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Mine Water Treatment Using a Vacuum Membrane Distillation System

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Abstract

Water scarcity and strict environmental regulations has seen the rapid development of membrane technologies in water and wastewater treatment. Effluent discharge from a local coal mine containing 2332 mg/L of TDS (Total Dissolved Solids), 14.4 mg/L of Ca, 2.72 mg/L of Mg, 1.92 mg/L of Fe and 3.38 mg/L of Al is treated by a vacuum membrane distillation system. This technology aims to remove particles and dissolved impurities by evaporation and condensation technique that mimics what occurs in nature within a water cycle. It employs a hollow-fiber membrane that enables to remove 99.9% of TDS from mine water. This paper discusses design configuration and demonstrates the response of flux rate to various process operating parameters, including vacuum pressure, feed water temperature, flow rate and feed salinity concentration. It is concluded that the quality of permeate meets the water quality standards for potable use, but may however, require mineralization efforts before direct human consumption.

Keywords: Mass transfer; Mine water; Vacuum membrane distillation; Water treatment.

1. Introduction

Coal mining has been an important industry in many parts of the world including Australia. Large amounts of brackish water need to be pumped out to the surface from the workings of mines and good quality water is

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also needed for various coal cleaning operations. Several processes such as mill, flotation and refining cause mine water quality deterioration with low pH, high sulphate content and different dissolution of dissolved ions [1]. Therefore, treatment of the contaminated water from a coalmine prevents serious damage to receiving waters and their ecosystems and can be reclaimed for other purposes. Water management in mining advocates a sustainable approach of using non optimal water instead of fresh water sources. Use of wetlands for mine waste water treatment in order to remove inorganic pollutants and the application of lime and sulphides, followed by ion exchange in precipitation of heavy metals were studied [2,3]. Although, a number of technologies have begun to address the treatment of mine water, very few studies have focused on low energy and chemical free treatment techniques. The main aim of this study is to develop a technology that can produce a high quality effluent along with low energy consumption without any usage of chemicals.

The use of membrane separation technologies in brackish water treatment are the result of the tightening of environmental regulations being placed on industry [4]. Membrane distillation (MD), a thermally driven physical separation process, comprises of four configurations such as direct contact membrane distillation, sweeping gas membrane distillation, air gap membrane distillation and Vacuum Membrane Distillation (VMD) [5]. A convective transport process occurs in VMD using a vacuum pressure on permeate side of the membrane to reduce the pressure below the saturation pressure of feed solution. The hydrophobic nature of the membrane prevents liquid solution from entering its pores and assists in the creation of a liquid-vapor boundary layer. The VMD system has a number of advantages over conventional MD techniques. Perhaps the most significant advantage is the production of pure distilled water at lower operating temperatures, resulting in lower operating costs [6]. Therefore, lower energy requirements are needed to achieve similar flux rates compared to other distillation and desalination processes [7]. VMD is a promising technology that has the potential to become as important as conventional distillation and pressure driven membrane technologies for water desalination [8]. Experimental monitoring of the performance of VMD and studying the sensitivity of flux to feed flow rates, temperatures and vacuum pressures will help to identify specific correlations that these parameters have on flux, contaminant removal, and thereby increasing reuse potential and treatment optimization.

2. Theoretical Background

Various types of mass transport mechanism are identified such as Knudsen flow model, viscous flow model, ordinary molecular diffusion model and/or a combination of the above to describe the flux through a MD system [5]. Both molecule-molecule and molecule-pore wall interaction occurs in a VMD process, hence the mass transport within the Knudsen-viscous transition region is considered [5]. For this case, the equation (1) is used to determine the clean water mass flux N (kg/m^2-s), however, it is noted that the saturation pressure on the RHS of the equation (part of Δp) is a function of heat transfer which in turn dependent on the mass flow rate (N) of vapor [5].

$$N = \frac{\Delta p}{RT}\left[\frac{2\varepsilon r_p}{3\tau}\left(\frac{8RT}{\pi M}\right)^{1/2} + \frac{\varepsilon r_p^2 P}{8\tau\mu}\right] \tag{1}$$

Where r_p is pore radius (m), Δp is changes in pressure between boundary and permeate side (kPa), M is molecular weight of water vapor (g/mol), μ is vapor viscosity (Pa-s), R is universal gas constant (J/kg-K), τ is the membrane pore tortuosity (m), ε is membrane porosity (-), T is temperature in Kelvin and P is mean pressure within pores (Pa). The actual mass flux will have to be calculated based on a simple iterative technique.

