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Performance of RO plant with solar preheated feed water

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ABSTRACT

An RO plant with capacity of 10 m^3/d was implemented and a solar preheated feed water system was fitted to the RO. Both devices were mathematically analyzed. The performance of the RO plant with the change of feed water temperature was analyzed and as a result an increase in the permeate for about a 40% for increasing in the feed water temperature of 15°C. Also the different applied pressures and different feed water temperatures was analyzed along with effect of feed water temperature on the permeate TDS. Cost analysis of the system was carried out as well in order to show the coupled solar system could save up to 10% on the current cost.

Keywords: Reverse Osmosis, Solar heater, Solar collector, Solar intensity, Recovery, TCF

1. Introduction

The performance of RO reverse osmosis system is affected by many factors such as the feed water composition, feed temperature, feed pressure, and permeate recovery ratio. Membrane compaction and fouling also affect membrane performance. Also the efficiency of pumps and energy recovery systems would affect the membrane performance.

The ratio of the amount of permeate produced by the RO relative to the amount of feed going to the RO is called the recovery ratio (RR). RR is extremely important in regard to RO performance. High recovery ratio saves on the cost of product water preparation prior to the osmosis process, and low recovery ratio saves on the energy cost of desalination. The optimal recovery ratio depends on the relative costs of these operations and may vary under different conditions.

The effect of operating conditions on the performance of membrane elements is studied by many researchers. El-Saie et al. [1] explained the experimental RO facility designed for Nuclear Power Plants Authority in Egypt to study the effect of the following parameters on the permeate quality, production, membrane life and aging and system's economy; feed water temperature; feed water pressure and recovery ratio.

Abou Rayan and Khaled [2] presented a case study of the operation and maintenance of 2000 m^3/d RO desalination plant over 6 y of operation. They concluded that the reverse osmosis system is sensible to change in feed water temperature, and the product quality is sensitive to the working pressure.

Goosen et al. [3] evaluated the influence of feed temperature; salinity and flow rate on permeate flow rate and salinity in spiral-wound seawater membrane elements. Their results show that the polymer membrane is very sensitive to changes in the feed temperature. The permeate flux appears to go through a minimum at an intermediate temperature between 20 to 40°C. There was up to a 40% increase in the

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permeate flux when the feed temperature was increased from 20 to 40°C, while there was up to a 100% difference in the permeate flux between feed temperatures of 30 and 40°C.

Also, doubling of the feed flow rate increased the permeate flux by up to 10%, but only at a high solute concentration.

Villafafila and Mujtabab [4] studied numerically the RO desalination process and the sensitivity of different operating parameters (feed flow rate, feed pressure) and design parameters (internal diameter, total number of tubes) on the recovery ratio. Their results showed that the higher the pressure, the higher the recovery ratio is. This is due to the increase in the driving force (difference between feed pressure and osmotic pressure) with the feed pressure. Operating at high pressures for the feed stream also reports a better product quality (lower salt concentration of permeate). When the feed pressure increases, the water flux across the membrane is higher, but the salt flux (determined by the membrane permeability) remains constant.

RO plant was installed in an arid area to the south east of Damascus (the place is called Deir-Alhajer). The brackish water in this area is not potable the water has Total Dissolved Solids (TDS) exceed 800 ppm, water chemical analysis is shown in Table 1. In order to provide pure water to the local center for general purpose services such as nuclear research reactor pool cooling (MNSR), radiation plant, in addition to drinking water the plant was installed.

The site of the plant is situated in an area that has about thirty cloudy days per year, therefore, the coupling of solar collector as feed water preheater to the RO is considered efficient.

Description of the RO plant and the solar collector heating system are illustrated and explained in detail.

The work done in this study showed how efficient is the coupling. Many different temperatures of feed water were passed through in order to show the behavior and performance of the RO plant. Also the quality of the water produced was analyzed against change of feed water temperature, and the same procedure was carried out for the feed water pressure against the feed water temperature.

