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Integrated Membrane – Based Desalination System

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Abstract

A comparative study of an integrated hybrid membrane – based system with an earlier locally designed RO unit, such system comprises of Nanofiltration (NF), Reverse osmosis (RO) and Membrane Distillation (MD) subsystems. The comparison is essentially based on using the NF technique in pretreatment section, while the MD was contributed to concentrate the two brine streams from both NF and RO. The proposed system was economically evaluated and compared with the RO unit.

Key words: Desalination, RO, NF, MD, membrane separation, costing.

Introduction

Water shortages affects 88 developing countries that are comprise to half of the world's population. Low cost methods of purifying freshwater and desalting seawater are required to contend with this destabilizing trend [1].

At 2001, the world population was 6.2 billion, the need for water is rapidly increasing, and current freshwater resources will not be able to meet all requirements. Water cannot be considered now as a natural, self-renewable, low-cost resource, easily accessible to all. Many years of drought at various locations, followed by desertification and movement of the population towards this essential resource calls for different considerations in terms of economic and social effects [2].

Desalination of sea (or saline) water has been practiced regularly for over 50 years and is a well-established means of water supply in many countries. It is now feasible, technically and economically, to produce large quantities of water of excellent quality from desalination processes. Challenges, however, still exist to produce desalinated water for relatively large communities, for their continuous growth, development, and health, and for modern efficient agriculture, at affordable costs.

Two main directions survived the crucial evolution of desalination technology, namely evaporation and membrane techniques. Membrane techniques penetrate deep in water treatment technology wherever possible. Many countries are now considering desalination as an important source of water supply.

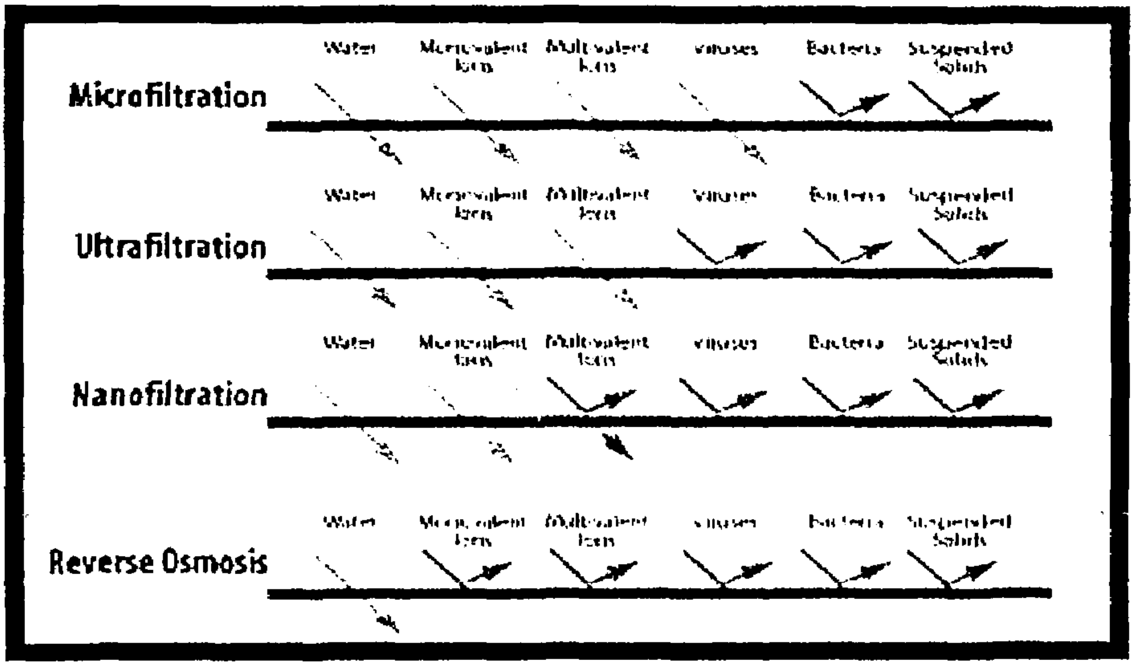
This article dealt with the study of a hypothetical hybrid system, composed of Nanofiltration as pretreatment step, Reverse osmosis and Membrane Distillation as a technique for water desalination.

