Performance Limits and Opportunities for Low Temperature Thermal Desalination

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Performance Limits and Opportunities for Low Temperature Thermal Desalination

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Low temperature thermal desalination, membrane distillation, least work, reverse osmosis

ABSTRACT:
Conventional low temperature thermal desalination (LTTD) uses ocean thermal temperature gradients to drive a single stage flash distillation process to produce pure water from seawater. While the temperature difference in the ocean drives distillation and provides cooling in LTTD, external electrical energy is required to pump the water streams from the ocean and to maintain a near vacuum in the flash chamber. In this work, an LTTD process from the literature is compared against, the thermodynamic least work and the minimum least work possible for the system, reverse osmosis (RO) and membrane distillation (MD), an alternative thermal desalination technology. In all cases compared, the product water flow rates, feed seawater inlet temperatures and cold seawater inlet conditions were held constant. Exergy and Second law analysis showed that for the LTTD system studied, under reversible operating conditions with no heat exchange with the atmosphere, a power production of 26 kWh/m^3 of product water was possible. At near zero recoveries (infinite warm feed flow rates) or allowing heat exchange with an infinite ambient at the warm water temperature, maximum power production possible was found to increase to 75 kWh/m^3. In contrast, the LTTD system in literature was found to consume 22 kWh/m^3 while standard seawater RO consumes 2.3 kWh/m^3. MD was found to be an effective alternative LTTD technology. Switching to MD from flash distillation eliminates the need for vacuum pumps and also reduces the pumping power consumption by reducing both the required cool and warm water flow rates through increased recovery ratios. Furthermore, pressure drops in the condenser on the cool side and the requirement of pumping brine back to atmospheric pressure from a near vacuum in a conventional LTTD flash chamber are avoided. The proposed LTMD system can potentially perform competitively with RO by operating with a specific power consumption less than 2.5 kWh/m^3, while retaining the environmental benefits of the conventional LTTD system.

1. INTRODUCTION

While India has 16% of the world population, it has only 4% of the world's fresh water supply making India highly susceptible to water shortages (Harris 2013). With a growing population, the problem of a lack of water is further exacerbated in India. Globally, desalination is increasingly being explored to meet the water demand. This is true in India as well with organizations like the National Institute of Ocean Technology (NIOT) in India taking leadership in exploring the low temperature thermal desalination (LTTD) technology (Kathiroli et al. 2008; Sistla et al. 2009). The LTTD technology as developed by NIOT is a single-stage flash distillation system driven by both temperature gradients in the ocean and external electrical power. The water temperature at the surface in tropical regions is around 30°C, whereas beyond about 200 m below the surface, the water temperature drops to about 10°C. Warm surface ocean water is flashed in a flash chamber and cold ocean water is used to condense the vapour generated to produce pure distillate. Electrical energy is required for pumping both the warm and cold seawater streams as well as to maintain sub-atmospheric pressures (20-50 mbar) in the flash chamber. From the values reported by Phanikumar et al. (Sistla et al. 2009) for 3 LTTD pilot plants, we have calculated that total power consumption per product water produced can vary between 8-20 kWh$_e$/m^3 with power required for maintaining a vacuum varying from 5-13 kWh$_e$/m^3 depending on the size of the plant. Thus, the total electrical energy consumption of the LTTD technology is quite high compared to other electrically powered desalination technologies (Mistry et al. 2011).

In this work, we investigate the effectiveness of LTTD in the context of advances in other desalination technologies. Firstly, to understand the theoretical limits of its operation and obtain the thermodynamic least energy requirement for desalination of seawater with the assistance of thermal gradients in the ocean, a Second Law analysis was conducted. Analytical modelling was used to evaluate energy requirements for reverse osmosis (RO) desalination, which is used as an additional benchmark for the analysis. General RO performance parameters were obtained from literature (Mistry et al. 2011).

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Subsequently, we looked at how the LTTD process could be further improved to reduce energy consumption. Power requirements for maintaining a vacuum in the conventional LTTD process were found to be difficult to reduce beyond what already has been achieved. Thus, we investigated permeate gap membrane distillation (PGMD) (Winter et al. 2011), an alternative LTTD technology where maintaining a vacuum was not necessary. The low temperature PGMD system is subsequently referred to in the paper as an LTMD system. To analyse PGMD, a detailed numerical model was developed in Engineering Equation Solver (EES) (Klein & Alvarado 2002).

2. METHODOLOGY

The methodology used for analysing LTTD, RO, LTMD and calculations for obtaining thermodynamic least work are presented in this section. Common parameters used to analyse each case are presented first followed by a detailed description of the methodology used in each case.