2. Description of the solar RO plant

As shown in Figs. 1 and 2, an RO plant of size 10 m^3/d permeate flow was fitted together along with pretreatment complex. In addition, the complete RO plant details include high pressure pumps with working pressure of 16 bar and maximum pressure 22 bar, two membranes of type Filmtech BW30–4040 fitted in two high pressure stainless steel vessels [5], two conductivity (one for feed water and the other for the permeate), pressure and temperature meters for the feed water, connections and three flow meters for feed, permeate and concentrate water, in addition a pre-treatment system consist of softener (Ion exchanger), sand filter and

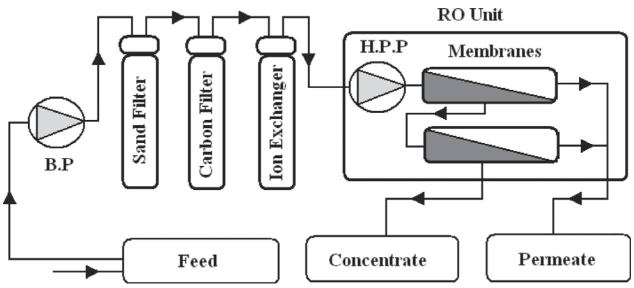

Fig. 1. Diagram of RO plant.

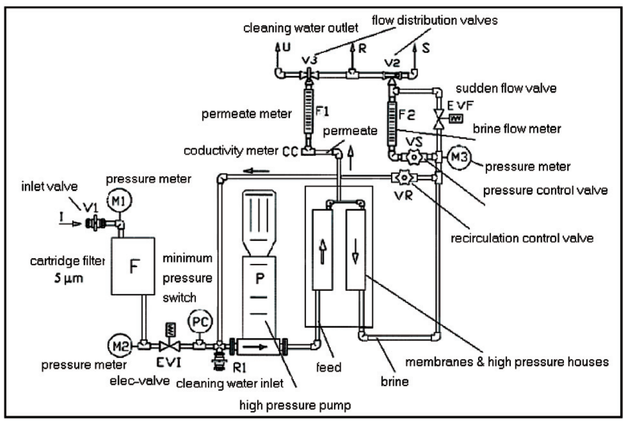

Fig. 2. Detailed diagram for the RO module.

Table 1
Deir Al – Hajar underground water chemical analysis

Ion ppm	HCO_3^- ppm	Cl^- ppm	SO_4^{-2} ppm	Ca^{+2} ppm	K^+ ppm	Na^+ ppm	Mg^{+2} ppm	Sr^{+2} ppm	PH	Fe	SiO_2	TDS ppm
	258	113	202	93	2	29	44	0.5	8.34	No trace	1.5 <3NTU	850

activated carbon filter as shown in Fig. 1. Table 2 shows the explored feed water conditions which suit the plant.

The solar heater coupled to the RO plant to heat up the feed water as shown in Fig. 3 was designed upon the required heat to heat up the feed water to the suggested working temperature, using the methodology in the later chapter. It was assumed that the mass flux of water to be heated is M = 1 m^3/d, the maximum temperature differences Δt is 20°C and the average water heat capacity C_p = 4.18 [kJ/kg.C°]. Applying the data in Eq. (6) to obtain the required thermal power for heating up the feed water (m = 1 m^3/d = 0.0277 kg/sec) taking into consideration the average sunny hours per day is 10 hours resulting in Q = 2322.22 [W]. The heat collector area was calculated using Eq. (5), as the collector efficiency is η = 50% (the collectors are connected in series and recently we had frost which made the glass broken and this resulted in drop of η), to obtain the heat collector area A = 6.67 m^2. Hence using the local manufactured default area size of the collector (2.10 × 1.30 m) 2.73 m^2, the number of solar heat collectors needed to heat the feed water to the required temperature were 3 collectors as shown in Fig. 3.

Table 2
The allowed feed water conditions

Turbidity	Less than 3 NTU
TDS	Less than 5000 ppm
Feed water temperature	10–40 C°
Feed water pressure	1–6 bar
Bacteria	Not allowed
Chlorine Cl_2	Less than 0.1 ppm
Fe Ferric	Less than 0.1 ppm
Si Silica as SiO_2	Less than 3 NTU
The feed electricity	50/3/400 – V/ph/Hz
Working high pressure	16 bar
Maximum high pressure allowed	22 bar
RO plant capacity at t = 15 C°	500 l/h

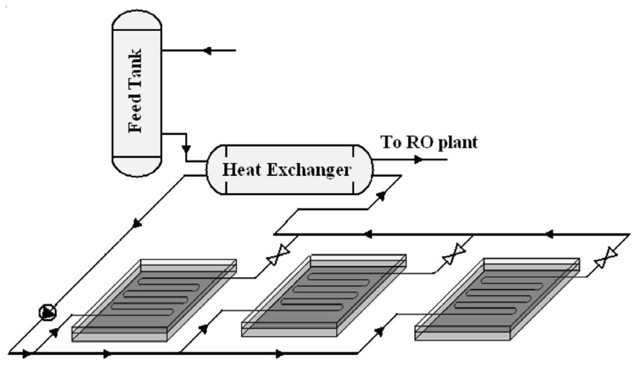

Fig. 3. Solar collector heating system setup.

