

Numerical Analysis & Technical Evaluation of a Newly Invented Desalination & Power Cogeneration Cycle

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ABSTRACT

This paper presents a numerical simulation & analysis and technical evaluation of a recently invented cogeneration cycle of combined desalination water production and power generation with salt recovery. The invented cycle claimed to provide a better alternative to the existing dual purpose cycles (higher cycle thermal efficiency and improved Top Brine Temperature (TBT) limitations over all currently operating thermal desalination - power generation dual purpose plants). A computer code was developed to quantitatively simulate the invented cycle and solve the governing heat, mass and salt balance equations. The code was verified against the published data of Al-Jubail-II desalination - power cogeneration plant (the world largest desalination plant). The invented cycle analysis covers; i) the thermal performance & TBT limitations, ii) the practicality and costs of the major components, iii) cycle chemistry and product water quality, and iv) environmental considerations. The cycle originality is also high lighted. The analysis concluded that the invented cycle does not provide a better alternative to the existing dual purpose cycles.

1- INTRODUCTION

Most of large thermal desalination plants are of dual purpose (cogeneration) type, by which the electricity is generated in conjunction with water production. Cogeneration desalination-power plants have many thermodynamics advantages and also have some limitations, Al-Khaldi [1] and Awerbuch [2]. One of the major problem and constraint in all thermal desalination plants is the scale formation on the heating surfaces.

In Multi Stage Flash (MSF) thermal desalination, for example, calcium sulfate precipitation limits the Top Brine Temperature (TBT) to about 120 °C. Many of the current researches are directed towards improving the TBT limitations through chemical pre-treatment (Nano-filtration) and the developments of better anti-scalents. Direct contact heat transfer process of brine heaters is another conceptual approach to increase TBT, however, its major problem was the selection of the heat transfer medium. Hydrocarbon and mineral oils have the disadvantages of emulsion formation, separation and thermal degradation. Superheated steam was also proposed where the super heat energy was used to evaporate part of the seawater.

Madani [3] & [4] proposed a new power - desalination cogeneration cycle using direct contact heat transfer and allows the recovery of salts. The invented new cycle, Figure (1), is based on a regenerative - reheat thermodynamics cycle with seawater as the working fluid. The invented cycle is claimed to provide higher thermal efficiency and improve TBT limitations over all currently operating thermal desalination-power plants.

This paper, as an extension of the published paper -by the same authors- Ref. [5], presents a numerical simulation & analysis and technical evaluation of the invented cycle Madani [4].

2- INVENTED CYCLE DESCRIPTION

Figure (1) illustrates the complicated configuration of the invented cycle. This configuration was simplified and rearranged, here, as a conventional power cycle, Figure (2), to clarify the cycle process description that can now be explained as follows (More detailed process description of the invented cycle is available in references [4] & [5]):

Seawater (which contains various salts of a total TDS of 34,450 ppm for standard seawater) enters the cycle as a coolant and feed water (points 1 & 2) through the condenser. After condensing the steam, most of the seawater is discharged back out of the cycle (point 4), while the rest of the preheated seawater enters the cycle as feed water (point 3). The seawater feed is further heated in the indirect feedwater heaters (FWHs), (point 5), and a group of the direct contact FWHs, where it is pumped to the evaporators (point 6). Part of the settled salts is removed from both FWHs (point 48) and evaporators (point 7).

In the group of evaporators, steam is generated (point 9) and super heated (point 22) in a steam heater. The generated superheated steam is divided into two parts; the first part is recirculated by a vapour fan (point 24) to evaporate the pressurised seawater in the evaporators (point 9), while the second part is used to drive the steam turbine (point 23). In the steam turbine, part of the steam is extracted (points 31b/c & 25c-25f) to preheat the sea water in the direct contact FWHs, and the indirect FWH (point 31a), while the rest is condensed in the condenser (point 27) after driving the turbine. The condensate from both the indirect FWH and the condenser is taken out of the cycle as plant product water.

3- INVENTED CYCLE ORIGINALITY

The main objective of the invented cycle is to overcome the TBT limitations caused by scale formation on the heating surfaces. Many of the research work were conducted to achieve this objective. The most interesting one is the patented cycle developed by Blaskowski [6] in 1967, which is very similar to the present invented cycle by Madani [4]. The following is a brief comparison between Blaskowski and Madani cycles that shows the similarity between the two to the extent that one may question the originality of the invented cycle by Madani [4].

i- The main concept

Both Blaskowski and Madani cycles produce water and generate electrical power using seawater as a feed to the steam power plant. The seawater (in both cycles) is heated in a group of direct contact FWHs to avoid scale formation on the heating surfaces. Then, the heated seawater is evaporated in direct contact evaporators using part of the cycle superheated steam. The evaporated steam is superheated to in a fuel fired steam heater to drive the turbine, then condensed in the condenser and used as product water.

ii- FWHs Line

In both cycles, seawater is used to condense the steam in the condenser. Part of this preheated seawater is used as a feed water to the cycle and heated in a series of direct contact FWHs with pumps transferring seawater between each two heaters. The only addition is that Madani suggested to use a filter after each heater to remove the precipitated salts out of the system.

iii- Evaporation Process

In both cycles, the heated seawater is evaporated by recirculating part of the superheated steam. Blaskowski suggested two methods of evaporation. The first method is to evaporate the whole seawater to slightly superheated steam, then, the salt is removed from the dry steam by a solids collection unit. The second is to use a liquid tank in which a continuous blow down is provided to control the precipitates. Madani suggested to

evaporate the seawater in a group of evaporators where filters are used after each evaporator to remove (and recover) the formed salts precipitants. Madani's arrangement may seem better due to; a) Blaskowski's first suggestion requires large quantity of steam in addition to the design and operational difficulties, and b) Blaskowski's second suggestion results in a considerable loss of energy.

iv- Steam Heater

Blaskowski suggested two steam heaters, one to superheat the steam evaporated in the evaporator where it is recirculated (using one steam compressor), and the second is to superheat the steam produced for rolling the turbine. Madani combined the two with one steam fan (compressor) before each evaporator.