In all cases, a saline feed stream is desalinated to obtain pure product water as well as a saline brine stream. For all cases, with the exception of RO, a cold seawater stream was used to assist the desalination process. Equations used for conserving the total mass flow rate of the desalinated feed stream ($\dot{m}_{\mathrm{f}}$) as well as its salt content are given by:

$$\dot{m}_{\mathrm{f}} = \dot{m}_{\mathrm{b}} + \dot{m}_{\mathrm{p}} \tag{0}$$

$$\dot{m}_{\mathrm{f}} S_{\mathrm{f}} = \dot{m}_{\mathrm{b}} S_{\mathrm{b}} + \dot{m}_{\mathrm{p}} S_{\mathrm{p}} \tag{0}$$

where, $\dot{m}_{\mathrm{p}}$ is the mass flow rate of the pure product water, $\dot{m}_{\mathrm{b}}$ is the mass flow rate of the brine discharged, S_{f} is the salinity of the feed stream, S_{f} is the salinity of the brine stream and S_{f} is the salinity of product (in g/kg). Recovery ratio (RR) is defined as the ratio of the mass flow rate of the product to the mass flow rate of the feed.

$$RR = \frac{\dot{m}_{\mathrm{p}}}{\dot{m}_{\mathrm{f}}} \tag{0}$$

The Total Recovery Ratio (TRR is defined as the ratio of the mass flow rate of the product to the total inlet mass flow rates of the feed stream as well as the cold seawater stream.

$$RR_{\mathrm{t}} = \frac{\dot{m}_{\mathrm{p}}}{\dot{m}_{\mathrm{f}} + \dot{m}_{\mathrm{csw}}} \tag{0}$$

The total power required for the process ($\dot{W}$) is used to calculate the specific power consumption W_{sp}.

$$W_{\mathrm{sp}} = \frac{\dot{W}}{\dot{m}_{\mathrm{p}}} \tag{0}$$

The operating expenses ($OpEx$) and the total capital expenses ($CapEx$) were used to evaluate the performance of each technology.

2.1. Conventional LTTD

Data from a LTTD pilot plant run by NIOT, given in Table 1, were used directly for analysis (Sistla et al. 2009). These include the temperatures of the inlet and outlet of the cold seawater stream, the temperature of the feed and brine streams, the power consumed by the cold seawater pump as well as that of the warm feed seawater pump and the total vacuum loading rate (i.e., total flow rate of gas being removed by the vacuum pump). For the LTTD plant considered, the product flow rate was 1.15 kg/s. Cold seawater was pumped from 300 m below the sea level using a 600 m long high-density polyethylene (HDPE) tube while warm feed seawater was pumped near the plant at sea level. Power consumption was reported to be 13 kW for the warm seawater pump and 26 kW for the cold seawater pump while the reported head was 6 m for the warm seawater pump and 10m for the cold seawater pump.

While, Sistla et al. also reported a value for specific power consumption, it was ambiguous whether this was for the complete system or whether it was just for the vacuum pump. Analysis of the power consumption of the vacuum pump using a simple product of the given total vacuum system loading rate and the pressure difference between the chamber and the environment (~1 bar),

$$\dot{W}_{\mathrm{p,vp}} = \dot{V}_{\mathrm{vp}} \times (P_0 - P_{\mathrm{flash}}) \qquad (0)$$

showed that the reported specific power consumption was just the specific power required to maintain a vacuum. From the reported specific power consumption value, the actual power consumed by the vacuum pump was 51.8 kW. Thus, the overall total specific power consumption was calculated to be 21.9 kWh/m^3. Sistla et al. had also not reported the product water temperature, but this was assumed to be the same as the brine temperature. Analysis of the pressure drops in the cold seawater side based on reported data showed that most of the pressure drop was across the condenser. The head required for pumping from the ocean depths and the friction losses by comparison contributed less than an estimated 3 m of the reported 10m total cold seawater pump head. Details on pump work calculations are given in Section 3.4.

