# EVALUATION OF NUCLEAR DESALINATION THERMAL COUPLING USING SECOND LAW OF THERMODYNAMICS

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**الملخص**

تقدم هذه الورقة تحليلاً ديناميكياً حرارياً مستنداً إلى القانون الثاني للديناميكا الحرارية لمحطة قدرة نووية من نوع PWR ربطت إليها محطة تحليه مياه متعددة التأثير (لمراحل) (Multi- Effect Distillation)

تهدف الورقة إلى دراسة أداء الربط الحراري من منظور القانونين الأول والثاني للديناميكا الحرارية عن طريق استخلاص البخار من عدة نقاط في تربينه الضغط الخلفي، وفي هذه الدراسة تم تثبيت كمية المياه المنتجة المحلاة.

حيث أظهرت النتائج التي تم الحصول عليها أن الكفاءة الحرارية $\eta_{I\ CO}$ للمحطة ثنائيه الغرض تتناقص بازدياد ضغط بخار الاستنزاف، وتزداد الكفاءة الحرارية بتناقص درجة الحرارة العليا للمحلول الملحي في محطة التحليه MED المشار إليها، وإن الفعالية الجزئية للربط الحراري $\eta_{II\ TCMED}$ تتناقص بازدياد ضغط بخار الاستنزاف وكذلك تتناقص بازدياد درجة الحرارة العليا للمحلول الملحي في محطة التحليه. بينما الفعالية الجزئية للقدرة الكهربية المنتجة $\eta_{II\ Elec.}$ لا تعتمد على ضغط بخار الاستنزاف ولكنها تتحسن تحسناً طفيفاً بازدياد درجة الحرارة العليا للمحلول الملحي في محطة التحليه.

## ABSTRACT

Thermodynamic analysis of Nuclear Power plant (pressurized water reactor) coupled with forward feed multi effect distillation (MED) were performed. The thermodynamic efficiencies are obtained by the extraction steam at different points from the back pressure turbine to steam transformer to generate heating steam of MED with effect of top brine temperature in the MED plant, and the amount of the produced potable water was fixed.

The first law efficiency of the plant decreases with increase of the extraction steam pressure and increases with decreasing of the top brine temperature of MED plant, the partial second law of desalination thermal coupling decreases with the increase of the extraction steam pressure and decreases with the increase of the top brine temperature for the MED plant. The partial second law efficiency of electricity production is not depending on extraction steam pressure, but little improved with increase of top brine temperature. The effect of the increasing of extraction steam pressure and increasing of top brine temperature are not efficient due to the increasing of the exergy flow consumption to steam provided for distillation plants $\dot{\Psi}_S$, in spite of improving of partial effectiveness of electricity $\eta_{II\ Elec.}$ when increasing the top brine temperature the thermal coupling behaves as regenerative cycle.

**KEYWORDS:** Exergy; Top brine temperature; Multi Effect Desalination MED; Extraction steam pressure.

## PHYSICAL DESCRIPTION

A nuclear powered steam plant is basically a conventional steam plant with a nuclear reactor replacing the combustion of fuel as the energy source.

