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Integration of Desalination Systems to Low Grade Heat Source in Site Utility

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Conventional desalination technologies are energy intensive and if the required energy hails from fossil fuel source, then the freshwater production will contribute to carbon dioxide emission and consequently global warming. Low grade heat source can be very useful to provide energy to the heat sink by upgrading low-grade energy (e.g. low pressure steam). The upgrade of low grade heat can be carried out by desalination technologies by recovering waste heat from various sources. The steam network of site utility system has a suitable potential for production of low grade heat. In this paper, evaluation of coupling different desalination systems which includes multi-stage flash (MSF), multiple effect distillation (MED), membrane reverse osmosis (RO), and hybrid (MSF/MED-RO) to steam network of site utility system with fixed heat supply have been considered. The integration of desalination systems to a low grade heat source has been evaluated using total site analysis and exergoeconomic analysis. In this regard, the computer code has been developed. A steam network of process utility system has been considered as a case study.

1. Introduction

Freshwater and energy are two inseparable and essential commodities for sustaining human life on earth. Rapid population growth and industrialization, especially in developing countries in the recent past, have placed pressing demands for both freshwater and energy. Typically, desalination processes are powered by energy derived from combustion of fossil fuels which contribute to acid rain and climate change by releasing greenhouse gaases as well as several other harmful emissions (Gude et al., 2010).

Despite iimproving energy efficiency of industrial energy systems has been regarded as one of important topics in process engineering communities, a considerable amount of this energy is still wasted via gas, liquid or solid discharge. However heat from streams of low thermal quality cannot be economically recoverable within the processes themselves and is currently rejected into the environment. This is referred to as low grade heat according to Ammar et al. (2012).

Recent study indicates that significant amount of low grade heat is still being wasted (Yu et al., 2008) and therefore, it is required to develop the methodology which evaluates energy saving potentials associated with low grade heat recovery and provides design guidelines for utilizing such low grade heat in process industries in a most economic and sustainable manner. Another strong incentive to investigate the recovery of low grade heat is related to potential benefits from the integration of

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industrial energy systems with district energy infrastructure, in which low grade heat from industrial sites can be effectively utilized, for example, as a heat source to desalination systems.

Up to 30 % of desalination cost is due to the energy requirement for the production of freshwater (Kalogirou, 2001; Busch and Mickols, 2004). Combining desalination technologies with available low-grade waste heat sources is beneficial and can improve the economics of the combined processes.

The study aims to develop integrated design frameworks which can systematically evaluate techno-economic viability of desalination systems using low grade heat in the context of total site. In order to examine the feasibility of using low grade heat for the desalination of seawater, an integrated site utility was chosen.

2. Desalination processes

Currently available desalination technologies can be categorized as follows:

(1) Phase change processes that involve heating the feed to ‘‘boiling point’’ at the operating pressure to produce ‘‘steam’’, and condensing the steam in a condenser unit to produce freshwater. Applications of this principle include multi-effect distillation (MED); multi-stage flash distillation (MSF); mechanical vapor compression (MVC) and thermal vapor compression (TVC).

(2) Non-phase change processes that involve separation of dissolved salts from the feed waters by mechanical or chemical/electrical means using a membrane barrier between the feed and product. Applications of this principle include electrodialysis (ED) and reverse osmosis (RO).

(3) Hybrid processes involve a combination of phase change and separation techniques (as in the case of non-phase change processes) in a single unit or in sequential steps to produce pure or potable water. Examples include: membrane distillation (MD); reverse osmosis combined with MSF or MED processes (Gude et al., 2010).

A comparison based on principle characteristics of the desalination processes is presented in table 1.

Table 1: Principal characteristics of different desalination processes

Characteristic	Type of process		
	Phase change	Non-phase change	Hybrid
Nature	Thermal process: MED, MSF, MVC, TVC	Pressure/concentration gradient driven: RO, ED	Thermal membrane: MSF/RO, MED/RO
Membrane pore size	-	0.1–3.5 nm	0.2–0.6 µm
Feed temperature	60–120 °C	<45 °C	40–80 °C
Driving force for separation	Temperature and concentration gradient	Concentration an pressure gradient	Temperature and concentration gradient
Energy	Thermal and mechanical	Mechanical and/or electrical	Thermal and mechanical
Form of energy	Steam, low-grade heat or waste heat and some mechanical energy for pumping	Requires prime quality mechanical/ electrical energy derived from fossil fuels or renewable sources	Low-grade heat sources or renewable energy sources
Product quality	High quality distillate with TDS <20ppm	Potable water quality TDS <500ppm	High quality distillate with TDS 20–500ppm

In this paper, evaluation of coupling different desalination systems which includes MSF, MED-TVC and hybrid (MSF/MED-RO) to steam network of site utility system have been considered.