Table 1. Reported (Sistla et al. 2009) and calculated (this work) performance parameters for an LTTD plant

Given Parameter	**Value**	**Unit**		**Given Parameter**	**Value**	**Unit**		**Calculated Parameter**	**Value**	**Unit**
$t_{\mathrm{csw,i}}$	12.3	°C		$\dot{m}_{\mathrm{csw}}$	180	kg/s		t_{p}	22.2	°C
$t_{\mathrm{csw,o}}$	16.9	°C		P_{flash}	0.027	bar		$\dot{W}_{\mathrm{p,vp}}$	51.8	kW
t_{f}	27.6	°C		$\dot{V}_{\mathrm{vp}}$	1650	m^3/hr		W_{sp}	21.9	kWh/m^3
t_{b}	22.2	°C		$\dot{W}_{\mathrm{p,f}}$	13	kW				
$\dot{m}_{\mathrm{p}}$	1.15	kg/s		$\dot{W}_{\mathrm{p,csw}}$	26	kW				
$\dot{m}_{\mathrm{f}}$	110	kg/s		$W_{\mathrm{sp,vp}}$	12.5	kWh/m^3				

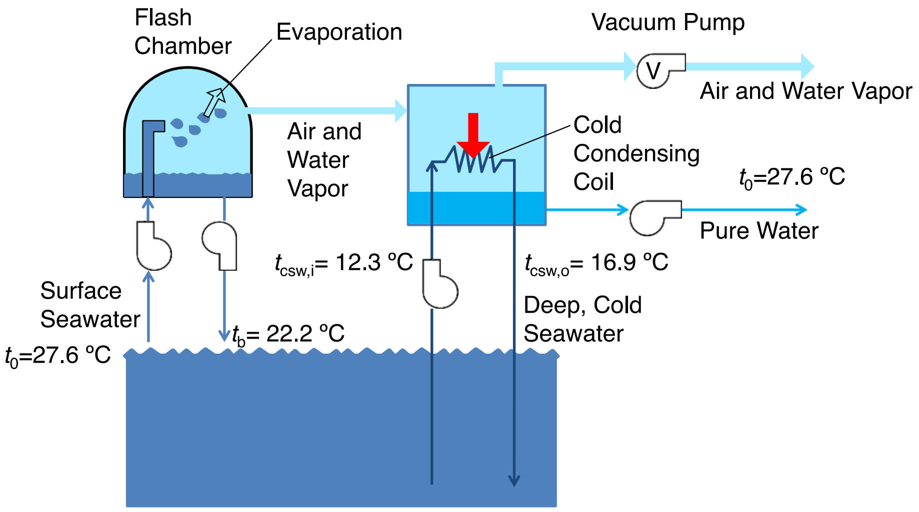

Figure 1. Diagram of LTTD system

2.2. Least Work and Minimum Least Work

To understand the theoretical limits of ideal performance for an LTTD system and to obtain the thermodynamic least energy requirement for desalination of seawater with the assistance of thermal gradients in the ocean, a First and Second Law analysis was conducted on the system control volume given in Fig. 2.

$$\dot{m}_{\mathrm{csw}}\left(h_{\mathrm{csw,i}}-h_{\mathrm{csw,o}}\right)+\dot{m}_{\mathrm{f}}h_{\mathrm{f}}-\dot{m}_{\mathrm{b}}h_{\mathrm{b}}-\dot{m}_{\mathrm{p}}h_{\mathrm{p}}+\dot{W}=0 \tag{0}$$

$$\dot{m}_{\mathrm{csw}}\left(s_{\mathrm{csw,i}}-s_{\mathrm{csw,o}}\right)+\dot{m}_{\mathrm{f}}s_{\mathrm{f}}-\dot{m}_{\mathrm{b}}s_{\mathrm{b}}-\dot{m}_{\mathrm{p}}s_{\mathrm{p}}+\dot{S}_{\mathrm{gen}}=0 \tag{0}$$

Here h refers to the specific enthalpy of each stream, s refers to the specific entropy, and $\dot{S}_{\mathrm{gen}}$ refers to the rate of entropy generation (in kW/kg-K). Properties for seawater such as enthalpy and entropy were obtained from seawater property correlations in literature (Sharqawy et al., 2010; Massachusetts Institute of Technology, 2013). The salinity of the feed and cold seawater streams was assumed to be 35 g/kg while the product pure water was assumed to be completely devoid of salts. Pure water properties were obtained from the IAPWS 95 formulation (Wagner & Pruβ, 2002). The analysis was done using the versions of the seawater and pure water properties in the 2014 library of the software, Engineering Equation Solver (EES) (Klein & Alvarado, 2002).

