
Cost (ZAR kW h^{-1})	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Energy (kW h kg^{-1})	0.17	0.12	0.11	0.13	0.14	0.12	0.12

4. Conclusions

From the experimental work done in treating brines by the process of freeze desalination using the HybridICE technology, it was concluded that the technology produced high-purity ice crystals without the need for introduction of freshwater to wash the ice crystals. This makes the technology simple and compact.

Figs. 2–5 show the salt removal achieved using the HybridICE™ technology. The average salt removal based on the average chloride analyses from the two runs from the batch experiment was 96%. The average salt removal from the continuous experiment was 82.8%.

The optimization of the HybridICE technology parameters was of importance in determining the best conditions for effective operation of the technology to yield best results. It was determined that the pump speed and gear motor speed have an effect on the rate of formation of ice and the purity of ice produced. The pump speed was found to be directly proportional to the flow rate of the effluent from the heat exchangers. As the pump speed increased, the rate of ice formation also increased. The ice purity was dependent on the pump speed. The pump speed of 31.2 Hz gave the maximum ice purity of 78.3%.

The gear motor speed had an inversely proportional relationship with the purity of ice. The ice purity was related to the gear motor speed by the equation $\ln F = k + \ln G$.

Three methods used for analyzing purity of ice were titrimetric, conductometric, and colorimetric methods. The purity of product ice samples were 77.2, 74.2, and 72.3% for titrimetric, conductometric, and colorimetric techniques, respectively. There was no statistical significant difference between the results of the different methods used.

Energy consumption was $100\,\mathrm{kW\,h\,m^{-3}}$ water. It was observed that the HybridICE™ technology based on freeze desalination was economically feasible in brine treatment, particularly where the ice slurry produced could be further utilized for cooling purposes.

The HybridICE was found to be a viable desalination technology for producing high-quality water at low energy consumption, and it can be easily combined into existing refrigeration systems.

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Symbols and abbreviations

C_{i} — pure ice fraction (%)
ED — electrodialysis
m_{b} — mass of brine (kg)
m_{h} — mass of hot water (kg)
m_{i} — mass of ice (kg)
m_{pi} — mass of pure ice (kg)
m_{s} — mass of ice slurry (kg)
m_{sh} — mass of slurry and hot water (kg)
R404A — refrigerant 404A
RO — reverse osmosis
T_{h} — temperature of hot water (°C)
T_{m} — temperature of mixture (slurry and hot water) (°C)
T_{s} — temperature of ice slurry (°C)
ZAR — South Africa Rand (currency)

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