Theoretical Aspects

Currently, about 80% of the world's desalination capacity is provided by two technologies: Multi-Stage Flash (MSF), and reverse osmosis (RO). MSF units are widely used in Middle East and they account for over 40% of the world's desalination capacity. MSF is a desalination (thermal) process that involves evaporation and condensation of water. A key design feature of MSF systems is bulk liquid boiling. The alleviate problems are scale formation on heat transfer tubes.

RO is a non thermal membrane separation process that recovers water from a pressurized saline solution. In essence, the membrane filters out the salt ions from the pressurized solution, allowing only the water to pass. A typical recovery value for a seawater RO system is 40%. Large scale RO systems are now equipped with devices to recover the mechanical compression energy from the discharged concentrated brine stream. The pretreatment of the feed water is an important consideration and can a significant impact on the cost of RO, especially since all the feed water, even the 60% that will eventually be discharged, must be pretreated before being passed to the membrane.

There is an increasing demand for membrane Nanofiltration (NF) processes on a world-wide basis. Important applications occur in the drinking water treatment and in environmental protection.



Membrane Process Characteristics

Figure (1): The Permeation through a membrane in different membrane processes

It obvious from Figure (1), the permeate of MF is mainly; water and dissolved salts, and perhaps some microorganisms, the permeate of UF is mainly the water and all dissolved salts, while the microorganisms are completely rejected, at NF further rejection of polyvalent ions will happen, the RO comes on the top, it rejects all microorganisms and all dissolved salts.

Membrane distillation (MD) is an emerging alternate technology for separations that are traditionally accomplished via conventional distillation or reverse osmosis. Specifically, membrane distillation refers to membrane separation processes with the following characteristics: 1- the membrane is porous, 2- the membrane is not wetted by the process liquids, 3- no capillary condensation takes place in the pores of the membrane, 4- the membrane does not alter the vapor-liquid equilibrium of the components of the process liquids, 5- at least one side of the membrane is in contact with the process liquid, 6- the driving force of membrane operation is a partial pressure gradient in the liquid phase . Pervaporation is a related technology that may employ wetted membranes.

MD has a number of potential advantages over conventional desalination processes such as evaporation and reverse osmosis. These include: 1- Low operating temperature, 2- low operating pressure, 3- reduced membrane mechanical strength requirements, 4- less vapor space requirements, and 5- potential 100% separation of solutes and non-volatiles.

As applied to desalination then, MD involves the transport of water from a liquid saline stream through the pores of a hydrophobic membrane. Since the hydrophobic membrane is wetted, water vapor passes through the membrane pores but aqueous solution is prevented from passing through the pores. Water vapor transfers across the hydrophobic membrane and are condensed or removed as a vapor from the permeate side of the membrane module. Since the liquid does not transport across hydrophobic membrane, dissolved ions are completely rejected by membrane. A variety of methods have been employed to impose a vapor pressure difference across the membranes for MD. As shown in Figure. (2), the four methods are:

- Direct contact MD, this configuration is the simplest mode of MD. In this arrangement vapor from a feed stream transverses the membrane and condenses directly into a solution flowing on the permeate side of the membrane.
- Air gap MD, in this case, an air gap separates the hydrophobic membrane from a cool condensing surface; this is one of the most versatile methods.
- Sweeping gas MD, a flowing gas is used to sweep the vapor out of the membrane permeates side, thereby maintaining the gradient necessary for transport. This is particularly useful for removing volatile components or dissolved gases from liquid streams.
- Vacuum MD, a vacuum is maintained on the permeate side to facility vapor transport across the membrane. Also useful for removing volatile components degassing liquids (2).

