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Combined water and power plant (CWPP) — a novel desalination technology

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ABSTRACT

In recent years, an enormous increase of fuel cost and greater demand for fresh water have imposed tremendous challenges for researchers to pursue a drive towards more energy-efficient desalination technology. In the search for a more energy-efficient desalination process, the next generation plants will use a combination of membrane processes with multi-stage flash (MSF)/multi-effect distillation (MED) thermal processes to harness the maximum thermal energy that would otherwise be wasted from a power plant. The novelty of this proposed combined water and power plant (CWPP) concept lies in the usage of the power plant at rated conditions most of the time, where the power plant is most efficient, and when demand falls in one area (electricity), resources can be directed to another area (i.e. desalination). A detail thermoeconomic analysis of the proposed plant under different loads has been used to quantify the benefits of the CWPP. This study includes a combined cycle (CC) power plant with stand-alone MSF, MED and RO; and CC with MSF-RO hybrid or MED-RO hybrid. The CWPP exhibits thermal efficiency of around 63% compared to conventional 44%. The specific energy consumption can be reduced by about 17% with the proposed CC+MED+RO system compared to CC+MSF+RO plants. Moreover, water can be produced from a MED/RO hybrid power plant at about US\$1.09/m^3 whereas for MSF/RO, the cost increases to about US\$1.65/m^3 at a fuel cost of 100 US\$/barrel.

Keywords: Combined water and power plant; MSF/RO; MED/RO; Thermal efficiency; Part load; Economics

1. Introduction

Earth may be the water planet, but 97% of its water is in the ocean. Most of the remainder (~2.1%) is locked in Antarctic icecaps or deep underground, leaving less than 1% available for human consumption that is accessible through freshwater lakes and rivers. Moreover, the differences in availability across and within regions further highlight the distribution problem [1]. Some places, such as Brazil and Canada, get far more water than they can use; others, such as countries in the Middle East, get much less than they need. Thus, the uneven distribution has further aggravated and triggered tremendous opportunity for developing a sustainable technology that can support the growing demand of water. Furthermore, the demand for water is exceeding that of power very fast, and this additional pressure possesses immense potential for research and development for combined water and power plants for the future.

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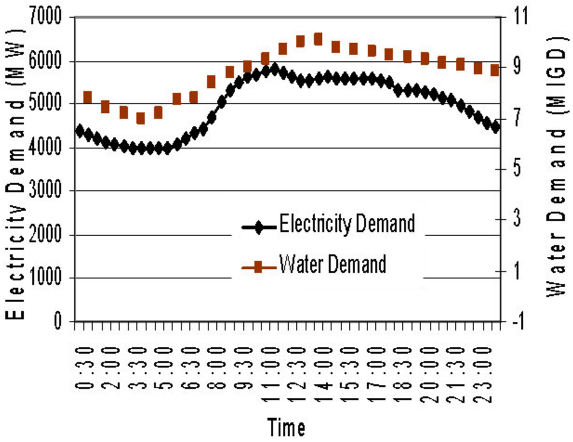

Fig. 1. A typical electricity and water load pattern.

Most of the research groups [2–4] have concentrated on adding MSF with RO because of MSF's long-term operational experience. Priority was given to maximize the utilization of primary fuel for the last few decades. Hybrids offer flexibility in operation, less specific energy consumption, low construction cost, high plant availability, and better power and water matching as observed by Almulla et al. [2].

A study by Kamaluddin et al. [3] reveals that demand for power, when compared with water, varies from 50% to 70% of the rated capacity during winter. Fig. 1 shows that the electricity demand can vary up to 30% during peaks whereas that of water varies about 10–11%. In recently built combined water and power plants (CWPP) the changing demand pattern of water requires partial operation of the thermal desalination plants. As a result, during periods of low power demand, steam raised directly from a separate fuel fired boilers leads to an increase in desalinated water costs. This is what conventional MSF fails to address.

On the contrary, the advantage of lower temperature operation of MED, as described by Mahbub et al. [5,6], has made it very suitable to couple it with a power plant heat recovery steam generator. This will certainly help in reducing the water cost as well as make the whole CWPP more eco-friendly. In short, MED with RO has the potential to reduce the cost of water by virtue of diverting the resources under part load condition in a combined water and power plant.

