Developing a Design and Simulation Tool for Coupling Thermal Desalination Plants with Nuclear Reactors by using APROS Simulator

Khairy Agha, , Khalid Al Fared, Ali Rashed, and Salem Ghurbal

Simulation Group, ESTC
Atomic Energy Establishment
Tripoli - Libya

Abstract

This study presents a detailed modelling and simulation algorithm for coupling thermal desalination plants with nuclear reactors. Different coupling techniques concerning co-generation systems for linking thermal seawater desalination units (MED and MSF) to nuclear power reactors using Advanced Process Simulation Environment (APROS) are presented and discussed. In addition to developing a simulation model for the coupling unit, a separate APROS simulation model for the thermal desalination processes is also constructed and assessed against design data of a 1200 m^3/day production capacity of thermal desalination plants available at the industrial desalination fabrication facility in Tripoli-Libya.

The simulation model developed is intended to serve as a design tool as well as for research purposes to study in particular thermal desalination (MSF and MED) coupling to nuclear reactors and/or fossil energy sources. It is designed to improve the understanding of the thermal desalination process by developing a control strategy for plant dynamics and thermodynamically optimise process operating conditions.

The developed simulation algorithm includes simulation modules describing the main components of the coupled system comprising the coupling unit, brine heater, and stages of distillation subsystem. The coupling unit which separates the nuclear side from the desalination side is simulated in two different ways. First, it was simulation to produce hot water at preset temperature and pressure. And then modelled to produce saturated steam. In addition to the thermal optimization of the coupling unit, the APROS algorithm simulating the coupling unit is developed in such away that avoids the possibility of both radioactive contamination of desalted water and penetration of brine water in turbine circuit.

1) Introduction

A major problem that faces Middle Eastern and North African States is access to sufficient water for domestic, industrial and agricultural use. Libya is one of these countries where river systems do not exist and the main water source in the country is the underground fossil water, which contributes more than 98% of the total water consumption. Libya is classified as an arid or semi-arid area, receiving less than 150 mm of rainfall per year and high evaporation rates ranging between 1700 mm/year in the north to about 6000 mm/year in the south [1,2].

The rapid population growth rates and the ever increasing rate of urban drift that has led to serious pressure on urban water supply worsen the problem. Industrialisation, particularly when it involved heavy industry, has made further demands on available water resources. As a result of the excessive water use, the water table has fallen markedly in many areas and has led to the intrusion of seawater into the aquifer. Recent studies on the water resources and water requirements for Libya have shown that there is an increase of more than 50% in the water demand between 2005 and 2025 [3]. this leads to the necessity of developing the water resources and increase the supply of water to sustain life in the country.

For Libya, only two possibilities exist. One is the use of subterranean fossil water that may or may not be recharged by rainfall. This needs the use of modern methods of water extraction, which can easily endanger what is, in effect, a fragile resource. Either the water table sinks or water raised proves to be saline and brackish. The second alternative is to use a desalination system, whereby seawater is purified to make it potable or useable for agricultural purposes. Desalination is an energy intensive process. Over the long term, desalination with fossil energy sources would not be compatible with sustainable development: fossil fuels reserves are finite and their intensive use raises increasing environmental concerns especially in relation to greenhouse gas emissions. The depleting sources and the future price uncertainty of the fossil fuels and their better use for other vital industrial applications is also a factor to be considered for sustainability.

Desalination technologies have been well established since the mid-20th century and widely deployed in the Middle East and North Africa. The contracted capacity of desalination plants has increased steadily since 1965 and is now about 38 million cubic metres per day worldwide [4].

It has been recognized since the early 1960's through a series of published reports and studies [4] that nuclear energy could be an option for electricity supply as well as thermal energy source for seawater desalination. However, the main interest during the 1960s and 1970s was directed towards the use of nuclear energy for electricity generation. Renewed interest in nuclear desalination has been growing worldwide since the early 1990's, as indicated by the adoption of a number of resolutions on the subject in the IAEA General Conferences [4]. This has been motivated by a variety of reasons that include: economic competitiveness in areas lacking cheap fossil fuel resources, energy supply diversification, nuclear power is a very well proven and mature technology, conservation of fossil fuel resources, spin-off effects of nuclear technology for industrial development, and environmental protection by avoiding emissions of air pollutants and green-house gases.

The performance analysis of a nuclear dual-purpose plant (power and water production) requires an intensive study and analysis of all units and cycles involving the coupling schemes. Responding to this trend, the present study mainly focuses on the thermodynamic analysis of different thermal coupling options for co-generation nuclear/desalination plant to basically set the ground for thermal optimum criteria. The thermal behaviour of a Multi Stage Flash (MSF) and the various schemes of coupling unit are presented and analyzed by developing a simulation model for the transient and steady state operating conditions of nuclear / thermal desalination plants using the Advanced Process Simulation Environment (APROS) [5]. The developed simulation model is for a desalination plant with a design capacity of 1200 m^3/day, for which the design data is available [6].

2) System analysis

2.1) Multi Stage Flash Evaporation (MSF) Desalination Plants

Multistage flash distillation (MSF) is the distillation process, which is most commonly used for the large-scale desalination of seawater and accounts for the largest fraction of installed desalination capacity of any desalination process. The economy of scale favours this type of plant and very large capacity plants of up to 390,000 m^3/d are already in operation [7].

The basic principle of the MSF process is that pre-heated seawater enters the evaporation chamber at reduced pressure, resulting in flash boiling of a fraction of the seawater. The vapour produced by flashing is then conveyed to the heat recovery section where it is condensed on the outside of tubes conveying cooler seawater to the hot end of the plant, thereby recycling the energy to pre-heat the seawater.

Flash evaporation makes use of the phenomenon that when water is introduced through an orifice into a chamber, the water pressure is reduced below that of the equilibrium vapour pressure required for the water to boil at that temperature. This results in vigorous boiling of the water at the existing water temperature. Agitation of the water as it is discharged from the orifice together with vigorous boiling increases the surface area of the water and enhances vapour production. Flashing continues until the temperature falls (due to the loss of heat of vaporisation) below the boiling point of the water at that pressure.

The MSF plant of interest in this paper has a capacity of 1200 m^3/day and augmented by a thermal compressor to remove the non-condensable gases and enhance the vaporization processes. It constitutes 12 flashing stages, brine heater, and the steam jet ejector.

2.2) Multi-Effect Distillation (MED) Plants

MED process is similar to the MSF process since it also operates in part by flashing. Moreover, in this process the majority of the distillate is produced by boiling.

MED has considerable theoretical potential for large-scale plants to be built with higher performance factors than MSF plants. There are various designs with much potential but the main limiting factor is that there are no large operating MED prototypes available. Most MED plants are rather small in comparison with the large MSF plants.

Figure (1) shows a schematic diagram of the flow sheet for the MED-TVC plant of interest in this paper. It has a capacity of 1200 m3/day. It consists of 2 effects, main condenser, and steam ejector. The steam ejector entrains a specified portion of the vapour formed in the second effect which is compressed by the motive steam to the desired temperature and pressure. The compressed vapour is then used to heat the brine recycle stream in the first effect.

