Energy cost for desalination evaporation versus reverse osmosis

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Abstract: The selection of the appropriate desalination technology between evaporation and reverse osmosis is grounded on several factors, including investment cost, maintenance cost, degree of availability, heaviness of the duty, and the required purity of the desalinated water. The main factor is often the running cost of the plant, and specifically the cost of the consumed energy. This paper intends to demonstrate that the real value of the steam bleed is a function of several factors, mainly of the cost of fuel and of its importance in the total cost of the energy. The lower the cost of fuel, the less is the value of the steam bleed up to the extent that the cost of the energy consumption can be lower for evaporation than for reverse osmosis.

Keywords: energy cost; energy consumption; desalination; reverse osmosis; cogeneration; evaporation; steam bleeding.

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1 Introduction

Some debate is now ongoing in India about the specific energy consumption of each process of desalination. The evaluation of this component of the cost of the desalinated water is actually a crucial point and the correct evaluation is necessary to support any new investment in desalination.

Other factors important in the selection of the most appropriate desalination plant are the quality of the seawater (turbidity, oil content, pollutants, total salinity), the use of the fresh water (industrial, make-up to boilers, drinking), the heaviness of duty (seasonal, intermittent, heavy duty), degree of availability (reliability of the plant, necessity of spare capacity), necessary ancillary facilities (buildings, sea water intake and reject, pre-treatment and post-treatment plants), investment cost as related to the amortisation time and interest rates.

This paper is only focused on the cost of the energy necessary to run the plant, which is generally considered in the range of 35–45% of the total cost of the desalinated water.

The expected scarcity and the increasing cost of energy are giving progressively more importance to the energy component versus any other component of the cost. Moreover, a desalination plant is normally designed for an expected life of at least 25 to 30 years, and the possible variation in the cost of the energy, in any time of the future life, shall determine the future convenience of the plant in the configuration that is designed at the present time.

In spite of the importance of this issue, some uncertainty in the evaluation of the cost of energy is still noticed in India quite often, both among the investors and among the consultants and technologists. The common understanding is that any evaporative plant consumes at least twice energy than a modern RO plant; but this common understanding is not correct and often based on wrong assumptions.

This paper comments the old criteria of evaluation of the steam value and evidences the wrong conclusions which such criteria can take to, suggests a more correct system of evaluation with specific reference to the comparison between reverse osmosis and evaporation. The new system of evaluation is applicable to the desalination plants installed in power plants, where the cogeneration effect can be achieved in the case of evaporation (LP steam feed) and for which the cogeneration effect has to be duly considered.

2 Old evaluation criteria

The old traditional way to evaluate the cost of the steam bleed from a steam turbine was to calculate the missed production of electricity caused by the limited expansion of the bled steam. The bleed at approximately 5 bar from the turbine of a modern steam cycle power plant shall cause a loss of about 30–35% of the power generation, being 65–70% of the power generated in the previous expansion. Therefore, by bleeding 6% of the steam at that low pressure, the loss in the production is expected approximately 2%.

These data are statistic because the actual loss in the power production is influenced by several factors, such as boiler pressure, degree of superheating and reheating, efficiency of the turbine.

By this system of calculating the value of the steam bleed, any thermal desalination plant would appear to consume eventually two times more energy than any equivalent RO desalination plant. In other words, it would appear as if it is more convenient to produce 100% electricity and self consume a part of it for the RO, than to produce less electricity because the steam for the thermal desalination plant is bled from the turbine.

In fact, the bleed of at least 100 kg/h is necessary to produce 1 t/h of desalinated water by a modern MED/TVC desalination plant. That 100 kg/h of steam, if further expanded in the turbine from 5 bar to the condensation pressure, would have generated approximately 6–8 kW, corresponding to the difference of enthalpy between 5 bar (2800 kJ/kg including the average 25°C of residual superheating) and 0.1 bar (2580 kJ/kg saturated). The production of 1 t/h by reverse osmosis shall totally require only from 3 to 5 kW of electrical energy, depending on the number of passes, pre-treatment duty and post-treatment process. Any evaporative desalination plant requiring more than 100 kg steam for the production of 1 ton fresh water (GOR less than 10) would be proven to be further less convenient and eventually require more than two times energy than the equivalent RO.

