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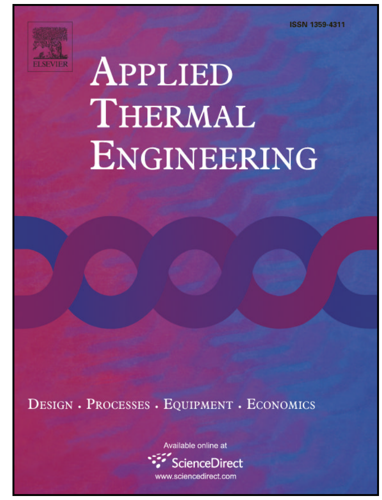

Research Paper

Desalination Processes Evaluation at Common Platform: A Universal Performance Ratio (UPR) Method

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Desalination Processes Evaluation at Common Platform: A Universal Performance Ratio (UPR) Method

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Highlights

Universal performance ratio (UPR) is a common platform to evaluate all kind of desalination technologies

In combined cycle arrangements, thermally driven desalination processes only consume 3-5% of primary fuel exergy.

All conventional desalination processes are operating at only 10-13% of theoretical limit.

The sustainable desalination can only be achieved by approaching 25-30% of theoretical limit.

The current hybrid cycles can achieve up-to 20% of theoretical limit, one of the best reported up-till now.

Abstract

The inevitable escalation in economic development have serious implications on energy and environment nexus. The International Energy Outlook 2016 (IEO2016) predicted that the Non Organization for Economic Cooperation and Development (non-OECD) countries will lead with 71% rise in energy demand in contrast with only 18% in developed countries from 2012-2040. In Gulf Cooperation Council (GCC) countries, about 40% of primary energy is consumed for cogeneration based power and desalination plants. The cogeneration based plants are struggling with unfair primary fuel cost apportionment to electricity and desalination. Also, the desalination processes performance evaluated based on derived energy, providing misleading selection of processes. There is a need of (i) appropriate primary fuel cost appointment method for multi-purposed plants and (ii) desalination processes performance evaluation method based on primary energy. As a solution, we proposed exergetic analysis for primary fuel percentage apportionment to all components in the cycle according to the quality of working fluid utilized. The proposed method showed that the gas turbine was under charged by 40%, steam turbine was overcharged by 71% and desalination was overcharged by 350% by conventional energetic apportionment methods. We also proposed a new and most suitable desalination processes performance evaluation method based on primary energy, called universal performance ratio (UPR). Since UPR is based on primary energy, it can be used to evaluate any kind of desalination processes, thermally driven, pressure driven & humidification-dehumidification etc. on common platform. We showed that all desalination processes are operating only at 10-13% of thermodynamic limit (TL) of UPR. For future sustainability, desalination must achieve 25-30% of TL and it is only possible either by hybridization of different processes or by innovative membrane materials.

Keywords: Desalination, performance ratio, exergy analysis, sustainability, universal performance ratio.

1. Introduction

The world's trend in water desalination industry has moved towards the efficient cogeneration concept where both power (electricity) and potable water are produced simultaneously. Cogeneration exploits the thermodynamic synergy of process integration where processes are arranged in the descending needs of exergy potentials. In a combined cycle gas turbine (CCGT) and desalination plants, high pressure steam produced in heat recovery steam generator (HRSG) by circulating high temperature burnt gases perform two important tasks such as: (i) the mechanical work generation by expanding in turbines that drives the electric generators for electricity production and, (ii) the extracted steam from the low-pressure turbines, utilized in desalination systems such as multi effect desalination (MED) and multi stage flash (MSF) to produce fresh water. In such dual purpose plants, the differentiation of grade or quality of working fluid utilized by the processes is important not only for their performance evaluation but also primary fuel cost apportionment. The conventional energy based analysis is unable to distinguish the grade of energy. In literature, group of researchers [1-11] presented energetic method for cogeneration plant analysis but they were unable to accommodate the quality of energy utilized by the process. Numerous publication [12-18] also presented desalination thermodynamic analysis based on energetic analysis neglecting grade of energy. Many authors applied similar energetic approaches for primary fuel cost apportionment in the past ignoring the effect of quality of working fluid in multi-purposed plants. In 1980s some authors [19] presented fuel cost apportionment concept taking into account irreversibility and thermodynamic efficiency for dual purpose plants. It is noticed that, for dual purpose plants, two methods were used for fuel cost apportionment in the past such as; i) method based on cost accounting of stream energy also called cost balance method and ii) method based on assigning capital cost and fuel cost directly to products produced also called cost allocation method. Saeed [20] proposed fuel cost allocation method based on total output (power + water) to total input (fuel) utilizing the heat values of output. Al-Sofi et. al. [21] presented first law of thermodynamics for dual purpose plant fuel cost allocation. They simply used output to steam flow rate factor for primary fuel cost distribution. Author also highlighted exergy accounting concept but all calculations were performed using energy of input stream to total output produced. Darwish [22] suggested four different methods based on fuel saving approach as if both plants operated separately. He also highlighted increased boiler capacity methods to match dual purpose plant requirement. Wade [23] presented cost distribution method based on energy consumed by the processes for five different schemes of power and desalters including MSF and reverse osmosis (RO). He used power plant efficiency as a reference for energy distribution. Mussati et. al. [24] proposed credit method for annual cost distribution in which they predetermined the value of one product and subtracted it from total annual cost to find the cost of second product. Wang et. al. [25] presented seven different cost allocation methods including energy of input streams, energy of outputs and exergy of oputputs etc. Kamal [26] investigated simple energy approach for costing and to estimate the attractive rate of return for power and desalination methods. Hosseini et. al. [27] explained total revenue required approach for economic analysis of dual purpose plants. They utilized exergy to investigate the system components efficiency. Hamed et. al. [28] presented an energy based cost allocation method for dual purpose plants. They also investigated different parameters effect on costing. Lozano et. al. [29] and Helal [30] proposed an energetic approach for cost allocation of tri-generation (power, desalination and cooling) plant. They simply used heat energy distribution among these processes. From above detailed literature review, it can be noticed that mostly authors focused on energetic analysis for performance analysis and primary fuel cost allocation in dual purpose plants.

