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Techno-Economics Study to Select Optimum Desalination Plant for Asalouyeh Combined Cycle Power Plant in Iran

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***Abstract*—**This research deals with techno economic analysis to select the most economic desalination method for Asalouyeh combined cycle power plant . Due to lack of fresh water, desalination of sea water is necessary to provide required DM water of Power Plant. The most common desalination methods are RO, MSF, MED, and MED–TVC. In this research, methods of RO, MED, and MED–TVC have been compared.

Simulation results show that recovery of heat of exhaust gas of main stack is optimum case for providing DM water required for injected steam of MED desalination. This subject is very important because of improving thermal efficiency of power plant using extra heat recovery. Also, it has been shown that by adding 3 rows of finned tube to de-aerator evaporator, which is very simple and low cost, required steam for generating 5200 m^3/day of desalinated water is obtainable.

***Keywords*—**Desalination, MED, thermodynamic simulation, combined cycle power plant.

I. Introduction

The lack of fresh water is not a temporary problem in a country or an area but a long-term and substantial problem concerning the survival of human being and development of societies in our planet. In the Middle East area, the majority of the states do not have access to sufficient fresh water sources even if they are surrounded by unlimited amounts of seawater. So sea water desalination is suitable solution for production of fresh water. It is well known that three kinds of process are commercially available for large size sea water desalination plant: multi-stage flash distillation (MSF), multiple effect distillation (MED) and reverse osmosis (RO). The significant difference between these processes consists of their different input energy requirements, i.e., input thermal energy for MSF and MED or electrical input energy for RO.

In the recent years many working gas turbines in an open cycle in Iran have been converted to combined cycle mode of operation in order to improve thermal efficiency. But in many plants, temperature of main stack exhaust gas is still high and it is possible to recover extra heat by reducing the exhaust gas temperature down to an allowable value and use it as an input energy source for thermal desalination plant. In the recent years many papers have been published about both new methods of sea water desalination and usage of dissipated heat of power plants in order to produce desalinated water.

Cohen et al. [1] investigated the possible integration of the low-temperature flash (LTF) desalination technology in existing IEC power stations. The LTF technology exploits the residual heat discharged by the seawater cooling system for its distillation, with a dramatic reduction in steam consumption compared to other distillation processes. Junjie et al. [2] proposed an enhanced multistage flash (E-MSF) seawater desalination system which considered the advantage of a multiple effect distillation (MED) seawater desalination system. Their calculation results show that the gain output ratio (GOR) could be increased by 74.1% and the mean annual capital cost of fresh water production decreases by 10.7% in comparison with conventional MSF. Gude et al. [3] presented a low-temperature phase-change desalination process configuration. Their configuration enables saline water to be evaporated at near-ambient temperatures under near-vacuum level pressures created by the barometric head without any mechanical energy input. The results suggest that reasonable yields can be maintained at lower specific energy demand at evaporation temperatures as low as 40^{o}C. Chacartegui et al. [4] presents a modified combined cycle – low temperature cogeneration power plant in the East of Spain. A parametric analysis was done for the most important operating conditions in order to identify alternative cogeneration applications. For this purpose, they used dissipated heat from condenser and heat of exhaust gas of main stack as heat source of desalination plant. They showed that the most feasible cogeneration solution would be a MED desalinization plant where condenser pressure is increased to 0.45–0.6 bara and the heat exchanger is installed at the top of the stack. Sommariva [5] discussed different schemes leading to fuel gas savings and reduction of combined thermal desalination and power generation heat rate and illustrated relative advantages and disadvantages. He showed that

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installation of additional cooling coils offers a better utilization of the waste heat in the flue gas system. However, it has also some drawbacks such as slightly decrease of the GT output due to the additional pressure losses in the flue gas system. El Saie et al. [6] presented a techno-economic study for dual purpose combined cycle gas turbine and steam turbine power generation with desalination plant in the vicinity of Sharm El Sheikh with about 500MW power as well as 25MIGD potable water production .