4- INVENTED CYCLE NUMERICAL SIMULATION

The invented cycle, Figure (1), was divided into five interconnected segments, Figure (3), namely; i) the condenser and the indirect FWH, ii) direct contact group of FWHs, iii) direct contact group of evaporators, iv) steam turbines, and v) steam heater. Each segment was treated individually to satisfy the heat, mass and salt balance of each component. Iterative technique was used to satisfy the overall cycle balance. The governing equations and the calculation procedure are well described in references [1] and [5].

A computer code was developed to quantitatively simulate the invented cycle. The program used Excel-5, PC computer spread sheet, to link the various relations of cycle components and segments. The code was verified against the published data of Al-Jubail-II power and desalination plant (the world largest desalination plant) before being used to obtain the detailed data of the invented cycle. Table (1) presents the validation of the simulated and the actual design data of Al-Jubail plant. The validation is satisfactory since the errors percentage is within the accepted engineering research work.

The invented cycle will now be evaluated based on the cycle; i) thermal efficiency & TBT limitations, ii) practicality and costs of the major components, iii) cycle chemistry & product water quality, and v) cycle environmental considerations.

5- RESULTS & DISCUSSION

5.1 Thermal Efficiency & TBT Limitations

The invented cycle as patented is mainly a power plant with water production as a byproduct. When its simulated results were compared with existing power-desalination cogeneration plant as Al-Jubail, the water production was found to be only 7 % of Al-Jubail's water production which is not acceptable as desalination unit product.

Two modifications were introduced to the invented cycle to increase its water production to a range comparable to Al-Jubail plant's cycle. The first was to replace the condenser by multi stage flash (MSF) evaporator. The simulated results of this modification show a slightly higher thermal efficiency than Al-Jubail plant. This result is expected because the invented cycle uses more feed water heaters in a reheating - regenerative cycle. The second was to eliminate reheating, use the same number of FWHs and apply similar turbine configuration as Al-Jubail to the invented cycle. This modification, Figure (4) provides more objective comparison between the two cycles. The results of this simulation shows that the invented cycle has slightly lower thermal performance for both power generation (power heat rate in kJ/MWe) and water production (Water heat rate in kJ/Ton of product water). From these results one will conclude that the invented cycle thermal efficiency does not exceed that of existing operating cogeneration cycles of the same limiting pressures and temperatures.

On the other hand, one main objective of the invented cycle was to overcome the TBT limitations. In current desalination technologies TBT is limited to 120 C to avoid scale formation. This limited TBT limits the MSF flashing range and therefore limits the water

production. The invented cycle succeeded to achieve this objective using the direct contact heat exchangers. However, the problems raised to achieve this objective question the practicality of implementing the cycle over the existing operating cycles.

5.2 Practicality & Costs of Major Components

The invented cycle poses some limitations to its practicality. In addition, for the invented cycle to operate with a thermal performance close to the current power-desalination plants, it has to operate with higher capital and operation costs. The practicality and cost effective of the invented cycle will now be evaluated.

i- Steam heater Efficiency

In the invented cycle, steam heater uses direct firing as the heat source to super heat the evaporated high pressure steam. The flue gases temperature (out of the steam heater) is very high leading to a very poor heater efficiency. In conventional plants flue gases are used to preheat the low temperature feed water (in the economiser) which is not present in the invented cycle. For steam heater of the size on conventional plants, Figure (5) shows that flue gas temperature of 635 °C with heater efficiency of 75.6 %. Increasing the steam temperature (to improve the thermodynamic cycle efficiency) will further decrease the heater efficiency due to the higher flue gas outlet temperature. On the other hand, the amount of superheated steam required to evaporate the water in the evaporator is too much (as seen in Figure (4), the super heated steam rate is 2342 tons/hr which is almost four times as much as conventional plant superheater rate of 645 tons/hr) which leads to higher heat transfer area of the heater and therefore the higher heater capital cost.

ii- High Pressure Evaporators & FWHs

With the required volume for direct contact heat & mass transfer, pressure vessels must be used for both evaporators and FWHs to overcome the operating pressure and temperature. The thickness and the cost of such pressure vessels are much larger than the only one pressure vessel (steam drum) in the boilers of conventional power plants. In addition, with the aggressive sea water working fluid at elevated pressure and

temperature, the special material required for vessel cladding will make it more expensive pressure vessels.

iii- Fan & Its Power Consumption

In the evaporators, feed seawater is evaporated using part of the superheated steam generated in the steam heater. The superheated steam is recirculated using a steam fan (compressor) to circulate large steam flow rate at very high pressure (above 150 bar) and very high temperature (above 550 C). Such unconventional equipment requires 1.77 MW electrical energy for each bar pressure drop. This is almost 90 times more power as compared to the conventional circulating boiler feed water pumps in conventional power plants which require only 19 kW / bar. As seen in Figure (4), the super heated steam rate is 2342 tons/hr which is almost four times as much as conventional plant superheater rate which leads to higher recirculating steam pressure drop and fan power. In addition, the fan requires special design to accommodate the salty water carry over. The carry over salts will deposit on the fan internals, deteriorates its performance and make its operation & maintenance cost very expensive.