3. Materials and Methods

In the VMD process, mine water in contact with feed side of the membrane is vaporized through the permeate side which is then condensed back into liquid state. The VMD system is shown schematically in Fig. 1. Mine water is heated and circulated through the membrane module by a digitally controlled Masterflex peristaltic pump. The Emflon PFR filter cartridge (Pall, Australia) contains a double layer PTFE membrane which is hydrophobic, chemically inert and designed for removal of bacteria and viruses acts as a barrier between aqueous and gas phases. The surface area and pore diameter of the membrane module are 0.8 m^2 and 0.2 µm, respectively. A vacuum pump (Javac) is used to create a vacuum pressure through the condenser at the permeate side of the membrane.

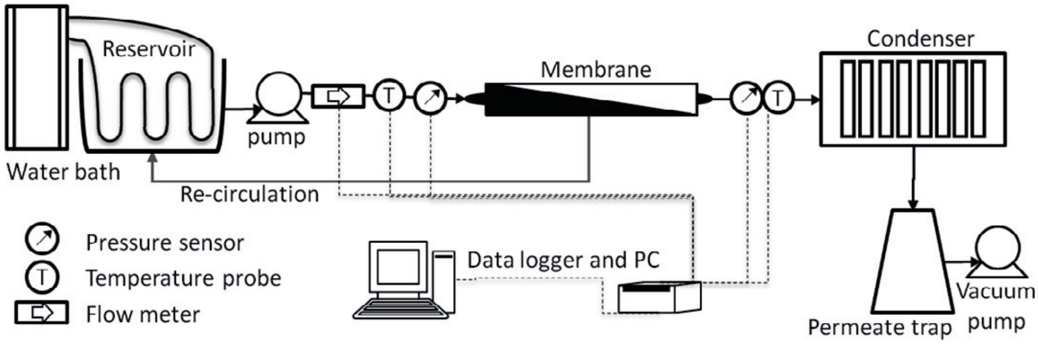

Fig. 1. VMD experimental arrangement

The effect of feed water temperature was investigated in this study by varying the temperature between 55 to 75 ˚C. The effect of feed water flow rate on flux was analyzed during experimentation, initially testing flow rates of 500 to 2000 mL/min. The vacuum pressure was varied between 5 to 20 kPa (abs) by incorporating a valve onto the vacuum pump and the flux response was investigated. Initial feed solution is made up of NaCl using varying concentrations (0-21 g/L) in order to simulate fresh, brackish and seawater. Finally, saline mine water collected from a local mine site located in Appin NSW was used.

4. Results and Discussion

Experiments were first carried out using distilled water and saline solutions that were made by combining NaCl with distilled water. The variation of flux permeation rate with temperature, feed flow rate, vacuum pressure and salinity of feed water is investigated while in each test other parameters remained constant with a vacuum pressure of 5 kPa, feed water temperature of 65 ˚C, feed water flow rate of 1000 mL/min and salinity concentration of 0 g/L. Feed water temperature had a considerable effect on vapor permeation flux for a given set of experimental conditions as shown in Fig. 2(a). The experimental data fits well with the modeled permeate flux using equation 1. It is clear that both the experimental and modeled flux steadily rises as feed water temperature increases. This can be attributed to the fact that water vapor pressure as a driving force for water vaporization increases with rise in temperature. Fig. 2(b) illustrates that an increase in absolute pressure on the permeate side of the membrane results in a severe decline in permeate flux rate due to a significant reduction in the driving force for transmembrane flux. These results are consistent with the equation 1 and many of the findings in the literature [5].

Experimental data show a small increase in flux with varying flow rate and this observation is well supported by the model prediction as shown in Fig. 3 (a). The most significant advantages of using VMD for desalination purposes is the negligible effects that increasingly salinity concentration has on the flux output. Fig. 3(b) illustrates the effect of increasing feed water salinity concentration on flux performance. The permeate flux rate decreases slightly as NaCl concentration increases because of the influence of the salt accumulation on the membrane surface. The increase in salinity also influences the temperature and concentration polarization phenomena resulting in a slight decline in flux. The various parameters that contribute to flux throughput is presented in Fig. 4. From the variables studied, vacuum pressure was found to have the most significant effect on flux followed by water temperature.

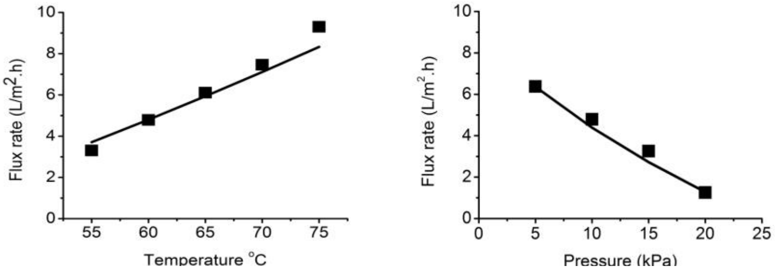

Fig. 2.(a) Effects of feed water temperature on flux; (b) Effects of pressure on flux. (—) Modeled flux (Eq.1), (■) Experimental flux.

