Fuel Allocation in Water and Power Cogeneration Desalination Plant

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Overview

Introduction

- Cogeneration refers to the simultaneous production of electricity and useful heat from a single energy source. The waste heat is harnessed for other purposes, such as industrial processes, e.g., desalination plants.
- Dual-purpose desalination plants combine seawater desalination with power generation. They offer several benefits over standalone desalination plants:
  - Cost Reduction: due to shared infrastructure and reduced capital expenses.
  - Energy Efficiency: waste heat utilization improves overall energy efficiency.
  - Water & Power Production: provide both freshwater and electricity, addressing water scarcity and energy needs simultaneously.
  - Environmental Impact: reduction in emissions by optimizing energy utilization.
  - Adaptability: tailored to specific energy and water demands.
  - Stability: Reliable power supply enhances the stability of water production.
  - Sustainability: Integrating with renewable energy sources.

- Fuel allocation refers to the distribution of energy resources (typically fuels) between the power generation and desalination components within a cogeneration system.
- The challenge lies in optimizing the allocation of fuel resources to achieve efficient energy utilization and cost-effectiveness.
- Fuel allocation determines how much of the available fuel is used for electricity production and how much is allocated to the desalination process.
- Efficient fuel allocation has several implications:
  - Energy Efficiency: effectively utilized waste heat for desalination.
  - Cost Optimization: reduction of operational costs.
  - System Performance: ensures stable power supply & reliable freshwater production.
- Fuel allocation plays a crucial role in achieving the delicate balance between power generation and desalination in cogeneration plants. It's a key factor in ensuring sustainable and cost-effective operation.

Methods for Fuel Allocation

- Methods used for cost allocation may be classified into three main groups:
  - engineering-based methods (e.g. separable costs and marginal costs),
  - market-based methods (e.g. alternative market value and power credit method),
  - thermodynamic methods (e.g. electrical equivalent method, energy method, exergy method).
- Each method offers unique approaches to achieving the delicate balance, and understanding their strengths and limitations can help determine the most suitable method for a specific situation.
- The most common methods for fuel allocation in integrated desalination plants are
  - Power to distillate ratio (PDR),
  - heat value for potable water and
  - exergy method.