For dual-purpose plants where more than two outputs are produced from one input, distinguishing the grade of energy utilized by the processes is very important. Exergy analysis can differentiate the quality of working fluid very efficiently. Although there are number of publications [31-57] are available on exergy analysis, but they only focused on system performance in case of single purpose plants and components performance improvement in dual purpose plants. Thus, there is real motivation to evaluate the exergy destruction of working fluid (steam) expands across the designed processes of a cogeneration plant such as turbines and desalination and to rationalize grade of energy utilized for performance evaluation as well as the fuel-cost apportionment for the processes, corresponding to the ratio of exergy destruction of the processes to the total available exergy of the plant.

2. Combined Cycle Gas Turbine + Desalination System Configuration

For discussion purpose, combined CCGT and desalination plant is presented in this paper. The detailed exergy flow of primary fuel across processes is shown in Figure 1. The desalination processes are integrated into combined cycle to activate by low exergy steam usually extracted from low pressure turbine at low pressures and temperatures. Although the exergy value of bled-steam is low, but its latent energy remains high. The low exergy of bled steam renders its suitability for power generation but it is an excellent source for MED where its latent energy is used multiple times according to number of effects. In MED, the vapor emanating from the previous stage is channeled to the tubes of the subsequent stage to reutilize the heat of condensation to evaporate the sprayed seawater. The multiple re-use of the latent energy of bled-steam is repeated from a top-brine (TBT) to a lower-brine (LBT) temperature of 65^{o}C to 42^{o}C, respectively. The lower limit of LBT is controlled by the ambient temperature which may fluctuate with the local seasons. Through these highly efficient condensation-evaporation processes, the distillate is produced and collected from every MED stage.

Figure 1: Primary fuel exergy flow across processes of a cogeneration components.

3. Exergy Approach

For a combined plant having 594 MW electricity and 2813 m^3/h desalination capacity as discussed in section 2, an exergy model is developed to investigate primary fuel proportions utilized by the processes. The detailed exergy model is presented in Table 1.