This study deals with techno economic analysis to select the most economic desalination method for Asalouyeh combined cycle power plant .Asalouyeh power plant is located at the south of Iran beside the Persian Gulf. Due to lack of fresh water, desalination of sea water is necessary to provide required DM water of Plant. In this study applicable methods to generate Plant make-up water like Reverse Osmosis, MED by utilizing main stack exhaust gas heat recovery and MED-TVC by employing steam extraction from HRSGs LP steam line are investigated.

II. Desalination Systems

Desalination technologies fall into two basic categories: 1- Distillation processes which use a liquid-vapor-liquid process to distill fresh water from salt water like multi-stage flash (MSF), multi-effect distillation (MED), and vapor compression technologies. 2- Membrane processes such as Reverse Osmosis (RO) and Electro dialysis (ED) which don't utilize phase change.

In the MED process which is used in this study, brine is distilled, i.e. evaporated to produce salt-free vapor, which is then condensed into fresh water. To increase system efficiency, heat is recovered from the condensing vapor and is used to evaporate additional brine at a lower pressure. An external source of heating steam is needed only for the highest-pressure brine evaporator. In this system, heating steam flows inside horizontal tubes and brine is sprayed on their external surface where it is partially evaporates. The efficiency of the MED process can be increased by adding a thermal vapor compression (TVC) system. With TVC, a fraction of the vapor from the final effect is entrained and compressed by a one- or two-stage steam jet ejector. A schematic figure of MED system can be found in Fig. 1.

III. Thermodynamics Simulation

A. Cycle simulation

As the first step, performance of combined cycle power plant has been simulated. The combined cycle block consists of two MAPNA V94.2.5 gas turbines each with gross power of 162 MW, two heat recovery steam generators and one 160 MW steam turbine. Asalouyeh power plant consists of four combined cycle blocks. Comparison of simulation results with available data published by manufacturers of main equipment reveals the adequate precision of simulation (For validation see Table I).

IV. Desalination Simulation

In this section, 3 types of desalination systems used in this study are examined. These methods are Ro, MED and MED-TVC. Some key parameters of MED system are listed as follows:

1- Effect numbers, which is one of the key design parameters for the MED system. The more is the number of effects, the more is the desalinated water productivity. But by increasing effect numbers, the capital cost of MED construction enhances. 2- 1st effect steam (Ts), which is the saturation temperature of the heating steam supplied to the first effect. A high value of this input decreases the desalinated water productivity and also decreases the capital cost of MED construction. To control corrosion on the evaporator tubes, this temperature should be limited to an allowable value.