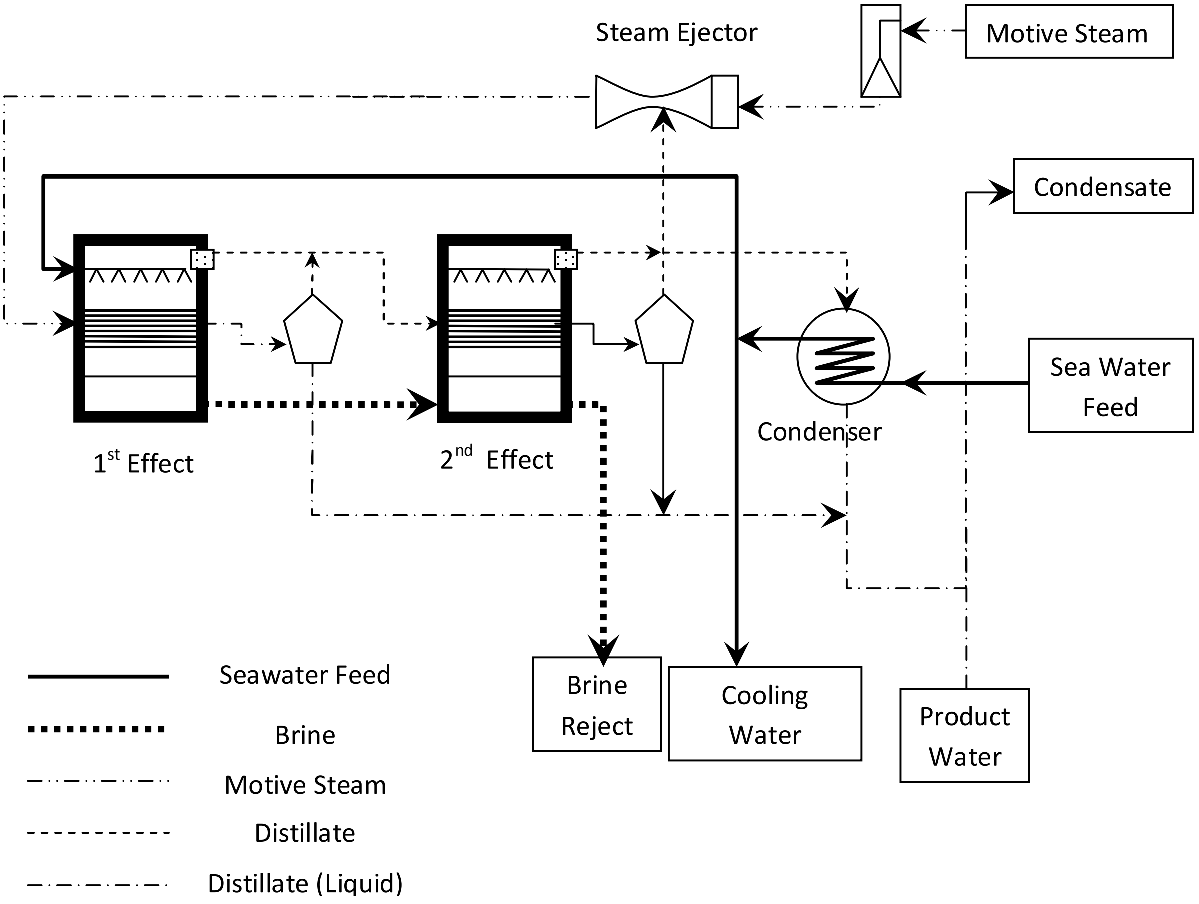

Figure (1) Flow Sheet of 2 effects MED-TVC plant

2.3) Characteristics of coupling unit

The main function of the coupling unit is to indirectly transfer thermal energy (heat) from the nuclear power plant to the desalination plant. It is, therefore, acts as a barrier to avoid leakage of radioactive material to fresh water. Steam is bled from the energy conversion loop of the nuclear plant, from back-pressure turbine or extraction turbine. Figure (2) shows a schematic diagram of the backpressure turbine and the coupling unit. In the present study, steam conditions (Pressure, temperature, and mass flow rate) were held constant for both cases of coupling options simulated. The thermal rating of the coupling unit were found through the energy balance, which can written as:

$$
\begin{aligned}
Q_{th} &= m_c * C_p * \Delta T \\
&= m_{st} * h_{fg}
\end{aligned}
$$

Where ΔT is the temperature drop across the water loop and h_{fg} is the enthalpy of evaporation of the steam.

The selection criteria toward the ultimate decision for the appropriate thermal coupling unit is influenced by many factors including, among others, economic viability, reliability, safety, thermal and hydraulic performance. However, in the assessment phase and during the phase of establishing a decision support system, it is useful to consider the thermal and hydraulic performance of the isolating loop, particularly in the dominant practical case. This section presents the thermodynamic analysis (energy and mass) of the coupling unit for generating steam to be supplied to MED or MSF. The following two cases were considered:

- Spray Flash Steam Chamber.
- Heat Pipe Heat Exchanger Loop.

A detailed description of both cases of coupling is presented in the following sections.

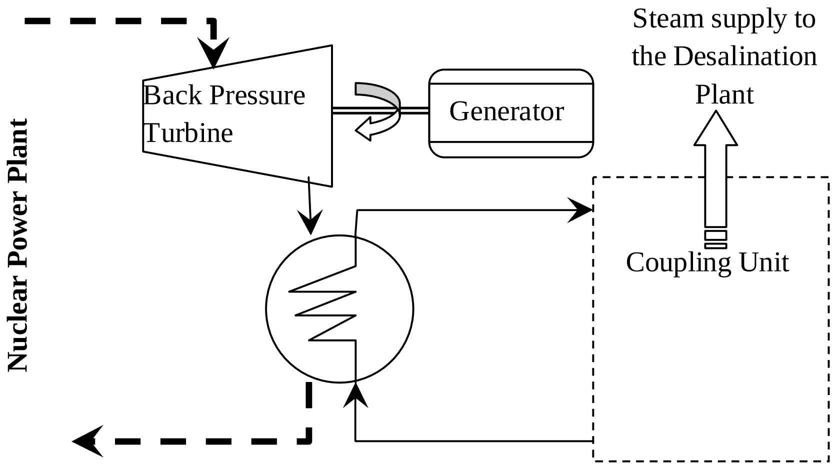

Figure (2) The coupling unit along with the back pressure turbine

- *Spray Flash Steam Chamber*

In this case, the isolation unit used a flash chamber to generate vapour in a closed loop as shown in figure (2). The flashing chamber is being kept at a pressure lower than that of the hot water stream. The hot water stream is heated by the steam extracted from the backpressure turbine (refer to figure (2)). Once the hot water sprayed in the chamber (and therefore exposed to a lower pressure) flushes at a lower pressure and lower temperature. The generated vapour directed to the brine heater transferring its thermal energy to the seawater (or re-circulated brine) and condenses.

The energy and mass balance have resulted in the following equations.