For the temperature and flow values of the warm seawater feed, brine, product and the cold seawater streams reported for the LTTD process in Section 2.1, the thermodynamic least work ($\dot{W}_{\mathrm{least}}$) was obtained by solving Eqs. (0), (0), (0) and (0) while setting entropy generation to zero and setting the brine temperature to the same temperature as the cold seawater outlet,

$$\dot{S}_{\mathrm{gen}}=0 \tag{0}$$

$$t_{\mathrm{b}}=t_{\mathrm{csw,o}} \tag{0}$$

However, this is still not the thermodynamic *minimum* least work ($\dot{W}_{\mathrm{min,\,least}}$) for the process since the cold seawater stream still exits at a temperature lower than the ambient temperature. Thus, the exergy of the cold seawater stream is still not fully recovered. $\dot{W}_{\mathrm{min,\,least}}$ can be obtained from an exergy analysis of the inlet streams (Sharqaqy et al., 2011). The warm seawater stream is already at ambient temperature and thus has no exergy. The same is true for the pure water product outlet stream that needs to be generated. The net exergy available for the system is just the exergy of the cold water stream,

$$\dot{E}_{\mathrm{csw,i}}=\dot{m}_{\mathrm{csw,i}}\left[(h_{\mathrm{csw,i}}-h_{\mathrm{sw,0}})-T_0(s_{\mathrm{csw,i}}-s_{\mathrm{sw,0}})\right] \tag{0}$$

where, $h_{\mathrm{sw,,0}}$ and $s_{\mathrm{sw,0}}$ is the enthalpy and entropy of seawater at the “restricted dead state”, i.e t = t_0,= 29.6 °C and S = S_0=35 g/kg. The minimum least work for desalination alone was calculated for the given temperature and salinity conditions by considering the limit of zero recovery using the following formulation from literature (Mistry et al. 2011) (pumping work is not considered in this analysis),

$$\dot{W}_{\mathrm{min,\,least,\,desal}}=\lim_{RR\to 0}(\dot{m}_{\mathrm{b}}g_{\mathrm{b}}+\dot{m}_{\mathrm{p}}g_{\mathrm{p}}-\dot{m}_{\mathrm{f}}g_{\mathrm{f}}) \tag{0}$$

where, g is Gibbs energy. Together, the total minimum least work for LTTD was,

$$\dot{W}_{\mathrm{min,\,least}}=\dot{W}_{\mathrm{min,\,least,\,desal}}-\dot{E}_{\mathrm{csw,i}} \tag{0}$$

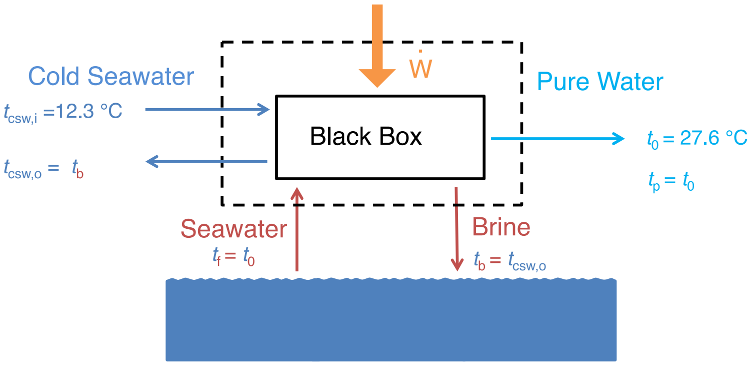

Figure 2. System Control Volume with warm and cold seawater streams, the product stream and work input.

2.3. Reverse Osmosis

Reverse osmosis (RO) is the most energy efficient mainstream desalination technology. This pressure-driven membrane process can desalinate seawater using only 2-4 times more energy than the minimum least work. Analytical modelling was used to evaluate energy requirements for reverse osmosis (RO) desalination, which is used as an additional benchmark for the analysis. General RO performance parameters were obtained from literature (Mistry et al., 2011).

2.4. PGMD

Membrane distillation is a compact thermal desalination technology in which a semipermeable hydrophobic membrane separates vapour from a salt solution, leaving behind saltier brine. The driving force for the separation process is a difference in water temperature and hence vapour pressure across the membrane.

In permeate gap membrane distillation (PGMD) (Winter et al. 2011), pure water fills a thin gap region between the membrane and condensing plate as shown in Fig. 3. Warm surface seawater flows on one side of the membrane from which pure water evaporates and condenses into the pure water in the gap. The condensation energy along with conduction heat loss from the warm side is transferred into the cold stream.

