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Coupling of a nuclear reactor to hybrid RO–MSF desalination plants

Ibrahim S. Al-Mutaz

Chemical Engineering Department, College of Engineering, King Saud University,
P.O. Box 800, Riyadh 11421, Saudi Arabia
Fax +966 (1) 4678770; e-mail: almutaz@ksu.edu.sa

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Abstract

Energy requirements in desalination plants can be supplied by coupling desalination units with nuclear reactors. Multistage flash (MSF) plants often use low-pressure steam as an energy source. The energy consumption in MSF plant depends on the distillate flow rate and the plant performance ratio. Reverse osmosis (RO) plants are operated by electrical power to derive the high-pressure pumps and other plant auxiliaries, mainly the pretreatment processes. RO power consumption depends mainly on water recovery and the working pressure. Low pressure and temperature steam extracted from nuclear heating reactors (NHR) may be used for supplying the necessary energy to derive the MSF units. Electricity can be generated from the nuclear power reactor (NPR) to derive the high-pressure pumps of the RO desalination plants. Coupling RO and MSF with nuclear steam supply system (NSSS) will yield some economical and technical advantages. The hybrid RO MSF system has potential advantages of a low power demand, improved water quality and possible lower running cost as compared to stand-alone RO or MSF plants. Developing the most appropriate plant configuration of nuclear reactor and desalination process is an important task that will determine the feasibility of nuclear desalination. The optimum coupling of hybrid RO MSF desalination processes with nuclear power plant will be presented in this paper.

Keywords: Nuclear desalination; Hybrid RO–MSF processes; Coupling schemes

1. Introduction

Nuclear power plants produce about 17% of world's power. There are about 438 nuclear reactors operating in various countries with a total net installed capacity of 353 GWe as of January 2002. These are of different capacities ranging from 100 to 1450 MWe.

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Nuclear desalination plants have been operated in Kazakhstan and Japan for many years[1]. In Aktau, Kazakhstan, the liquid metal cooled fast reactor (LMFR) BN-350 has been operating as an energy source for a multi-purpose energy complex since 1973 supplying 135 MWe of electricity, about 80,000 m^3/d (21 mgd) potable water and heat to the local population and industries. While in Japan, ten electric power companies are operating fifty-one nuclear power plants as of March 1997. The first Japanese nuclear power plant, a gas-cooled reactor (GCR), came into operation in 1966. The first Japanese nuclear power and seawater desalination plant started operation in 1978 at the Ohi Nuclear Power Station. The plant used a 1175 MWe pressurized water reactor (PWR) coupled to a MSF distillation process with a capacity of 1300 m^3/d (0.34 mgd). Nine additional nuclear seawater desalination plants were installed by 1998.

India has been engaged in desalination research since the 1970s. It has successfully operated an experimental facility in Trombay since 1984 and is planning to couple a 6300 m^3/d (1.66 mgd) hybrid RO MSF plant to its Kalpakkam pressurized heavy water reactor (PHWR) in Tamil Nadu.

RO MSF hybrid plants exploit the best features of each technology for different quality products. The hybrid RO MSF system offers several interesting prospects for water cost reduction. Integration of RO and MSF systems at the same location offers the opportunity to meet diverse requirements for product water quality [2]. MSF can produce water with high purity. The high TDS product water of RO plant can be blended with for MSF distillate. The different rates of blending can be done depending on the type of water quality requirement.

Coupling RO and MSF with nuclear reactor has economical and technical advantages. It shows promising advantages of a low power demand, improved water quality and possible lower running cost as compared to stand-alone RO or MSF plants. This hybrid scheme allows an increase in the RO productivity. The rate of water permeation through the membrane increase as the feed water temperature increases since the viscosity of the solution is reduced and higher diffusion rate of water through the membrane is obtained. Water recovery is increased in RO as the feed water temperature increases. Extra cooling of product water in MSF can be obtained.

2. Features of RO MSF hybridization

Energy is a controlling parameter in the desalination cost. Desalination plants require significant amounts of energy in the form of heat and/or electricity. Desalination is considered as energy intensive process.