The proposed solution to this situation (to generate additional water to meet future water demand which is rising at a greater pace than that of electricity) is to install electricity-consuming desalination plants (RO and/or MED) within existing or new cogeneration stations that utilize the daily/seasonal variation of power generation capacity.

2. Combined water and power plant (CWPP)

The proposed CWPP consists of two areas: the combined cycle power plant and the other desalination.

2.1. Combined cycle power plant

The combined cycle power plant consists of gas turbines (GT) with a steam turbine (ST), as shown in Fig. 2. The GT exhaust is connected to a heat recovery steam generator (HRSG) to extract the heat from the exhaust flue gas. This flue gas runs the HRSG to exchange heat with the incoming boiler feed water. This in turn becomes steam and expands in the ST to produce electricity. The amount of steam produced can vary according to the electrical load demand.

2.2. Desalination plant

When the power plant is running under rated conditions, there will be only waste heat available to drive the MED plant. On the other hand, when the power plant is running at part load condition (<85% of the rated condition), there will be extra resources (i.e. steam) available. This steam can be used as a prime energy source for MED or it can be expanded in a low pressure steam turbine to produce electricity, which is the prime energy for an RO plant. Effectively, the power plant can be operated under rated conditions and, whenever there is a drop in demand, the difference between rated power and the load can be made available to the RO plant to produce water.

3. Modeling and simulation

In this study, a Visual Fortran based simulation model has been developed (refer to Fig. 3) for the power plant and the desalination technologies. This simulation software includes a power plant along with MSF, MED and RO modules. The basic parameters of the combined power plant, MED and RO are shown in Tables 1–3, respectively. More details on the models are available in Mahbub et al. [5,6] and Avlonitis [7]. In the power plant model for part load conditions, empirical correlations obtained from Zhang et al. [8] were used to modify the design values.

3.1. Combined cycle

The combined cycle is divided in two subsystems, as shown in Fig. 2, viz. the gas turbine cycle and the steam turbine cycle. The model developed here will use the Alstom GT26 combined cycle plant with net output of

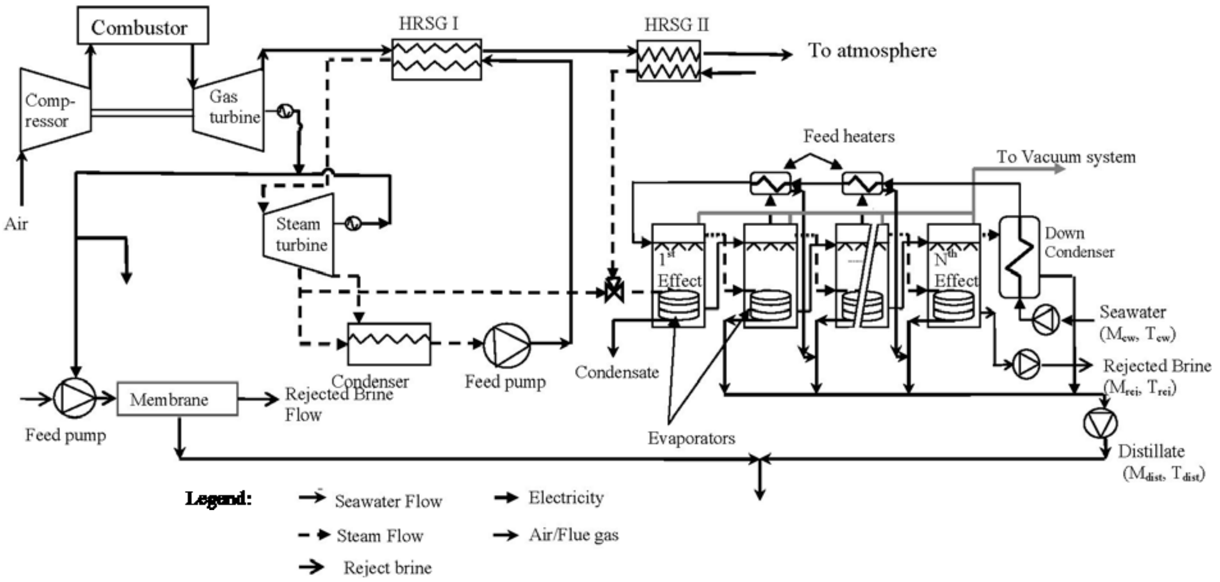

Fig. 2. Schematic diagram of the combined water and power plant.

