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Pilot trial of membrane distillation driven by low grade waste heat: Membrane fouling and energy assessment

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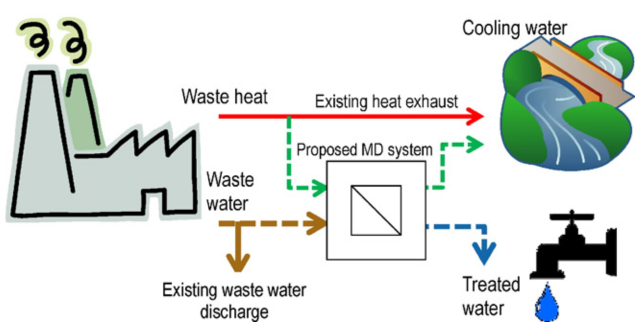
HIGHLIGHTS

- Direct contact membrane distillation (DCMD) was trialled for three months.
- Trial pilot plant supplied with waste heat <40 °C from power station
- Water recovery 92.8% reached treating ion exchange regeneration effluent
- Trial fluxes between 2 to 5 L/(m^2·h), sensitive to heating or cooling temperatures
- Membrane fouling observed, while total dissolved solid rejections always >99.8%.

GRAPHICAL ABSTRACT



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ABSTRACT

Direct contact membrane distillation (DCMD) supplied with waste heat was demonstrated for water recovery from saline demineralisation regeneration waste. The pilot plant was located at a gas fired power station which provided the <40 °C waste heat and wastewater to the DCMD system with 0.67 m^2 of membrane area. The trial was operated over three months without replacing the membranes or module and achieved 92.8% water recovery. Flux was approximately 3 L/(m^2·h) and was dependant mostly on the waste heat temperature being supplied. Membrane fouling affected flux and thermal energy demand only at the very end of the trial. The system produced a high quality distillate product with average 99.9% dissolved solids rejection. Small amounts of ammonia and carbon dioxide however were found in the permeate. Membrane analysis post-trial revealed fouling was principally inorganic scale but organic matter on the membrane was also evident. Permeate side fouling was also observed, attributed to corrosion of the cooling heat exchanger. Based on the available energy for a continuously operating 500 MW (electric) rated power station, the treatment potential was estimated at up to 8000 kL/day, which is practical for supplying water to numerous industrial, residential or agricultural sites.

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1. Introduction

Due to increasing demand on potable water resources, industry is turning towards alternative water supplies which include recovering water from its own waste streams. This has the benefit of reducing water supply volumes and trade waste costs simultaneously, while also removing the risks from rising water service prices. A technology that promises to achieve this aim is membrane distillation (MD). MD is well suited to industry water recycling because it can take nearby sources of heat and convert it to treated water. This heat can be low-grade 'waste' heat, being a heat of no perceived value where best practice is to exhaust to the environment, or heat can be transferred within the industry process [1]. The concept of utilising the heat drawn from the MD cooling cycle for town heating has also been proposed [2]. In any case, MD promises to be a compact thermal water treatment process that is conveniently integrated into industrial processes for water recycling purposes where the water to be treated is typically of 'challenging' chemistry, i.e. containing high levels of inorganic and organic species that easily contaminate processes. MD conveniently manages this issue by separating the heating component (heat exchanger) from the membrane surface. This enables features such as capture of scaling salts prior to entering the module which can in turn offer concentration of wastes to near saturation [3]. Broadly, MD application has progressed significantly, with outcomes of pilot trials being reported in the last decade [4–11]. Studies of fouling have shown impact to performance, followed by testing of successful cleaning techniques [12,13]. Most of these studies have focussed on the application of desalination of seawater or synthetic solutions with only few studies on industrial waste waters. Further, studies have mostly been concerned with heat provided by solar energy. Application of MD using engine waste heat was explored for ship-borne seawater desalination [14]. However experiences of the practical constraints and variabilities of real industry waste heat over the longer term, and the discussion of membrane fouling for a diverse range of industrial wastes, are needed to broaden application of MD in the industrial context.