iv- Additional Equipment

The invented cycle require additional non-standard (large size, special materials, ..etc.) equipment and components as salts separation filters, transferring pumps and piping system with its ancillaries. Special design filters is required since the filtration (and salt recovery) is a basic and essential part of the invented cycle. Transferring pumps between high pressure evaporators to handle highly concentrated brine at elevated pressure and temperatures are needed. Piping systems with its ancillaries (valves, steam traps, filters & strainers,...etc.) should be specially designed to accommodate the aggressive concentrated brine operation conditions.

v- Operation & Maintenance Cost

Using sea water and highly concentrated brine at elevated pressure and temperatures will result in high rate of corrosion, erosion and scale deposits. The plant outage frequency

will be very high with long shut down periods which increase the operation costs. The high rate of corrosion, erosion and scale deposits will increase the rate of spare parts replacements and increase the man-hours and, therefore, maintenance costs.

5.3 Cycle Chemistry & Product Water Quality

The current operating steam power plants are designed to use a well treated feed water with a recommended TDS of not more than 15 ppm. On the contrary, the invented cycle is based on using seawater (which contains various salts of a total TDS of 34,450 ppm for standard seawater) as continuous feed water. The seawater feed enters the cycle and leaves it as a product water and very concentrated brine (or salt). When seawater is used in the cycle at elevated temperature and pressure, three main potential problems occur. These are; i) scale formation, ii) corrosion, and iii) un-acceptable product water quality. These potential problems will now be discussed with its impact on the invented cycle practicality.

i- Scale Deposits

In the invented cycle, salt separation and recovery is one potential bi-product. Scale (salts) deposits, particularly the hard scale (as Calcium Sulfate - CaSO_4 - and Silica (SiO_2 -)) is one of the main desalination problems that deteriorate the plant performance. There are common methods in which the problems associated with the scale formation are possibly reduced. These are i) Controlling the operation TBT (up to about 120 C) and concentration range, ii) Removing the scale forming salts from seawater (pre-treatment), iii) Adding chemical additives that can stop Crystal growth, and, iv) Adding a seed for fast crystal formation in the free solution to avoid supersaturation and consequently scale formation during temperature rise.

Although the invented cycle eliminates scale deposits on the heat transfer surfaces (by using direct contact heat transfer equipment), scale formation will take place over various parts of plant components, impose a problem to the whole plant. For example, the TDS values at the evaporators section, Figure (6), vary from 47,300 ppm to 332,000 ppm.

These values are extremely high and unacceptable at such high temperature (310 °C) and pressure (99 bars). As a result the following serious problems will arise:

- 1- The sudden scale formation, due to the precipitation of CaSO_4 , would reduce heaters and evaporators volume and might clog the transfer pipes. The settlements of the suspended solids will also deposit on the connecting pipes and pumps blades & casing. This will increase pumping pressure and deteriorates the pumps operation performance.
- 2- Scale formation usually helps in inhibiting rate than conventional desalination-power plants. In the current method to control CaSO_4 precipitation (the seeding method), the corrosion-erosion rates will be very high due to the existence of the suspended crystals.
- 3- By heating seawater, a scale of mixed salts deposits is expected, and there will be no control over the type of salt precipitation. This is obvious because at high temperature, most of the existing salts will reach supersaturation condition and any salt seed will act as a nucleus for the rest.
- 4- Scale prevention additives for such operating conditions (of high temperature & temperature / high concentration) are not available in the market and not scientifically proven and expected to be very expensive.
- 5- Due to the above problems, the shut down frequency (and outage time period to re-start) will not be accepted as compared to proven conventional plants.

For the remaining direct contact heaters, Figure (6), the dilution rate is not significant and the temperature is very high. For example after FWH # 1 (TDS = 29,585 ppm & T = 164.3 °C), after FWH # 2 (TDS = 27,908 ppm & T = 194.3 °C), after FWH # 3 (TDS = 26,010 ppm & T = 229.2 °C). The operation of these FWHs will also be complicated.

ii- Corrosion & Erosion

Another potential problem of using seawater as feed water to the plant is the expected high rate of corrosion on plant components. Although the dissolved gases are easily removed in the direct contact heaters and evaporators, the high salinity of seawater and

the elevated temperature enhances the corrosion rate. Only high expensive alloys (as titanium, see Table 2) are needed to overcome such aggressive operation conditions. In addition to corrosion, the presence of high rate of scale deposits causes serious erosion problems before they could be totally filtered. On the other hand, the current steam power plant faces the difficulties from the high rate of erosion in the turbine blades due to carry over. In the invented cycle, the carry over of salts to the steam system is expected to be higher than conventional power plants due to the very concentrated brine in the evaporators, see Figure (6). With higher concentration of salts in the carry over the steam problems will be worse (erosion in high pressure and corrosion in low pressure section of the turbine - an expensive, sensitive and important piece of plant equipment -). This will deteriorate the turbine performance, availability and maintainability. On the other hand, Salts carry over will cause serious problems in the high temperature steam heater tubes that will lead to tube failure.

The scale deposits and the corrosion-erosion problems associated with invented cycle make it un-acceptable from plant chemistry point of view. The cycle solved the heating surface problem, but, creates many problems all over the plant.

iii- Product Water Quality

The turbine steam contains some conditioning chemicals and additives that make it more protective for the plant equipment. Some of these chemicals will be transferred from the seawater feed into the steam through carry over salty water and volatile substances. For example, hydrazine, (N_2H_4 , an de-oxygenation agent). The steam condensate, as the invented cycle product water, will not, therefore, suit direct human use. Product water post treatment of these additives is rather un-economical.