3. Methodology

- RO

Osmosis is a natural phenomena described as a direct transfer of liquid from low concentrated solution to a higher concentrated solution through a semi-permeable membrane Partitioning the two solutions. The driving force of the RO plant is called osmotic pressure which is directly related to the salt concentration in the feed water as well as its temperatures and other notable parameters. The osmotic pressure can be defined by the following equation [6,7]:

$$P = 8.314 \times T \times \sum C \tag{1}$$

where P is the osmotic pressure kPa, T is the solution temperature (K), and $\sum C$ the solution salt concentrations (total dissolved solids) kmol/m^3.

As it is well known that RO plant has three main streams the feed water which is the input of the RO plant and the output of the plant are the permeate water and concentrate water. The changes in quantity, quality and the physical property of the feed water would effect on the other two output streams. In this setup we analyzed the effect of feed water temperature on the quantity of the other output streams (permeate and concentrate) [8].

The RO process enables us to remove approximately 99% of the dissolved solids and other contaminations, depending on the quality of both: feed water and membrane, and feed water temperature. The main parameter in the RO plant is recovery (or the Performance ratio) which can be defined as:

$$\text{Pr} = \text{permeate flow/feed flow} \tag{2}$$

- Experimental formula

The following formula was developed by Dow Liquid Separations FILMTEC [9] as an experimental fitting for the permeate flow against the feed water temperature:

$$Mf = N_E.S_E.\overline{A}.\overline{\pi}.(TCF).(FF).\left(P_f - \frac{\overline{\Delta P_{fc}}}{2} - P_p - \pi_f.\left[\frac{\overline{C_{fc}}}{C_f}.p_f - \left(1-\overline{R}\right)\right]\right) \tag{3}$$

where N_E the number of elements in system, S_E the membrane surface area per element $\left(ft^2\right)$, $\overline{A}$ the average membrane permeability at 25(°C), $\overline{\pi}$ the average concentrate-side osmotic pressure for system(*psi*), *TCF* the temperature correction factor for membrane permeability, *FF* the membrane fouling factor, P_f the feed pressure, the concentrate–side pressure drop (*psi*), P_f the permeate pressure (*psi*), π_f the feed osmotic pressure (*psi*), $\overline{C_{fc}}$ the average concentrate-side concentration for system(*ppm*), C_f the feed concentration (*ppm*), and p_f the concentration polarization factor, and $\overline{R}$ the average fractional salt rejection for the system. These parameters are either given from the RO plant specifications and operating assumptions or have been calculated such as TCF (the temperature correction factor for membrane permeability) can be calculated using experimental Eqs. (4).

$$TCF = EXP\left[3480 \times \left\{\frac{1}{298} - \frac{1}{273 + t}\right\}\right] \text{for } t \le 25\ °C$$
$$TCF = EXP\left[2640 \times \left\{\frac{1}{298} - \frac{1}{273 + t}\right\}\right] \text{for } t \ge 25\ °C \quad (4)$$

All these parameters for this RO plant are given in Table 3.

- Solar collector

Coupling RO plant with a feed water heating system increases the desalted water flow rate. The area where the RO plant is situated is very convenient for using a solar collector as the heating system. The solar heating system consists of solar collector, heat exchanger, water tank and circulation pumps.
The active area of the solar collector is considered as the main factor and can be calculated as follow [10,11]:

$$A = \frac{Q}{\eta \times G} \quad (5)$$

where η is the collector efficiency, and Q is the required thermal power to heat up the feed water. It is given in the following equation: [11]

$$Q = \dot{M} \cdot C \cdot \Delta T \quad (6)$$

where $\dot{M}$ is mass flow rate of the water [kg/s], C heat capacity of the water and, ΔT is the water temperature difference, G the solar intensity received by a horizontal surface and it is in general defined by the sum of the direct, diffused solar radiation and the solar radiation reflected from the ground [12,13].

$$G = G_{b,t} + G_{d,t} + G_{gr,t} \quad (7)$$

where $G_{b,t}$ is the direct solar intensity on the slope surface and it is given in Eq. (8), below [14,15]

$$G_{b,t} = r_b \cdot G_b \quad (8)$$

where r_b is a constant related to the angle of the falling solar radiation on the surface, and G_b is the vertical solar intensity on horizontal surface. Furthermore Gd,t in Eq. (7) is the diffusion solar intensity on the slope surface and it is given in the Eq. (9) [16,17]:

$$G_{d,t} = G_d \cdot \cos^2\left(\frac{S}{2}\right) \quad (9)$$

where S is the angle of the surface slope and G_d is the vertical diffusion solar intensity on horizontal surface.