The energy requirements for MSF are low temperature heat and some electricity, with heat being the main portion. The energy consumption in MSF plant depends on the distillate flow rate and the plant performance ratio. About 3–9 kg (6–20 pounds) of product water is produced by 1055 kJ (1000 Btu's) of input energy. For Large MSF plants, about 4–6 kWh/m^3 of electrical energy is consumed. Heat consumption is in the range of 55–120 kWh/m^3 of thermal energy. In general, the thermal efficiency of MSF plant is expressed in kg of water produced per kg of steam used. This ratio is called the gain output ratio (GOR). Values of GOR range from 8 to 10 with a practical maximum of 12, which corresponds to about 55 kWh/m^3 of thermal energy. GOR of 3, 8 and 10 correspond without loses to thermal energies of 216, 82 and 65 kWh/m^3, respectively. Also MSF consumes 3.5–5 kWh of electric energy for pumping per one m^3 of product water [3].

MSF process can be designed on bases of once-through or brine recirculation flow systems. The once through system has the following features [4]:

- Simple plant operation with few process control since the brine recirculation pump is omitted as well as the heat rejection section,

- The brine concentration at the exit of the brine heater is lower if compared with the brine recirculation design,
- The cost of chemical dosing is higher than for the recirculation system

On the other hand, the recirculation system has the following characteristics [4]:

- Limited make-up flow rate which means small amounts of antiscalant chemicals to be injected,
- The heat rejection section acts as a deaerator and degasifier for the make-up seawater thus help to minimize the corrosion problems in the evaporator,
- Higher concentration of flashing brine compared with the once-through arrangement.

Comparison of the two design arrangements clearly indicate that the once-through option is more economical particularly for MSF units of large capacities due to its simplicity of construction and lower pumping power requirements. The maximum unit capacity of MSF plants is 57,000 m^3/d (15 mgd). This capacity is expected to steadily increase to 100,000 m^3/d (26.4 mgd).

RO plants are operated by electrical power to derive the high-pressure pumps and other plant auxiliaries, mainly the pretreatment processes. RO power consumption depends mainly on water recovery and the working pressure. For typical seawater of about 35,000 ppm total dissolved salts (TDS), the minimum energy needed to separate 3.785 m^3 (1000 gallons) is 3 kWh. Typical energy consumption of RO with 30% water conversion is about 9.7 kWh/m^3 without energy recovery. When using energy recovery turbines of 80% efficiency, the electrical energy consumption will be reduced to 6.5 kWh/m^3 [5], where about 30% of the input energy can be recovered. The percentage of recovered energy increases as the plant size increases because the pump and motor efficiencies improves with sizes. Roughly 4.5–7 kWh of electrical energy is required for producing one cubic meter of potable water. About 85% of this energy consumption is required for the high-pressure pumps. The exact figure depends on the design, unit size, site conditions, water quality requirements, membrane properties, and feed water temperature and salinity as well as the usage of energy recovery system.

The following are summarization of the technical differences between RO and MSF [6]: Seawater intake in MSF is twice that of RO.

- Energy consumption per cubic meters in MSF is about three times that of RO.
- Volume and area required for MSF is large compared to those required for RO.
- Pumping energy in RO is about 25% that required for MSF. A possible decrease in pumping consumption in RO might be while using energy recovery systems.
- RO has no thermal energy consumption. In 22,710 m^3/d (6 mgd) MSF, about 89 MW of thermal energy is consumed. This can be very expensive if not extracted from steam turbine.
- Heavy foundation and extensive civil work is required by MSF due to its heavy weigh.

The benefits of RO against MSF can be stated in the following points:

- Limited make-up flow rate which means small amounts of antiscalant chemicals to be injected.
- The flexibilities in RO in meeting various water and power ratio while maintaining maximum process efficiency [7].
- Corrosion problems are much less in RO than MSF.
- Energy consumption is low in RO than MSF.

The hybrid RO MSF system offers the optimum combination of the features of the two processes. It has potential advantages of a low power demand, improved water quality and possible lower running cost as compared to stand-alone RO or MSF plants. It also offers additional advantages such as decrease post treatment cost and improve water quality by blending MSF distillate and RO permeate as well as greater flexibility and more efficient operation in dual-purpose plants [8]. Hybrid plants allow a better match between power and water requirements. Significant reduction in capital and operating costs in hybrid RO MSF seawater desalination plant is expected for a given water production.

