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Investigating the prospects of water desalination using a thermal water pump coupled with reverse osmosis membrane

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ABSTRACT

This paper presents the design and experimental analysis of a thermal water pump coupled with a reverse osmosis desalination membrane. The operation, thermodynamic cycle and design of the proposed system are explained with the aid of system schematics and thermodynamic process diagrams, while the experimental performance of the thermal water pump in combination with a reverse osmosis membrane is presented and discussed. It is shown that for feed water at a salt concentration of 1184 ppm and a heat source temperature of 86 °C, the proposed system is shown to be able to produce fresh water at a rate of 1.27 L/h with a specific energy consumption of 165 MJ/m^3. The recovery ratio obtained under these conditions is shown to be 26%. The performance and characteristics of the proposed system are contrasted with data for existing multi-stage thermal desalination systems as well as Rankine cycle–reverse osmosis desalination systems and it is shown to compare favourably to both for low salinity applications.

1. Introduction and background

Along with an increasing global population the demand for fresh, clean water is also rising. In addition, for many regions of the world, a reliable energy supply is still hard to come by. In recent years many developing countries have experienced a rapid increase in primary energy demand [1] however approximately 80% of the world's primary energy comes from fossil fuels which are becoming scarce and are also one of the main contributors to global greenhouse gas emissions.

This issue is not new, and desalination technologies have been used extensively in high demand and high drought regions worldwide, with more than 60 million m^3 of desalinated water produced globally every day. The desalination processes most widely used are very energy intensive and rely primarily on energy from fossil fuels [2,3]. This has motivated substantial research and development of sustainable desalination systems powered by renewable energy.

In addition to a focus on renewable energy sources for desalination processes, the use of industrial waste heat as an energy source has also gained attention [4,5]. There are many industrial processes however that only generate waste heat at low temperatures (below 100 °C). This heat usually cannot be converted efficiently to useful work and most of it is discarded by industry. A good example of the opportunities for pairing waste heat sources with desalination technologies that has received some attention by researchers is the shipping industry [6,7]. Most ships are still powered by internal combustion diesel engines due to their low cost, relatively inexpensive fuel and high efficiency compared with all other heat engines. Nevertheless, the diesel engines used on-board most ships still only have an efficiency of approximately 50%. This means about 50% of the fuel energy is lost in the form of heat through exhaust gas and engine coolant [8]. On ocean going vessels, fresh water is not a readily available resource, while access to saline sea water is abundant; therefore, most of these vessels have on-board desalination plants. To date, the most commonly used desalination systems are Reverse Osmosis (RO) which uses mechanical work input and Multi-Stage Flash (MSF) which utilises thermal energy, however there has also been research into the use of alternative thermally driven systems such as membrane distillation (MD) [6] that could effectively utilise engine waste heat.

Desalination processes can be classified into two main categories as shown in Fig. 1; phase change or distillation processes and single-phase processes. The most commonly used phase change processes are Multi-Effect Distillation (MED), Multi-Stage Flash (MSF) and solar stills. Recently membrane distillation (MD) has shown potential for large scale desalination systems. The main single-phase process is Reverse Osmosis (RO) desalination, while MED, MSF and RO are the main technologies used globally in the production of desalinated water [2,3,9,10].

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Nomenclature

c	Specific heat (kJ/kg·C)
foC	Fraction of Carnot
HE	Heat exchanger
HPF	High pressure feed water line
HTF	Heat transfer fluid
LPF	Low pressure feed water line
m_{WF}	Mass of working fluid (kg)
$\dot{m}_{HE}$	Mass flow rate through heat exchanger (kg/s)
MED	Multi-effect distillation
MD	Membrane distillation
MSF	Multi-stage flash desalination
ORC	Organic Rankine Cycle
P	Pressure (Pa)
Q_{in_S}	Sensible heat input per stroke (J)
Q_{in_L}	Latent heat input per stroke (J)
Q_{out_S}	Sensible heat output per stroke (J)
Q_{out_L}	Latent heat output per stroke (J)
RO	Reverse Osmosis
RR	Recovery ratio (%)
S.E.C.	Specific energy consumption (MJ/m^3)
$t_{interval}$	Data logger record interval (s)
T	Temperature (°C)
T_{B_in}	Temperature at boiler inlet (°C)
T_{B_out}	Temperature at boiler outlet (°C)
TPP cycle	Thermal power pump cycle
TWP	Thermal water pump
V	Volume (m^3)
$\dot{V}$	Volume flow rate (m^3/s)
W_D	Work done on high pressure feed water – delivery work (J)
W_S	Work done on low pressure feed water – suction work (J)
W_{out}	Total work done per stroke (J)
ρ	Density (kg/m^3)
η_t	Thermodynamic efficiency (%)
η_{Carnot}	Carnot efficiency (%)
ν	Specific volume (m^3/kg)