Table 1: Detailed exergy model for a combined power and desalination plant

	Exergy Calculation	Comments
1-2	$\Delta E_{1-2} = \dot{m}_1\left[\left(h_2 - h_1\right) - T_o\left(S_2 - S_1\right)\right]$	Specific exergy destruction across compressor
3-4	$\Delta E_{3-4} = \dot{m}_3\left[\left(h_4 - h_3\right) - T_o\left(S_4 - S_3\right)\right]$	Specific exergy destruction across GT
4-5	$\Delta E_{4-5} = \dot{m}_4\left[\left(h_5 - h_4\right) - T_o\left(S_5 - S_4\right)\right] = \Delta E_{HRSG}$	Specific exergy destruction across HRSG
2-3	$\Delta E_{CC} = \Delta E_{fuel} - \Delta E_{1-2} - \Delta E_{3-4} - \Delta E_{4-5}$	Specific exergy destruction across CC
6-8	$\Delta E_{6-7} = \dot{m}_6\left[\left(h_6 - h_7\right) - T_o\left(S_6 - S_7\right)\right]$ $\Delta E_{7-8} = \dot{m}_7\left[\left(h_7 - h_8\right) - T_o\left(S_7 - S_8\right)\right]$ $\dot{m}_7 = \dot{m}_6 - \dot{m}_{desal}$	Specific exergy destruction across STs
	$\Delta E_{cond} = \dot{m}_7\left[\left(h_8 - h_{f(T_O)}\right) - T_o\left(S_8 - S_{f(T_O)}\right)\right]$	Specific exergy destruction across condenser
	$\Delta E_{Desal} = \dot{m}_{desal}\left[\left(h_7 - h_{f(T_O)}\right) - T_o\left(S_7 - S_{f(T_O)}\right)\right]$	Available work from extracted steam
	$\%E_{GT} = \dfrac{\Delta E_{1-2} + \Delta E_{3-4} + \Delta E_{4-5}}{\Delta E_{fuel}}$	Percentage of exergy utilized by GT
	$\%E_{HRSG} = \dfrac{\Delta E_{4-5}}{\Delta E_{fuel}}$	Percentage of exergy utilized by HRSG
	$\%E_{ST} = \dfrac{\Delta E_{6-7} + \Delta E_{7-8} + \Delta E_{cond}}{\Delta E_{HRSG}} \%E_{HRSG}$	Percentage of exergy utilized by STs
	$\%E_{Desal} = \dfrac{\Delta E_{Desal}}{\Delta E_{HRSG}} \%E_{HRSG}$	Percentage of exergy utilized by Desalination

It is calculated that 73.17% of primary fuel exergy is destructed across gas turbine cycle and remaining 26.83% is carried over by exhaust gases. This energy is recovered across HRSG to produce steam. Approximately 23.11% exergy of produced steam is utilized by steam turbines for further power production and only a small fraction, 3-4%, of low-grade steam from the last stages of low pressure steam turbines is bled-off to operate the MED for seawater desalination.

Table 2 summarized the primary fuel proportions utilization by cogeneration components based on exergy and energy analysis

Table 2: Primary fuel proportion utilization by cogeneration components based on exergy and enthalpy analysis

These proportions are based on grade of energy consumed by the processes and can be utilized to convert derived energies of desalination processes to primary energy. Conventionally, the industrial desalination processes performance also called performance ratio (PR) is based on

Process	Conventional Energy method (%)	Proposed Exergy method (%)	Over/lower charging (%)
GT (including combustor, air compressor)	43.67	73.17	-40.32
HRSG	56.33	26.83	
STs (HP, MP & LP)	39.58	23.11	71.2
Thermal Desalination	16.75	3.72	350.8
Negligible amount of exergy is carried away by exhaust gases from HRSG			

derived energy such as electrical and thermal as presented in equation 1. Since different derived energies are not same in terms of quality (work potential) so conventional PR is misleading concept for different desalination technologies comparison.

$$PR = \frac{evaporative\_energy}{derived\_energy\_input} = \frac{h_{fg\_vapor}}{\left(\frac{kWh}{m^3}\right)_{electrical} + \left(\frac{kWh}{m^3}\right)_{thermal}} \quad (1)$$

We proposed UPR based on primary energy that can provide common platform for comparison of all kind of desalination processes. In proposed UPR, as presented in Equation 2, the derived energies are multiplied with respective conversion factors to convert into primary energies those can be then added to calculate total input to desalination process.

$$UPR = \frac{evaporative\_energy}{primary\_energy\_input} = \frac{h_{fg\_vapor}}{3.6\left\{CF1\left(\frac{kWh}{m^3}\right)_{electrical} + CF2\left(\frac{kWh}{m^3}\right)_{thermal} + CF3\left(\frac{kWh}{m^3}\right)_{renewable}\right\}} \quad (2)$$

where h_{fg_vapor} is equivalent vapor energy, CF1 is the conversion factor for electricity to the primary energy, CF2 is the conversion factor for thermal input to the primary energy and CF3 for renewable to primary energy. The kilo-watt hour per cubic meter (kWh/m^3) is the specific energy consumption in terms of electrical, thermal and renewable. The conversion factors are calculated on the basis of exergy destruction across the components corresponding to primary fuel exergy. On the basis of these conversion factors, the derived specific energies are converted to the equivalent primary energy. The UPR values are calculated based on primary energy consumption as presented in Table 3.

Table 3: Primary energy of three conventional desalination processes and universal performance ratio.