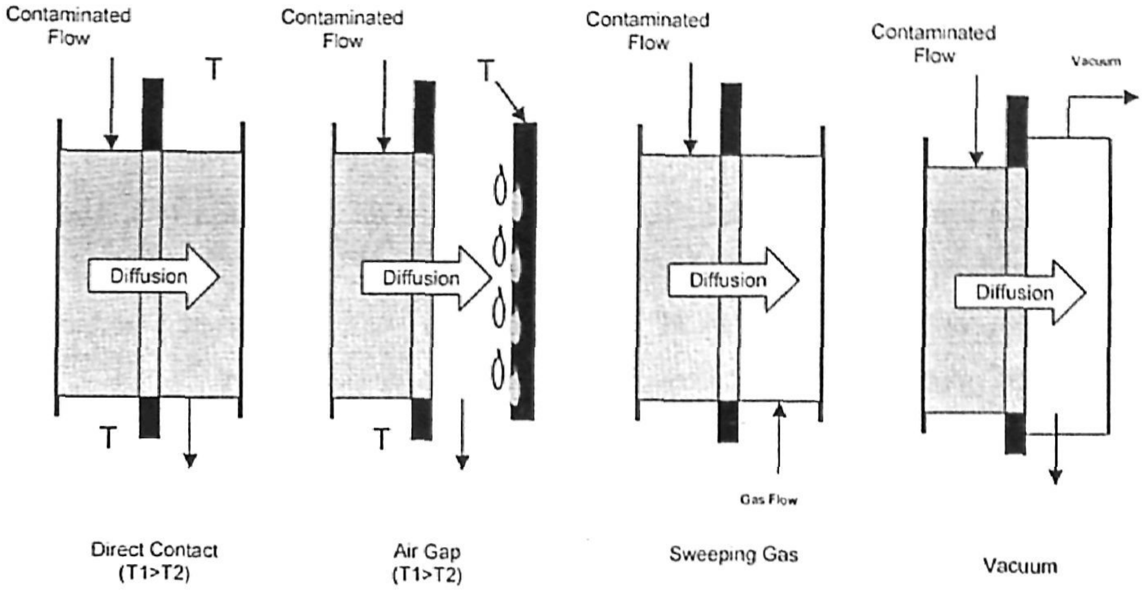


Figure (2): The different mode of MD

The general features of MD Unit:

- Simple with no replaceable parts, enabling the system to be maintenance free.
- Can be used with fluctuating heat source of relatively low temperatures (30 to 100° C), therefore, water is possible using unused energies (waste heat or solar energy).
- The highly salty water generated by desalination can be used in thalassotherapie (sea treatment) and salt production, industrial use, etc.
- It is possible to keep running costs low.

Principle of Nanofiltration and Vacuum membrane distillation

1. Nanofiltration:

In all hybrid systems, NF as a water pretreatment method is applied and a considerable decrease in scale forming components is achieved. Higher recovery may be then reached when desalting in comparison to traditionally treated water. Very compact NF membranes are applied which results in a very high rejection of divalent ions and relatively high rejection of sodium chloride. A simultaneous decrease in NaCl concentration in NF process is then obtained which enables to increase the RO recovery since the osmotic pressure value of NF permeate is diminished. The recovery and rejection coefficient of NF is affected by the applied pressure, results obtained at a pressure of 22 bar showed that the NF unit removed hardness ions of Ca^{++}, Mg^{++}, $SO4^{--}$, $HCO3^{-}$, and total hardness by 89.6%, 94%, 97.8%, 76.6% and 93.3%, respectively. The system also resulted in the reduction of the monovalent ions of Cl^{-}, Na^{+}, K^{+} each by 40.3% and the overall seawater TDS by 57.7%. This made it possible to operate both the SWRO and MSF pilot plants at water recovery: 70% and 80%, respectively.

The concentrations of different ions in NF permeate [3], may be calculated using the equation (1):

$$Cp = C_f \{1 - [1 - (V_p / V_f)]^{1-R}\} / (V_p / V_f) \quad (1)$$

The simple form to calculate the permeate concentration is:

$$R = 1 - C_p/C_f \quad (2)$$

2. *Vacuum membrane distillation*

Vacuum membrane distillation consists in applying a vacuum or a low pressure on the permeate side of a hydrophobic microporous membrane. When the feed is a water containing salts, the water will be vaporized close to the pores and will then pass as a vapor through the membrane pores. It will then be condensed outside the module. The driving force for the process is linked to both the partial pressure gradient and the thermal gradient between the two membrane sides. VMD can be characterized by the following steps: - vaporization of the more volatile compounds at the liquid/vapor interface and diffusion of the vapor through the membrane pores according to a Knudsen mechanism.
It should be pointed out that the membrane does not affect the separation selectivity, which is mainly dependent on the liquid/vapor equilibrium if the membrane has been correctly chosen [4].