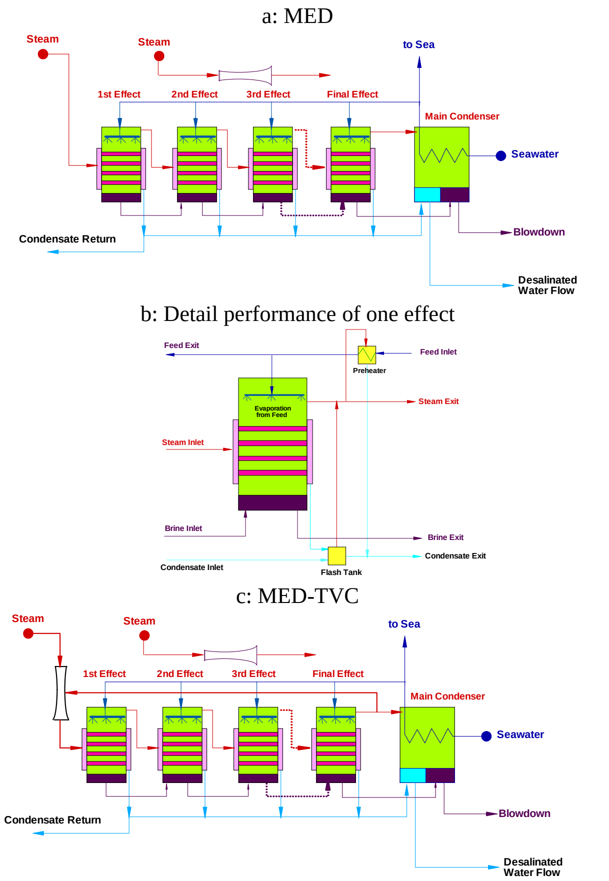

Fig.1 Schematic diagram for MED-TVC desalination

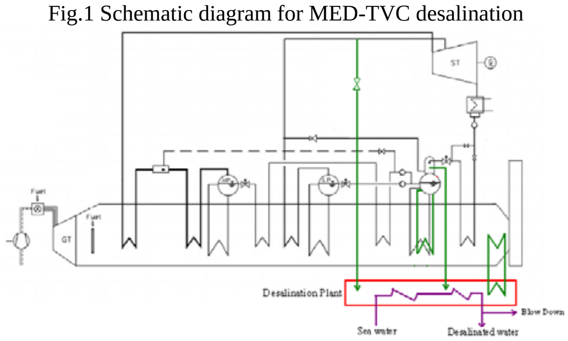

Fig.2 Schematic diagram for combined cycle power plant showing

different possible position of feed steam to desalination plant.

TABLE I
COMPARISON OF SIMULATION RESULTS WITH AVAILABLE DATA PUBLISHED BY MANUFACTURERS OF MAIN EQUIPMENT

Site Condition			
	Unit	Actual Results	Present Results
Ambient temperature	°C	24.5	24.5
Site Elevation	m	17	17
Relative humidity	%	63	63
Fuel LHV	kj/kg	48737	48749
GT Performance Parameters			
GT Model		V94.2.5 TUGA	V94.2
Intake pressure loss	mbar	10	10
Exhaust pressure loss	mbar	30	30
Gross power output at generator terminals	KW	147082	147090
Gross efficiency at generator terminals	%	33.14	33.09
Fuel mass flow rate	kg/s	9.106	9.118
Turbine Exhaust Temperature	°C	548.3	548.4
Turbine Exhaust Mass flow	kg/s	509.11	509.1
HRSG Performance Parameters			
Duct Burner Fuel Mass Flow / Boiler	kg/s	0.2	0.2
HRSG Stack Exhaust temperature	°C	139.1	139
HRSG Efficiency	%	79.47	78.75
ST Performance Parameters			
Condensate Pressure at Condenser Oulet	bara	0.146	0.146
HP steam Flow at turbine inlet	kg/s	134	134
HP steam Temperature at turbine inlet	°C	520	520
HP steam Pressure at turbine inlet	bara	90	90
LP steam Flow at turbine inlet	kg/s	18	18
LP steam Temperature at turbine inlet	°C	230	230
LP steam Pressure at turbine inlet	bara	8.5	8.5
Gross power output at generator terminals	KW	158720	158610
LP Turbine Exhaust Flow	kg/s	151.576	152
LP Turbine Exhaust Pressure	bara	0.146	0.146
LP Turbine Exhaust Quality	%	87.9	87

3- Final effect temperature, which is the evaporation temperature of final effect. Lower values allow designs with larger number of effects and increased system size and relevantly cost. In this simulation, this input is considered 40^{o}C.

4- Sea water temperature, which is also one of the key design parameters for MED system. Since ambient design temperature of steam portion is 24.5^{o}C, sea water temperature in this ambient temperature which is 22^{o}C is considered as design value.

5- Weight percent of impurities existed in Persian Gulf is about 4.5%.

For RO system simulation, efficiency of this system is considered equal to 40%.

To select optimum value of mentioned parameters, economic optimization is employed. The simulation was performed for 1st effect steam Ts = 70, 80 and 90^{o}C, the effect numbers 4 and 5, with using of dissipated heat in main stack (T = 139^{o}C) for steam generation with P = 1.1 bar. This calculation was performed for desalinated water flow rate equal to75 t/h (1800 t/day). With considering of power generation income 2 Cent/kwh, allowable top brine temperature about T = 70^{o}C, the optimum case is case with Ts = 80^{o}C and 4 effects. It can be seen in the following table that cases 1 and 4 have high top brine temperature and Cases 3 and 6 have high cost. The case no. 5 is better than case 2 because it has lower cost in comparison with case 2.The temperature decrease of gas in the main stack in this case is almost 12.7^{o}C. Decrease of the GT power output due to the additional pressure losses in the flue gas system also has been considered in this calculation. Table II shows the results of this simulation.