365 MW. Basic data used for the plant are shown in Table 1. For this study, the designed load of 365 MW is that of the combined cycle power plant used at the Senoko power plant [9].

The cases selected for cost comparison include the following:

1. Combined cycle power plant (CCPP) with MSF (CC+MSF).

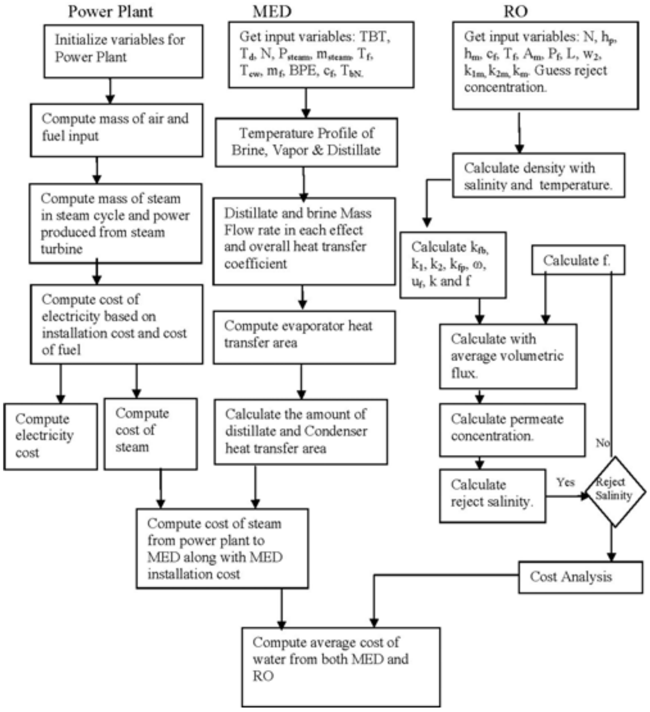

Fig. 3. Simplified flow chart of the CWPP plant simulation software.

2. Combined Cycle power plant (CCPP) with MED (CC+MED).

3. Combined Cycle power plant (CCPP) with RO (CC+RO)

4. Combined cycle power plant with MSF and RO hybrid (CC+MSF+RO).

5. Combined cycle power plant with MED and RO hybrid (CC+MED+RO).

3.2. Water cost analysis

The cost of each component used has been taken from Alasfour and Bin Amer [10]. It consists of direct capital cost, indirect capital cost and operating cost. The direct capital cost includes equipment cost, land cost, site development whereas indirect capital cost involves freight cost, construction, overhead, owners cost, contingency cost. Annual operating costs are for energy, pumping,

Table 1
Different input parameters for Combined cycle power plant

Gas turbine work output, $W_{GT(full\text{-}load)}$	246.7 MW
Steam turbine work output $W_{ST(full\text{-}load)}$	118.35 MW
Air Inlet temperature, T_1	308 K
HRSG I condensate inlet pressure, P_d	60 bars
Temperature of water after exit of HRSG I , T_d	500°C
Pressure of bled steam, P_e	3 bar
Pressure at condenser, P_b	0.07375 bar
Efficiency of gas turbine at design load, η_{GT}	0.92
Efficiency of compressor at design load, η_{Comp}	0.89
Efficiency of steam turbine	0.9
Temperature of flue gas leaving HRSG II, T_6	85°C

Table 2
Input variables for MED plant [17]

Number of effects	12
Top brine temperature (°C)	65
Steam flow rate (kg/h)	51,012
Salinity of seawater (ppm)	46,000
Seawater flow rate (kg/h)	1,641,600
Outer diameter of tubes (m)	0.016
Inner diameter of tubes (m)	0.014
Velocity of brine outside evaporator tubes (m/s)	1.8
Steam temperature	70
Seawater temperature	28
Thermal conductivity of tube (W/ m. K)	50
Temperature of seawater at condenser exit (°C)	35

Table 3
Different input parameters for RO plant [7]

Feed concentration, ppm	45,000
Feed temperature (°C)	25
Area of membrane (m^2)	1.50E+01
Operating pressure (bar)	60
Capacity (MIGD)	15

steam, labor, chemicals, maintenance, insurance, etc. The plant amortization was considered to be about 20 years at an interest rate of 8%.