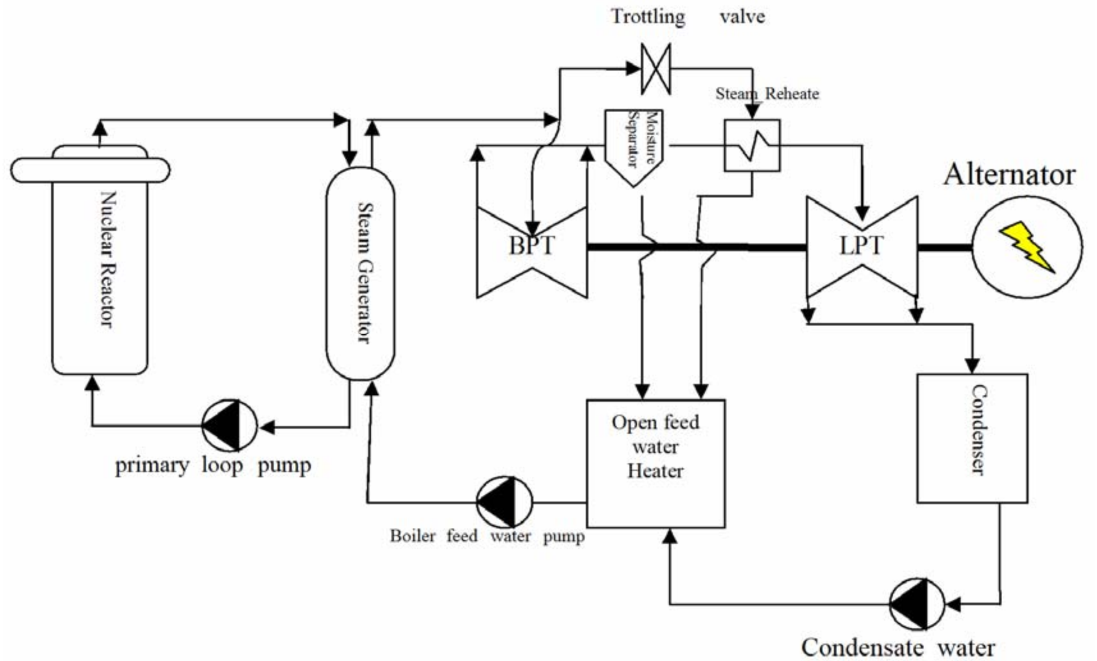


**Figure 1: Typical nuclear powered steam power plant with a pressurized water reactor.**

However, the design of the entire plant must be adjusted to the characteristics of the nuclear reactor. In nuclear power plant using the pressurized water reactor (PWR) Figure1 is cooled by pressurized water circulated without boiling between the reactor and the steam generator. In the steam generator, heat transfer from the primary coolant (pressurized water) to the secondary circuit (low-pressure water) generates steams which circulate through the turbine and the condenser. The turbine, condenser, feed water pumps, and regenerative feed water heater are similar to the same components in the fuel-fired plant. The major difference here the turbine must expand wet steam because of the rather low-maximum temperature in the reactor. In order to handle wet steam, the turbine has both internal and external separators to separate moisture drops from the steam flow. In addition, Figure (1) shows how steam delivered directly from the steam generator can be used to reheat intermediate pressure steam and reduce the amount of moisture passing through the low-pressure turbine [1].

### THERMAL DESALINATION COUPLING ASPECTS

Desalination plants can be coupled with nuclear reactor as a single purpose plant or a co-generation plant. In the case of a single purpose nuclear desalination plant, energy is exclusively used for the desalination process. Moreover, the desalted water is the only product output. The nuclear reactor is fully dedicated to supplying energy for desalting. In case of the co-generation plant, only a part of the energy is utilized for desalting. A co-generation plant produces both electricity and desalinated water simultaneously, when a nuclear reactor is used to supply steam for desalination, the method of coupling has a significant technical impact. The optimum method of coupling depends on the size and type of the reactor, the specific characteristics of the desalination process and the desirability and value of electricity generation as a dual product.