In many cases (reheated steam) the degree of superheating at the steam bleed can be much higher than 25°C and the relevant enthalpy can be considered eventually close to 3000 kJ/kg. Hence, the general convenience of RO would have been demonstrated in the respect of the energy demand.

Actually the real case is not like that and a more precise calculation method is proposed in this paper, by which the cost of the energy consumption of RO and thermal desalination are quite similar and often inverted, and the convenience of one process over the other is to be evaluated case by case according to the working data of the power generation plant.

3 Power generation cycle

The newly proposed evaluation of the cost of the steam bleed is based on the analysis of the actual steam cycle from which the steam is bled.

In typical steam cycle, the steam is generated at a high pressure, superheated and eventually reheated after the first stage of expansion to an intermediate pressure.

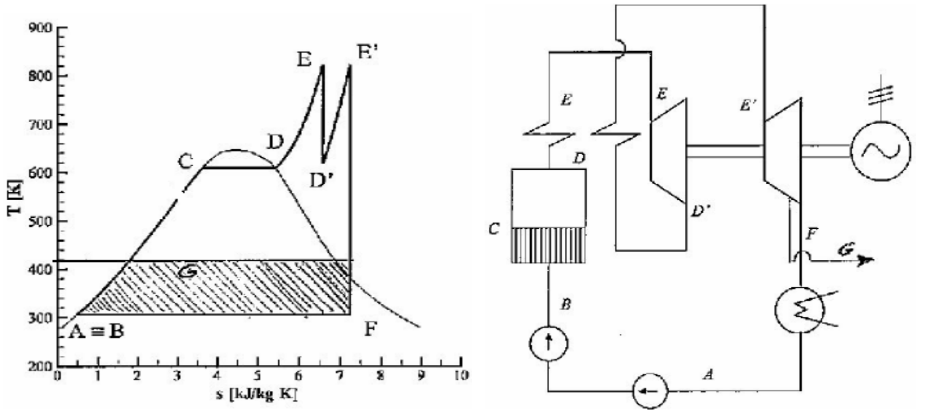
Therefore, the steam produces energy before being bled according to a ratio factor to be calculated case by case in detail, but generally evidenced in the sketch shown in Figure 1 for the quick visual acknowledgement.

Normally the steam shall produce approx 65% power before the bleed and 35% after the bleed, being this ratio depending on the specific cycle features. The missed production after the bleed can be balanced by some overproduction before the bleed. According to the typical ratio 65:35, the production of each kg of steam bleed can be replaced by approximately 0.35 kg of additional steam to be fully expanded without any impact in the total production of electricity according to the rate of the generator.

The capacity of the boiler to produce this excess steam, and the flexibility of the turbine to expand it up to the bleeding pressure, is in general available in any commercial equipment to a certain minimum level. The bled steam required for a typical 10,000 m^3/day

(417 t/h) desalination plant is only 3% and the additional main steam required to compensate the reduction in the thermal energy is less than 1% and this can be very well managed by any thermal plant system.

Figure 1 Steam cycle



The typical power group rated 500 MW processes approximately 1600 t/h steam and the bleed of 50 t/h (without any impact on the power generation), ensures the daily production of over 10,000 m^3 of desalinated water. Much higher production can be achieved, if necessary, still without any loss in the sale of electricity.

In this scheme, the additional cost for the production of the additional steam is only consisting in the additional requirement of fuel necessary to keep the same capacity of production of energy equal to the maximum rated by the power generator.

The economical results of this method of calculation are quite different from the old system, because the cost of the fuel is only a part of the cost of the electricity, being the other parts consisting in the amortisation of the investment, personnel and running costs, maintenance and spare parts.

The cost of the fuel is actually a portion of the total electricity costs according to a ratio that is quite different from plant to plant, and is a function of the type of fuel, pressure of the boiler and cycle efficiency. Normally the cost of fuel is in the range of 30–50% of the total cost of the electricity.