TABLE II
THE SELECTION OF OPTIMUM MED FOR PRODUCING OF DM WATER REQUIRED FOR POWER PLANT WITH USING OF DISSIPATED HEAT IN MAIN STACK

		1: Ts = 90 C/ 5 Effects	2: Ts = 80 C/ 5 Effects	3: Ts = 70 C/ 5 Effects	4: Ts = 90 C/ 4 Effects	5: Ts = 80 C/ 4 Effects	6: Ts = 70 C/ 4 Effects
Gross Power Output	kW	453,335	453,337	453,341	453,309	453,312	453,315
Power Consumption	kW	9,057	9,057	9,057	9,057	9,056	9,057
Desalination Power Cons.	kW	107	106	105	123	123	121
Net Power Output	kW	444,171	444,174	444,179	444,129	444,133	444,137
Stack Temperature	C	128.5	128.8	129	126	126.3	126.6
MED Steam Heating	t/h	16.98	16.57	16.17	21.17	20.64	20.13
Top Brine Temp.	C	82.46	73.94	65.59	80.12	72	64.11
Plant Life Cycle	Year	20	20	20	20	20	20
Net Power Output Income	USD	1,556,375,184	1,556,385,696	1,556,403,216	1,556,228,016	1,556,242,032	1,556,256,048
Power Output Income decrease in Comparison With Design Case	USD	911,040	900,528	883,008	1,058,208	1,044,192	1,030,176
Desalination Plant Capital Cost	USD	1719988	2,000,378	2,471,113	1,558,176	1,770,543	2,111,810
Inflation Rate		0.15	0.15	0.15	0.15	0.15	0.15
Net Present Value of Total Costs	USD	2,512,197	2,783,446	3,238,946	2,478,357	2,678,536	3,007,615

V. RESULTS AND DISCUSSION

At the first step of this study, three types of desalination methods to supply water consumption of power plant are investigated briefly. DM water consumption of one combined cycle block is approximately 35 tons/hr, while make-up water consumption in 4 blocks like Asalouyeh combined cycle power plant is about 75 tons/hr. Three types of desalination methods which are used in this study are:

- RO desalination
- MED desalination that the injected steam will be provided through dissipated heat in the main stack.
- MED-TVC desalination that steam injection is the part of the LP steam extracted from LP steam produced by HRSG.

After selecting the best system in terms of technical and economical issues, maximum possible production of fresh water by usage of dissipated heat in the main stacks of four blocks combined cycle is investigated. In continuance, easier and cheaper alternative method than the above mentioned method by installation of equipment in main stack to produce fresh water will be introduced. Figure 2 illustrates a schematic diagram of combined cycle power plant showing different methods used in this study for steam production required for MED or MED-TVC desalination system.

A. Technical and economical comparison to select proper desalination system to produce fresh water:

In this section the technical and economical study on the usage of three types of desalination systems: RO, MED, and MED-TVC are investigated. Comparison of technical and economical issues relevant to fresh water supply for 35 and 75 tons per hour capacities have been mentioned in tables III and IV. To do economical comparison, the net present value (NPV) of 3 above mentioned desalination plant types are compared at the end of tables III and IV. In this regard, the following items are important:

- As expected, Gross power output in case of MED-TVC is much less than other options. This matter is an effect of injection of a part of LP steam to desalination instead of expansion in the steam turbine. In MED, since there is additional pressures drop in the exhaust gas path and also due to provide required steam for ejector from LP steam line, we face just with little power loss.

-Net power output in MED system, due to expectedly low power consumption, is more than other options. Net power output in RO system is less than MED, because of higher power consumption. But MED-TVC has the lowest net power output.

-MED has highest and MED-TVC has lowest cycle efficiency. But CHP efficiency which is the ratio of sum of the net power output and energy of injected steam in desalination to fuel heat value, in MED-TVC system is higher than RO. However highest CHP efficiency belongs to MED.