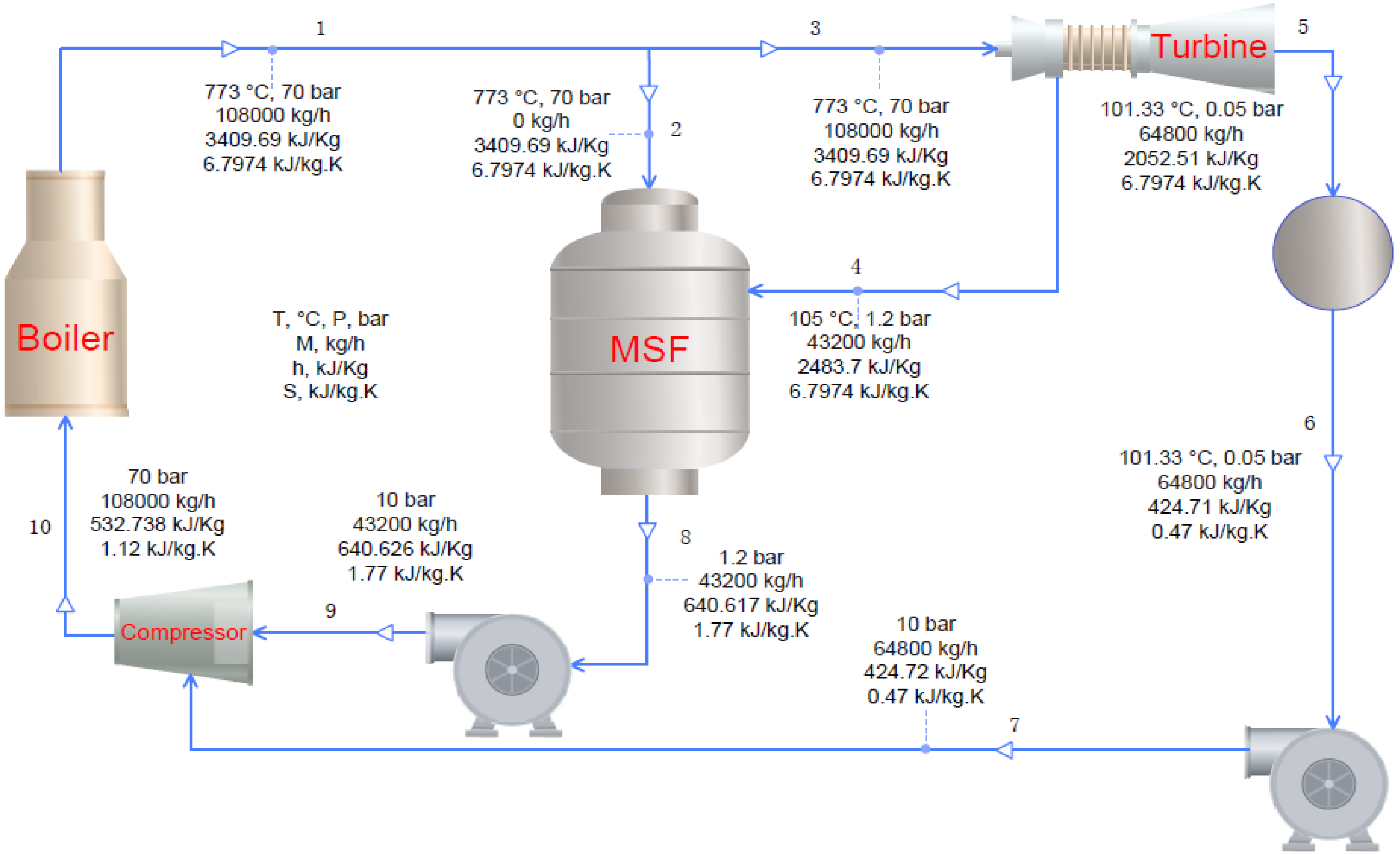
Method	Description	Advantages	Disadvantages
Power to Distillate Ratio (PDR)	This method simply divides the power output (P) by the water production rate (W) of the plant. PDR = P (kW) / W (m^3/h)	Easy to understand and implement. Requires minimal data: just power and water production.	Ignores the actual energy requirements of each process. Doesn't account for plant efficiency or variations in desalination technology. It is not suitable for detailed analysis
Heat Value for Potable Water	This method assigns a specific heat value (HP) to the produced water, representing the energy theoretically required for desalination. Fuel allocation is then based on the combined heat demands for power generation and desalination. Fuel allocation = (P x Efficiency_power + Wx HP) / Overall_plant_efficiency	Considers the desalination process as a heat sink. Offers a more realistic approach than PDR. Simpler than exergy analysis, recognizes desalination energy demand	Selecting the appropriate heat value (HP) can be subjective and depend on desalination technology. Requires knowledge of overall plant efficiency, which might not be readily available.
Exergy Method	This advanced method uses the concept of exergy (usable energy) to account for the thermodynamic quality of energy streams within the plant. Exergy balances are established for both power and desalination processes, allowing for a more accurate allocation of fuel based on the actual energy demands.	Most rigorous and theoretically sound method. Provides a clear picture of energy utilization within the plant. It identifies efficiency improvements	Requires complex calculations and detailed thermodynamic data for the plant. Data collection and calculations can be complex and time-consuming.

Objectives

- This work focused on the analysis of fuel allocation between water and power in cogeneration desalination plants, as fuel cost is the main shared component.
- The three approaches were used in this study.
  - Power to distillate ratio (PDR),
  - heat value for potable water (HVW) and
  - exergy method.
- The accuracy of each methodology was determined and compared.
- The appropriate method was implemented in Al-Jubail Phase I desalination plant.