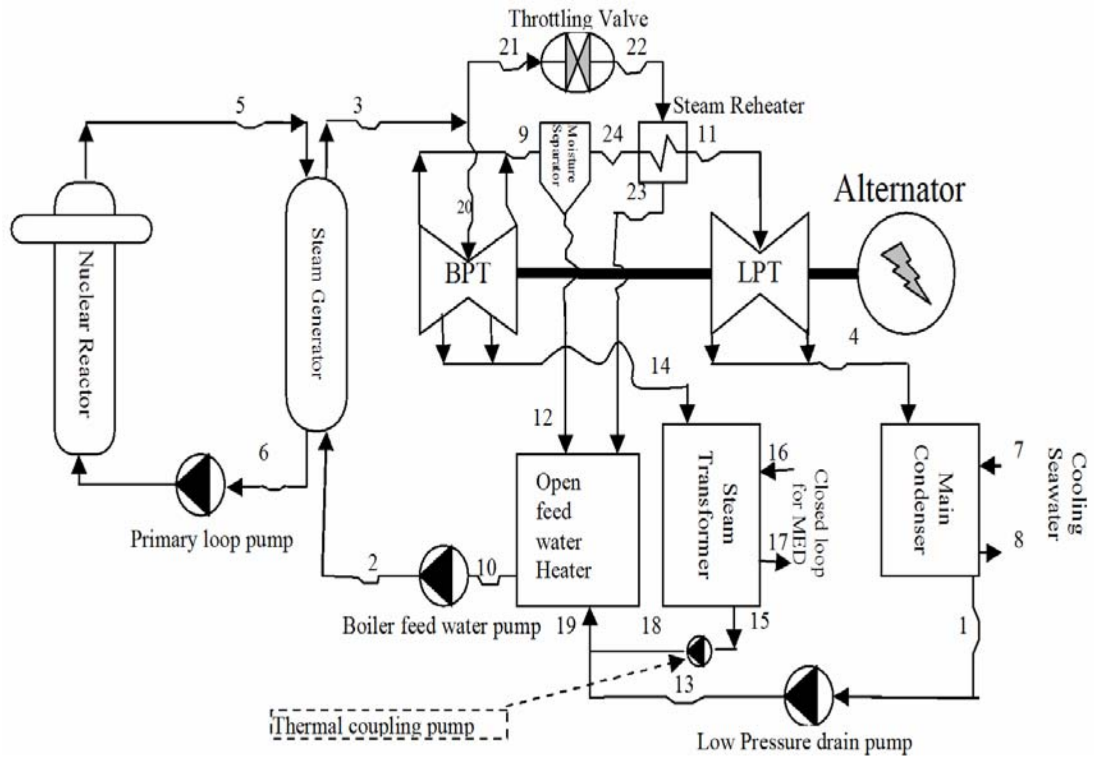


**Figure 2: Diagram of nuclear power plant coupled with desalination plant (MED)**

The nuclear power plant can be coupled to multi stage flashing (MSF), MED, reverses osmosis (RO) plants, and hybrid desalination plant (MSF or MED with RO). However, there are three methods of coupling [2]: desalination plant coupled to power reactors, desalination plant coupled to heating reactors, and desalination plant coupled to co-generation reactors. However, this study is directed to forward feed multi effect desalination plant coupled with parallel co-generation pressurized water nuclear reactor. In parallel co-generation, electricity is produced as co-product along with desalted water by diverting a part of the steam to the turbine to produce electricity in the conventional manner and part of the steam to the desalination plant. This configuration allows increased flexibility in energy use. However, the total energy consumption would be the same as if the steam for desalination and electricity had been produced separately. Coupling arrangements of pressurized water power reactor (PWPR) with a MED plant are shown in Figure (2) and Figure (3).

Usually, the coupled plant uses the steam transformer loop as an isolation barrier [2]. Therefore, the thermal coupling of MED with the PWR power plant is implemented by the steam transformer. Backpressure turbine extracted steam is condensed in the steam transformer condenser. The latent heat of condensation is transferred to a circulating water stream Figure (3). A portion of water flashes in the steam transformer, thereby forming a steam for the first effect of MED, and the condensate steam delivered from the first MED effect goes back to the steam transformer.