$G_{gr,t}$ is the solar radiation reflected from the ground and it is calculated as follows [16,17].

$$G_{gr.t} = \rho_{gr} \cdot G \cdot \sin^2\left(\frac{S}{2}\right) \quad (10)$$

where ρ_{gr} is a ground reflection constant.

For this case, taking in account the average length of the day in February is 10 h and the solar radiation intensity is $G = 694.54 \quad [W/m^2]$, the calculations are performed as follow:

The thermal energy required for heating feed flowrate:

$$Q = M \cdot C_P \cdot \Delta t$$
$$= 1000 \times 4.18 \times 20 = 83600\,[kJ/\text{d}]$$
$$= \frac{83600}{10 \times 3600} = 2322.22[W]$$

where temperature difference $\Delta t[°C]$, $C_P[kJ/kg \cdot °C]$ heat capacity, $M[kg/\text{sec}]$ feed flow rate.

The Required solar collectors surface :

$$A = \frac{Q}{\eta \cdot G} = \frac{2322.22}{0.5 \times 694.54} = 6.67 \quad \left[m^2\right]$$

The number of collectors is:

$$N = \frac{A}{A1} = \frac{6.67}{2.73} = 2.44 \approx 3$$

where A1 is a single solar collector surface.

Table 3
Value of parameters which in permeate flow equation

N_E	2	TCF	0.96	P_P	0	P_f	1.23
S_E	78	FF	0.85	π_f	0.47	$\overline{R}$	0.995
$\overline{A}$	3	P_f	133.76	$\overline{C_{fc}}$	1767.51		
$\overline{\pi}$	13.46	$\overline{\Delta P_f}$	10	C_f	888.76		

4. Results and discussion

- Experimentally measured values of the desalinations parameters:

The feed water temperature varies from day to day throughout the year. It was assumed that the feed water temperature did not exceed the 34°C (for membrane safety). Therefore, the different feed water temperatures varied between 19 and 34°C, permeate flow rate was measured for these temperature as shown in Table 4. As a result the feed water temperature was chosen to be maintained at 30°C through heating the feed water using the solar collector and the heat exchanger and the mixer tank.

- Discussion

In this work, the effect of feed water temperature changes on the main parameters of the RO plant with capacity of 10 m^3/d was analyzed, and as a result the efficiency of the RO process with solar pre-heating is better than without pre-heating, which is shown in the following:

1. The permeate flow rate increases with the increase of feed water temperature, and the increase is 40% for the increase in feed water temperature of 15°C Fig. 4 shows this increase experimentally. This leads to the increase in the recovery of about 16% as shown in Fig. 5. [19,20,21]
2. It is shown experimentally that, within the increases of feed water temperature, the increase in feed flow rate pressure leads to decrease in feed flow rate, the reason is decreasing the permeate flow rate would lead to increase the concentrate flow rate between (19.5–20.25) bar and after that the concentrate becomes constant verses the feed water pressure changes. As shown in Fig. 6. [19].

Table 4
Comparing of recovery

Temperature (°C)	Measured value		Calculated value	
	Permeate flow (L/h)	Recovery	Permeate flow (L/h)	Recovery
19	725	0.64	661.2	0.588
20	750	0.65	684.8	0.595
21	780	0.66	709.1	0.601
22	800	0.66	734.1	0.612
23	840	0.67	759.8	0.613
24	860	0.68	786.2	0.624
25	890	0.68	813.4	0.631
26	940	0.7	871.7	0.651
27	980	0.71	897.6	0.655
28	1010	0.72	924.0	0.667
29	1040	0.74	951.1	0.679
30	1060	0.75	978.8	0.697
31	1090	0.76	1007.1	0.707
32	1110	0.77	1036.0	0.724
33	1140	0.78	1065.5	0.737
34	1170	0.79	1095.7	0.748

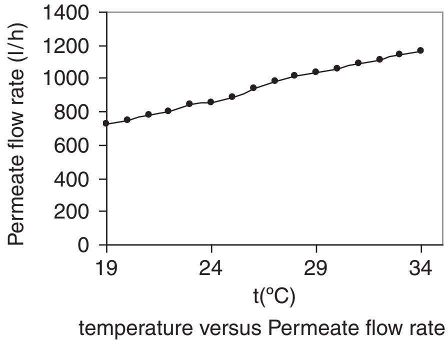

Fig. 4. Permeate flow rate versus Temperature.