-Reduction of the exhaust flue gas temperature and usage of heat recovery from it to produce steam in order to supply MED is approximately 5.9^{o}C and 12.7^{o}C for cases 35 and 75 t/h respectively.

-Reduction of electricity sales income in comparison with design mode by assuming 20 years of life cycle in MED is less than other options.

- Net present value (NPV) of MED and MED-TVC system have been calculated based on the capital cost and decrease in power generation in comparison with design case. So the system with smallest net present value is the most economic system. Net present value of MED system is about 50% less than RO system. NPV of RO system is about half of relevant parameter of MED-TVC. So recovery of heat of exhaust gas of main stack is optimum case for providing DM water required for injected steam of MED desalination. Figure 3 shows thermodynamic data of designed MED system to supply 1800 m^3/day DM water flow rate.

TABLE III
TECHNO-ECONOMIC COMPARISON OF 3 TYPES OF DESALINATION METHOD FOR PRODUCTION OF DM WATER REQUIRED FOR ONE BLOCK OF CCPP

		Original	RO	MED	MED-TVC
Gross Power Output	kW	453,491	453,491	453,381	452,335
Cycle Power Consumption	kW	9,060	9,059	9,058	9,029
Desalination Power Cons.	kW	0	318	57	62
Net Power Output	kW	444,431	444,114	444,266	443,245
Net Fuel Input	kW	907902	907902	907,820	907,902
Gross Efficiency	%	49.95	49.95	49.94	49.82
Total Net Efficiency	%	48.95	48.92	48.94	48.82
CHP Efficiency	%	48.95	48.92	49.64	49.38
Efficiency increase	%	0.00	-0.03	0.69	0.43
Stack Temp	C	139.00	139.00	133.10	138.40
GOR				3.63	5.02
Plant Life Cycle	Year	20	20	20	20
Power Output Income	USD	1,557,286,224	1,556,175,456	1,556,708,064	1,553,130,480
Power Output Income decrease in Comparison With Design case	USD	0	1,110,768	578,160	4,155,744
Desalination Plant Capital Cost	USD	0	1,314,397	1,023,129	1,148,200
Evaporator installation cost	USD	0	0	200,000	0
Inflation Rate		0.15	0.15	0.15	0.15
Net Present Value of Total Costs	USD	0	2,280,282	1,725,877	4,761,890

TABLE IV
TECHNO-ECONOMIC COMPARISON OF 3 TYPES OF DESALINATION METHOD FOR PRODUCTION OF DM WATER REQUIRED FOR 4 BLOCKS OF ASALOUYEH CCPP

		Original	RO	MED	MED-TVC
Gross Power Output	kW	453,491	453,492	453,312	451,014
Cycle Power Consumption	kW	9,060	9,060	9,056	8,994
Desalination Power Cons.	kW	0	678	123	136
Net Power Output	kW	444,431	443,754	444,133	441,884
Net Fuel Input	kW	907902	907902	907,785	907,902
Gross Efficiency	%	49.95	49.95	49.94	49.68
Total Net Efficiency	%	48.95	48.88	48.92	48.67
CHP Efficiency	%	48.95	48.88	50.44	49.87
Efficiency increase	%	0.00	-0.07	1.49	0.92
Stack Temp	C	139.00	139.00	126.30	138.40
GOR				3.63	5.02
Plant Life Cycle	Year	20	20	20	20
Power Output Income	USD	1,557,286,224	1,554,915,067	1,556,242,032	1,548,361,536
Power Output Income decrease in Comparison With Design case	USD	0	2,371,157	1,044,192	8,924,688
Desalination plant Capital Cost	USD	0	2,605,711	1,770,543	1,991,899
Evaporator installation cost	USD	0	0	350,000	0
Inflation Rate		0.15	0.15	0.15	0.15
Net Present Value of Total Costs	USD	0	4,667,586	3,028,536	9,752,497