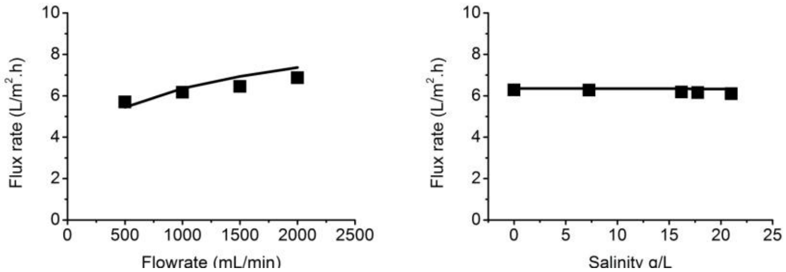

Fig. 3.(a) Effects of feed water flow rate on flux; (b) Effects of salinity on flux. (—) Modeled flux (Eq.1), (■) Experimental flux.

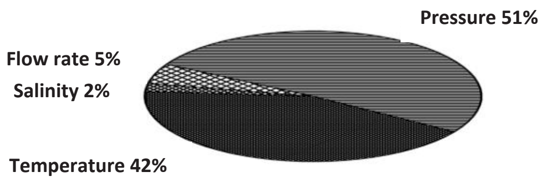

Fig. 4. The contribution of four parameters on flux.

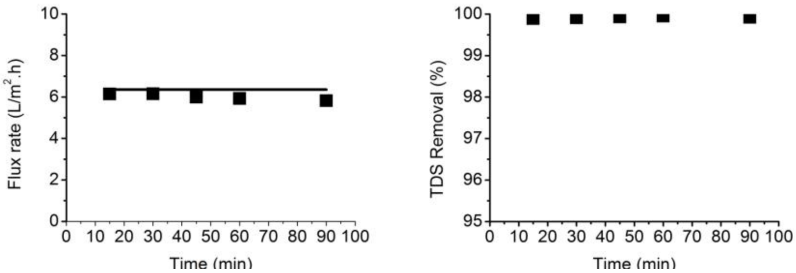

Fig. 5.(a) Flux decline in treatment of mine water; (b) Removal efficiency of TDS in treatment of mine water. (—) Modeled flux (Eq.1), (■) Experimental flux, (■) Removal efficiency.

The treatment of mine water being discharged by a local coal mine was investigated by running the sample through the VMD system for 90 minutes and the flux were measured at various time intervals. A decrease in flux of 5.3% was observed over the 90 minute duration as shown in Fig. 5(a). This was mainly due to the deposition of inorganic precipitates and other particulates within the water source. High TDS removal efficiency of 99.9 ± 0.05% was achieved in this experiment as shown in Fig. 5(b). Table 1 presents the average results from water quality analysis of mine water treatment. The pH values dropped between the feed water and permeate caused by the removal of alkalinity as calcium carbonate and adsorption of carbon dioxide in the permeate. The removal efficiency of major ions and metals was investigated by measuring the concentration in feed water and permeate samples using atomic absorption spectroscopy. Removal efficiency remained about 98% for Fe and recorded 100% in all cases for Al.

Table 1. Water quality analysis of mine water

Parameter (mg/L)	Feed water	Permeate	% Removal
TDS	2332	2.66	99.9
pH	7.68	6.32	N/A
Calcium	14.4	0.74	94.9
Magnesium	2.72	0.03	98.9
Iron	1.92	0.04	97.9
Aluminum	3.38	0.00	100

5. Conclusion

A VMD system was used to treat mine water. A Knudsen flow model based on an iterative solution was able to predict the clean water vapor flux successfully. The effect of various operating conditions on flux rate was investigated using distilled water and saline water at different concentrations. It was shown that VMD system is capable of successfully desalinating and treating mine water to acceptable standards with TDS removal up to 99.9%. Sensitivity analysis was performed by experiments on the VMD process to investigate the influence of various operating parameters on flux rate. Each of the parameters; feed temperature, salinity, flow rate and vacuum pressure were varied independently from one another and the corresponding flux rate was recorded. It was found that, for a pleated membrane module, vacuum pressure was the most influential parameter; followed by feed water temperature, feed water flow rate and salinity.

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