The governing equations for thermodynamic modeling the desalination plant are given by El-Dessouky (2002). All of these models are developed from the basic of mass, energy balance and heat transfer equations. In addition, these models are supported by equations for calculating the thermal and physical properties of brine and distillate waters as functions of temperature and salt concentration. Also, the model formulated by Kimura and Sourirajan cited by Helal et al. (2003) has been used in this work for the RO plant. This is a mechanistic model which assumes the membrane has a microporous structure and is based on the “preferential sorption capillary flow” mechanism suggested by Sourirajan.

3. Materials and methods

The design procedure for evaluation of integration of low grade heat upgrade technologies with an existing site utility system is shown in Figure 1. The characteristics of low grade energy, such as available heat load at temperatures for use in desalination, is obtained from total site analysis (Klemeš et al., 1997; Smith, 2005). Computer code is used to obtain the performance indicators, for example, GOR and exergoeconomic parameters, for low grade heat utilization technology.

The performance indicators from computer code simulator are fed to the total site to determine the energy savings and electricity demand obtained by heat upgrade options. Integration of desalination system affects cooling utility and electricity demand. This demand change is evaluated from total site composite curves.

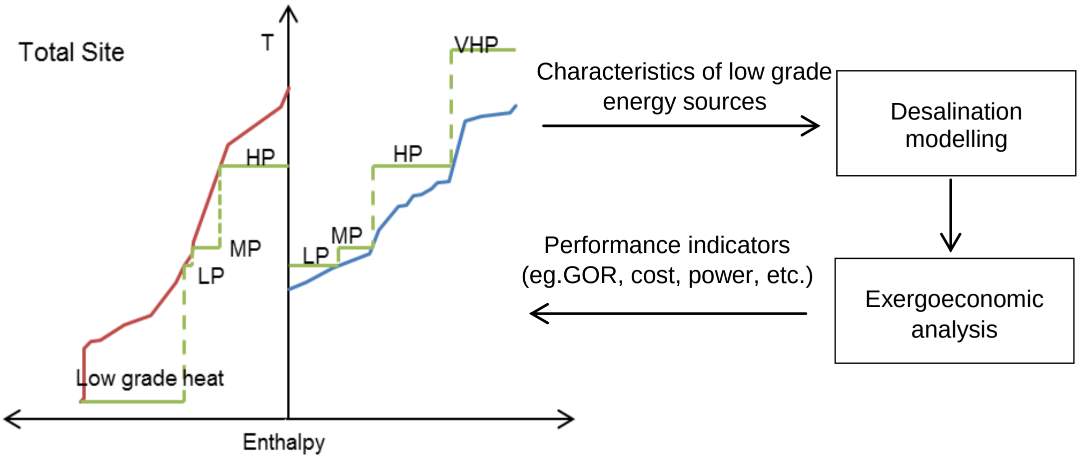


Figure 1: Procedure for evaluation of low grade heat upgrade technology.

3.1 Exergy analysis

All parts of systems were modeled and simulated and exergy equations were developed and applied to evaluate performance of combined system (Bejan et al.,1996).

3.2 Thermoeconomic analysis

Thermoeconomic analysis is applied to calculate the expenditure cost and the unit product cost and also to point out the unit that needs more improvement. Thermoeconomic analysis requires solving energy, exergy and cost balance equations of the considered different components. The governing equation of thermoeconomic model for the cost balancing of an energy system is written as:

$$C_F + Z = C_P \tag{1}$$

By defining exergy cost of each stream, c, Eq. (1) could be changed to

$$c_F E_F + Z = c_P E_P \tag{2}$$

The above relations are global cost balance equation, which should be applied for different component. Here, for each component of combined system, cost balance equation is taken into account.

3.3 Economic Analysis

In order to perform the economic analysis, the purchase cost of equipments must be determined. The purchase cost of the equipments are determined by some correlations that proposed by El-sayed

(2003). The cost of chemicals and labor is estimated as a fraction of the fixed cost according to El-Dessouky (2002). All costs due to owning and operating a plant depend on the type of financing, the required capital, the expected life of a component, and so on. The annualized cost method of Moran was used to estimate the capital cost of system components in this study Bejan et al. (1996).