Results

- 1.0 Fuel allocation was estimated using a simplified configuration of a cogeneration desalination plant as follows



- 1.1 Power to Distillate Ratio (PDR) Method
  - Evaluate delta (δ =PDRca/PDRci): the ratio of the actual power to distillate ratio and the ideal power to distillate.
  - PDRci $= \frac{[\,0.5 * (Ts - Tx) + 28\,]}{GOR}$ where Ts, Tx is the turbine inlet and outlet steam temperatures.
  - if (δ) <1 then $y_1 = 1 - (\delta) * [1 - (Tx/Ts)]$, z_1 = 1- y …. where z is fuel fraction allocated to power.
  - If (δ) ≥ 1 then $y_2 = \left(\frac{1}{\delta}\right) * \left(\frac{Tx}{Ts}\right)$, z_2 = 1- y_2 …. where y is fuel fraction allocated to desalination.
  - PDRca = 61.2 KWh/kL and PDRci = 45.47 kWh/kL. Then δ = 1.3.
- So, the fuel fraction allocated to power (z_2) is 90%, and the fuel fraction allocated to distillate (y_2) is 10%.

M. A. K. Al-Sofi and M.M. Srouji, "Fuel allocation in dual-purpose plants", Desalination 100, 65-70, 1995.

- 1.2 Heat Value For Potable Water (HVW) Method
  - It utilizes the overall fuel efficiency of the system for fuel allocation to power and desalination.
  - Then balancing the energy input against the output of power and desalination plants based on the specific plant data. Power and desalination plants are evaluated and compared on an equal basis,
    i.e., under similar conditions of operational strategy; inputs and outputs, as to which plant gives better results overall, when water production and electrical power are combined or separated.

- 1.2 Heat Value For Potable Water (HVW) Method ………… Cont.
- The specific fuel energy consumption of desalination is 8% of fuel consumption and 92% of the fuel is shared by electricity, the calculations as follows:

The specific heat consumption of desalination (SH_d) is:

$$SH_d = \frac{\Sigma Hs}{\Sigma Wp} = \frac{\text{heat contant of steam}}{\text{water production}}$$

The heat value of desalinated water is given by:

$HV_d = R * SH_d * K$, … where R recovery ratio and K is the utilization factor.

Heat value of water (H_w): $\Sigma Hw = \Sigma Wp * HV_d$

Knowing that the is given as 112181.4 KJ/s. So, the ratio of water produced to

The total heat value of fuels (Ew) is: $Ew = \frac{\Sigma Wp * HVd}{\Sigma Hf}$ … where H_f is the heat content of the fuel.

The overall thermal efficiency (Ef): $Ef\ \% = [Ee + Ew] * 100\%$ or

$1 = \frac{Ee}{Ef} + \frac{Ew}{Ef}$ and $1 = Fe + Fw$

Where Ee is the ratio of power generated to total heat value of fuels, Fe is the fuel share for electricity generation and Fw is the fuel share for water production.

The respective fuel heat values to be allocated to the corresponding products are given by the following expression: $\Sigma Hf = (Fe * \Sigma Hf) + (Fw * \Sigma Hf)$

where Fe and Fw are the fractions specifying the fuel shared by electricity and water, respectively.

M. N. Saeed, "Fuel Efficiencies, Allocation of Fuels and Fuel Costs for Power and Desalination in Dual Purpose Plants: A Novel Methodology", Desalination 85(2), 213-229, 1992.

- 1.3 Exergy Method
  - Exergy requires detailed exergy analysis of key components in both power generation and desalination cycles.
  - Determine the exergy destruction associated with each component. This involves assessing the irreversibility and inefficiencies within the system.
  - Divide the total fuel exergy by the total stream exergy (including both electricity and freshwater production).
  - Usually, the unit of this allocation is expressed as (kJ fuel exergy)/(kJ stream exergy).