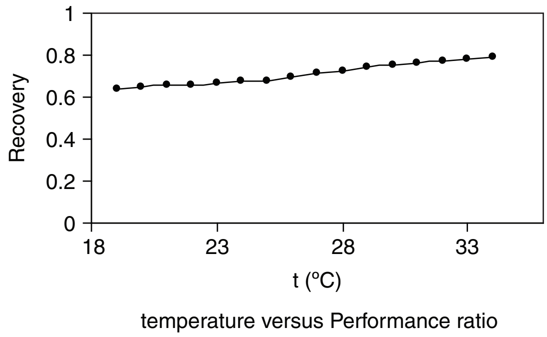

Fig. 5. Recovery versus temperature.

3. Comparing between the calculated and measured (Using Eq. (3) to calculate the permeate flow rate) permeate flow rate is made. The increase of 39% in the calculated permeate flow rate verses 15 temperature difference, but experimentally the increase in permeate flow rate is 40% verses 15 temperature difference as shown in Fig. 7 and Table 4.
4. Also comparison between calculated and measured recovery was made. The increase of 12% in the calculated recovery verses 15 temperature difference, while the increase of 15% in the measured recovery verses the same temperature difference as shown in Fig. 8 and Table 4.
5. Quality of permeate water was analyzed for the different feed water temperature as show in Fig. 9 it indicates that an increase in feed water temperature leads to increase in the permeate TDS [19].

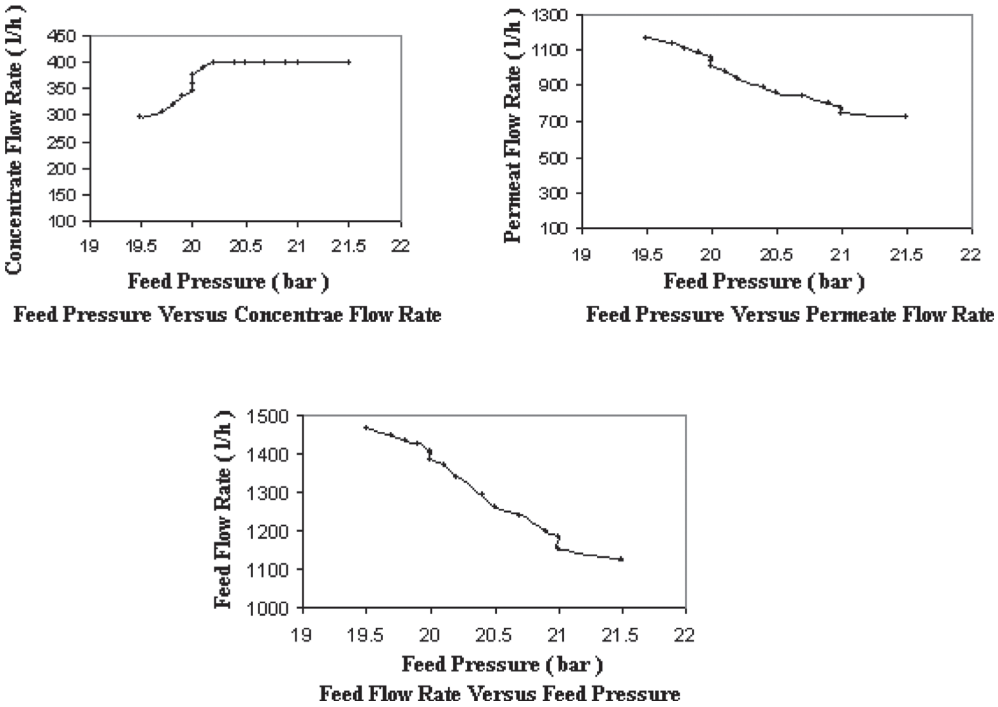

Fig. 6. Feed, permeate and concentrate flow rate versus feed pressure within the increase of feed water temperature.