4. Case study

Various design options for low-grade heat upgrade and recovery are evaluated in a case study. The base case design taken from Aguillar (2005) is shown in Figure 2, which consists of four boilers, four back-pressure turbines between VHP and HP levels, and one back-pressure turbine between HP and LP steam levels. Two multi-stage turbines are available for the expansion of steam between HP-MP and MP-LP respectively, while there are four mechanical pumps to be driven by either steam turbines or electric motors, and an electric motor is used for the supply of the feed water to the boiler.

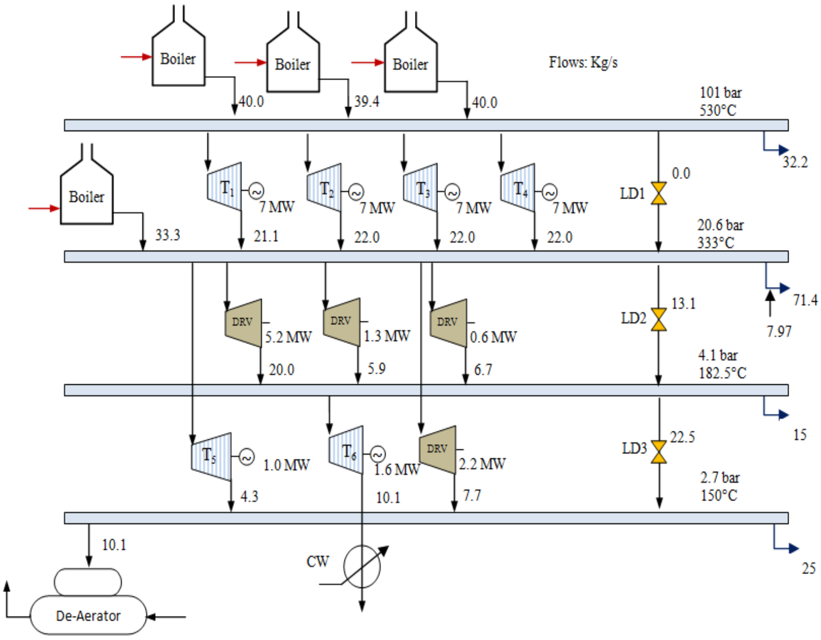


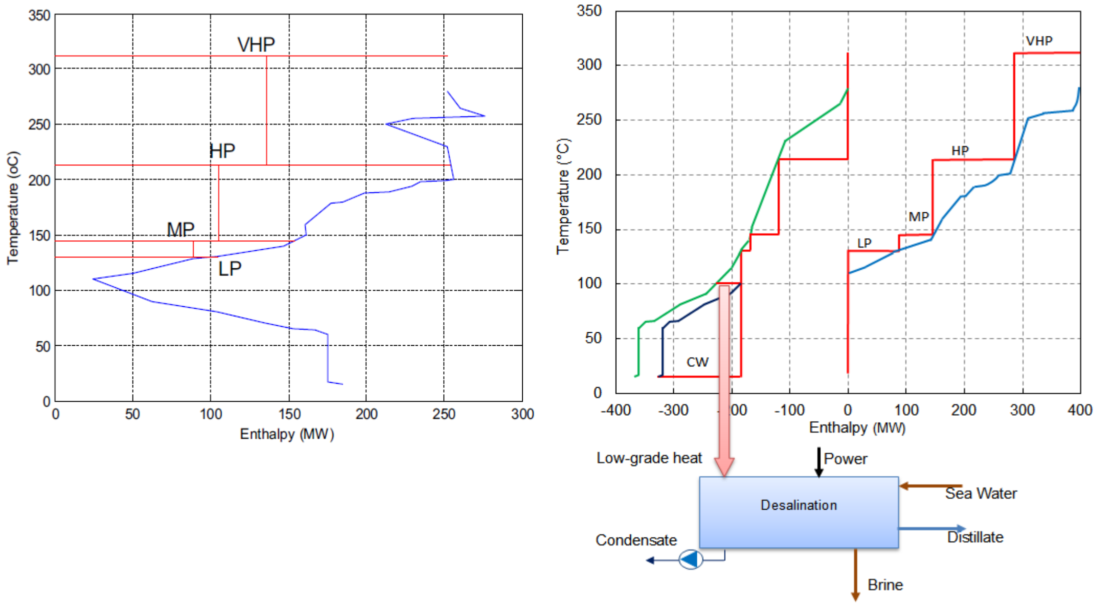
Figure 2: Base case design Aguillar (2005)