A one-dimensional numerical model of MD was implemented on EES. The modelling methodology is similar to what has been described previously in the literature (Summers et al. 2012; Swaminathan & Lienhard, 2013). The warm and cold seawater streams flow counter-current to each other. Pure water is allowed to fill the gap region, from where it exits at a rate equal to the rate of pure water production by evaporation from the warm side. Variables such as temperature and flow rate are allowed to vary along the length direction, but held constant along the width direction. In the depth direction, temperature and concentration polarization effects are accounted for by considering the thermal and mass transfer boundary layer resistances. The membrane is modelled in terms of a permeability value and sensible heat transfer through the membrane in the form of conduction is considered. Heat transfer across the thin liquid gap region is modelled as conduction.

The important advantages of PGMD over the single-stage flash distillation conventional LTTD process are associated with eliminating the need for the vacuum pump. Also, since there is no vacuum, the condensation process can occur at higher temperatures. RR_{t} can be higher by about 30% relative to the conventional LTTD process. As a result, lower pumping requirements exist for the pumping process. The head required for pumping the warm and cold water streams can be reduced within the MD module to less than 1 kWh/m^3. Compared to the pressure drop within the heat exchanger in the condenser and the pipes in the flashing chamber in a conventional LTTD process, the pumping power requirement in MD is found to be lower.

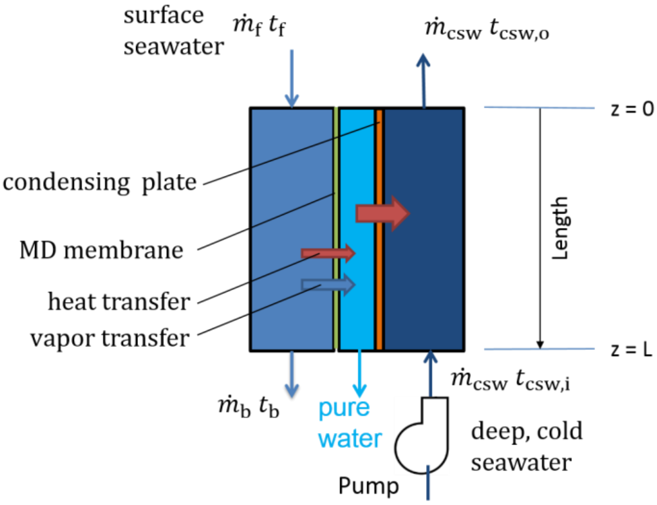

Figure 3. Diagram of PGMD system

3. RESULTS

3.1. Least Work and Minimum Least Work

Table 2. Least work and minimum least work for input conditions mentioned in Table 1.

Common Parameter	**Value**	**Unit**	**Output Parameter**	**Value**	**Unit**
$t_{\text{csw,i}}$	12.3	°C	$\dot{E}_{\text{csw,i}}$	313	kW
t_{f}	27.6	°C	$\dot{W}_{\text{least}}$	-109	kW
$\dot{m}_{\text{p}}$	1.15	kg/s	$\dot{W}_{\text{min, least, desal}}$	-3	kW
$\dot{m}_{\text{csw}}$	180	kg/s	$\dot{W}_{\text{min, least}}$	-310	kW
			$W_{\text{sp,least}}$	-26	kWh/m^3
			$W_{\text{sp,min,least}}$	-75	kWh/m^3

The results for the least work and minimum least work calculations are given in Table 2. The $\dot{W}_{\text{least}}$ calculated for the LTTD process for a feed flow rate of 110 kg/s was -109 kW, i.e., 109 kW of power production. The exergy of 180 kg/s of cold seawater was quite high at 313 kW. The minimum least work, $\dot{W}_{\text{min, least, desal}}$, was 3.2 kW for the given feed inlet salinity of 35 g/kg and feed inlet temperature of 27.6 ºC. The minimum least work for the entire LTTD system was thus -310 kW, i.e., 310 kW of net power production.

To illustrate the process differences between the least work and the minimum least work cases, a plot of the temperature change against the total absolute enthalpy change in the cold seawater and warm feed seawater streams given by

$$|\Delta H_{\text{csw}}| \;=\; |\dot{m}_{\text{csw}} h_{\text{csw,o}} - \dot{m}_{\text{csw}} h_{\text{csw,i}}|$$

$$|\Delta H_{\text{f}}| \;=\; |\dot{m}_{\text{f}} h_{\text{f}} - \dot{m}_{\text{b}} h_{\text{b}} - \dot{m}_{\text{p}} h_{\text{p}}|$$

is shown in Fig. 4. The difference in total absolute enthalpies of the two streams is the work produced in the process. The entropy generation is zero in both processes. The work produced relative to the enthalpy changes is small. Thus, the plots could be approximated as temperature vs. position diagrams in a hypothetical cycle. Heat transfer occurs from the hot stream to the cold stream through a series of infinitesimal Carnot cycles producing work. The work production is limited by the temperature to which the cold seawater can be increased. To implement the thermodynamic minimum least work, extremely high mass flow rates are needed in the warm seawater feed stream to approximate a constant temperature heat source at ambient temperature, t_0 and thus, completely recover the exergy of the cold seawater stream.