5.4 Environmental Considerations

The environmental aspect of the invented cycle, as claimed, is not different from conventional plants. For example, i) in order for the invented cycle to generated a specified electrical power and produced a specified rate of water, it must burn the same amount of fuel as conventional cogeneration plant and generate the same amount of gas

pollutants to the environment, ii) the concentrated disposal of the conventional desalination plants could be treated similar to the invented cycle, and iii) the quantity and quality of the chemical additives to be used in the invented cycle (to handle sea water) will be as much or even more than that required for conventional desalination-power plants.

6- CONCLUSIONS

A numerical analysis and technical evaluation of a newly invented cycle by Madani [4] has been carried out. The cycle was proved to be a modification of Blaskowski's cycle, [6]. The advantages claimed of higher thermal efficiency was proved to be not justified. Although the invented cycle was able to overcome the TBT limitation, using direct contact heat exchangers, the cycle does not provide a better alternative to the existing cogeneration cycle. The following are the cycle main drawbacks:

- 1- For the same boiler and condenser pressures, the water production of the invented cycle (as patented) does not exceed 7% of the production of Al-Jubail II plant. In addition, the water produced can not be used directly since it is contaminated with different chemicals to suit its main function as boiler-turbine working fluid.
- 2- The invented cycle thermal efficiency is not better than the currently available power cycles. The results shows that the invented cycle performance is slightly lower than conventional cogeneration plants for both power generation (power heat rate in kJ/MWe) and water production (Water heat rate in kJ/Ton of product water). The claimed increase in cycle efficiency is mainly due to the high steam pressure which is a rule of thumb for power plant. Under equivalent design conditions, For example, the invented cycle shows lower thermal efficiency when compared with Al-Jubail plant-II.
- 3- The invented cycle poses some limitations to its practicality due to the unavailability of conventional equipment, to operate at high working fluid salinity and elevated temperature and pressure. This equipment includes; circulating fans, direct contact seawater FWHs and evaporators (pressure vessels), transferring seawater pumps, filters ... etc.

- 4- With direct contact evaporators, the settlements of the suspended solids will deposit on the vessel walls, connecting pipes and pumps blades and casing. This will reduce the vessels size, increase pumping pressure and deteriorates the pumps operation performance. Scale prevention additives for such operating conditions are not available in the market and not scientifically proven and expected to be very expensive.
- 5- When seawater is used as a feedwater for the power cycle, the plant chemistry and the related problems (such as high rates of corrosion, scale formation, and carry-over) are much more complex than conventional plants. The high frequency of the plant outage and long shutdown duration is, therefore, likely to occur during plant operation which increases operation & maintenance costs.
- 6- Although the invented cycle saves the capital cost of the MSF units, its water production cost can not, still, compete with the existing dual purpose plant, due to the high costs of the special components & equipment required, and the cost of product water post treatment.
- 7- The environmental aspect of the power side of the patented cycle is not different than conventional plants, as claimed. The concentrated disposal of the conventional desalination plants could be treated similar to that of the invented cycle.

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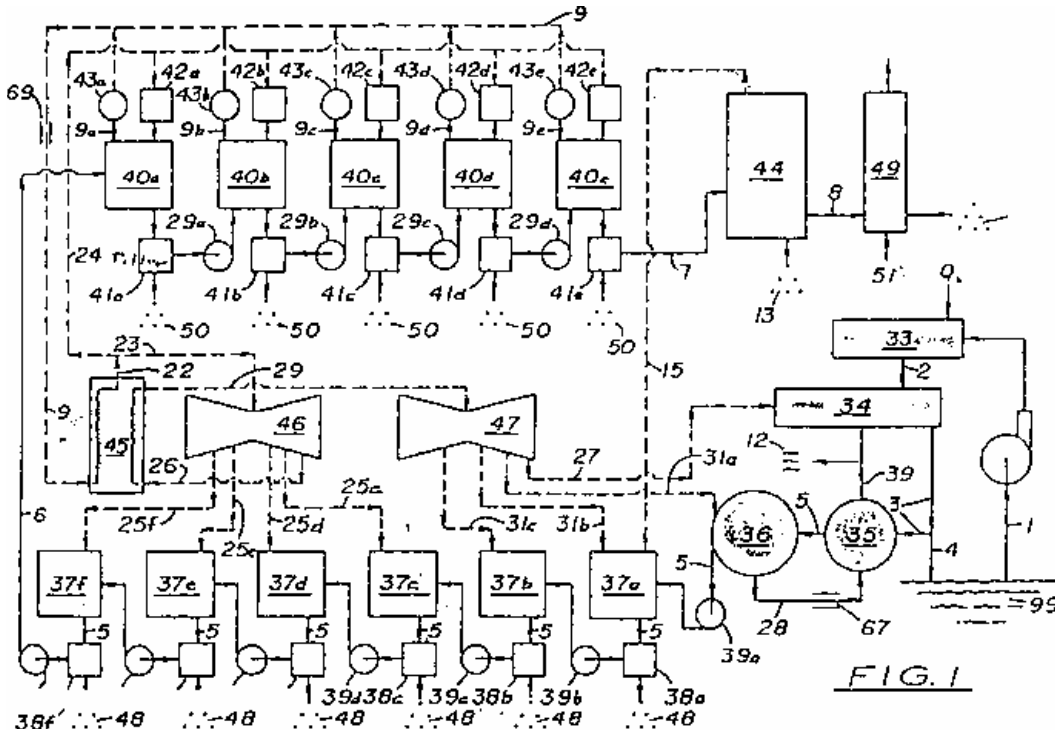