In India the cost of fuel is rather low whenever local coal is burnt, even if the relevant power cycle efficiency is usually below 40%. Lower is the cost of the fuel and higher is the efficiency, the cost of fuel shall be a lower ratio of the cost of the electricity, and therefore the convenience to overproduce steam and balance the bleeding, shall be better matched.

As per typical Indian data, 1 kg of steam bleed is balanced by 0.35 kg of additional steam generated by the boilers, which means approximately 0.06 kg of additional coal for the production of 10 kg of desalinated water. Hence the energy content of 1 m^3 of desalinated water is equivalent to 6 kg of local coal, if produced by MED/TVC. This cost can be compared to the energy content of approximately 4.5 kWh (average including pre-treatment) of 1 m^3 of desalinated water produced by two passes RO.

The economical comparison is then to be made between the cost of 6 kg of local coal and 4.5 kWh of electricity. Should the cost of 1 kg of coal be less than 75% of the price of 1 kWh, the convenience of MED/TVC is proven in respect of the cost of the consumed energy.

This conclusion is obviously to be checked case by case according to a number of factors, such as:

- MED/TVC actual design GOR (steam-specific consumption)
- gross calorific value of the fuel
- cost of coal or fuel
- efficiency of the power cycle
- bleeding pressure and superheating degree (total steam enthalpy)
- type and efficiency of the installed boiler and turbine, and working flexibility.

The examples shown in Tables 1 and 2 provide the calculation applicable to:

EXAMPLE A: a typical Indian case with boiler working at 170 bar plus reheating at 40 bar and low calorific value coal (4000 kcal/kg)

EXAMPLE B: a typical supercritical case with boiler working at 252 bar plus reheating at 58 bar and high calorific value coal (6200 kcal/kg)

Table 1 Example A: Typical Indian power generation plant

Example A Typical Indian Power Generation Plant							
Rated Power Generation	MW	535					
Efficiency	%	38					
Fuel		Coal	Feed	t/h	310		
Gross calorific value	kCal/kg	4000	equal to	kJ/kg	16700		
SH Steam Generated	t/h	1700	at Press	barg	170	at Temp	°C
SH Steam Reheated	t/h	1515	at Press	barg	46	at Temp	°C
Specific Power Generation	kW/kg (Fuel)	1.726	kW/kg (Steam)		315		
Cost of Fuel	In Rs/kg	3					
Price of electricity	In Rs/kWh	5					
Percentage of cost of fuel in the total price of electricity					35%		
Case of Installation of SWRO plant rated 10MLD with pre-treatment and 2 passes							
Estimated Power consumption	for pre-treatment.	kWh/m^3	1.2				
	for 1^ pass	kWh/m^3	2.5				
	for 2^ pass	kWh/m^3	1				
	TOTAL	kWh/m^3	4.7				
Total electricity consumption		kW	1960				
Total Energy cost		In Rs/h	9800				
		In Rs/m^3	23.50				
Case of Installation of MED/TVC plant rated 10 MLD with GOR 10							
LP Bleed		t/h	41.7	at bar	4.5	Enthalpy	kJ/kg
Condensation Enthalpy at		°C	45			Enthalpy	kJ/kg
Theoretical loss of energy at the bleed		kW	2050				
Coal necessary to replace the loss		t/h	1.19				
Cost of the additional fuel		In Rs/h	3564				
		In Rs/m^3	8.57				
In addition to that, the MED/TVC plant shall consume electricity for the auxiliary equipment as follows:							
Total Electricity consumption estimated		In Rs/h	1148	for	kW	230	
		In Rs/m^3	2.80	for	kW/m^3	0.56	
Comparison between the energy cost of RO and MED/TVC							
		RO	MED/TVC				
Total cost of Energy per m^3	In Rs/m^3	23.50	11.37				
Total cost of energy for 10 MLD	In Rs/h	9800	4712				
Difference in 1 year	Crores	4.07					