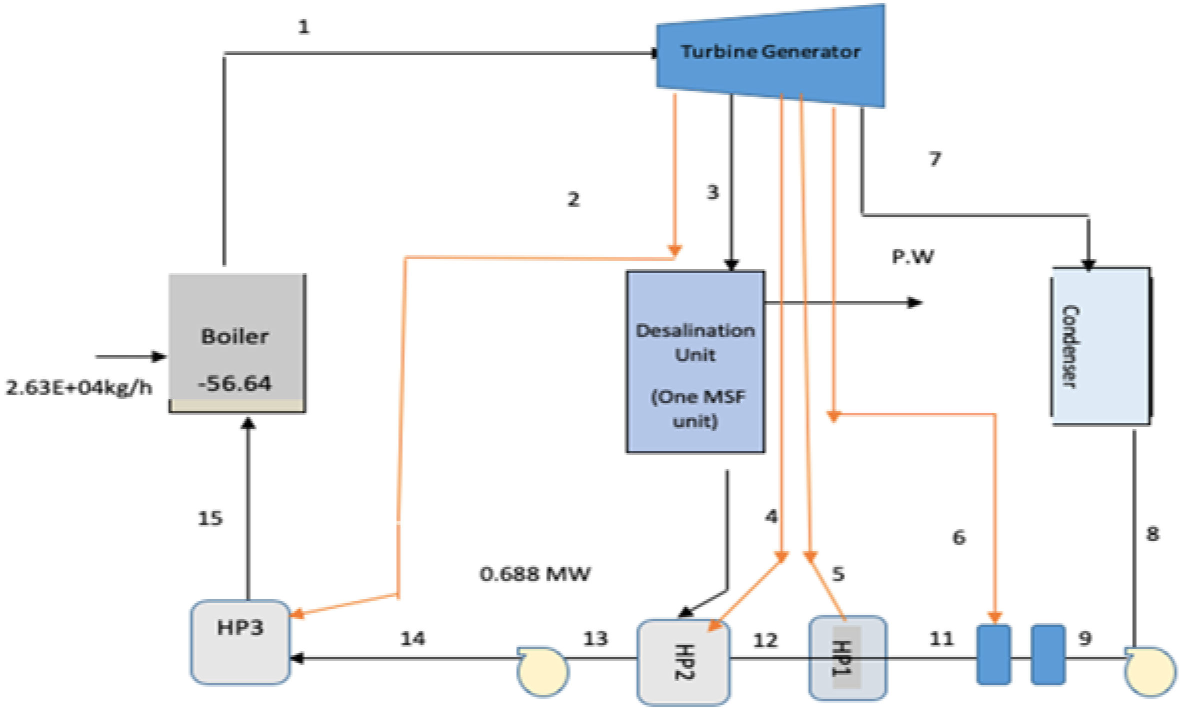
Properties of various streams

Points	Temp., °C	P, bar	M (kg/h)	h (kj/kg)	S (kJ/kg.K)	ψ (kJ/kg)	X (MW)
1	773	70	108000	3409.69	6.797	1388.652	41.660
2	773	70	0	3409.69	6.797	1388.652	0
3	773	70	108000	3409.69	6.797	1388.652	41.660
4	105	1.2	43200	2483.70	6.797	462.662	5.552
5	101	0.05	64800	2052.51	6.797	31.4724	0.567
6	101	0.05	64800	424.71	0.470	289.237	5.206
7	180	10	64800	424.72	0.470	289.247	5.206
8	105	1.2	43200	640.617	1.770	117.744	1.413
9	180	10	43200	640.626	1.770	117.753	1.413
10	286	70	108000	532.737	1.120	203.565	6.107
Product	40	7.2	345600	167.93	0.570	2.6576	0.255

- 1.3 Exergy Method …………. Cont.
  - Fuel allocation for power = energy allocation for power +((energy allocation for power/ (energy allocation for power + energy allocation for water)) * common energy shared by power and water) = 101.345 MW.
  - Fuel allocation for water = energy allocation for water +((energy allocation for water/ (energy allocation for power + energy allocation for water)) * common energy shared by power and water) = 26.328 MW.
- Since the total exergy of the system is 118.912 MW, then the percentage of fuel allocation for power and water are 85% and 15%, respectively.
- 1.4 Comparison of Between Various Studied Methods for Fuel allocation.

Method	PDR	HVW	Exergy
Fuel energy allocation to water	10%	8%	15%
Fuel energy allocation to power	90%	92%	85%

- 2.0 Case Study: The exergy method applied to Al-Jubail Phase I desalination plant to estimate the fuel allocation between power and water.
  - Al-Jubail Phase I plant consists of 6 cogeneration units which are all fired by natural gas with heavy fuel oil (HFO) available as a reserve fuel. The schematic diagram of one 60 MW unit and 1000 m^3/h is shown below.



Flow diagram for the design condition of Al-Jubail Phase I desalination plant.