Figure (1) The Invented Cycle By Madani [4], As Patented

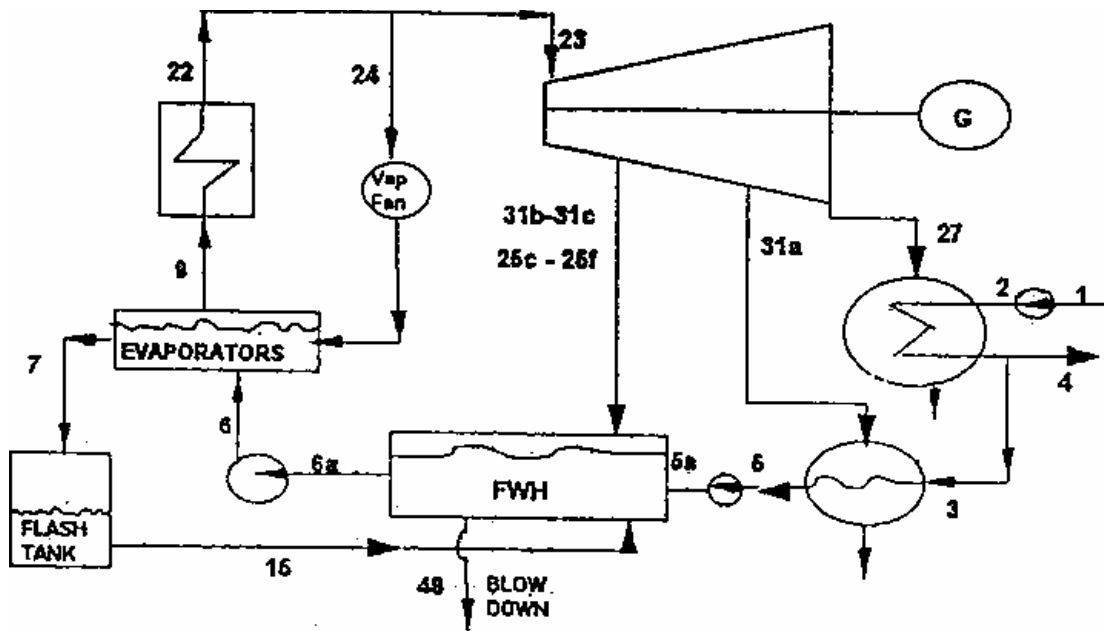


Figure (2) The Invented Cycle