Desalination processes	**Derived energy**		**Conversion efficiency** Exergy proportion of primary energy		**Primary energy**	**UPR**	**% of thermodynamic limit (TL)***
	Electrical	Thermal	Electrical	Thermal			
RO	3.5	NA	47%	NA	7.45	86	10.4%
MSF	3.0	80.6		5.4%	10.73	60	7.2%
MED	2.3	71.7		3.4%	7.32	88	10.6%

*Thermodynamic limit (TL):
Minimum separation work= 0.78kwh/m^3
Minimum separation energy=2.8 kJ/kg

$$E\left(\frac{kJ}{kg}\right) = 0.78\left(\frac{kWh}{m^3}\right).3600\left(\frac{sec}{h}\right).\frac{1}{1000}\left(\frac{m^3}{kg}\right) = 2.8\frac{kJ}{kg}$$

$$TL = \frac{h_{fg\_vapor}\left(\frac{kJ}{kg}\right)}{E\left(\frac{kJ}{kg}\right)} = \frac{2326}{2.8} = 828$$

The calculated UPR numbers can't provide the real picture unless it compared with thermodynamic limit for separation. The thermodynamic limit is calculated based on minimum separation work theory. According to minimum separation work theory, the minimum energy required for separation at 35000ppm concentration is 0.78 kWh/m^3 [58]. The UPR theoretical limit based on minimum separation work theory is 828 as presented in Table 3. It can be seen that the conventional desalination processes are only operating within 10% of TL, highly un-sustainable for future water supplies. It can also be noticed that MED performance (UPR=88) is slightly better as compared to RO processes (UPR=86) and it is due to low grade steam utilization that has very small proportion in primary energy. The MSF processes performance is the lowest because they consume high temperature steam and high electricity that makes more share in primary energy.

Figure 2: Chronological trend of universal performance ratio and thermodynamic limit of 40 World desalination plants.

Over 40 commercial desalination plants data has been collected from all over the World and UPR trend has been presented in Figure 2. Despite more than 3 decades of design improvements in the mentioned processes, the efficiency improvement is seen to be gradual. The authors believe that a quantum jump in efficiency for desalination can only be derived when there is a fresh paradigm change in the technology break-through in material development or the implementation of hybridization of existing thermally-driven methods so as to enhance their thermodynamic synergy.

Recently, desalination hybridization trend have been presented by many researchers. MED hybridization with AD cycle [59-70] have made great strike towards improving the efficacy of practical desalination methods. The hybridization of the conventional MED method with the adsorption (AD) desalination cycles has been extensively investigated at the King Abdullah University of Science and Technology. The AD cycle is attached to the bottom-brine stage of the MED, acting as a vapor compressor to lower the bottom-brine temperature of MED. The detail schematic of hybrid MEDAD cycle is presented in Figure 3 where last stage of MED is combined with AD cycle to break lower brine temperature. Owing to the excellent thermodynamic synergy between these cycles, the water production yield of the MED stages is almost double whilst the thermal heat input to the MED remains unchanged. The additional thermal heat input is the regeneration heat required for desorption of adsorbent that facilitated the batch-operation of AD cycles. Our experiments show a quantum jump in the efficiency where the universal performances ratio (UPR) attained by the MED+AD cycle has increased from 113 to 175 as shown in Figure 2. This demonstrates that a quantum jump in the desalination efficiency is only possible when there is a methodology shift in the desalination technology. Otherwise, the improvement in desalination efficiency can depict a marginal increase, as evident in the gradual improvement in the efficiency over a three decade period of Figure 2. The other noticeable hybridizations presented recently are MSF-MED [71, 72] and RO-MSF [73-80] are also evolving to improve processes performance by overcoming conventional methods limitations. Thermally driven processes hybridization improve thermodynamic synergy and thermal system with membrane technologies improve fresh water recovery.

Figure 3: MED+AD hybrid cycle detailed flow schematic.

Conclusion

The challenge facing all scientists and engineers is not to squabble over which desalination method available hitherto is better but instead, how to achieve a higher performance ratio for any desalination method in order to achieve sustainable desalination for the future. As the present universal performance ratios for all practical seawater desalination are less than 15% of the thermodynamic limit for seawater desalination, it is plausible that future desalination methods could attain an efficiency level up to 30% of the ideal limit. In this paper, we have demonstrated that the goal for sustainable seawater desalination can be reached by hybridizing the existing processes and development of the high flux permeable membranes such as aquaporins, graphanes, etc., but these developments are still at their infancy stages in terms of their potential for commercialization.

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Abbreviation

AD	Adsorption
CC	Combustion chamber
CW	Cooling water
CCGT	Combined cycle gas turbine
CF	Conversion factor
GCC	Gulf cooperation council
GT	Gas turbine
HRSG	Heat recovery steam generator
HW	Hot water
HP	High pressure
IEO	International energy outlook
LP	Low pressure
LBT	Lower brine temperature
MP	Medium pressure
MED	Multi effect desalination
MSF	Multi stage flash
MW	Megawatt
OECD	Organization for economic cooperation and development
PR	Performance ratio
RO	Reverse osmosis
ST	Steam turbine
TL	Thermodynamic limit
TBT	Top brine temperature
UPR	Universal performance ratio

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