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Thermodynamic optimisation of multi effect distillation driven by sensible heat sources

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HIGHLIGHTS

- We couple multi effect distillation systems with sensible low-grade heat sources.
- Gain output ratio and performance ratio are incongruent with sensible heat sources.
- We posit a novel waste heat performance ratio (PR_{WH}).
- Using PR_{WH} raises freshwater yield by 40% for multi effect distillation systems.

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ABSTRACT

While the multi effect distillation desalination industry has made definite strides in terms of improving efficiency, the potential of low-grade heat sources and renewable energies remains overlooked. Although the basic principle remains the same, the nature of sensible heat sources requires different optimisation approaches than conventional steam driven systems. We hold that the conventional performance measure is incongruent with such applications and posit a new benchmark. We demonstrate this with the optimisation of multi effect distillation systems, so that freshwater yield can be improved by up to 40% for both conventional and advanced systems. This *modus operandi* significantly stretches the viability of multi effect distillation, and rejuvenates the potential of waste heat streams.

1. Introduction

By rendering the vast sources of saline water accessible, desalination is a key component toward a sustainable water supply for the ever increasing global population. Heretofore over 16,000 desalination plants have been commissioned globally, providing an online capacity of over 74.8 million m^3/day [1] or effectively over 10 l of freshwater per human/day worldwide [2]. Despite being a remarkable amount, this is just a fraction of the overall water consumptions and desalination still has a lot to contribute.

One major reason is the energy intensive nature of desalination and the heavy reliance on electricity or fossil fuels. This not only makes desalination exclusive to relatively affluent countries, but also contributes much to environmental impacts [3,4].

Consequently, heightening desalination efficiency as well as exploiting hitherto untapped, preferably renewable and sustainable, energy sources remain a holy grail. A repertoire of desalination technologies has since been developed, with new technologies still emerging [5].

There are two major categories of separation processes used in desalination, namely (1) processes based on a phase change of the feed liquid, and (2) processes without a phase change. The first category mimics the natural water cycle, where pristine water vapour is formed during the evaporation. This category includes, among others, multi effect distillation (MED), multi stage flash distillation (MSF), thermal vapour compression (TVC), mechanical vapour compression (MVC), and membrane distillation (MD). The second category includes desalination processes achieved by other separation methods, with the diffusion based reverse osmosis (RO) being the most dominant.

While phase change based methods are exhibiting generally higher energy requirements, their main advantage is that they embrace a broad range of thermal energy, particularly low-grade heat. Electricity is only used sparingly as mainly pumping power.

This is strategic when we consider waste heat applications (e.g. [6–8]) and renewable energies [9–12], such as geothermal energy [13–15], at temperatures below 100 °C. Low-grade heat is a parasitic

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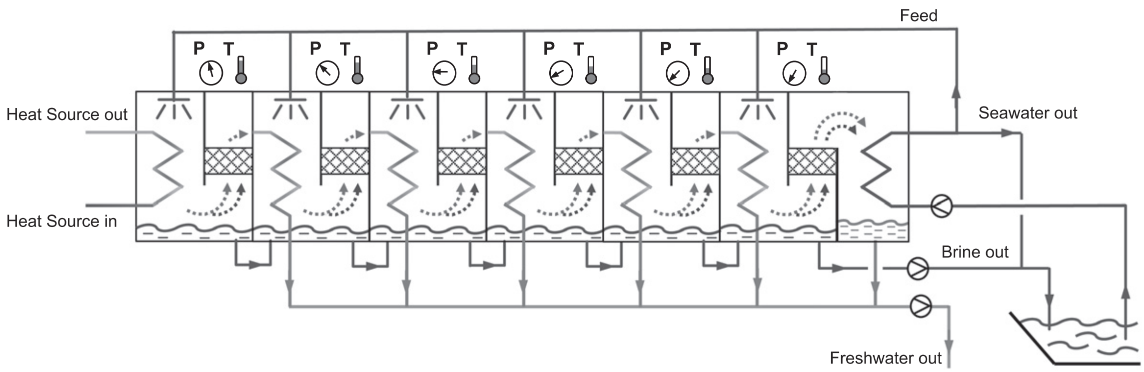

Fig. 1. Schematics of a conventional 6-effect parallel feed MED system.

by-product of a broad range of industrial processes [16], power generation, and many other activities [17]. Conventionally due to a lack of economic incentives, they are invariably rejected to the environment.