After Simplification & Re-arrangement

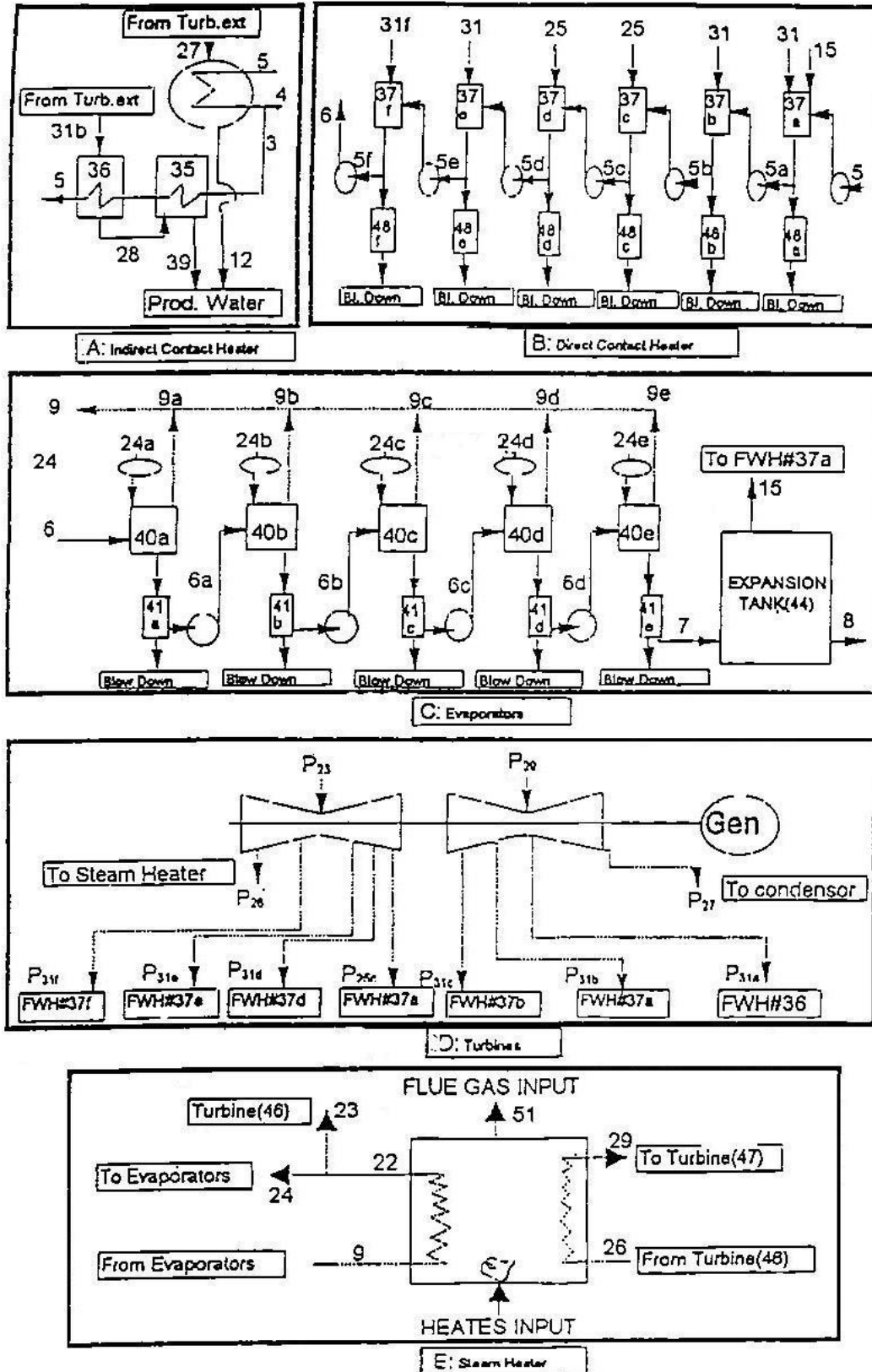


Figure (3) The Simulated Five Segments of the Invented Cycle