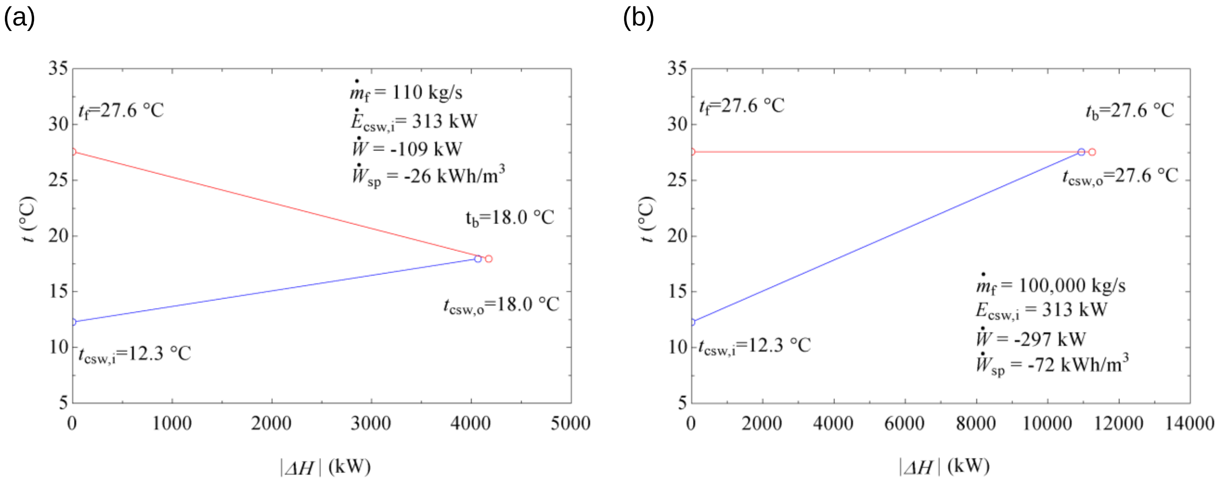

Figure 4. Temperature vs. Enthalpy change diagram for (a) Least work case and (b) an approximation to the minimum least work case. The curves show the source and sink temperatures with inlet states on the left. Carnot cycles would operate between these temperatures to produce the maximum amount of work.

3.2. RO

Mistry et al. report the specific power consumption for a 35 m^3/day RO system with pressure recovery device to be 2.35 kWh/m^3. Among all the desalination systems considered in the comparative study, RO was found to have highest second law efficiency and hence we use this as another baseline to compare the performance of LTTD technologies.

3.3. PGMD

The recovery ratios in the LTTD process are RR=0.0104 and RR_t =0.004. In the MD process, the membrane area was varied by increasing membrane length at fixed width of 70 m and channel depth of 0.0075 m, to achieve similar recovery ratios for a fair comparison. Figure 5 shows the effect of membrane length on the recovery ratios of the system. To match the RR_t, a length of 40 m is sufficient. In order to achieve an RR of 0.0104, an effective length of about 70 meters is required.

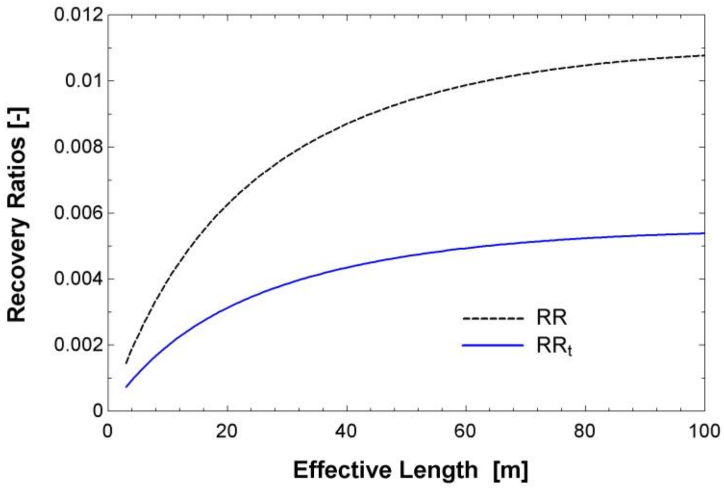

Figure 5. LTMD system effect of module size on recovery ratios

One of the trade-offs associated with using a larger membrane area is the higher capital expenditure of the system. Figure 6 shows the effect of module size on both CapEx and specific CapEx. Membrane unit cost of \$36/m^2 (INR 2160/m^2) and thin metal condenser unit cost of \$10/m^2 (INR