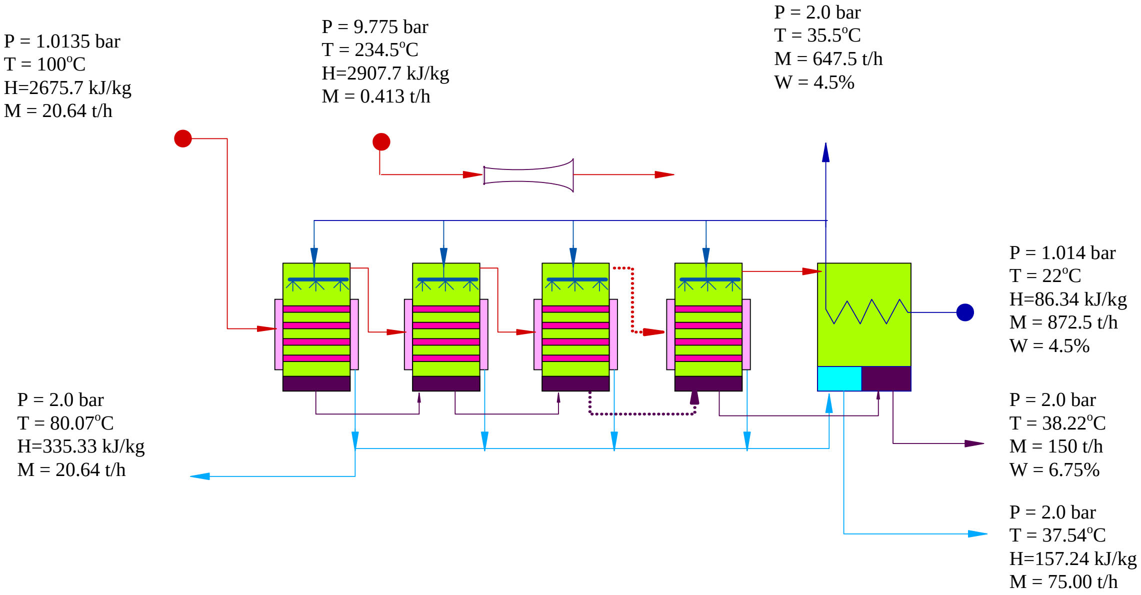

Fig.3 The designed MED system to supply 1800 m^3/day

B. Maximum fresh water productivity by utilizing heat recovery in the main stack of Asalouyeh combined cycle power plant:

In this section, maximum flow rate of fresh water which can be obtained by main stack dissipated heat recovery in case of MED system employment will be investigated. As already shown in table I, in design mode, the main stack exhaust flue gas temperate is 139°C. If an evaporator and relevant drum is installed at the end of HRSG and hence reduction of flue gas temperature to allowable value, steam required for desalination plant can be obtained. By that maximum fresh water flow rate can be achieved as well as CHP efficiency increasing.

Figure 4 shows fresh water production flow rate, CHP efficiency, Plant net power output decrease and also the capital cost of desalination system versus main stack exhaust flue gas temperature. As it can be seen clearly, in four blocks of combined cycle power plant, a reduction of 20 °C in main stack exhaust gas temperature generates 11000 m^3/day desalinated water. Also by this, the CHP efficiency will be increased by 2% and net power of each combined cycle block will be decreased by 430 kW. Capital cost of such desalination plant is about 8.5 million dollars.

C. Steam production required for MED-TVC using De-aerator evaporators

Since installation of separate equipment such as evaporators and drum at the end of HRSG or in the main stack to produce steam may be faced with some difficulties in installation, steam required to desalination can be provided from HRSG as another simple alternative. In this alternative, 3 rows of finned tube will be added to de-aerator (which is simple and incorporates relatively low cost and is not associated with too many un-tolerable changes in HRSG) which in turn can supply approximately 6 ton/hr additional saturated steam with pressure around 6 bar in each HRSG. So in each block approximately 54 ton/hr of fresh water can be produced which is much more than required make-up water in the Plant. In four blocks of Asalouyeh plant which includes eight HRSGs, by this way required steam to provide 5200 tons per day of fresh water can be produced.