4. Results and discussion

The water production rate for a MED and RO plants were compared respectively for validation with the simulation results. From there, it was extended to a CWPP plant. These results were compared against a conventional power plant to evaluate improvement of performance. Fuel energy savings ratio is another important indicator which gives the amount of primary energy savings. For the same amount of fuel energy input, the net power output and water output were observed. Lastly, the sensitivity of water cost to fuel cost is shown.

The results obtained were found to be within an accuracy level of ±7%. The performance of MSF, MED and RO has been validated against published literature before extending it to the current study [12–17]. Moreover, the simulation results for RO were verified by the experimental results of Avlonitis [7], which showed a variation of ±5% with the experimental results.

4.1. Water production rate comparison for an MED and a RO plant

For the validation of the simulation results, the product flow rate was compared with that of Darwish et al. [18], as shown in Fig. 4. It was done for a MED plant with 12 effects and a top brine temperature of 65°C. The results matched very closely (less than 3% variation).

When the results are compared with Avlonitis et al. [7], the results agree quite closely (less than 2% deviation), as shown in Fig. 5. When the feed pressure decreases, the amount of distillate produced decreases accordingly (56–58 bar).

As shown in Fig. 6, the CC power plant has the lowest efficiency among the different modes of operation considered here. When the MED plant is coupled to it, the thermal efficiency increases by about 20%.

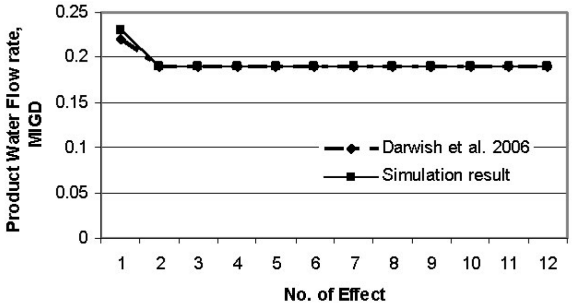

Fig. 4. Variation of water production rate along a MED plant.

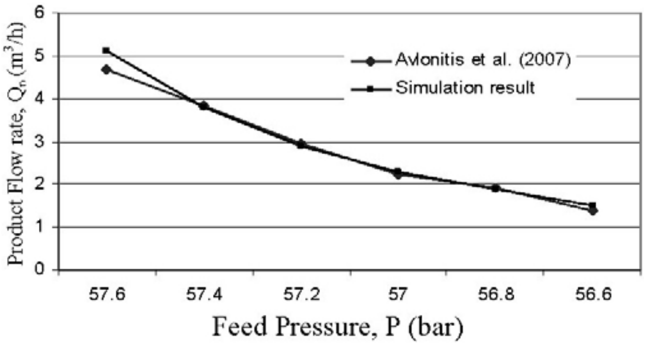

Fig. 5. Variation of water production with feed pressure.

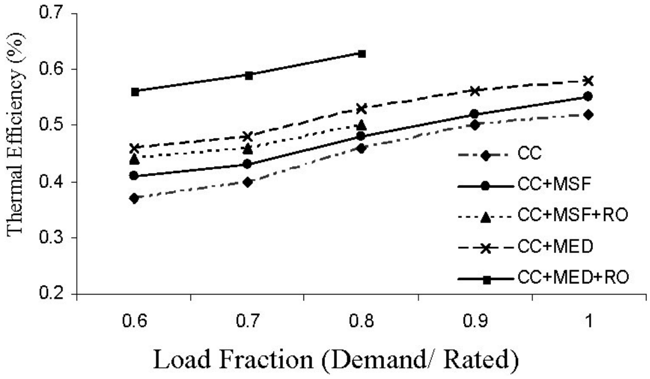

Fig. 6. Thermal efficiency of the combined water and power plant as a function of load fraction.

4.2. Thermal efficiency of the CWPP

In addition to that, when the RO plant that operates at 5% of the capacity (i.e. 365*0.05 = 18.25 MW) of the power plant is added on top of the existing electrical load, there is a further increase of about 15%. Therefore, the efficiencies of the CWPP will increase with an increasing capacity of the RO plant. The CWPP graphs show more sensitivity across the cases rather than on the load itself. These results show a tremendous prospect in terms of savings in the primary energy consumption and output of the CWPP.