600/m^2) were used to evaluate these costs (Khayet & Matsuura, 2010). The costs associated with the membrane and the metal are the major part of the total module CapEx and are the ones that are plotted here. While the absolute capital expenditure increases linearly with module size, the specific cost increases slower initially before increasing faster due to the diminishing returns associated with large membrane area, as seen in Fig. 5. The required capital investment for the MD module is of order INR 1 crore ($0.17 mn), which is comparable to the INR 5 crore ($0.83 mn) investment for the LTTD plant of same capacity.

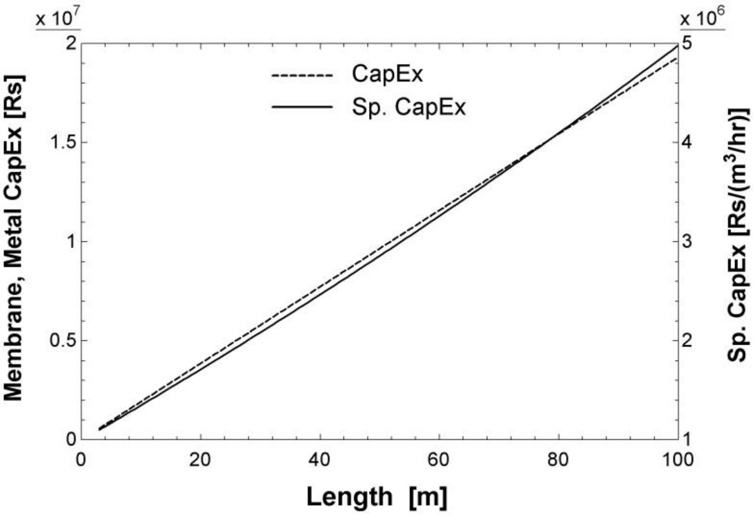

Figure 6. Membrane and metal capital expenditure and specific CAPEX as a function of module size

Figure 7 shows the specific power consumption within the module. A specific power consumption of approximately only 1 kWh/m^3 is required for pumping the feed warm and cool water streams through the MD module channels. This power requirement is much lower than that for the condenser heat exchanger.

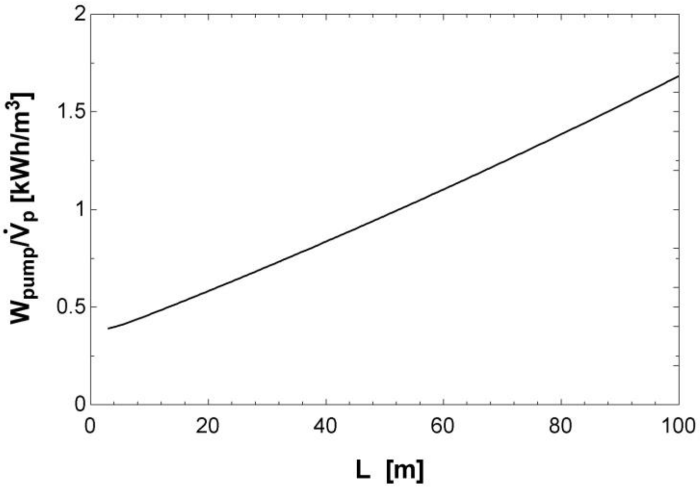

Figure 7. Specific electric power consumption of the pumps as a function of module size

The temperature profiles within the MD module and the MD computational cell with different internal temperatures labelled are illustrated in Figs. 8 and 9. Figure 8 illustrates a sample temperature profile within the PGMD system for L = 60 m case. The top and bottom curves represent the bulk temperatures in the two streams: warm surface seawater entering at z = 0 m and cool deep seawater entering at z = 60 m. These two streams flow counter-current to each other and exit at a terminal temperature difference of about 5 °C in this case. With increase in module size, the terminal temperature difference would decrease. As mentioned previously, since a vacuum is not maintained, condensation can occur over a wide range of temperatures in different sections along the module length.