The amount of vapour generated is;

$$m_v = \frac{Q_{th}}{h_{fg\ @\ Chamber\ Pressure}}$$

The energy conservation over the flash chamber gives;

$$\mathrm{m_{cw}} * \mathrm{C_p} * \mathrm{T_0} = \mathrm{m_v} * \mathrm{h_{fg\ @\ TBT}} + (\mathrm{m_v} + \mathrm{m_L}) * \mathrm{C_p} * \mathrm{T_{Flash\ Chamber}}$$

Taking an energy and mass balance, results in the feed flow ratio (FR) as, after re-arrangement;

$$\mathrm{FR} = \frac{\mathrm{m_{cw}}}{\mathrm{m_v}} = \frac{\frac{\mathrm{h_{fg@TBT}}}{\mathrm{C_p}} - \mathrm{T_{fch}}}{\mathrm{T_0} + \mathrm{T_{fch}}} = \frac{\mathrm{T_b} - \mathrm{T_{fch}}}{\mathrm{T_i} - \mathrm{T_{fch}}}$$

Since the liquid is directly converted to vapour in the flash chamber and, therefore, there is no need for the heat transfer area. And the main driving force of vaporization process is the temperature drop during flashing. The chamber dimensions can be estimated by predicting the volume to be occupied by the vapour generated.

3) **APROS Simulation Model**

Modelling refers to formulating a set of equations that describe mathematically an industrial process under consideration. In the simulation phase, the formulated model is solved by using a suitable solution procedure, as well as by entering the values of independent process variables. There is a wide range of simulation tools and packages available commercially. APROS is one of the well advanced softwares available. APROS is a process simulation software which is capable of modelling thermal hydraulic processes, automation and electrical circuits. It includes models for nuclear power plants and conventional power plants. APROS operates under Windows NT.

The goals of modelling and simulation in the desalination industry include improving and optimizing designs, developing better insight into the working of the process, and ultimately leading to the optimal operation and control of the process.

In simulating a plant, different units were separately represented and then assembled together to form the complete plant. The individual representation of the units and the subsequent assembly should be carried out according to the physical and mathematical models reflecting all the major actual processes.

The following sections introduce the MSF process, and the modular and equation-solving approaches used to develop the steady-state and dynamic simulations.

3.1) Simulation of Thermal Desalination Plant

Due to the complexity of numerical treatment governing the thermal desalination process which needs *constitutive equations in addition to the basic conservation equations*. The thermal desalination subsystem is modelled by using the 5-equation model in which, the liquid and vapour momentum equations are replaced by the mixture momentum equation accommodating the phase separation by utilizing the diffusion equation of void fraction. This algorithm provides a powerful simulation tool due to its capability in accounting for wall heat transfer effects, interfacial heat transfer effects between liquid and vapour, and wall friction for vapour and liquid mixture.

The first component to be modelled is the brine heater. The brine heater consists of two inlet streams and two outlet streams. One inlet stream is the recirculating brine ready to be heated to the desired temperature. The second inlet stream is the steam used to heat the recirculating brine. Both streams exit accordingly, without mixing.

APROS simulation software has the model type HEAT EXCHANGER which is sufficient to represent the process of the brine heater. This model type were used to simulate the brine heater model. The top brine temperature (TBT) were controlled through two controllers. One controller is to control the brine concentration level, while the other is to control brine flow rate at the inlet to the brine heater.

Figure (3) shows the APROS simulation model for the brine heater. In the next sections, a brief description of the simulation models for both MSF and MED is presented.

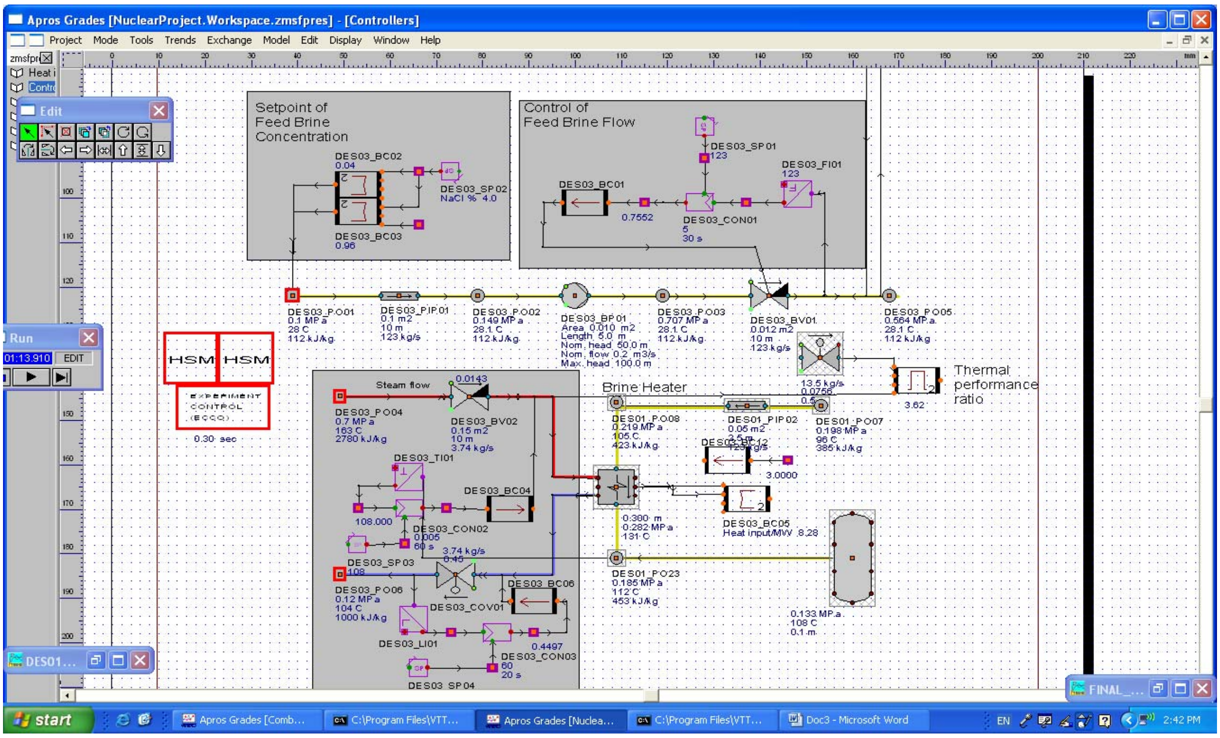

Figure (3) APROS Simulation Model of Brine Heater

i) *Simulation Model for MSF-TVC*

The MSF process is similar to multi-component distillation, but there is no exchange of material between the counter current streams. Actually, the MSF process is a flash evaporation process in vacuum, where the vacuum changes from one stage to the next and the evaporation temperature decreases from the first to the last stage.
From the modelling point of view, it is easier to split a single flash stage into two compartments, which can be treated separately. The two compartments are: flash tank and tube bundle condenser. In the condenser, the vapour generated in the flash tank condenses and changes to liquid.

Each fluid stream communicating with the individual stage has four characterizing variables: flow rate, temperature, pressure, and salt concentration. From these variables, the physical properties, namely, enthalpy, density, and specific heat of the stream were calculated as dependent variables. Figures (4 - 6) show the resulting APROS simulation model for the 12 stage MSF plant of interest which has a capacity of 1200 m^3/day.