Permeability (K_m) was calculated using the inner membrane area as a reference, whatever the module configuration is. It is obtained from the equation (3).

$$J = (K_m / \sqrt{M}) [p_{sat} (T_m) - p_p] \quad (3)$$

Parametric Study for the affecting variable in NF and MD

a- Nano Filtration (NF):

Theoretical study of the effect of feed pressure to NF module of specific rejection coefficient towards the different ions, the seawater characteristics used for this step is illustrated in Table 1.

Table (1) Water characteristics

Item	Mg/l	Item	Mg/l
Ca	562	HCO3	199
Mg	1592	SO4	3721
Na	15206	Cl	26734
K	534	TDS	48447

Tables 2, 3 and 4 depict the permeate concentration which are calculated by using equation (2) at different pressures, and according to the rejection of certain specific NF module [5].

Table (2) water characteristics at P_f= 18 bar and 50, 55 and 60 Recovery %

P_f=18			R=50%		R=55		R=60	
Rej.%	RW ions	C_f	C_p	C_c	C_p	C_c	Cp	C_c
80.7	Ca	562	108.5	1016	108.5	1116	108.5	1242
88	Mg	1592	191	2993	191	3304	191	3693
27	Na	15206	11100	19310	11100	18860	11100	21380
30	K	534	373.8	694	373.8	730	373.8	774
64	HCO3	199	71.6	326	71.6	355	71.6	390
94	SO4	3721	223	7219	223	7996	223	8988
27	Cl	26734	19520	33950	19520	35580	19520	37160
	Sum	48.548	31388	65508	31388	67941	31388	73627

Table (3) Water Characteristics at P_f= 22 bar and 50, 55 and 60 Recovery %

P_f=22			R=50%		R=55%		R=60%	
Rej.%	RW Ions	C_f	C_p	C_c	C_p	C_c	C_p	Cc
89.6	Ca	562	58.5	1066	58.5	1177	58.5	1317
94	Mg	1592	95.5	3088	95.5	3421	95.5	3837
46.3	Na	15206	8166	22250	8166	23810	8166	25770
48	K	534	277.7	790.3	277.7	747	277.7	919
76.6	HCO3	199	46.6	351.4	46.6	385	46.6	428
98.8	SO4	3721	44.7	7397	44.7	8214	44.7	9236
46.3	Cl	26734	14360	39110	14360	41860	14360	45300
	Sum	48.548	23049	74053	23049	76193	23049	86607

Table (4) Water Characteristics at P_f= 31 bar and 50, 55 and 60 Recovery %

P_f=31			R=50%		55%		60%	
Rej.%	RW ions	C_f	C_p	C_f	C_p	C_f	C_p	C_f
89.3	Ca	562	60	1048	60	1175	60	1315
90.8	Mg	1592	147	3038	147	3359	147	3760
57.7	Na	15206	6432	23980	6432	25930	6432	28370
60	K	534	214	854	214	926	214	1015
81.3	HCO3	199	37	361	37	397	37	442
92.8	SO4	3721	268	7174	268	7941	268	8901
57.7	Cl	26734	11310	42160	11310	45590	11310	49870
	Sum	48.548	18408	78615	18408	85255	18408	93670

Figure (3) depicts the change of permeate and concentrate TDS with changing the feed pressure at different recovery%, it is obvious that, the permeate concentration is not affected by changing the recovery%, and that may be attributed to the governing equation for permeate concentration, equation (2), which is not a function of recovery. On the other hand the concentrate TDS is decreased, that due to the decrease in volume concentrate, with increasing the recovery%, so the rejected stream concentration will be increased.