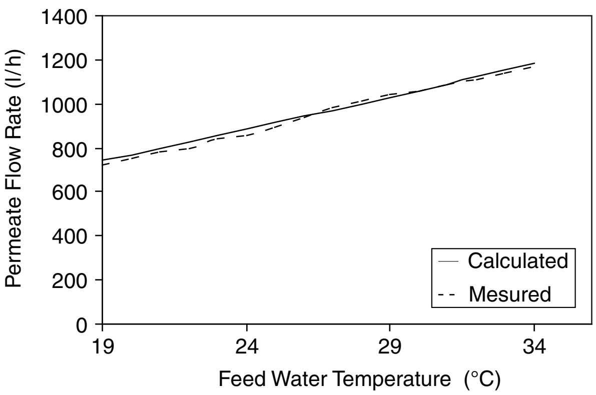

Fig. 7. Permeate flow rate versus temperature.

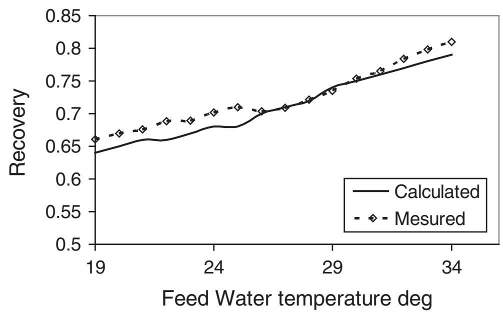

Fig. 8. Recovery versus the feed water temperature.

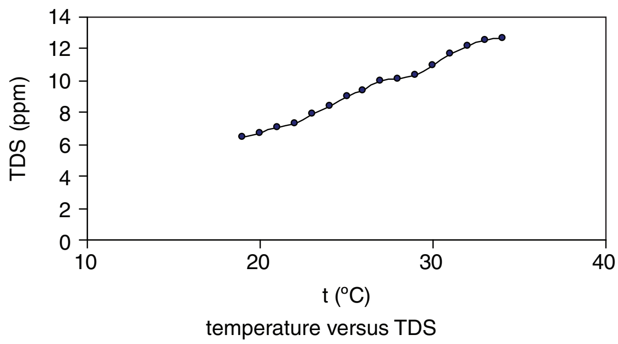

Fig. 9. Feed water temperature versus permeate TDS.

Fig. 7, 8 show how close the measured result and the calculated results of the recovery and permeate versus the feed water temperature. Which explain the efficiency of applying the feed water temperature increase.

5. Economic evaluation

The specific water cost is defined as an annuity of potable water expenditures divided on the annuity production of water [22].

Table 5
Specific water cost

	RO plant stand alone	RO plant with solar heating system
Annuity construction cost ($/year)	730	766.5
O&M + Chemical additive cost ($/year)	222.65	229.95
Power cost ($/year)	835.85	631.45
The annuity of potable water expenditures (C_0) ($/year)	1788.5	1627.9
The specific water cost ($/m^3)	0.49	0.44

The annuity of potable water expenditures (C_0) includes capital cost C_{ca}, operation, and maintenance $C_{O\&M}$ and power consumption cost C_P.

$$C_o = C_{ca} + C_{O\&M} + C_P \tag{11}$$

where C_{ca} is the annuity capital cost defined as:

$$C_{ca} = C_{TO} .a_n \text{ and } a_n = \frac{r.(r+1)^n}{(1+r)^n - 1} \tag{12}$$

where r is the discount rate and n is the lifetime of the plant. It was assumed that r = 7% and n = 30 y, Hence a_n= 0.11. C_{TO} is the total construction cost.

The specific water cost (SWC) can be determined by Eq. (13):

$$SWC= (C_0 \,/\, (V*365))* Z \tag{13}$$

where V the plant capacity (m^3/d) and Z the plant outrage factor (about 3%). Cost calculations were preformed using Local prices for items and labor, foreign supplier prices and the cost methodology mentioned above to calculate the specific water cost as shown in Table 5.

6. Conclusion

In this paper we have shown that an increase in feed water temperature leads to an increase in the recovery. And in turn, this reduces the cost of water production by at least 10% through energy saving. The work was elementary and it had many other details. Future work to be confirmed due to the effect of feed water temperature on all other parameters, the relation of these parameters among themselves and the set up of the best water temperatures for the plant to work. In addition, enlarging the solar collector size might be quite useful in order to permit the plant to be heated all day long, by adding heating storage system to the solar collector. This would allow feed water to be maintained heated during the night time as well.

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