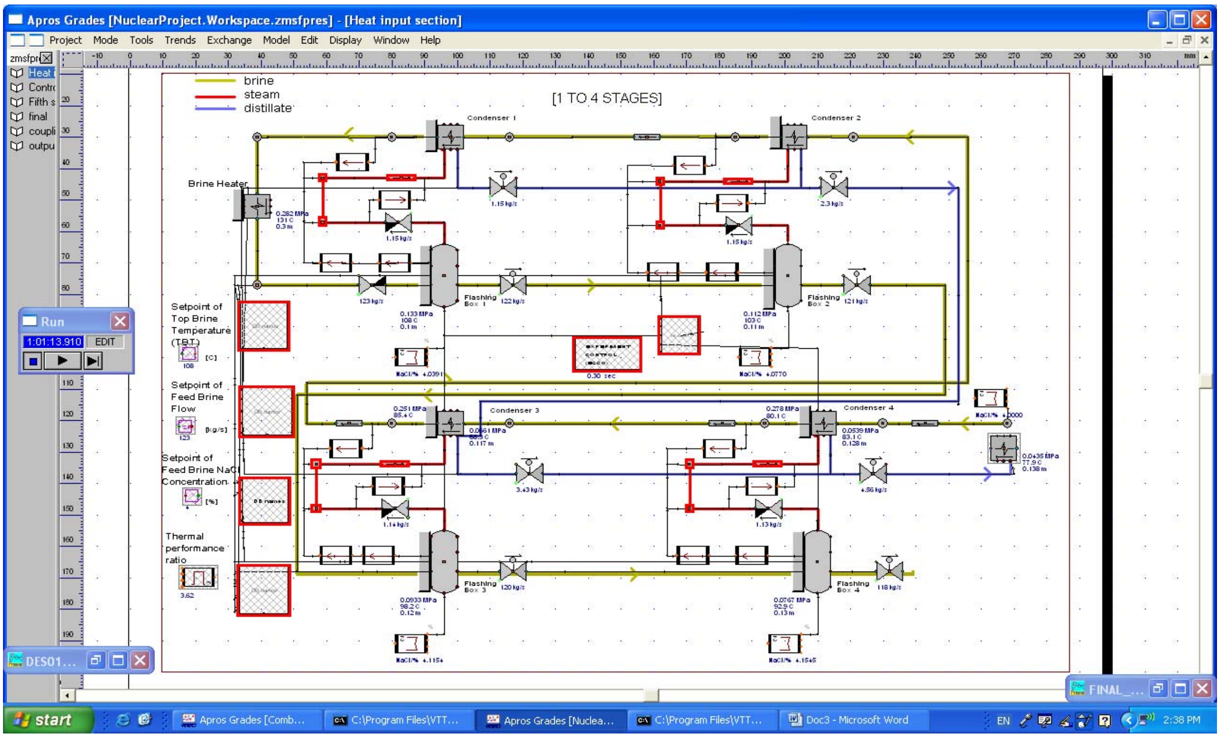

Figure (4) Flow sheet of first 4 stages of 12 stage MSF-TVC desalination plant

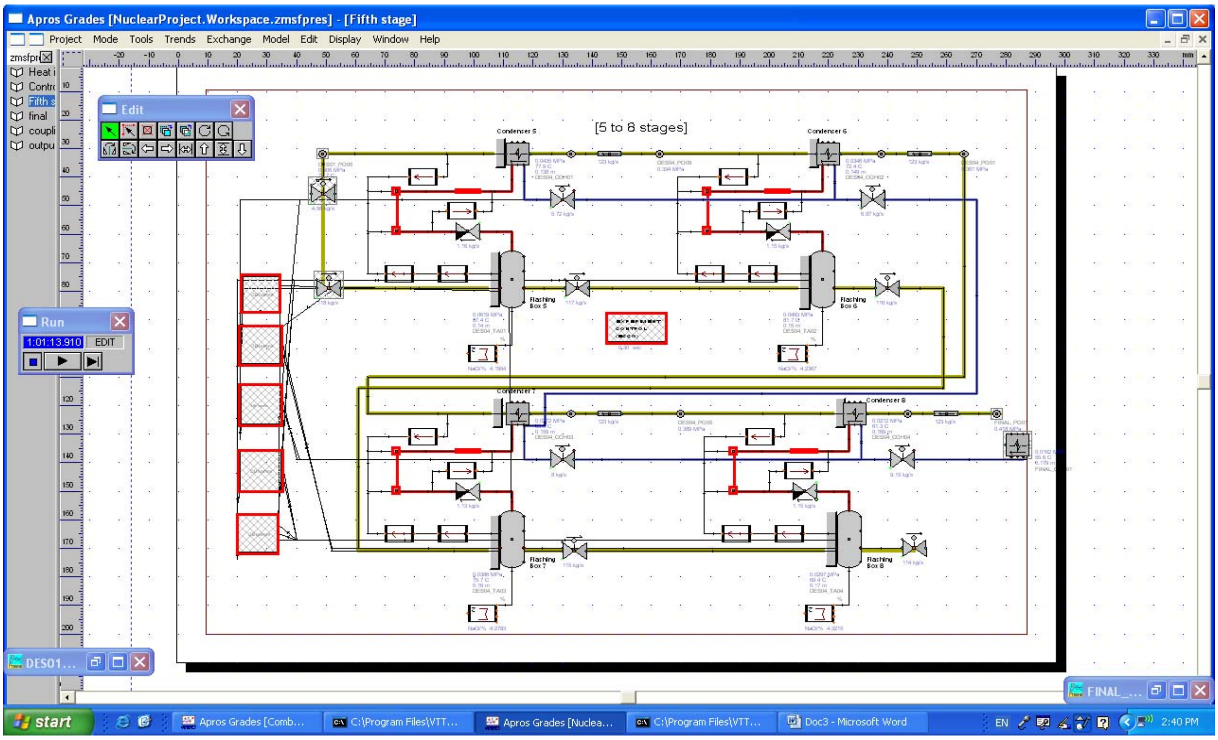

Figure (5) Flow sheet of stages 5 to 8 for 12 stage MSF-TVC desalination plant

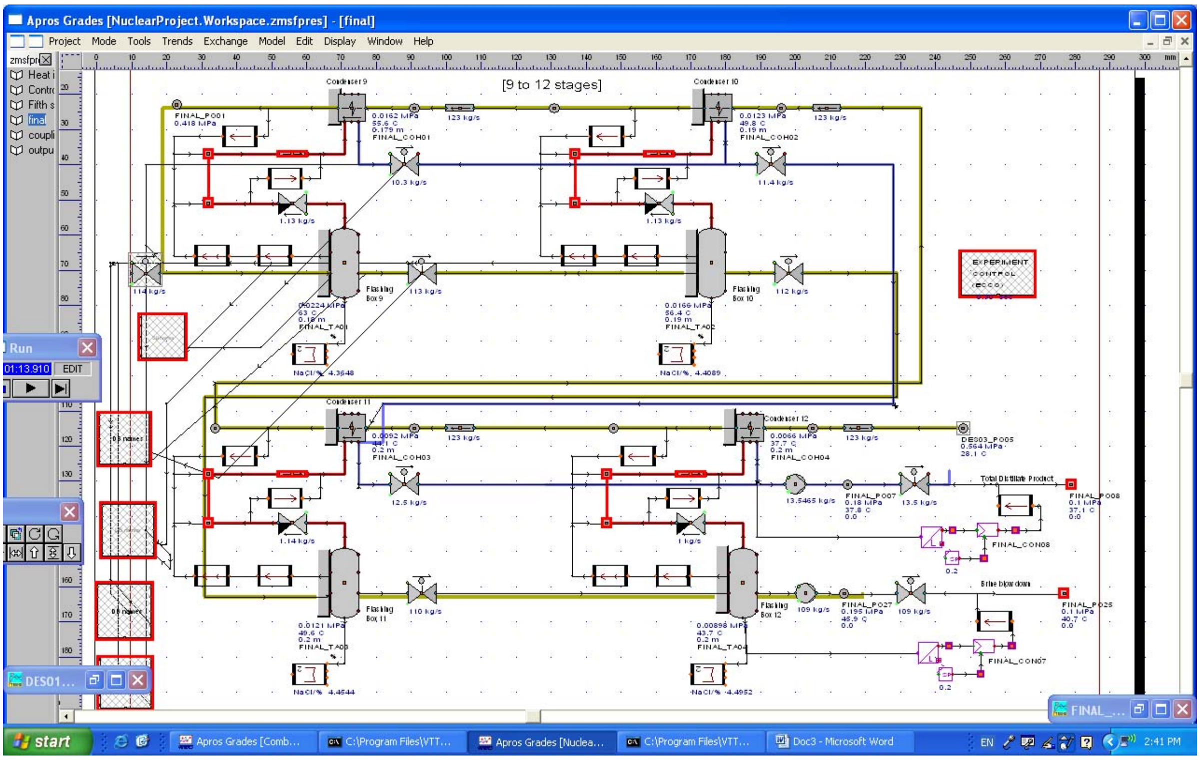

Figure (6) Flow sheet of stages 9 to 12 for 12 stage MSF-TVC desalination plant

ii) *Simulation Model for traditional MED-TVC*

Figure (7) shows a schematic diagram of the resulting APROS simulation model for MED-TVC flow sheet with 2 effects whose capacity is 1200 m^3/day. Beside plant capacity and number of evaporators, the input data includes feed stream, concentration factor, type of heat transfer area in evaporators and feed pre-heaters, approach temperature for pre-heaters, and extent of non-condensable venting. In addition to specific thermal energy requirement (in kWh/m³ distillate), the output data from simulation model include temperature, pressure, concentration, flow rates, heat transfer coefficient, and area profiles for all evaporators and pre-heaters for each flow stream (Distillate (liquid and vapour), brine, and sea water). It can be clearly seen that, as in the case of MSF simulation, each effect were modelled as two separate components (evaporator and condenser) by using the five equation model utilizing the diffusion equation of void fraction. Figure (8) shows the simulation model for the ejector as it is being coupled to the second effect (refer to Figure (1)).

It should be noted that it is equally easy to simulate other MED configurations such as parallel and parallel/cross flow systems.