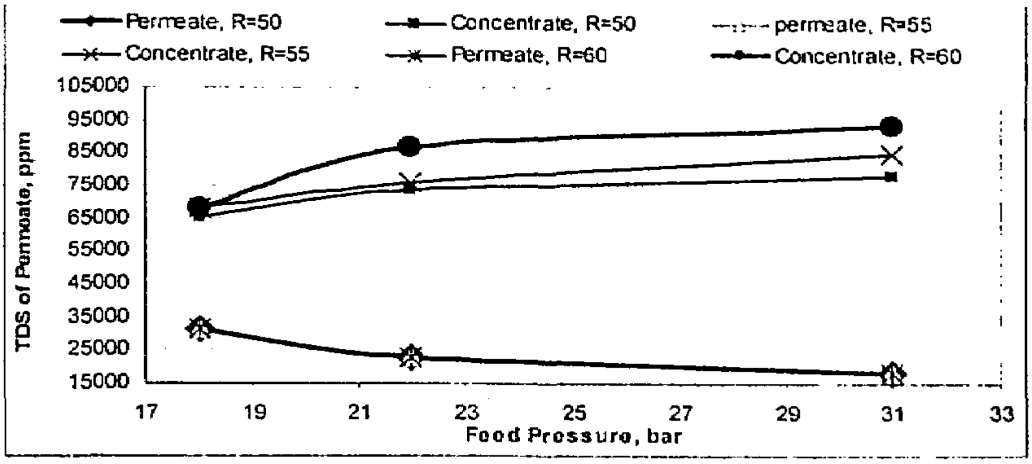


Figure (3): The effect of changing of feed pressure on permeate and concentrate TDS at different recovery%

b- Membrane Distillation (MD):

The influence of feed temperature and vacuum pressure on flux through a nonporous hydrophobic membrane, of permeability (Km) of 3.4 x E-07 s. $mol^{1/2}.m^{-1}.kg^{-1/2}$, were tested and calculated according to equation (3). The results are shown in Figures (4) and (5) which illustrate, that, the increase of feed temperature increasing the Tm, and consequently increase the P_{sat}, therefore, the driving force increased the flux through the membrane. Also, the increase of the vapor pressure P_p leads to minimize the driving force, so, the flux is decreased.

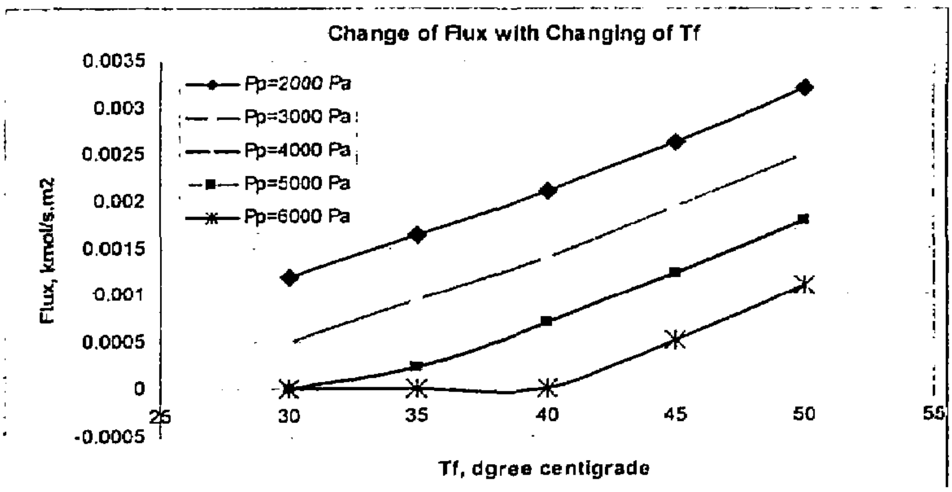


Figure (4): The effect of change of Permeate of MD module vs. feed temperature at different vacuum pressure.