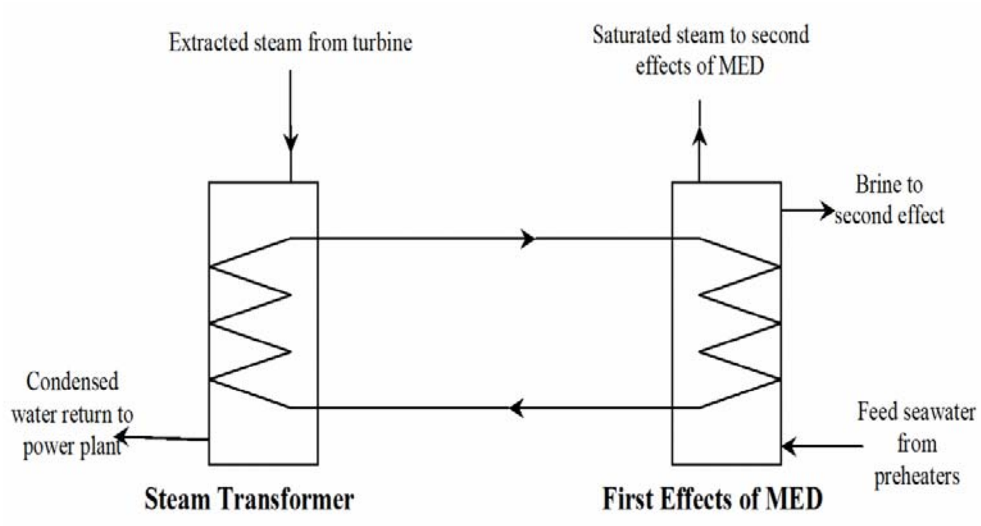


**Figure 3: Schematic diagram shows the circulating loop between steam transformer and first effects of MED plant.**

## MATHEMATICAL MODELING

A simplified pressurized water reactor plant (PWR), which has two coolant systems was illustrated in Figure (2). The reactor using light water as both coolant and moderator. The analysis are taken place by considering the component of the systems of the plant by applying continuity, energy balance and exergy balance to each of the control volume (component). The basic assumptions are steady state thermodynamics analysis, neglecting the effect of pressure drop in the transmission lines, neglecting the effect of kinetic and potential energies and adiabatic process to surrounding. Temperatures versus fractional length are plotted in Figure (4), the minimum primary to secondary temperature difference occurs at the axial location of the onset of bulk boiling in the secondary side.

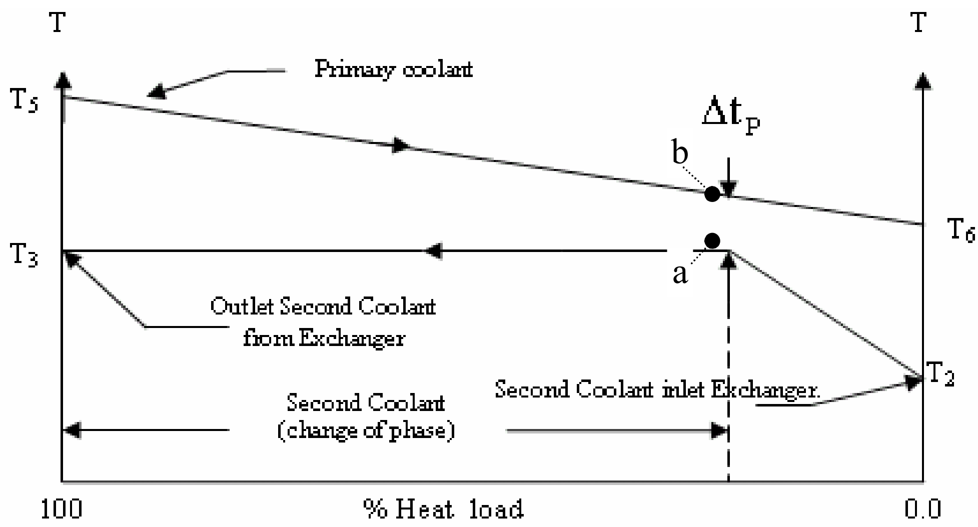


**Figure 4: steam generator temperatures distribution with heat load' %'**

All temperatures are related to this minimum, or pinch point. Therefore the specification of the pinch point temperature difference is an important design choice based on tradeoff between cost and irreversibility, and the initial thermodynamic PWR operating conditions [5]:

- The pressure and temperature at point 5 are $P_5$ is 155 bars, $T_5$ is 599 K.
- The pressure and temperature at point 6 are $P_6$ is 155 bars, $T_6$ is 565 K.
- The core power is 1870 MW.
- The minimum pinch point between primary and secondary cooling systems is $\Delta T_p = 14.4\ \text{K}$.
- The extracted steam temperature to entering open feedwater heater at point (10) in Figure (2) is given by $T_{10} = T_3 - \frac{T_3 - T_4}{2}$
- Number of units in the MED plant is eight units coupled in parallel with steam transformer to operate more flexible.
- The distilled water within MED plant is 288000 $m^3$/day.

The exergy analyses of the power plant coupled with the desalination plant MED is needed to calculate the exergies flow $\dot{\Psi}_E$ and $\dot{\Psi}_S$ which are required to produce the total amount of electricity and steam driving the MED respectively. The exergy flows $\dot{\Psi}_C$ can be assigned to the generation of electricity as well as to the production of steam.

The exergy flows of $\dot{\Psi}_E$ and $\dot{\Psi}_S$ are calculated by following equations:

$$\dot{\Psi}_C = \dot{I}_{NR} + \dot{I}_{SG} + \dot{I}_{FH} + \dot{I}_{FP} + P_{Aux} \tag{1}$$

Where: $(\dot{I}_{NR}, \dot{I}_{SG}, \dot{I}_{FH}, \dot{I}_{FP}, P_{Aux})$ are the irreversibilities of (nuclear reactor, steam generator, feed heaters, feed pumps) and electrical auxiliary loads respectively?