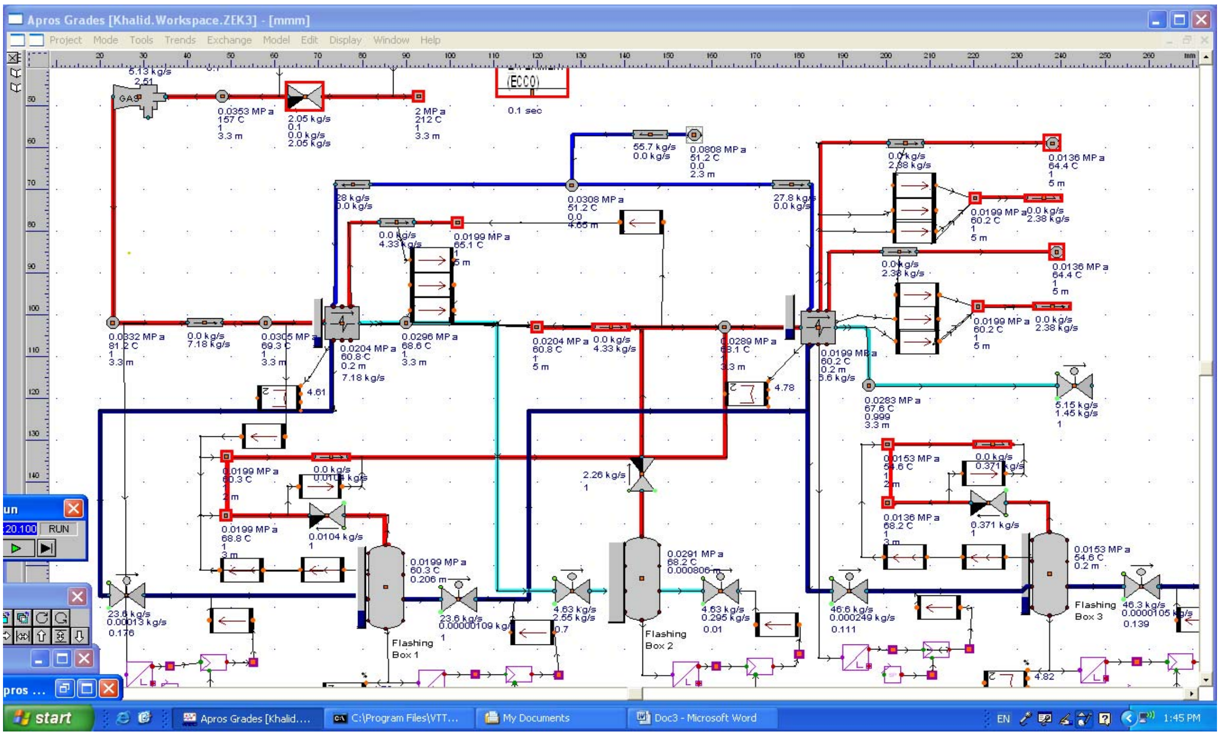

Figure (7) Flow sheet of 2 effect MED-TVC desalination plant

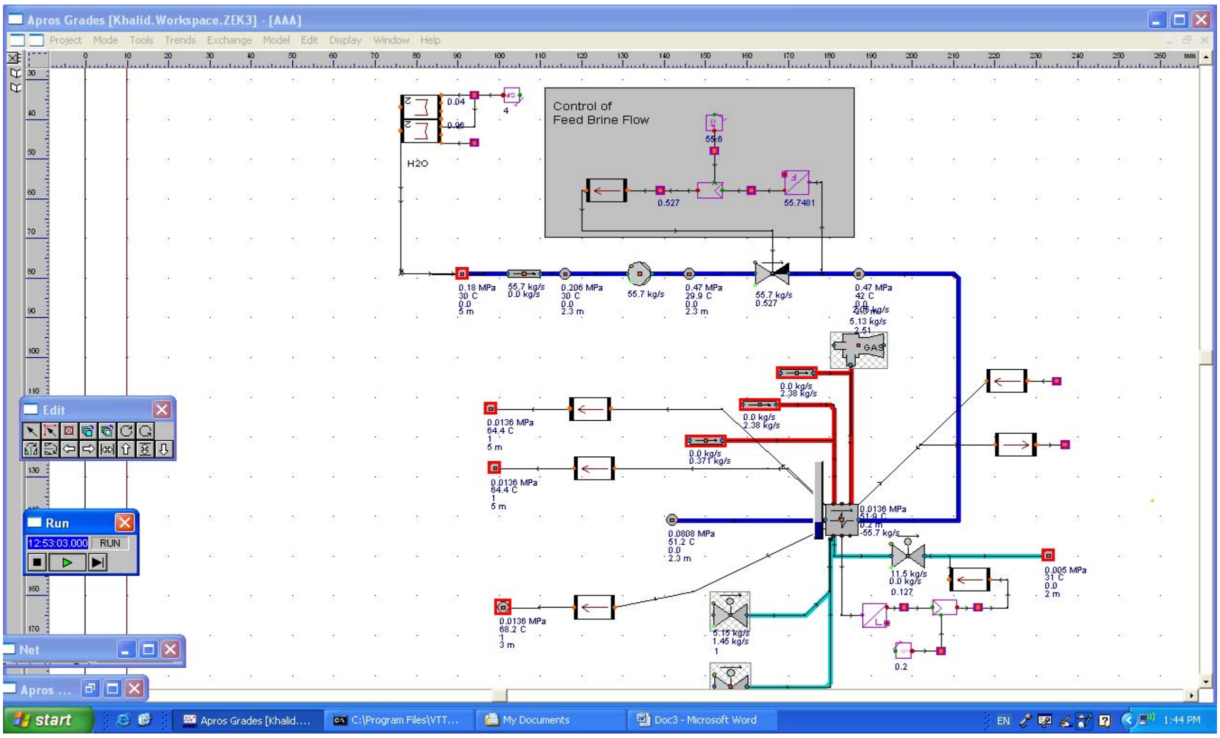

Figure (8) Simulation Model of steam ejector for MED desalination plant

iii) *Simulation Model for the coupling unit*

As explained above, two types of the coupling unit were simulated. The first type is a flash chamber and the second type is a heat pipe heat exchanger loop. Both types were simulated such that the steam output supplied to the brine heater is in vapour status. Figure (9) shows the resulting APROS simulation model for the flash chamber. It can be seen that the flash chamber is simulated by utilizing two components (a heat exchanger and a flash tank). First a pressurised water is heated to the desired temperature which is than exposed to a lower pressure in the flash tank to be partially evaporated. The generated saturated steam extracted from the flash tank is directed to the brine. And the remaining liquid mixed with the condensate returned from the brine heater flows back to be re-heated again after increasing it pressure, so that the coupling unit works in a closed loop.

Figure (10) presents the resulting APROS simulation model for the second type of the coupling which is based on the heat pipe heat exchanger loop principle. In this type, the vapour is being generated in a shell and tube heat exchanger.

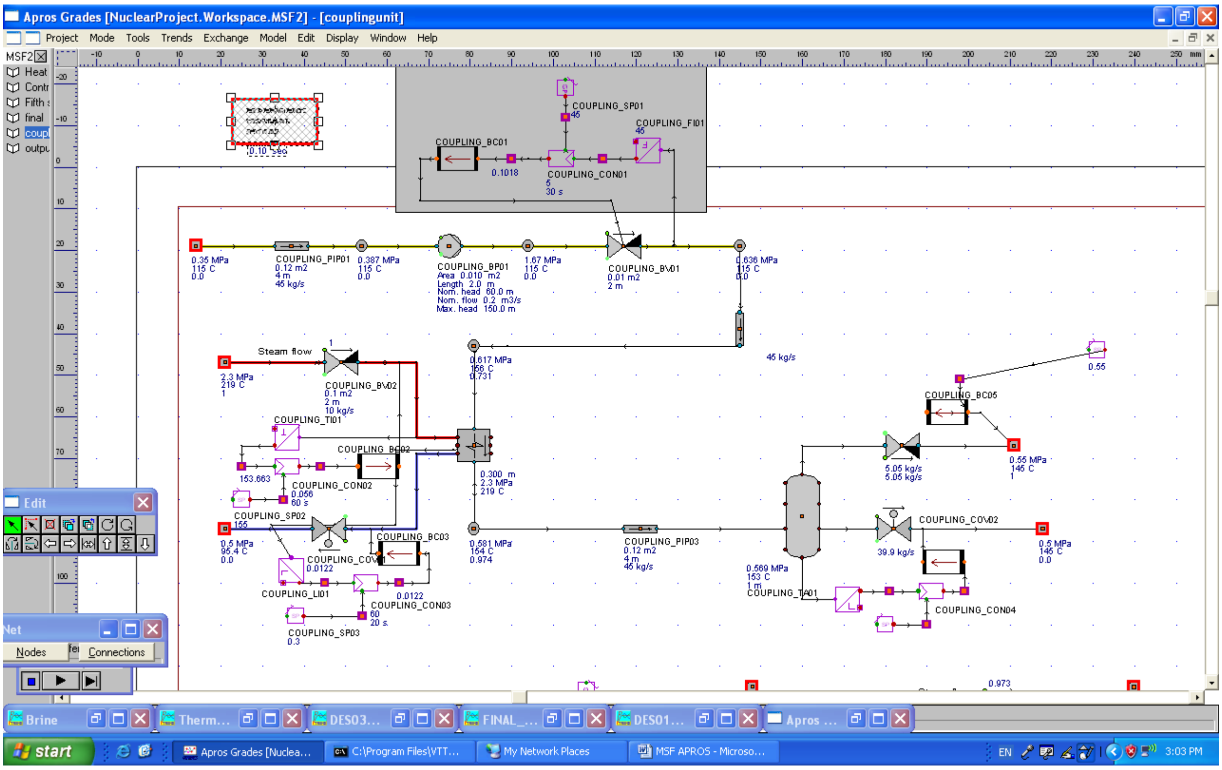

Figure (9) APROS Simulation Model for the coupling unit (type I – Flash Chamber Concept)