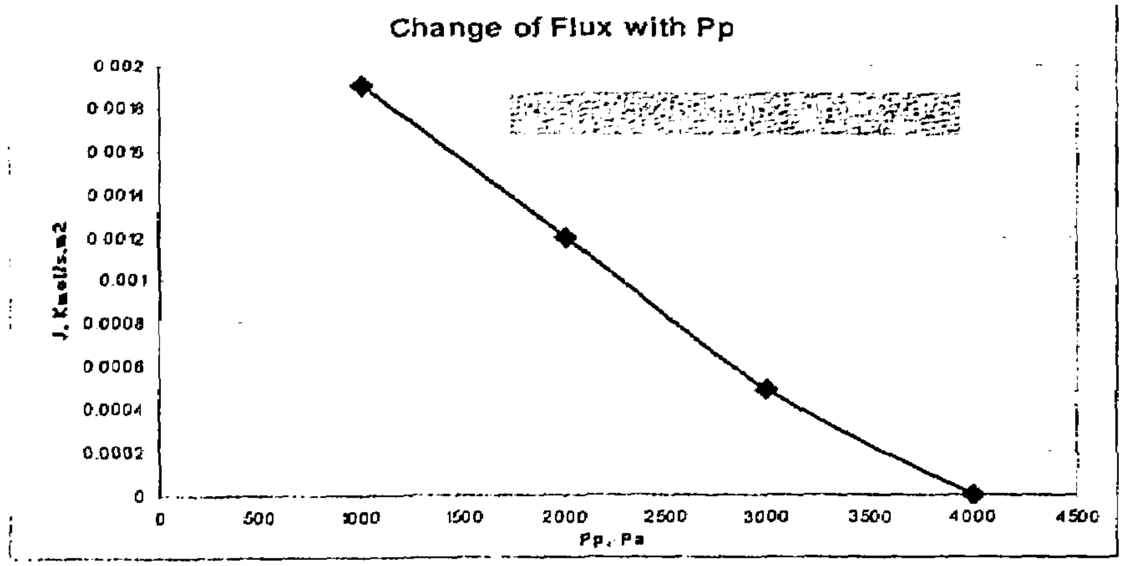


Figure (5): The effect of change of Permeate of MD module vs. vacuum pressure at P_{sat} = 0.42463 lb/in^2 and Tm 27 °C.

The Proposed System

Suggested system is presented in Figure (6). It consists of NF unit as pretreatment section for RO unit, the concentrates of the NF and RO units was estimated to be gathered with each other to compose a one feed stream to the MD unit, the permeate of RO and MD are then mixed and gave the gross product of the proposed system.

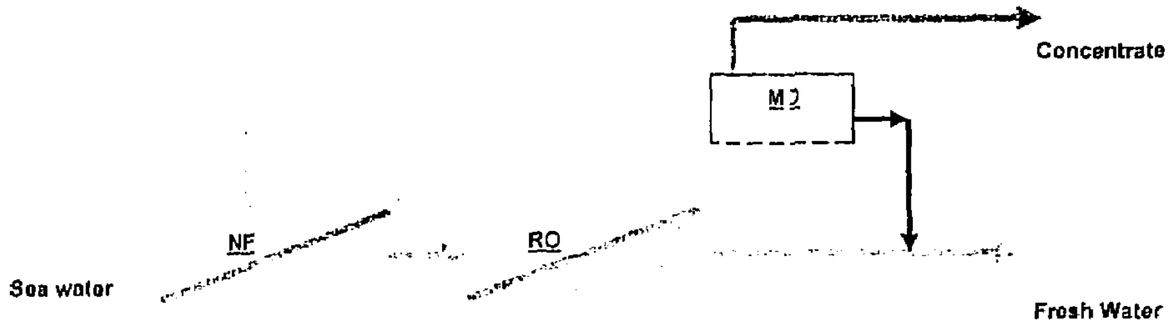


Figure (6): The schematic diagram of proposed hybrid system

It was assumed that the system was fed by 100 m^3/d sea water of analysis corresponds to Table (1). The performance of the NF unit was suggested to be as follows:

- Feed Rate : 100 m^3/d
- Feed pressure : 31 bar
- Recovery % : 70
- TDS : 48447

Permeate and concentrate streams were calculated according to the equation (2) and it gives the following streams characteristics:

Item	**Permeate**	**Concentrate**
Flow rate	70 m^3/d	30 m^3/d
Pressure	2 bar	29 bar
TDS	184078	118900

The permeate of NF was directed to the RO unit, which is considered as feed, by use of Software of Fluid System Company, a detailed design was executed at the following operating conditions:

- Recovery : 60%
- Permeate rate : 42 m^3/d
- Feed pressure : 34.2 bar
- Use 8 modules of TFCL 2822 elements

The product of the RO unit was as follows:

Item	**Permeate**	**Concentrate**
Flow rate	42 m^3/d	28 m^3/d
Pressure	2 bar	34.8 bar
TDS	562	45162

The mix of the two concentrates streams, which are coming from the NF and RO is used as feed of the MD unit, the characteristics of this stream is:

- Flow Rate : 58 m^3/d
- TDS : 83354
- T_f : 35 °C
- Tm : 32.5 °C

The suggested operating conditions of the MD unit:

- Tm : 32.5 °C
- Pp : 1000 Pa
- Permeate flow rate : 34.2 m^3/d
- Salt concentration from 83 g/l to 203 g/l

The flux was estimated using equation (3), considering P_{sat} at (Tm = 32,5 °C), was 5321 Pa. Hence; J = 3.4X10-7 (5321- 1000) / $\sqrt{18}$, and it will be equal to *0.52* $m^3/d.m^2$.

The needed mass and heat transfer area is supposed to be 46 m^2, to give distillate equal to ~ 34.2 m^3/d, the actual design area is taken ~60 m^2. The final reject of the MD unit has approximately 203,000 ppm or 200 g/l, which is within the allowable permissible limit of concentration, (15 – 300 g/l), to avoid the concentration polarization. Figure (7) illustrate all stream characteristics.

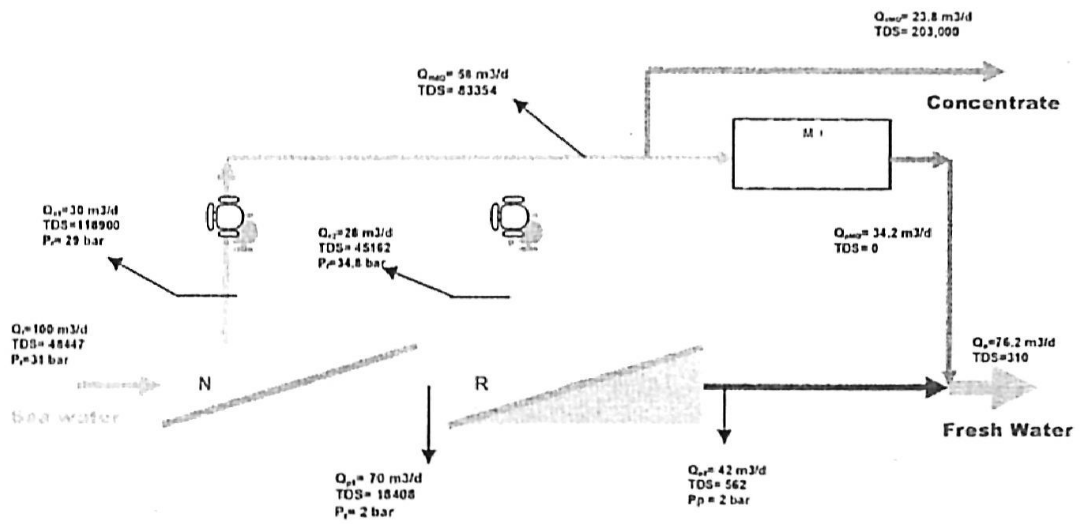


Figure (7) Schematic flow diagram of the proposed

Cost Estimation of Water Production from Conventional RO and NF-SWRO-MD Processes:

The cost of water production in $/m³ was calculated for the suggested system and compared with an earlier designed and manufactured unit at the National Research Centre, with the following operating conditions:

- Permeate : 100 m³/d
- Operating pressure : 1000 psi
- Recovery % : 30
- Permeate TDS : ~500
- 2 stages RO units
  - ➢ First Stage comprises 4 modules of B10 Twin, HFF of Dupont
  - ➢ Second Stage comprises 7 B9 brackish water, HFF of Dupont

Figure (8) depicts all conditions and stream characteristics. It is obvious that there is 230 m³/d, is eventually rejected even the cost spent for treatment. The production cost was $1.29 /m³/d (the world reported figure is ranged from $1-1.25/m³/d).