In our previous work, we surveyed five industries located in Western Melbourne, Australia, for process suitability for MD application [15,16]. The outcomes of this survey are summarised in Table 1. The industries included a plastic foam producer, a frozen food producer, an electricity generator, a chemical manufacturer and a plastics manufacturer. Three of the sites investigated presented a number of possible streams that would benefit from MD treatment, and possessing large sources of waste heat. Effluent water samples from these sites were tested at bench scale to investigate potential membrane fouling and other site specific process issues. Water recoveries during these experiments easily exceeded 90%, supporting the proposition that one of the benefits of MD is high recovery operation. The correct notation for the recovered water being either distillate or permeate was not established, nevertheless for the purposes of this work the treated water was labelled permeate. Average initial permeate flux of 30–35 L/(m^2·h) declined over the duration of the experiments (between 25–150 h) at rates dependant of feedwater quality. Some effluents experienced significant membrane fouling, but were successfully managed by the addition of antiscalant as has been observed by others on studies of MD on surface waters (lake and seawater) containing calcium salts [17–19].

The conventional approaches to operate MD fit well in the context of major water supply from ocean sources. Solar power is also considered in remote applications, such as in the recovery of water from coal seam gas extraction [20]. In such cases, significant quantities of heat are required to be purposely taken to the MD plant location or collected by solar panels driving the need for high thermal efficiencies, translated as high gain output ratios (GORs). The GOR is the ratio of the latent heat of water vaporisation to the amount of thermal energy required to produce the product water, and therefore relates to how thermally efficient the system is compared to conventional evaporation. However, designs which offer high GOR (i.e. >2) classically operate with temperatures above 60 °C in order for efficient internal heat recovery at reasonable fluxes. While these temperatures are obtained from solar collectors or combusted fuel, they are not as common in many industrial plants which adopt efficient heat recovery systems to reduce fuel consumption and maximise output. This is the case for power generation, where large quantities of waste heat are available at temperatures as low as 40 °C due to efficient vacuum operated condensers in the steam cycle. For example, a gas fired power station with an electrical output of 500 MW would need to exhaust 700 MW of thermal energy, where 500 MW of this is drawn from the steam-cycle condensers and the 200 MW balance leaves through exhaust gases. In such a case of abundant low grade heat, there is an option to trade GOR for increased equipment water productivity (i.e. membrane flux) [21]. Considering the low temperature in our case will likely lead to impractically low fluxes, there is a strong need to achieve highest fluxes possible. This can be achieved in MD systems by increasing flow across the membrane to minimise temperature drop along the membrane module, which in turn increases driving force across the membrane. However in this mode heat recovery is not possible and GOR will be low (<1). To further increase flux, the well-known direct contact MD (DCMD) mode is ideally suited.

DCMD is regarded as a high flux MD configuration [22] due to its ability to transfer heat and water to and from the feed and permeate sides of the membrane respectively. This is achieved by the intimate contact of water on both sides (feed and permeate) of the membrane. The major drawback of this beneficial effect is the higher conductive losses which are the reason air gap designs are pursued where thermal efficiencies are more important than the higher flux [23]. However we propose the use of DCMD in the case of abundant low grade heat

Table 1
Summary of survey of industrial sites for application of MD [15,16].

Industry type	Waste heat supply potential	Waste water to be treated	Potential use of MD treated water	Water recovery obtained (bench test)	Observations
Plastic foam production	Cooling water return (60 °C)	Cooling tower blowdown. 30 to 200 mg/L TDS	Permeate used as boiler feed or cooling tower makeup	80%	Potential for zero liquid discharge.
Electricity generator	Condensers (35 °C)	Neutralised IX regeneration solution. 3500 mg/L TDS	High quality permeate replaces more saline town water	95%	Significant waste heat supply. Potential for reduced IX regeneration. 76% of ammonia in feed captured in permeate.
Plastics manufacturer	Steam ejector (LP steam) or cooling water return	Cooling tower blowdown. 1300 mg/L TDS	High quality permeate for cooling tower makeup	92%	Fouling from calcium and iron scale. Fouling removed by citric acid clean. Enhanced performance with use of antiscalant.

TDS = total dissolved solids; LP = low pressure, IX = ion exchange.