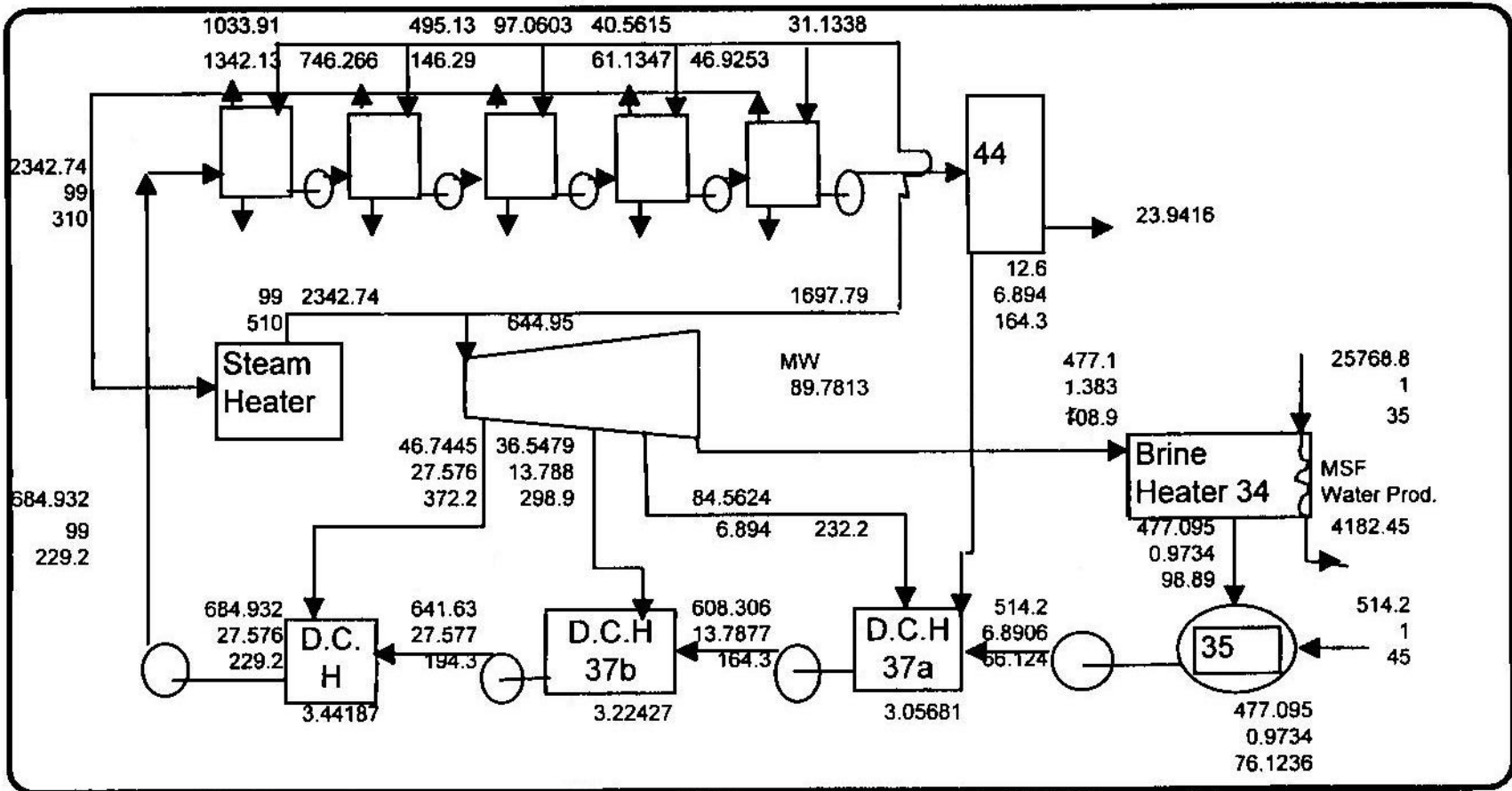
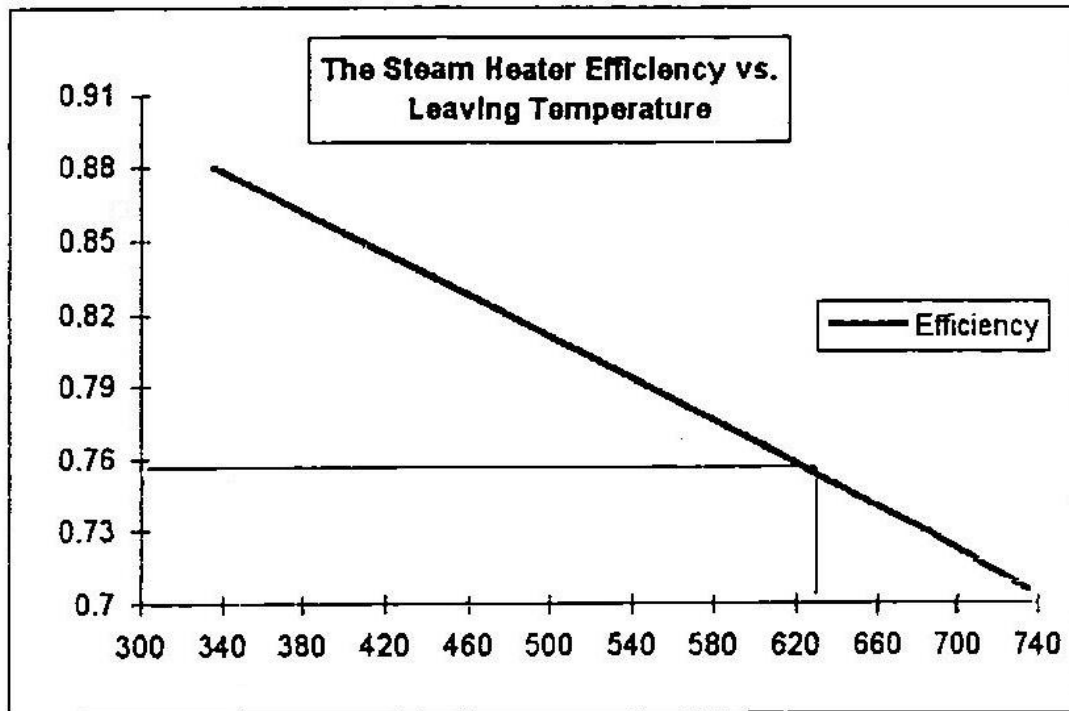
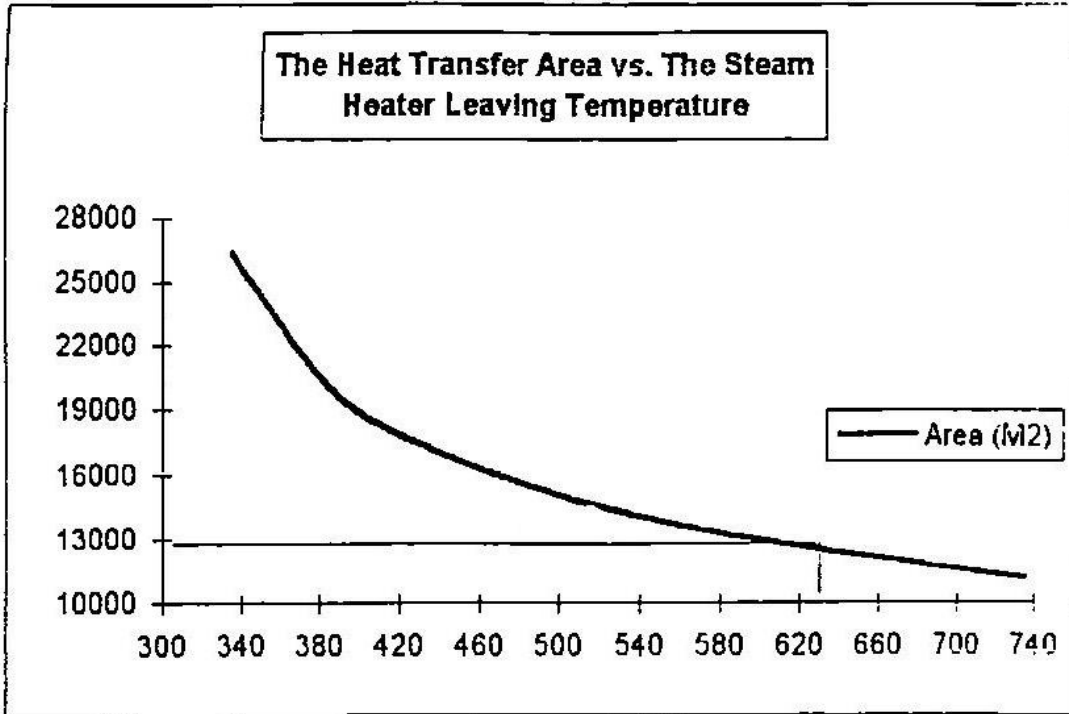