Table (4) illustrates the production cost referring to 76.2 m³/d fresh water.

Table (4): Production Cost/m³/d

Item	Cost/m³/d, $	Per m³/d end system permeate, $
SWRO	1.25 (1), 1.29 *	1.5
NF	0.3 (6)	0.28
BWRO	0.4	0.22
MD	1.0	0.45
Total		0.92

* The local cost

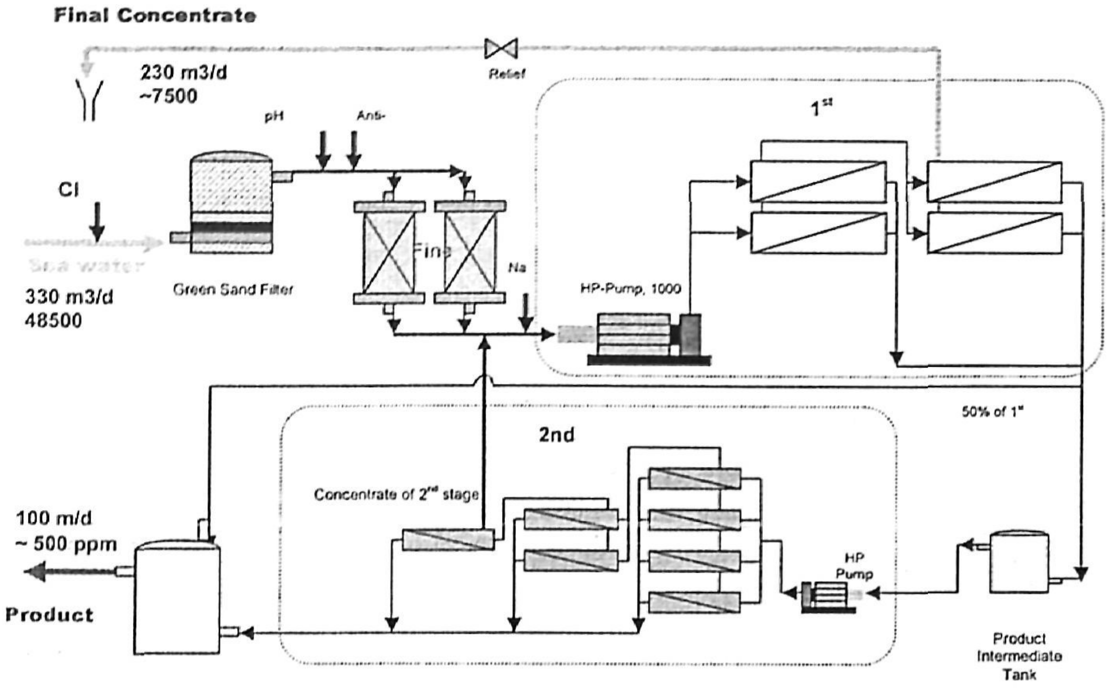


Figure (8) Schematic flow diagram of Local RO system

It is obvious that, the production cost of 1 m^3/d was improved and it less than the cost of RO only by approximately 25%, that is might be attributed to the increase in the total production rate, where the recovery is increased from 30 - 35% to 76.2%.

The obtained data will be verified in the next article.

The over all concentrate from the integrated system can be oriented to produce salts by concentration, or to use for thalassotherapie (Sea Treatment) [6].

Conclusion

From the data presented, it is obvious, that the integration of many membrane operations improve the performance of seawater desalination unit. Thus 76.2% water recovery is obtained. The water production cost is equal to \$ .92/m^3. The above data demonstrates that the water cost is competitive compared to those of potable water produced in SWRO system.

List of Symbols

C	Concentration	mg/l
V	Volume flow rate	m^3/d
R	Rejection coefficient	
J	Flux	$mol\ s^{-1}\ m^{-2}$
Km	Permeability	$s.mol^{1/2} m^{-1} kg^{-1/2}$
M	Molecular weight	
P_{sat}	Saturated vapor pressure at Tm (equation, 3)	Pa
P_v	Vapor pressure (equation, 3)	Pa
m	Mean temperature between in/out membrane side	°C
	Referred to permeate	
	Referred to Feed	

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