The exergy flows are allocated exclusively to the generation of electricity.

$$\dot{\Psi}_{E_e} = \dot{I}_T + \dot{I}_{Con} + \dot{I}_G + P_{net} \tag{2}$$

Where $(\dot{I}_T, \dot{I}_{Con}, \dot{I}_G, P_{net})$ are the irreversibilities of (turbines, Condenser, Alternator (generator)) and electrical net power, respectively.

The exergy flows are allocated exclusively of steam provided for distillation plants.

$$\dot{\Psi}_{S_e} = \Delta\dot{\Psi}_{TCMED} = \dot{m}_{14}\,\psi_{14} - \dot{m}_{15}\,\psi_{15} \tag{3}$$

$\psi_{14}, \psi_{15}$ are the streams or flow exergies of stations 14, 15 respectively.

And $\psi_{14} = h_{14} - h_o - T_o\,(s_{14} - s_o)$ (4)

$$\psi_{15} = h_{15} - h_o - T_o\,(s_{15} - s_o) \tag{5}$$

The exergy flow of fuel $\dot{\Psi}_F$ is calculated by:

$$\dot{\Psi}_F = \dot{\Psi}_C + \dot{\Psi}_{E_e} + \dot{\Psi}_{S_e} \tag{6}$$

The exergy flow consumption for electricity $\dot{\Psi}_E$ is calculated by:

$$\dot{\Psi}_E = \dot{\Psi}_{E_e} + \dot{\Psi}_C \cdot \frac{\dot{\Psi}_{E_e}}{\dot{\Psi}_{E_e} + \dot{\Psi}_{S_e}} \tag{7}$$

The exergy flow consumption to steam provided for distillation plants $\dot{\Psi}_S$ is calculated by

$$\dot{\Psi}_S = \dot{\Psi}_{S_e} + \dot{\Psi}_C \cdot \frac{\dot{\Psi}_{S_e}}{\dot{\Psi}_{E_e} + \dot{\Psi}_{S_e}} \tag{8}$$

Detailed description of thermal analysis of forward feed MED can be found elsewhere [4]. In order to evaluate the efficiencies of the co-generation plant. It is necessary to calculate the thermal quantities:

The absorbed heat with 1st effects of MED plant $\dot{Q}_{TCMED}$ is calculated by:

$$\dot{Q}_{TCMED} = \dot{m}_S \lambda_S$$

Where $\dot{m}_S$ : amount of mass flow rate of saturated steam driving MED plant, $\lambda_S$ : latent heat at $T_s$.

The absorbed heat with distilled water $\dot{Q}_{dw}$ is calculated by:

$$\dot{Q}_{dw} = \dot{M}_d \overline{C}p (T_{Cn} - T_{Sea}) \quad (9)$$

Where $\dot{M}_d$ : total mass flow rate of distilled water within MED plant, $\overline{C}p$ is specific heat at constant pressure of distilled water, $T_{Cn}$ is the temperature of outlet distilled water from MED, $T_{Sea}$ is the temperature of sea water.

The amount of absorbed heat with rejected brine for MED $\dot{Q}_{bw}$ is expressed by;

$$\dot{Q}_{bw} = (\dot{m}_b)_n Cp (T'_n - T_{cw}) \quad (10)$$

Where $(\dot{m}_b)_n$ : is rejected brine water from MED plant, $Cp$ is specific heat at constant pressure of brine water, $T'_n$ is the temperature of outlet brine water out last effect MED, $T_{Sea}$ is the temperature of sea water

The amount of absorbed heat with rejected coolant seawater for MED $\dot{Q}_{CW}$ is expressed by;

$$\dot{Q}_{CW} = \dot{m}_{CW} Cp \, (T_f - T_{Sea}) \quad (11)$$

Where $\dot{m}_{CW}$ : is rejected cooling seawater from MED plant, $Cp$ is specific heat at constant pressure of cooling seawater, $T_f$ is the temperature of seawater flow out the down condenser MED.