4.3. Fuel energy savings ratio (FESR)

FESR is the ratio of fuel consumed by the CWPP over fuel consumed by the individual power plant and desalination plant as a stand-alone plant. It is used to indicate how much of primary fuel energy can be saved compared to the base case. In this study, the 365 MW combined cycle power plant is taken as reference plant. In Table 4, the CC+MSF+RO plant exhibits the lowest FESR whereas a CC+MED+RO shows a tremendous improvement in terms of fuel savings of 33%.

On top of that, it also shows that CWPP offers a lot of flexibility in terms of operation. In one study [3] it was shown that the electrical load can vary daily (60–70% of the load for 16 h compared to 80% for 6–8 h). On the other hand, water demand remains fairly constant over 24 h (with a maximum variation of 5–8%).

On the other hand, maximum water production will occur when it runs on the MED+RO mode. The water production in CC+MED+RO is almost three times the most common desalination plants using CC+MSF.

4.4. Effect of load on water production

Here, the effects of electrical load variation on water production are investigated. It was found that, for a fixed primary energy input, as the electrical load increased water production decreased and vice versa. This can be explained by the amount of waster heat available in the flue gas. On the other hand, when electrical load decreases there is available steam that can be bled. Now this steam can be diverted to either MED plant as source or it can be expanded further to generate electricity, which can be used to run the RO plant.

Table 4
FESR, net power output and water output for each of the cases

	Net power output of CWPP, MW	Maximum water production, MIGD	Fuel energy savings ratio (FESR)
CC+MSF	365	14.40	0.07
CC+MED	365	22.51	0.17
CC+RO	365	40.04	0.20
CC+MSF+RO	365	30.61	0.15
CC+MED+RO	365	47.96	0.33

Fig. 7 shows the trend of water production or main advantage that can be derived through utilizing the part load condition (for electrical load <80% of the rated load). Referring to Fig. 6, CC+MED+RO demonstrates the best efficiency, which is why the impact of using MED with RO is analyzed here and compared with that of CC+MED. As the trend suggests, with gradual decrease in the electrical load, the amount of water produced can triple (from 12 MIGD to 30 MIGD). In addition to that, it will increase the part load efficiency of the combined power plant (refer to Fig. 6).

4.5. Effect of fuel price

The unit water cost for different fuel price is shown in Table 5. The proposed CCWP (CC+MED+RO) yields the lowest unit cost of all the fuel prices considered. The variation among the competing technologies (mainly CC+MSF+RO and CC+MED+RO) is better exemplified at higher fuel cost (0.35 US\$/m^3 at 70\$/barrel to 0.47 US\$/m^3 at 120 \$/barrel).

From Fig. 8, the unit water cost shows much more sensitivity towards MED load rather than combined cycle

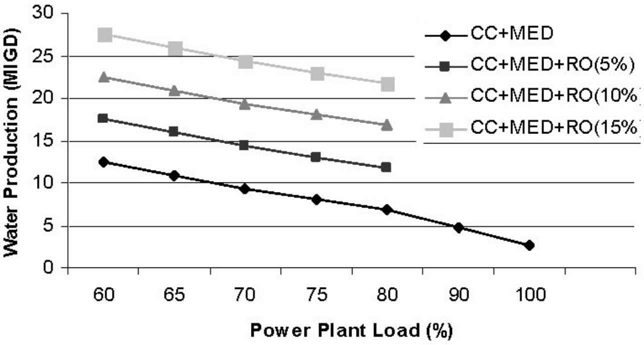

Fig. 7. Trend of water production with varying electrical load.

Table 5
Water production cost (US\$/m^3) for different fuel price

Fuel price US\$/barrel	30	70	80	100
CC+MED+RO	0.62	0.90	0.99	1.09
CC+RO	0.71	1.01	1.11	1.22
CC+MED	1.16	1.66	1.82	2.01
CC+MSF+RO	0.9	1.25	1.38	1.65
CC+MSF	1.36	1.89	2.08	2.70

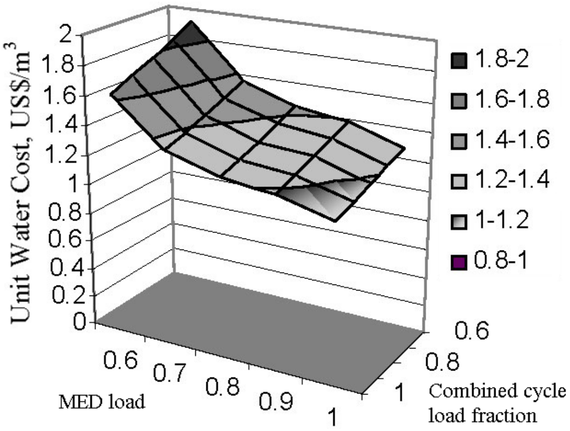

Fig. 8. Unit water cost variation with combined cycle load and MED load.