HP: high pressure heater, PW: product water

- 2.0 Case Study
  - Steam is superheated to 783 K and 87 bar in the steam generator and fed to the turbine.
  - Operating conditions of Al-Jubail Phase I desalination plant as well as energy / exergy calculations are listed below.

Points	Temp °C	P bar	M (kg/h)	h (kj/kg)	S (kj/kg.k)	ψ (kj/kg)	X (mw)
1	510	87	281143.35	3415.995	6.712	1420.540	110.938
2	190	12.51	33360.35	2785.202	6.507	850.659	7.883
3	119	2	122469.93	2684.226	6.847	648.395	22.058
4	119	1.9	11413	2637.708	6.581	681.197	2.160
5	60	0.32	763	2510.519	6.728	510.205	0.108
6	250	25	295	2880.864	5.516	1241.777	0.102
7	42	0.082	106013.6	1976.759	6.314	99.852	2.940
8	42	0.082	113962.81	175.812	0.599	1.881	0.060
9	42	7.4	113962.81	176.132	0.599	2.201	0.070
10	45	7.4	113962.81	188.437	0.639	2.708	0.086
11	52	7.4	113962.81	217.697	0.730	4.862	0.154
12	57.55	7.2	113962.81	240.906	0.800	6.983	0.221
13	119	7.2	281206.09	499.535	1.517	52.047	4.066
14	120	129.5	284776.63	513.325	1.528	62.616	4.953
15	175.4	129.5	284776.63	742.910	2.095	123.235	9.748
16	54.5	0.85	5136.93	228.150	0.762	5.773	0.008
17	125.8	1.36	33360.35	528.471	1.590	59.219	0.549
Product Water	40	3.6	948800	167.541	0.572	1.537	0.405
desal condensate	119	10	122469.93	762.683	2.138	130.011	4.423

- 2.0 Case Study
  - The fuel specific exergy is calculated as: ψfuel = Ef * LHV, where Ef = 1.06 is the exergy factor based on the lower heating value (LHV). Pump input power was calculated as η = 0.95, is the combined pump/motor efficiency.
  - The following table shows that the exergy destruction rate of the boiler is dominant over all other irreversibility in the cycle. It counts alone for 259 MW of exergy destruction in the plant, the exergy destruction in the turbine and desalination unit is 15.7 MW and 22.6 MW, respectively, while the total exergy destruction of the other components is only 8.4 MW.

Boiler	Turbine/ generator	Desalination plant	Condenser	G.C	HP#1	HP#2	Deaerator heaters	pumps	Total exergy losses	Net Power output	Product water exergy
259.07	15.78	22.63	2.87	0.034	0.033	2.73	2.53	0.189	305.90	55	0.40
71.913	4.38	6.28	0.79	0.009	0.009	0.76	0.70	0.053	84.912	15.267	0.11

  - It was also found that the fuel allocation for power generation is 74%, while that for water production is 26% at a power generation of 60 MW.
  - The fuel allocation for power generation became 60% when the power generation is reduced to 30 MW, raising the fuel share for water production to 40%. Al-Jubail Phase I desalination plant is employing extraction condensing turbine, so it is expected that the percentage of fuel energy allocated to power of 74% is within the expected range between 70% to 85%.

O. A. Hamed, "Fuel Utilization of Power/Water Cogeneration Plants", The International Desalination Association World Congress on Desalination and Water Reuse 2017, São Paulo, Brazil. 8-12, May 2017.
Y. Wang and N. Lior, "Fuel allocation in a combined steam-injected gas turbine and thermal seawater desalination system", Desalination 214, 306-326, 2007.

Conclusion and Recommendations

- Three methods for fuel allocation were reviewed: the power to distillate ratio (PDR), the heat value for potable water and the exergy method.
- The exergy method was found to offer better estimate of fuel allocation in cogeneration (dual purpose) desalination plants.
- The exergy destruction rate of the boiler, the turbine and the desalination unit were 259 MW, 15.7 MW and 22.6 MW, respectively. Clearly, the boiler is accountable for most of the exergy destruction in the plant, more than 71% of exergy destruction. It offers room for cost improvement, and it is recommended to be subjected to further studies.
- It was observed that the fuel share for water production increases significantly when power generation is reduced. It is recommended to investigate effect of manipulating power production on the water production cost via the fuel allocation methods.

Thank You