The utilized heat loads for MED $\dot{Q}_u$ given by:

$$\dot{Q}_u = \dot{Q}_{TCMED} - \dot{Q}_{dw} - \dot{Q}_{bW} - \dot{Q}_{CW} \quad (12)$$

And, hence the first law of thermodynamic efficiency of the plant $\eta_{I\ CO}$ is defined by;

$$\eta_{I\ CO} = \frac{P_{net.} + \dot{Q}_u}{\dot{Q}_{NR}} \quad (13)$$

The partial second law of thermodynamic efficiency of thermal coupling for MED $\eta_{II\ TCMED}$ is defined as

$$\eta_{II\ TCMED} = \frac{\dot{Q}_{TCMED}}{\dot{\Psi}_S} \quad (14)$$

The partial second law of thermodynamic efficiency of Electricity generation of the plant $\eta_{II\ Elec.}$ expressed by:

$$\eta_{II\ Elec.} = \frac{P_{net}}{\dot{\Psi}_E} \quad (15)$$

## RESULTS AND DISCUSSIONS

The first and second laws of thermodynamics are applied to predicate the behavior of co-generation process in terms of the following parameters:

**The effect of the extraction steam pressure and the top brine temperature on the first law of thermodynamic efficiency $\eta_{I\ CO}$**

Thermal efficiency is plotted versus both the extraction steam pressure from BPT and top brine temperature of MED plant as shown in Figure 5. It's found that thermal efficiency of the plant decreases with increasing the extraction steam pressure, the thermal efficiency drops 26% from its original value at extraction steam pressure of 1.66 bars to extraction steam pressure of 59.44 bars at top brine temperature equal 60$^o$C.

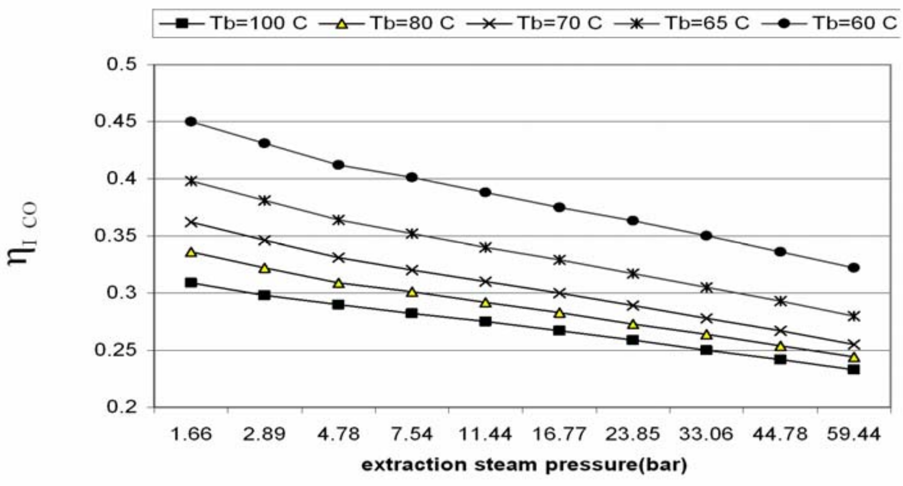


**Figure 5: Effects of the extraction steam pressure and top brine temperature on the $\eta_{I\ CO}$**

The thermal efficiency drops 28% from its original value at extraction steam pressure of 1.66 bars to extraction steam pressure of 59.44 bar at top brine temperature equal 100$^o$C. The thermal efficiency drops 31% from its original value at top brine temperature of 60$^o$C to top brine temperature of 100$^o$C when the extraction steam pressure is 1.66 bars, the thermal efficiency drops 27% from its original value at top brine temperature of 60$^o$C to top brine temperature of 100$^o$C when the extraction steam pressure is 59.44 bars.

**The effect of extraction steam pressure and top brine temperature on partial effectiveness of thermal coupling $\eta_{II\ TCMED}$**

The partial second law of thermodynamic efficiency (effectiveness) of thermal coupling for MED plant which was defined by equation 14 is plotted versus both extraction steam pressure and top brine temperature of MED is presented in Figure (6). The partial effectiveness of thermal coupling $\eta_{II\ TCMED}$ drops 64 % from its original value at extraction steam pressure of 1.66 bars to extraction steam pressure of 59.44 bars at top brine temperature equal 60$^o$C. The partial effectiveness of thermal coupling $\eta_{II\ TCMED}$ drops 51.2 % from its original value at extraction steam pressure of 1.66 bars to extraction steam pressure of 59.44 bars at top brine temperature equal 100$^o$C. And that decreases with increase of the top brine temperature, These effects caused by the increasing of the exergy flow consumption to steam provided for distillation plants $\dot{\Psi}_S$ or the increasing of total irreversibility due to the temperature difference between extraction steam and TBT of MED, the increasing of the extraction steam pressure and increasing of top brine temperature are not efficient due to the increasing of the exergy flow consumption to steam provided for distillation plants $\dot{\Psi}_S$.