Table 2 Example B: Typical supercritical power generation plant

Example B	**Typical Super critical Power Generation Plant**						
Rated Power Generation	MW	660					
Efficiency	%	42					
Fuel		Coal	Feed	t/h	212		
Gross calorific value	kCal/kg	6200	equal to	kJ/kg	26000		
SH Steam Generated	t/h	1920	at Press	barg	252	at Temp	°C
SH Steam Reheated	t/h	1580	at Press	barg	58	at Temp	°C
Specific Power Generation	kW/kg (Fuel)	3.11	kW/kg (Steam)		344		
Cost of Fuel	In Rs/kg	5					
Price of electricity	In Rs/kWh	5					
Percentage of cost of fuel in the total price of electricity					32%		
Case of Installation of SWRO plant rated 10MLD with per-treatment and 2 passes							
Estimated Power consumption	For per-treatment.	kWh/m^3	1.2				
	for 1^ pass	kWh/m^3	2.5				
	for 2^ pass	kWh/m^3	1				
	TOTAL	kWh/m^3	4.7				
Total electricity consumption		kW	1960				
Total Energy cost		In Rs/h	9800				
		In Rs/m^3	23.50				
Case of Installation of MED/TVC plant rated 10 MLD with GOR 10							
LP Bleed		t/h	41.7	at bar	4.5	Enthalpy	kJ/kg
Condensation Enthalpy at		°C	45			Enthalpy	kJ/kg
Theoretical loss of energy at the bleed		kW	2050				
Coal necessary to replace the loss		t/h	0.66				
Cost of the additional fuel		In Rs/h	3293				
		In Rs/m^3	7.92				
In addition to that, the MED/TVC plant shall consume electricity for the auxiliary equipment as follows:							
Total Electricity consumption estimated		In Rs/h	1148	for	kW	230	
		In Rs/m^3	2.80	for	kW/m^3	0.56	
Comparison between the energy cost of RO and MED/TVC							
		RO	MED/TVC	Difference			
Total cost of Energy per m^3	In Rs/m^3	23.50	10.72	12.78			
Total cost of energy for 10 MLD	In Rs/h	9800	4441	5359			
Difference in 1 year	Crores			4.29			

In those plants where coal with higher calorific value is burnt (example 6000 kcal/kg) and eventually the cycle efficiency is higher (example 42%) like in the super-critical condition of steam generation, the fuel equivalence of the steam bleed is even lower, and it can be calculated as follows (data taken from a real case of European super-critical cycle):

- 211.5 t/h coal boils 1900 t/h steam, and the turbine generate 660 MW
- the bleed at 5 bar reduces the power generation by less than 28%
- 1 kg steam bleeding is to be replaced by 0.28 kg steam at the boiler, that requires 0.031 kg of additional coal
- the production of 1 t/h desalinated water requires for 3.1 kg/h of additional coal if produced by MED/TVC
- the cost of 3.1 kg of coal is to be compared with the price of 4.5 kWh, as consumed by a modern RO (average two passes, including pre-treatment) to produce the same amount of desalinated water.

The cost of the coal shall be higher in this case according to the high calorific value, but the relevant consumption is reduced remarkably and the economic convenience of MED/TVC over RO is well proven and even exceeds the convenience calculated in a traditional sub-critical power plant.

The convenience of MED/TVC over RO is large enough in many cases that even any remarkable reduction in the RO energy consumption shall not revert the convenience.

All the above comparison is made between RO and MED/TVC, that is usually preferred among the other evaporative desalination plants, owing to its smaller dimension and lower investment cost than MSF. Other evaporative processes are anyway available and the MED desalination plant (without thermo compressor) can be fed with LLP steam at approximately 0.35–0.4 bar. In this case GOR less than 10 is to be considered and actually GOR 7 can be considered an excellent achievement with nine installed effects. In this case the convenience of evaporation in terms of energy content is reduced dramatically, being the steam bleeding enthalpy (at saturated condition) approximately 2630 kJ/kg. This condition reduces the additional demand of coal by approximately 80%, down to 20% of the calculated amount for MED/TVC.

In spite of its higher investment cost, the convenience of MED versus MED/TVC is huge and eventually huge is its convenience versus RO too, in terms of energy consumption. Also in the case of MED, the detailed calculation of the coal equivalence is to be made cases by case and the plant efficiency optimised accordingly.