Subscript

1	Thermodynamic property at point 1
2	Thermodynamic property at point 2
2′	Thermodynamic property at point 2′
3	Thermodynamic property at point 3
4	Thermodynamic property of working fluid at point 4
WF	Working fluid
DF	Delivery fluid

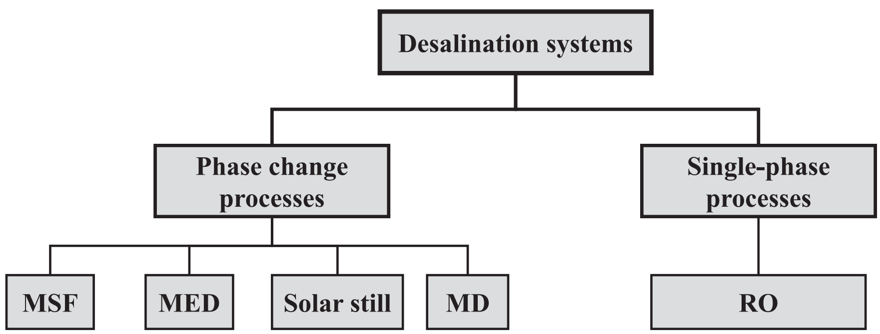

Fig. 1. Simplified overview of desalination technologies.

Desalination is an energy intensive process and the specific energy consumption (energy consumption per m^3 of desalinated water produced) varies with the process used. Table 1 shows the range of specific energy consumptions for various processes, along with the primary energy type used and the range of recovery ratios obtained [9,11].

The MED and MSF processes, as their names imply, have multiple stages or effects that make the processes complex and the systems very large compared to RO systems. From Table 1 it can be seen that the RO process is the most energy efficient process. However, RO desalination needs high quality electrical energy for operation, whilst the MED and MSF processes utilise lower quality thermal energy.

RO systems use high pressure water pumps to force the saline water through a semipermeable membrane, which allows water molecules to pass while retaining the salt molecules on the pressurised side of the membrane. The most energy intensive component of the RO process is the high-pressure water pump, and in the majority of cases, these pumps are electrically driven. Therefore, in order to investigate the potential of combining the low S.E.C. of RO desalination with the abundance of low grade thermal energy, it is worth reviewing the thermal energy driven water pumping systems developed in the past.

In recent years attempts have been made by researchers around the world to develop an Organic Rankine Cycle (ORC) heat engine driven RO system with a number of researchers proposing the use of ORC heat engines directly coupled to the high-pressure water pumps of the RO system [2,10,12–15]. So far, there have been limited applications using ORC-RO systems [16] with specific mechanical energy consumptions of between 2.5 and 10 MJ/m^3 reported [11]. When considering the thermal efficiencies of the ORC systems used (generally less than 5% [11]), the specific thermal energy consumption of these systems, as shown in Table 1, can be anywhere between 13 and 250 MJ/m^3.

Table 1
Performance range of desalination technologies [9,11].

Process/technology	Feed water type	Specific energy consumption MJ/m^3 (kWh/m^3)	Main energy type	Recovery ratio %
MSF	Brackish water, seawater	291–518 (80.8–143.9)	Thermal	0.6–6
MED	Brackish water, seawater	180–698 (50.0–193.9)	Thermal	6–38
Conventional RO	Brackish water, seawater	4.8–68 (1.2–18.9)	Electrical	10–51
ORC - RO	Brackish water, seawater	13–250 (3.6–69)	Thermal	10–51