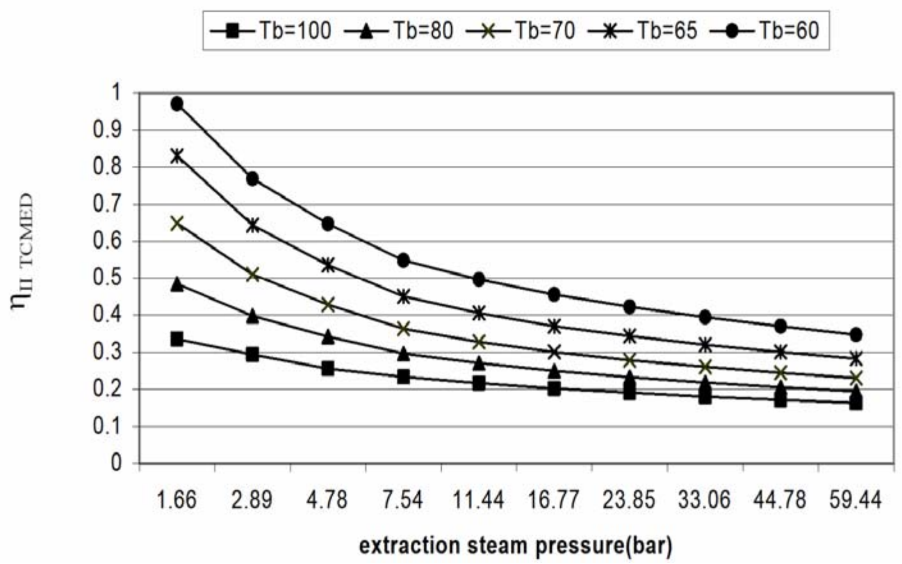


**Figure 6: Effects of the extraction steam pressure and top brine temperature on the partial effectiveness of thermal coupling $\eta_{II\ TCMED}$**

**The Effect of the extraction steam pressure and top brine temperature on effectiveness of electricity production $\eta_{II\ Elec.}$**

The partial second law of thermodynamic efficiency of Electricity production $\eta_{II\ Elec.}$ of the plant which given by equation 15 versus both the extraction steam pressure and the top brine temperature of MED is plotted in Figure (7).

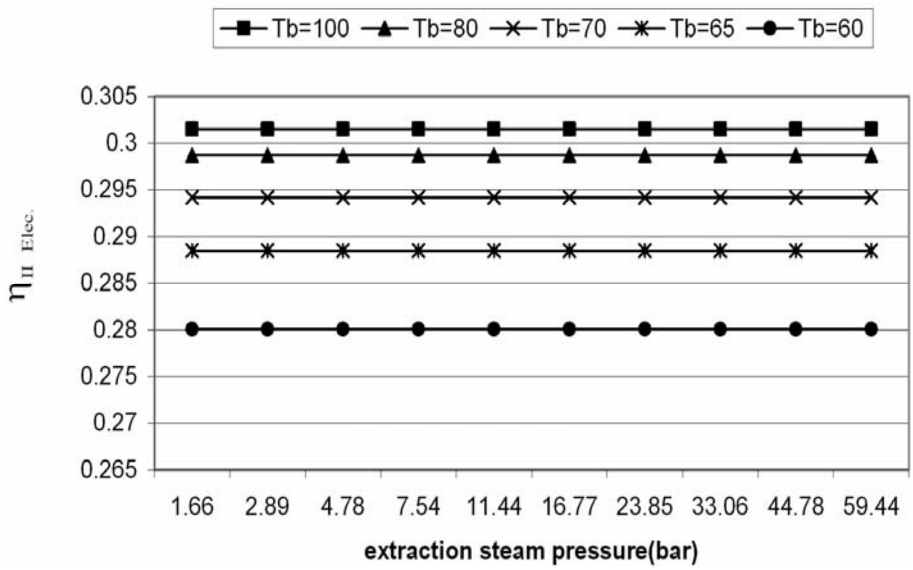


**Figure 7: Effects of the extraction steam pressure and top brine temperature on the partial effectiveness of electricity production $\eta_{II\ Elec.}$**

Figure (7) shows that the partial effectiveness of electricity production does not depend on extraction steam pressure, but it increases as the temperatures of the top brine temperature increase, this is because of increasing of electricity production, the latent heat of desalination thermal coupling decreases with increase of top brine temperature of MED, also thermal coupling works as regenerative cycle, when the TBT was increased. But the improving of partial effectiveness of electricity production is small compared with the improving of partial effectiveness of desalination thermal coupling.