5. Results

The grand composite curves (GCC) of the individual process are modified by removing the pockets corresponding to additional heat recovery within the process. These modified process GCC are then combined together to form the total site sink and source profile. The site utility grand composite curve (SUGCC) represents the horizontal separation between the source and the sink. Steam demand at VHP, HP, MP and LP levels are 110.8, 21.4, 9.3 and 73.6 MW respectively. Power generation potential is represented as areas in the SUGCC with VHP-HP, HP-MP and MP-LP cogeneration potential of 79.8, 58.4 and 49.1 MW (Figure 3a) when a full steam recovery is made within the site utility systems.

The total site source and sink profiles after integration of the desalination are shown in Figure 3b.The amount of low grade heat available at a temperature higher than 115 °C is 43.17 MW as determined in Figure 3b. The temperature of 115 °C corresponds to a supply temperature of 100°C and minimum approach temperature of 15 °C. Site source profile below 115 °C is shifted by 43.17 MW to account for the extraction of low grade energy and hence the cooling water requirement for the total site is decreased by 43.17 MW.

Also, table 2 determines the techno-economic evaluation of desalination technologies. As shown in table 2, the MED-TVC has the best GOR and MED-RO has the highest desalinated water flow and the highest desalination cost. Moreover, table 3 determines the cost of desalinated water production for desalination technologies. As shown in the results, with considering fixed utility cost in the site utility system and heat recovery of low grade heat for production of desalinate water, the lowest desalinated water production cost is related to MED-TVC option (0.65$/m3) and the simple payback is 5.7 y. The worst scenario is related to MSF-RO option (0.84$/m3) and the simple payback is 7.3 y.



(a) (b)

Figure 3: (a) Site utility grand composite curve,. (b) Site composite curve with desalination integration

Table 2: Techno-economic evaluation of desalination technologies

Options	Cold utility (MW)		Desalination power consumption (MW)	Desalinated water flow (kg/s)	GOR	Desalination cost (M$)
	Base	Summer				
Base	368	368	-	-	-	-
MSF	324.83	324.83	1.94	134.4	8.4	15.2
MED-TVC	324.83	324.83	0.94	148.7	9.3	16.5
MSF-RO	324.83	324.83	5.01	249.4	8.4	26.1
MED-RO	324.83	324.83	4.02	263.5	9.3	27.4

Table 3: Comparison between different desalination technologies

Options	Total utility cost (M$/y)	Electricity cost (M$/y)	Water cost rate ($/m^3)	Exergy destruction cost rate (M$/y)	Exergetic efficiency	simple payback (y)
Base	94.06	23.77	-	55.64		-
MSF	94.03	24.75	0.77	59.78	1.85	6.9
MED-TVC	94.03	24.25	0.65	57.56	2.16	5.7
MSF-RO	94.03	26.31	0.84	60.13	4.15	7.3
MED-RO	94.03	25.81	0.76	57.91	4.82	6.2

It should be noted that care must be taken to interpret these results, as the calculation is based on the particular cost parameters, specified site conditions, and fixed operating conditions of upgrading technologies. With different economic costing parameters, especially, the relative cost between electricity and fuel, the trend given in this case study could be different. Site-wide energy flow information including site profiles is case specific and therefore, the availability of low grade heat and its quality are different to the base case shown in this study. This implies the selection of upgrading or recovery technologies and its design should be made in the context of site utility systems.

6. Conclusion

Wide range of technologies is available for upgrading or recovering low-grade heat in process industries, and its techno-economic impact has been addressed with the aid of simultaneous consideration of site utility systems optimization and performance of upgrading technologies.

As shown in the results, the integration of desalination system with low grade heat of site utility system is very good option in view of thermodynamic and economic and the MED-TVC is best option for integration.

It should be emphasized that the selection and design of low grade heat upgrading or recovery should be made in the simultaneous consideration of the system-wide environment and constraints, as the best heat upgrade technology is strongly dependent on the site fuel and electricity cost, condensate management system, and characteristics of low grade heat. The methodology developed needs to be further extended to accommodate the integration of renewable energy sources, such as solar, wind, geothermal, etc. to the total site and to consider over-the-pence process integration between process sites and community energy systems. Another work to be considered in future is to improve the applicability and practicality of the proposed design method in practice, for example, engineering limitation, geographical constraints and regulatory barriers existed in the implementation of low grade heat recovery and utilization.

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