4 Operation

The operator of any power plant is well trained and familiar with the regulation of the fuel flow to the burners.

The usual practice is to feed fuels of different gross calorific values, even in the range of ±25%. Therefore, the flow of fuel is regulated in that range as necessary to ensure the requested electricity at the generator output, whatever is the gross calorific value. In the case of LP bleeding, the fuel flow shall be automatically increased by a rate that is much smaller, and the electricity output kept at the rated value accordingly.

The bleed of any reasonable amount of steam therefore shall not disturb the electrical production and shall not require any special operation procedure in that respect. Both the steam production (in the boiler) and the turbine inlet flow, enjoy a sufficient degree of flexibility and ensure the regulation requested by the generator within any reasonable quantity of LP bleed to be compensated.

5 Final observations

The production of only electricity in a power plant and the following consumption of part of it for running RO desalination plant have no effect of cogeneration in the overall economics of the total production of electricity and water.

The bleed of steam and its feeding to the evaporative desalination plant ensures full cogeneration effect for the portion of steam that had produced electricity before the bleed and then produces water after the bleed.

It is commonly understood that cogeneration is an energy advantage for any power plant.

In the old energy evaluation criteria, the cogeneration effect was just forgotten or neglected by considering the bleed as a loss of production. The energy cost of desalinated water by evaporation was evaluated as if the steam was just produced by an auxiliary boiler working at the bleed pressure, without any expansion in the turbine and debiting the full enthalpy of that steam to the bled steam cost.

In the newly proposed evaluation criteria of fuel equivalence, the cogeneration effect is duly considered and its assessed convenience made explicit in economical terms. Cogeneration in fact means the production of both energy and heat, whilst the old calculation criteria was considering the take of heat like a loss of energy, as if the production had to be either energy or heat.

It is easy to understand that the reduced amount of fuel demand for the additional generation of steam is much smaller (about one third) than the loss of enthalpy in the bleed. This is actually the cogeneration advantage.

From another point of view, it can be appreciated that the cost of the fuel is only a portion of the total cost of the electricity, being the other portions consisting in a number of items like the amortisation of the investment, the personnel and the running costs, the spare parts and the maintenance. Actually only the fuel cost is to be debited to the additional amount of generated steam, being the other costs paid by the sale of the electricity, without any reduction in the total quantity. Therefore, the value of that steam is to be correctly referred to the only cost of the fuel and not to the full cost of any (unmissed) production of electricity.

6 Practical calculation method

The calculation of the cost of the steam bleed can be easily calculated in each case of power plant as described in following paragraphs.

Firstly, the efficiency of the cycle is to be assessed. The number of kWh generated is a percentage (efficiency) of the enthalpy provided with the fuel. Hence the key data can be calculated as ‘kWh/kg fuel’. Then, the amount of theoretical energy loss at the bleed is to be calculated as difference of enthalpy between the steam at the bleeding condition and the steam at the condensation condition. This theoretical energy loss can be calculated as number of kWh to be replaced by burning additional fuel.

The amount of additional fuel necessary to replace the theoretical loss of energy can be calculated on the basis of the ‘kWh/kg fuel’.

The cost of the additional fuel calculated can be determined upon the unit cost of the fuel actually burnt in the power plant. This is the cost of the energy taken at the bleed.

Normally in India the efficiency of a power plant coal fired is in the range between 36% and 42% and the amount of ‘kWh/kg fuel’ is in the range of 1.5–3.

Hence, the cost of replacing each kWh of theoretical loss at the bleed is approximately 30–35% of the cost of each kWh produced for sale. The energetic cost of many MED/TVC plant is lower than the equivalent RO for whichever efficiency of the thermal desalination plant not lower than GOR = 5 or eventually higher as necessary. Because the usual MED/TVC desalination plants are designed with GOR in the range of 6 to 10, the economical convenience of MED/TVC becomes quite remarkable in most cases.

In other words, it is always possible to calculate the GOR of the evaporative desalination plant necessary to even the cost of the additional fuel to the price of the electricity consumed by the equivalent RO.