## CONCLUSIONS

In this study a mathematical model has been developed to evaluate the thermal coupling of nuclear power pressurized water reactor plant (PWR) with multi effect distillation (MED) plant. The behavior of the thermal coupling is investigated in terms of extraction steam pressure and top brine temperature. The results show that; the increasing of the extraction steam pressure leads to a decreasing in first law efficiency of the co-generation power plant $\eta_{I\ CO}$ as well a decreasing in second law efficiency $\eta_{II\ TCMED}$, while the impact of extraction steam pressure on the effectiveness of electricity production $\eta_{II\ Elec.}$ is insignificant. The present study, however, has shown that $\eta_{I\ CO}$ is increasing with the decreasing of the top brine temperature, while $\eta_{II\ TCMED}$ decreases as a result of top brine temperature increases, but $\eta_{II\ Elec.}$ is slightly improving due to increasing of top brine temperature, since thermal coupling process works as a regenerative cycle.

The present model, although it is much more general, it is also reliable and enough accurate from engineering point of view in the analysis of nuclear desalination technology.

We emphasize that the second law analysis used in this study also facilitate a means of identifying the plant components with high exergy destruction (irreversibilities).

Thermo economic evaluation of such plant of co-generation is a future task of research, to answer the questions of the impact of the mentioned parameters on the cost of desalination of water via thermal coupling with nuclear power plant.

**Acknowledgment**

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**NOMENCLATURE**

| | |
|---|---|
| PWR | Pressurized Water Reactor |
| NPP | Nuclear Power Plant |
| MED | Multi Effect Distillation |
| TBT | Top brine temperature of MED plant |
| Cp | Specific heat at constant pressure over the temperature T |
| $h_o$ | Enthalpy of fluid at temperature $T_o$ |
| $\dot{m}_f$ | Mass flow rates of feedwater of MED |
| $\dot{M}_d$ | Total mass flow rate of distilled water within MED plant |
| $(\dot{m}_b)_n$ | Rejected brine water from MED plant |
| $\dot{m}_{CW}$ | Rejected cooling seawater from MED plant |
| $P_{net}$ | Electrical net power, kW |
| $P_{Aux}$ | Electrical auxiliary loads with the exception of feedwater pumps and reactor coolant pumps, kW |
| $\dot{Q}_{TCMED}$ | The heat absorbed by thermal coupling of MED |
| $\dot{Q}_{NR}$ | Heat source of nuclear reactor |
| $\dot{Q}$ | Heat rate, kW |
| $\dot{I}$ | The irreversibility rate, kW |
| $\Delta T_P$ | The pinch point temperature difference between primary and secondary loops of PWR. |
| To | Dead point at environment temperature, $^oK$. |
| $T_{Cn}$ | The temperature of outlet distilled water from MED. |
| $T_{Sea}$ | The temperature of sea water |
| $T'_n$ | The temperature of outlet brine water out last effect MED. |
| $T_f$ | The temperature of seawater flow out the down condenser MED. |
| $\lambda_S$ | Latent heat associated to temperature $T_s$ . |
| S | Entropy of the flow |
| $\dot{\Psi}_E$ | Exergy consumption for electricity |
| $\dot{\Psi}_S$ | Exergy consumption to steam provided for distillation plants. |
| $\dot{\Psi}_C$ | The exergy flows. |
| $\dot{\Psi}_{Ee}$ | The exergy flows are allocated exclusively to the generation of electricity. |
| $\dot{\Psi}_{Se}$ | Exergy of steam provided for distillation plants |
| Plant | |
| $\eta_{I\ CO}$ | The thermal efficiency of the co-generation power plant. |
| $\eta_{II\ TCMED}$ | The partial effectiveness of desalination thermal coupling. |
| $\eta_{II\ Elec.}$ | The partial effectiveness of electricity production. |