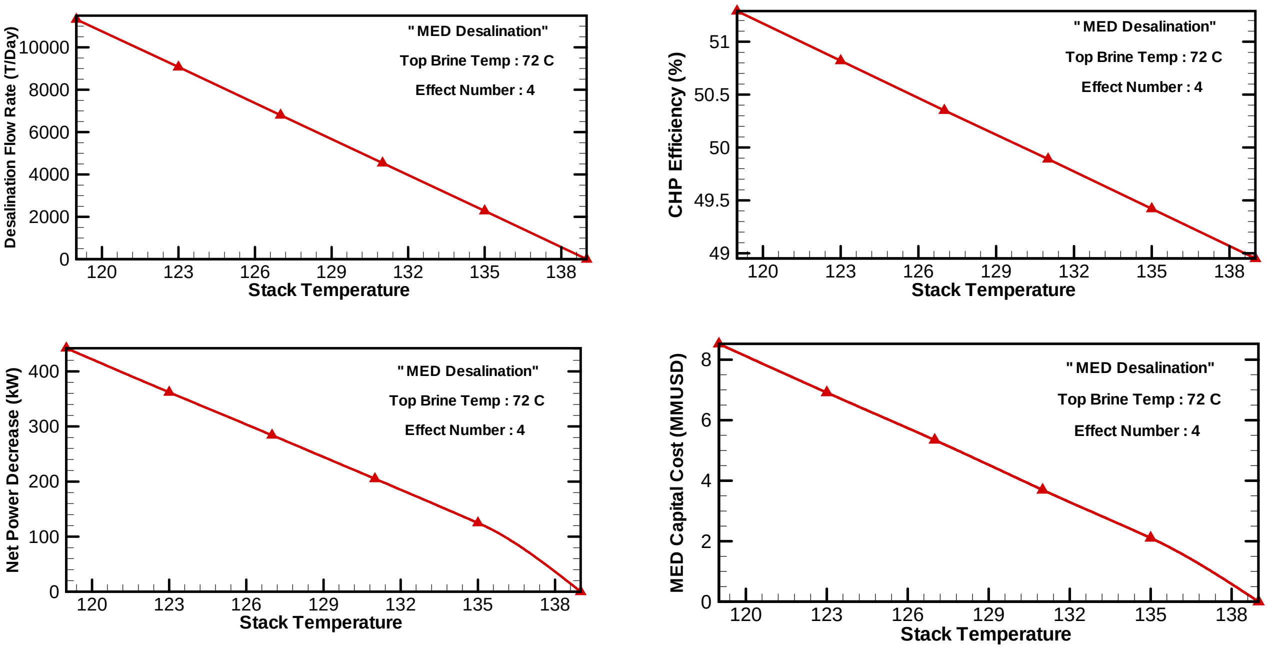

Fig. 4 Flow rate of fresh water production, CHP efficiency increase, reduction of the net power output of plant and also the capital cost of desalination system in the different temperatures of flue gas temperature in the main stack

VI. Conclusion

In this paper, techno economical analysis was performed to select the most feasible desalination method for Asalouyeh combined cycle power plant. Applicable desalination methods to generate DM water which was investigated in this research are: Reverse Osmosis, MED utilizing main stack exhaust gas heat recovery and MED-TVC employing steam extraction from LP steam line of HRSG. The highlights of the presented study are given below:

1- Results show that net present value (NPV) of MED system is 50 % less than RO system. NPV of RO system is about half of NPV of MED system-. So heat recovery of main stack exhaust gas is an optimum case to provide steam required to inject to MED desalination system in order to supply make-up water to CCPP.

2- It has been shown that a reduction of 20 °C in main stack exhaust gas temperature tends to daily generation of 11000 m^3/d DM water. Also by this, the CHP efficiency will be increased by 2% and net power of each combined cycle block will be decreased by 430 kW.

3- It has been shown that by adding 3 rows of finned tube to de-aerator, which is very simple and associates with low cost, required steam to generate 5200 ton of DM water on a daily basis is obtainable.

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