This paper focuses on the application of the well-established method of multi effect distillation (MED) to access such untapped low-grade heat sources, especially where copious sensible heat is present. Currently, MED systems are primarily coupled to latent heat sources. Consequently, most of the thermodynamic analyses, simulations and optimisations of MED [18–30] systems have been done on steam driven systems.

While the majority of the unit processes are fully applicable to sensible heat driven systems, their unique characteristic requires modifications and common efficiency measures which are industrial norms are not applicable to these heat sources. A new benchmark is required to address this.

2. Multi effect distillation process

The principle of MED is based on distillation, where the differences in the volatilities of a solution are utilized for the separation of a mixture. In general, MED can be applied to a broad range of liquids, including industrial wastewater, spent liquor from the Bayer process, or other contaminated waters. While the following description of the basic process is based on the most common application of seawater desalination, certain process details have to be modified for the aforementioned niche applications.

A basic MED (Fig. 1) consists of a series of heat exchangers, known as "effects". The heating medium enters the first heat exchanger, or 'evaporator'. The opposite side of this heat exchanger is wetted by feed seawater. The feed side of the heat exchanger is subject to sub atmospheric pressure, so that as the sub 100 °C boiling point is reached, a portion of the feed is evaporated subsequently. This generated vapour passes through a demister to avoid the carryover of droplets, and enters the heating medium side of the subsequent effect. The remaining concentrated liquid, or brine, is collected below the heat exchanger. In the next effect, the vapour condenses into pure product water and passes its latent heat again to incoming feed seawater. This is repeated several times in the downstream effects at progressively decreasing temperatures and pressures. In the last effect, seawater is used to condense the vapour. The preheated feed stream is then taken from this cooling water flow.

Based on the basic MED, several design variations like thermal vapour compression, feed preheating, and internal heat recovery are possible.

Table 1
Input parameters used for the present simulations.

Seawater salinity [ppm]	35,000
Seawater temperature [°C]	28.0
Heating medium [–]	Water
Specific heat of heating medium [kJ/kgK]	4.187
Feed/vapour ratio [–]	1.8
Minimum ΔT of heat exchanger [°C]	3.0
Maximum top brine temperature [°C]	70.0
Maximum ΔT of cooling water [°C]	10.0
Minimum ΔT between injection steam to injected effect [°C]	2.0

3. Numerical analysis of the MED system for sensible heat sources

We use a thermodynamic simulation model to optimise the MED process. The model is predicated on steady state mass and energy balances coupled with the heat transfer equations for each individual effect as well as the recovery ratio of the evaporations process.

The model is partly adopted from the literature [19,21,22,31,32] and has been validated against performance data of market available MED systems [33,34]. Our main focus here is the simulation outcomes vis-à-vis low-grade heat sources. Hence only the general structure and key parts of the model are presented below.

For sensible heat driven systems, the energy balance for the first effect, or the "evaporator", can be expressed as

$$\begin{aligned}\dot{Q}_{1,i} &= \dot{m}_{h,i} c_{p,h} \left(T_{1,1,i} - T_{1,1,o}\right) \\ &= \dot{m}_{1,f} c_{p,f} \left(T_{1,2,o} - T_{1,2,i}\right) + \dot{m}_{1,v} h_{fg,1,2}\end{aligned} \tag{1}$$

where $c_{p,h}$ and $c_{p,f}$ are the constant pressure specific heat capacities of the heating medium and the feed, respectively; h_{fg} is the latent heat of evaporation, which depends on the boiling temperature and can be calculated by the vapour saturation temperature, T_{vs} [19].

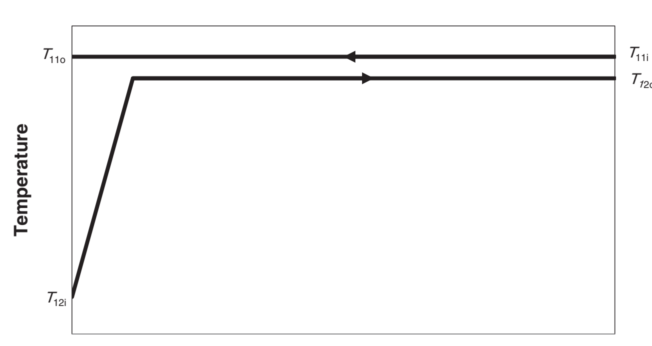

Fig. 2. Schematic temperature profile of the first effect of a latent heat driven MED system.