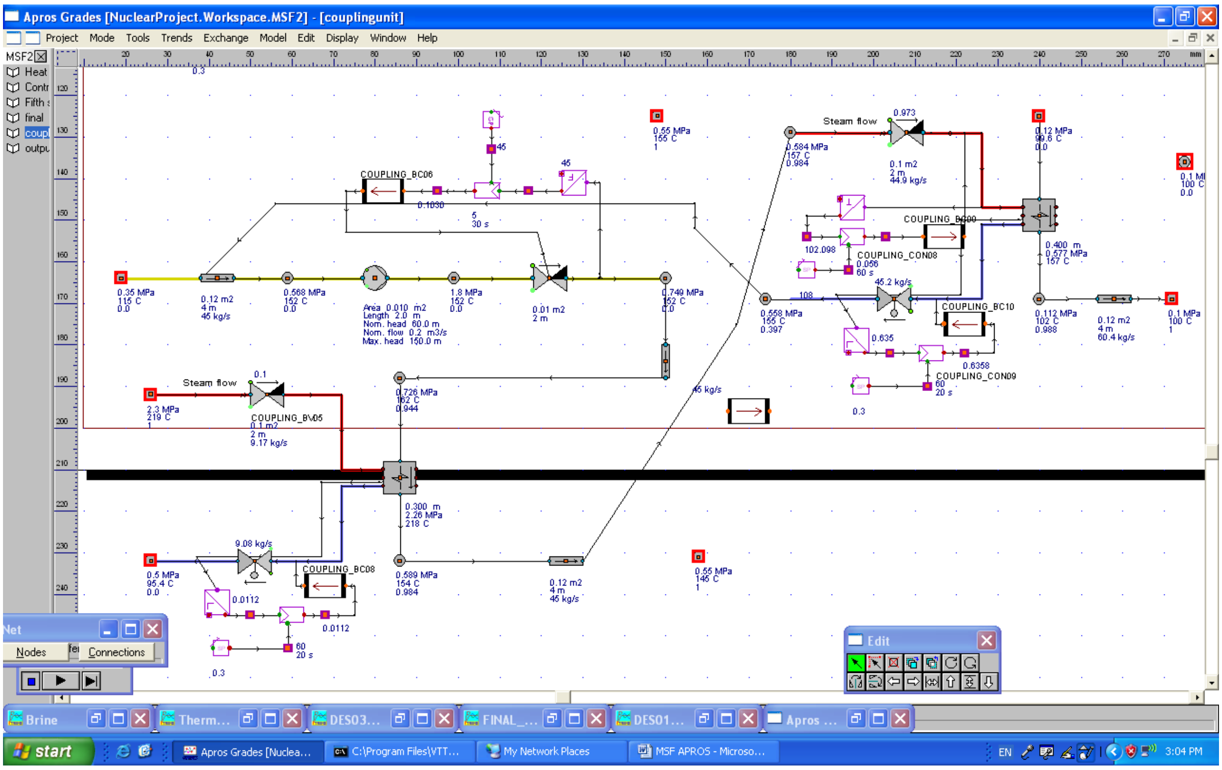

Figure (10) APROS Simulation Model for the coupling unit (type II – Heat Pipe Concept)

4) **Results and discussion**

Although the developed model is fully capable of simulating the desalination plant and the coupling unit under transient as well as steady state conditions, only the results related to the steady state operating conditions will be presented in this paper.

Figure (11) depict the simulated results for pressure and concentration gradients within the MSF-TVC plant. All the stages starting from stage 3 operate under vacuum (below atmospheric pressure) through the help of the ejector.

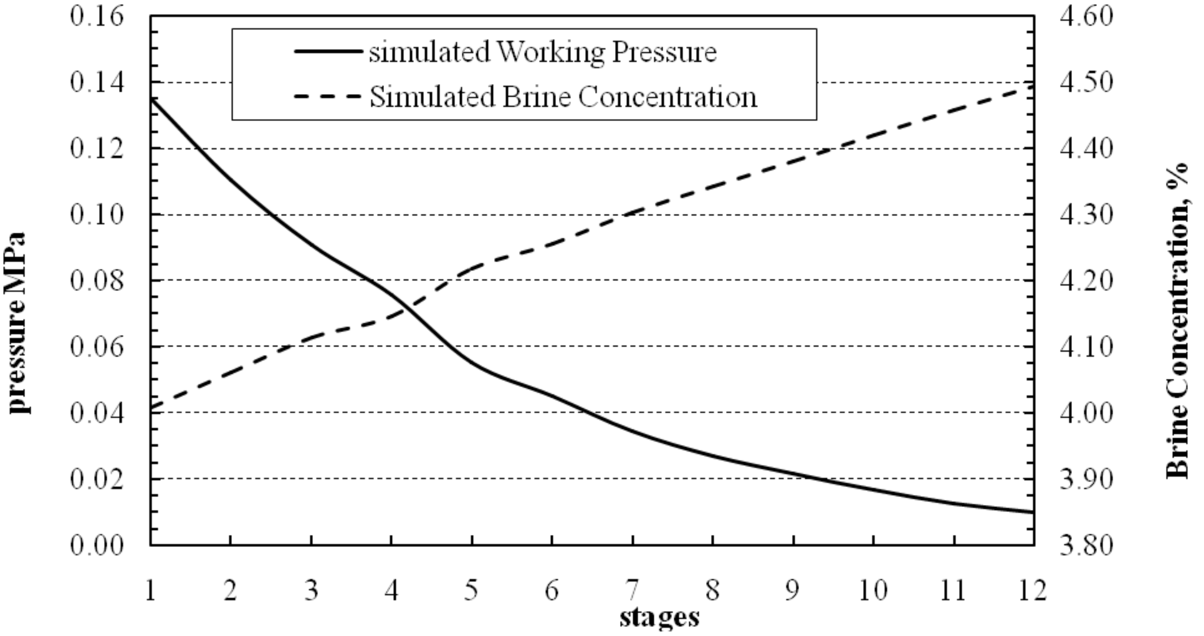

Figure (11) Simulated results for stage wise pressure and brine concentration

The simulated results were validated by the technical design data. Figure (12) shows a good agreement between the simulated results and technical design data for the brine temperature within each stage of MSF-TVC plant. It shows that the maximum error was about 4.2% and occurred in stage 7. The simulated results gets closer to the design data at the two ends of the plant, this is attributed to the fact that the two are closer to a preset boundary conditions namely seawater temperature and top brine temperature.

The validation process of the APROS simulation model for MSF plant is further manifested by comparing the obtained results for stage wise brine flow rate with those of the technical data as shown in Figure (13). These results were again in good agreement with the data showing a maximum error of well below 1%. Once again the maximum error occurred around the middle of the plant.

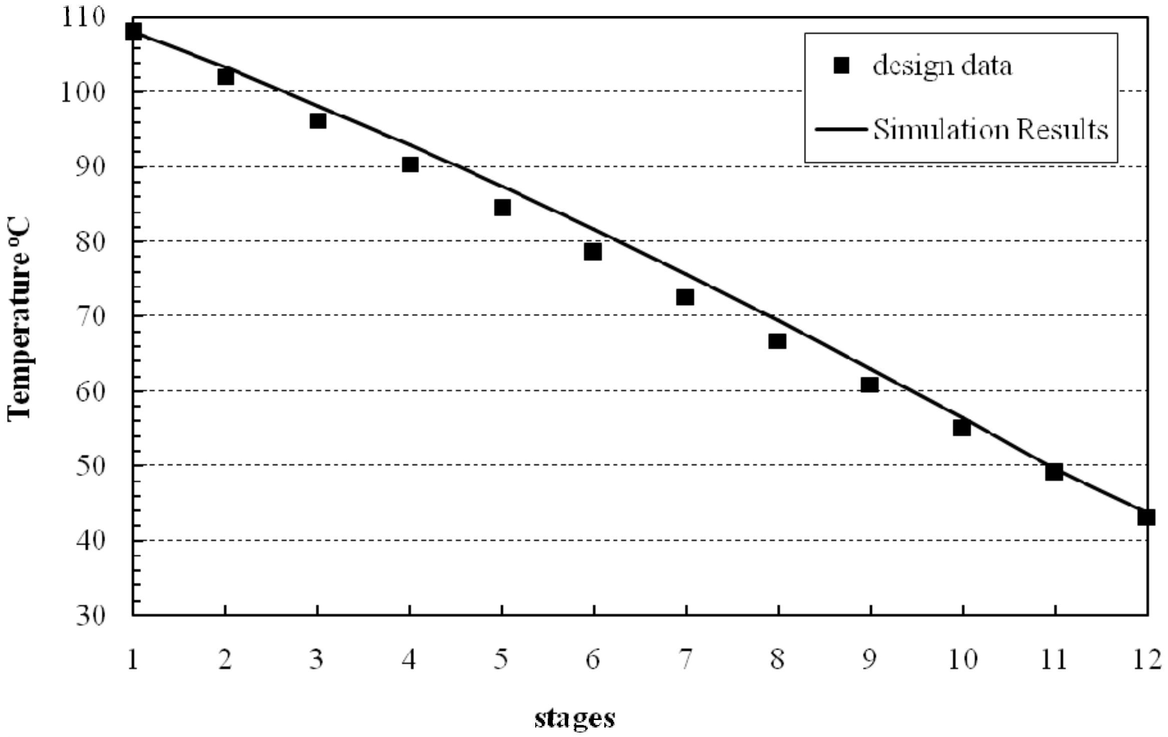

Figure (12) A comparison between APROS simulated results and technical design data for 12 stage (1200 m3/day) MSF-TVC plant