load fraction. The water cost illustrates a change of 50% if the MED load is changed from 1 to 0.6 whereas for the same change in combined cycle load it is 16%. There is a general decreasing trend with the additional use of MED plant.

5. Conclusions

A detail thermodynamic and economic analysis has been done for different modes of CWPP to show the advantages of using low grade waste heat from the power plants. Among the modes of CWPP, CC+MED+RO shows the best fuel savings compared to conventional CC+MSF+RO mode. The saving is even higher in terms of fuel savings and unit water cost reduction when it is operated at part load condition. The total fuel savings for the CWPP can be up to 33% of the reference plant. Moreover, the unit water cost can be reduced up to 30% if MED/RO hybrid is used as opposed to MSF/RO hybrid. This study will be helpful for retrofitting or designing new generation combined water and power plants.

References

[1] United Nations Human Development Report, 2006.
[2] A. Almulla, A. Hamad and M. Gadalla, Integrating hybrid systems with existing thermal desalination plants, Desalination, 174 (2005) 171–192.
[3] B.A. Kamaluddin, S. Khan and B. Makkawa Ahmed, Selection of optimally matched cogeneration plants, Desalination, 93 (1993) 311–321.
[4] L. Awerbuch, S. May, R. Soo-Hoo and V. Van Der Mast, Hybrid desalting systems, Desalination, 76 (1989) 189–197.
[5] F. Mahbub, M.N.A. Hawlader and A.S. Mujumdar, Combined water and power plant: A solution to freshwater shortage in 21st century and beyond", International Conference on Water and Flood Management, Bangladesh, 2 (2007) 665–674.
[6] F. Mahbub, M.N.A. Hawlader and A.S. Mujumdar, A sustainable technology for conversion of seawater to potable water, Conference of ASEAN Federation of Engineers, Philippines, 2007.
[7] S.A. Avlonitis, M. Pappas and K. Moutesidis, A unified model for the detailed investigation of membrane modules and RO plant performance, Desalination, 203 (2007) 218–228.
[8] N. Zhang and R.X. Cai, Analytical solutions and typical characteristics of part-load performances of single shaft gas turbine and its cogeneration, Energy Conv. Manage., 23 (2002) 1323–1337.
[9] Senoko Power Data Sheet, http://www.senokopower.com.sg/pdf/Senoko Combined-Cycle Plants 3 - 5.pdf.
[10] F.N. Alasfour and A.O. Bin Amer, The feasibility of integrating ME–TVC + MEE with Azzour south power plant: Economic evaluation, Desalination, 197 (2006) 33–49.
[11] I. Kamal, Thermo-economic modeling of dual-purpose power/desalination plants: steam cycles, IDA World Congress on Desalination and Water Reuse, Madrid, 1997.
[12] M.H. Ali El-Saie and Y.M.H. Ali El-Saie, Optimization of dual purpose steam power and MSF desalination plant, Desalination, 76 (1989) 155–175.
[13] L. Awerbuch, V. Van Der Mast and R. Soo-Hoo, Hybrid desalting systems — a new alternative, Desalination, 64 (1987) 51–63.
[14] L. Awerbuch, Power–desalination and the importance of hybrid ideas, IDA World Congress on Desalination and Water Reuse, Madrid, 1997.
[15] M.A. Darwish, On electric power and desalted water production in Kuwait, Desalination, 138 (2001) 183–190.
[16] A.A.J. Al-Zubaidi, Technoeconomics of power/desalting cogeneration plants in Kuwait — A preliminary study, Desalination, 76 (1989) 121–154.
[17] A.M. El-Nashar, Cogeneration for power and desalination — state of the art review, Desalination, 134 (2001) 7–28.
[18] M.A. Darwish, F. Al-Juwayhel and H.K. Abdulraheim, Multi-effect boiling systems from an energy viewpoint, Desalination, 194 (2006) 22–39.