Figure (4) The Modified (Back Pressure Turbine) Invented Cycle to Simulate Al-Jubail Desalination & Power Plant



**Figure (5) Steam Heater Area and Thermal Efficiency
Versus Flue Gas Temperature**

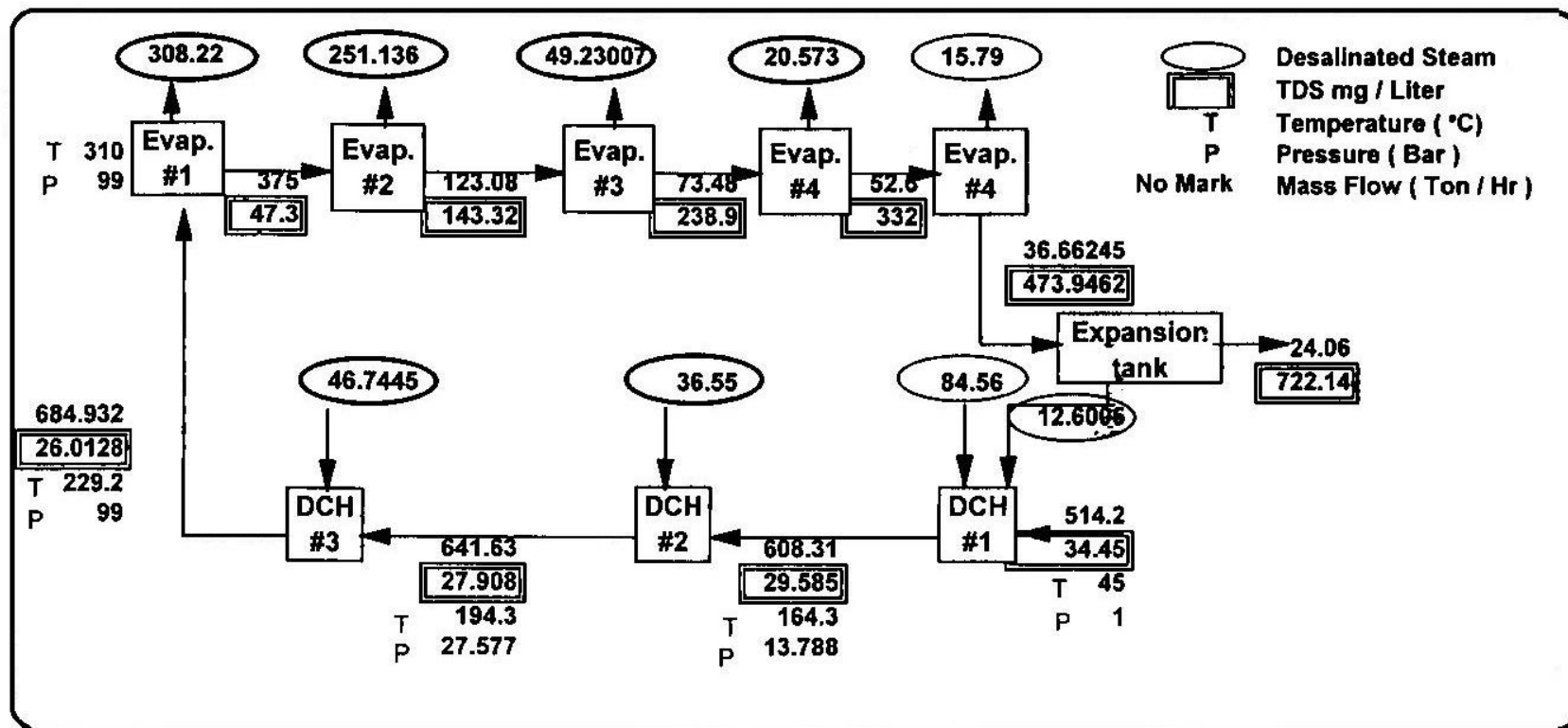


Figure (6) Invented Cycle Main Simulated Parameters
(Mass Flow, Pressure, Temperature, and Total Dissolved Solids -TDS-)

Table (1) The Simulated and Published Data for Al-Jubail-II Plant

| AL Jobail-II Plant | Simulated Mass Flows | Given Design Data | % Diff |
|--|----------------------|-------------------|--------|
| POWER (MW) | 89.78 | 89.88 | -0.11 |
| WATER (Ton/Hr) | 3781.02 | 3781.02 | 0.00 |
| Fuel cons (GJ) | 1676.53 | 1680.00 | -0.21 |
| kW/kJ | 0.19 | 0.19 | 0.10 |
| M3/KJ | 0.00 | 0.00 | 0.21 |
| Line# 1 Mass Flow Steam to Turbine | 618.93 | 620.20 | -0.20 |
| Line# 2 Mass Flow 1st Ext. Flow | 45.57 | 45.68 | -0.25 |
| Line# 3 Mass Flow 2nd Ext. Flow | 27.97 | 29.15 | -4.04 |
| Line# 4 Mass Flow 3rd Ext. Flow | 58.56 | 58.53 | 0.05 |
| Line# 5 Mass Flow Steam to Condenser | 486.84 | 486.84 | 0.00 |
| Line# 6 Mass Flow Condensate Flow | 486.84 | 486.84 | 0.00 |
| Line# 7 Mass Flow Condensate before FWT | 486.84 | 486.84 | 0.00 |
| Line# 8 Mass Flow Feed Water before FW Pump | 618.93 | 620.18 | -0.20 |
| Line# 9 Mass Flow Feed Water after FW Pump | 618.93 | 620.18 | -0.20 |
| Line# 10 Mass Flow Feed Water before Heater#2 | 618.93 | 620.18 | -0.20 |
| Line# 11 Mass Flow Feed Water before boiler | 618.93 | 620.18 | -0.20 |
| Line# 12 Mass Flow Condensate to Heater#1 | 45.57 | 45.68 | -0.20 |
| Line# 13 Mass Flow Condensate from Heater#2 | 73.53 | 74.83 | -1.73 |

Table (2) Metals Potentials Series in Seawater

| | |
|--|--|
| Noble end | |
| Titanium | |
| Monel (67% Ni, 30% Cu, 1.2% Fe) | |
| * Passive stainless Steels | |
| Inconel (80% Ni, 13% Cu, 6.5% Fe) | |
| Nickel | |
| Copper/Nickel 70 730 | |
| Copper/Nickel 90/10 | |
| Aluminium bronze | |
| Copper | |
| Alpha brass (70% Cu, 30% Zn) | |
| Aluminium brass | |
| Muntz metal (60% Cu, 40% Zn) | |
| Tin | |
| * Active stainless steels | |
| Cast iron | |
| Mild steel | |
| Aluminium | |
| Zinc | |
| Magnesium | |
| <hr/> | |
| * Passive stainless steel is covered with an oxide film and resists corrosion. Active stainless steel is of the same composition, but the oxide film has been destroyed and the alloy behaves in a much less noble manner. | |