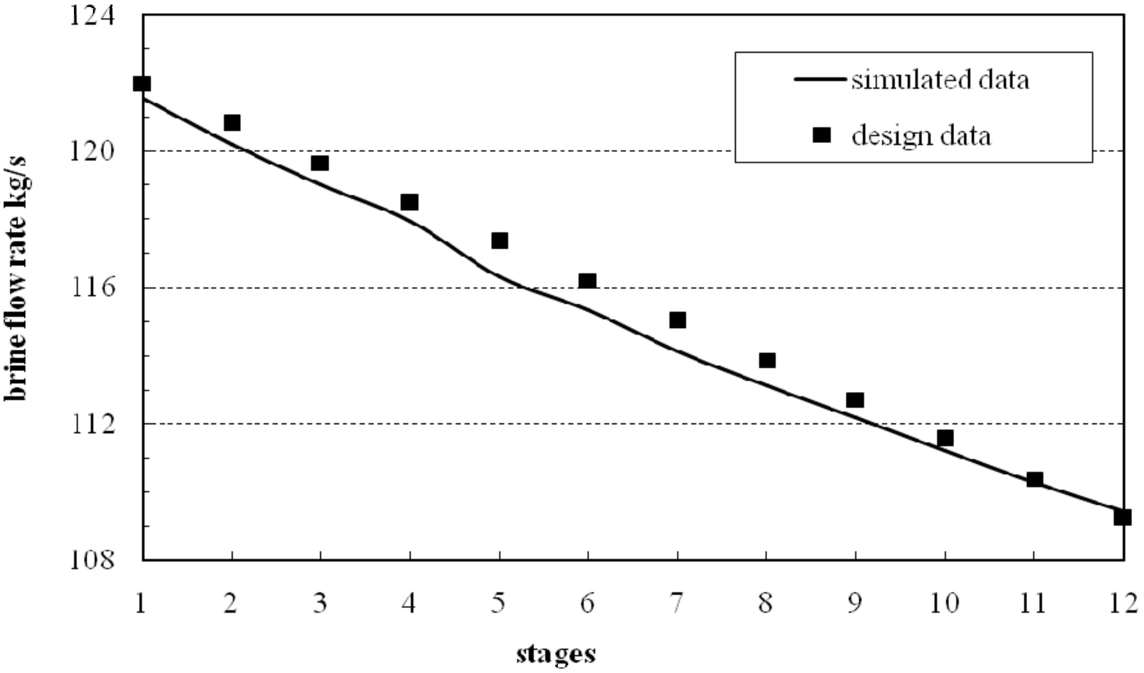

Figure (13) A comparison between the APROS simulated results and design data for brine flow rate at the inlet of each stage of the MSF-TVC.

Figure (14) depicts the comparison between the obtained results for the product water flow rate and the design data for MSF-TVC. These product water flow results were not in good agreement as those related to the other operational parameters. This is becuase, the water flow rate representes the accumulated rate upto that stage and therefore a buildup of error. But as the simulation process approches stage 12 (end of plant) a sharp drop was error was noticed due to the enforced boundary condition.

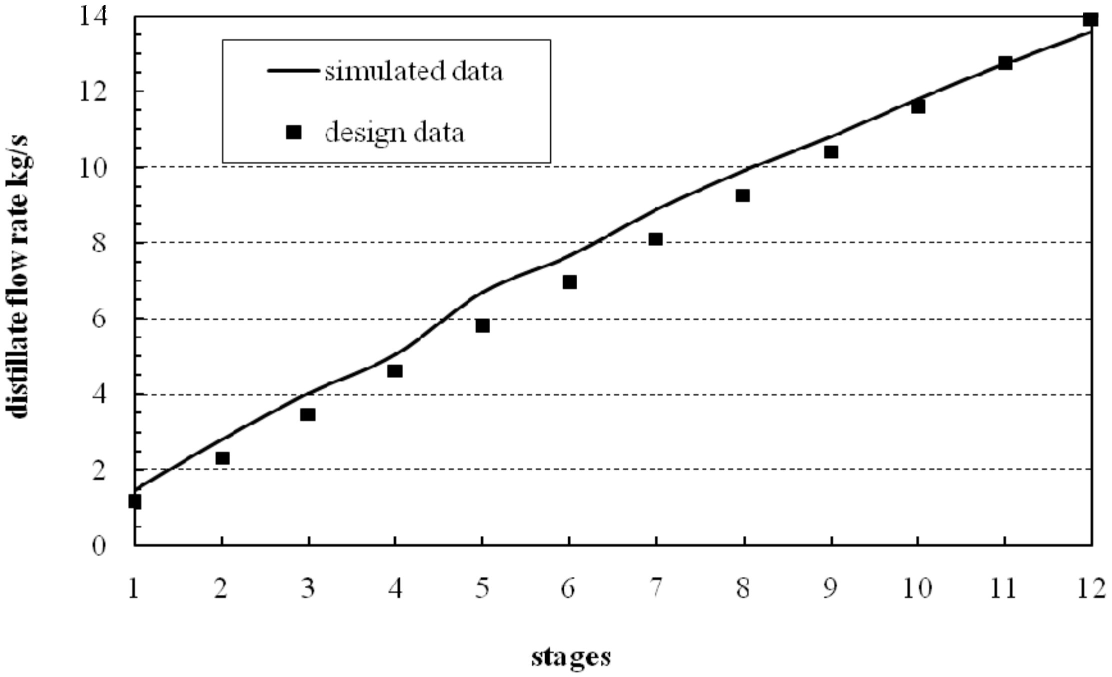

Figure (14) A comparison between the obtained APROS simulation results and design data for distillate product flow rate (accumulated values).

5) **Conclusion**

An APROS simulation model describing the steady state thermal and hydraulic behaviour of thermal desalination plants (MSF and MED) along with the necessary subsystems namely brine heat and steam ejector were developed and discussed. APROS simulation model for the coupling unit utilizing two different concepts has also been developed. Considering the results of this model for each set of circumstances, the following conclusions were drawn;

- APROS Simulation Models for MSF and MED were developed and compared against Design Data.
- A model for the coupling unit taking into account the pressure reversal condition was developed.

- The APROS Simulation Model were validated and assessed against a real design data of 1200m^3/day capacity

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