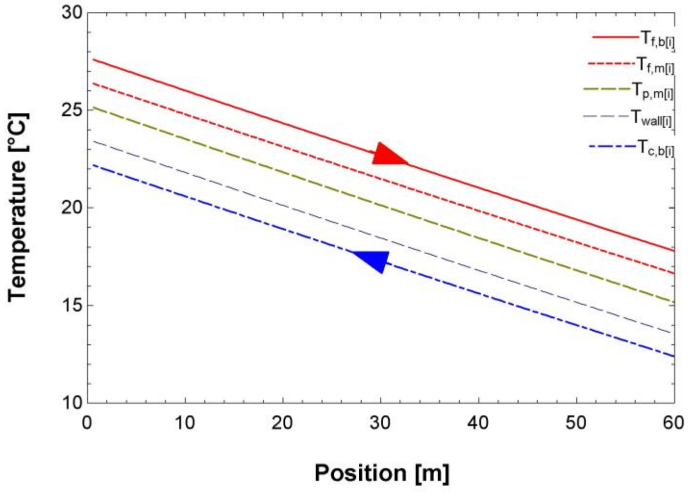

Figure 8. Temperature profiles within PGMD module

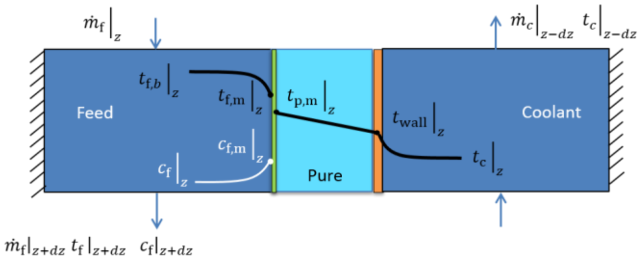

Figure 9. Temperature profiles within PGMD module

3.4. Pumping Power

Even if the vacuum pumping power is eliminated by using alternative LTTD technologies such as MD, significant electrical energy consumption still exists in the warm and cool water pumps for the LTTD plants. The total pumping power requirement in the pipes used was estimated based on 600 m of pipe length for the cool side and 1 km each way for the inlet and outlet pipes for the warm surface water fluid. The pipe diameters are equal to 0.63 m and about ten elbows, inlets, outlets, tee junctions and other features are assumed to get an estimate of the minor loss coefficient. A total loss coefficient of K=20 is estimated. This would contribute to a pressure drop corresponding to $\Delta P=K\times(0.5\rho v^2)$. Friction pressure drop was estimated using the standard friction factor formulation as $\Delta P = f\frac{L}{D}\left(\frac{1}{2}\rho v^2\right)$. For the cool water, additionally there can be a pressure drop associated with differences in the density of the fluid with changes in depth. This pressure drop was approximated as an upper limit as $\Delta\rho gh$ where $\Delta\rho$ is the density difference between warm and cold seawater.

The total power consumption for the cool side is found to be about 5 kW and 0.5 kW for the warm seawater pump. This is much lower than the 26 kW and 13 kW of pumping power reported for the LTTD plant. These power consumption numbers correspond to a specific electricity consumption of 1.23 kWh/m^3 and 0.13 kWh/m^3. As a result, significant pumping power consumption in the LTTD plants must be in other parts not considered in this calculation: pressure drop in the condenser heat exchanger on the cool side and the flash chamber on the warm side. The equivalents of these losses for the MD system are channel pressure drops that have already been considered separately in Section 2.3.

Therefore the total pumping power consumption in the proposed LTMD system would be the sum of these electrical energy inputs, which is lesser than about 2.36 kWh/m^3. This specific power consumption is very competitive with RO and other conventional systems.

4. Conclusions

The least work and the minimum least work for an LTTD system was calculated. In both cases, the system produces net work even while desalinating a feed stream to obtain pure product water. Due to the high exergy content of the cold seawater stream, the overall potential for power generation is high with a specific power production of 26 kWh/m^3 of product possible in the least work case without heat exchange with ambient and 75 kWh/m^3 of power production is possible in the minimum least work case, where heat exchange with an infinite ambient stream is also allowed. For comparison, the conventional LTTD system consumed 22 kWh/m^3 of electrical power while RO systems required 2.35 kWh/m^3. To achieve better performance using a thermal technology, an LTMD system was proposed. The proposed LTMD system shows promise for achieving low temperature thermal desalination with external specific power input less than 2.5 kWh/m^3. The vacuum pumping power, and pressure drops in the condenser heat exchanger and in the flash chamber of conventional single-stage flash LTTD process are found to be significant contributors to the high overall electrical energy consumption seen in this system. By switching to a compact membrane process and eliminating the need for the vacuum pumps and low pressure operating conditions, it is possible to make LTTD competitive with RO on a specific power consumption basis.

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