Hybrid RO MSF desalination-power process has the following advantages:

- The capital cost of the combined RO MSF plant can be reduced.
- A common seawater intake is used.
- Product waters from the RO and MSF plants are blended to obtain suitable product water quality.
- A single-stage RO process can be used and the RO membrane life can be extended because of the reduced product-water specification. The life of the RO membrane can be extended from three to five years, or the annual membrane replacement cost can be reduced by nearly 40%.
- Electric power production from the MSF plant can be efficiently utilized in the RO plant, thereby reducing net export power production.
- Blending with RO product water reduces the temperature of the MSF product water. RO for high-pressure brine without energy recovery can be used to cool the MSF product water.
- Preheat RO feed water increases the recovery significantly.

Different integration schemes were studies on RO MSF hybrid systems. Many design configurations have been proposed [9]. One of the simplest integration schemes is to have the reject stream leaving the heat rejection section of a recirculation-type MSF plant fed to the RO plant. In this scheme, the distillate from the MSF plant is blended with RO permeate to obtain the required product water quality. This eliminates the need for blending the MSF distillate with local groundwater. This scheme keeps the RO feed water temperature in the range of 28–35°C. It was estimated that an increase in the RO feed water temperature by one degree would cause an increase in RO membrane flux by about 2.5–3%. The RO plant can be a single stage. Elimination of the second stage not only reduces capital cost but also reduces membrane replacement and energy costs.

Fig. 1 shows the optimum RO MSF hybrid process scheme. In this hybrid RO MSF scheme,

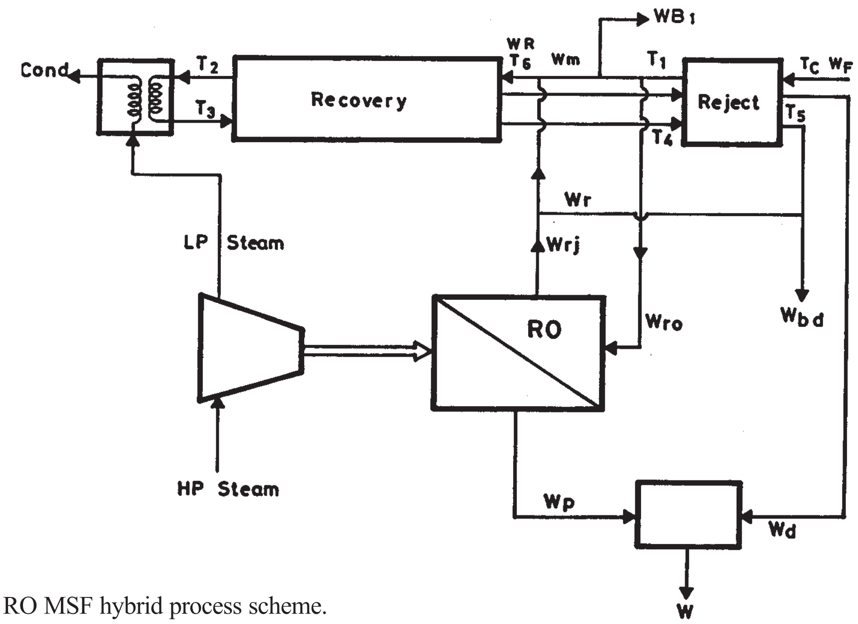

Fig. 1. Optimum RO MSF hybrid process scheme.

the MSF process draws waste steam from the power plant and uses the energy in the steam to preheat seawater which is then distilled in the MSF unit. The RO unit uses electricity from the power station and operates during periods of reduced power demand, thus optimizing the overall efficiency of the entire operation. This hybrid scheme allows an increase in the RO productivity.

Jeddah I rehabilitation plant (1986–1989) is the first large-scale RO MSF hybrid process with a capacity of 56,800 m^3/d (15 mgd) for RO plant and 321,725 m^3/d (85 mgd) for MSF units. The RO units have the following design criteria:

- Feed water quality with TDS of 43,300 mg/l, chlorides as Cl^- is 22,400 ppm, pH of 8.2, water temperature is 24.5–32.5°C;
- Operating pressure at 60 kg/cm^2 with maximum design pressure at 70 kg/cm^2;
- A single-stage design, including 10 RO trains, with each train including 148 RO modules;
- Hollow fine fiber (Toyobo Hollosep made of cellulose triacetate) RO module with 10 inch diameter;
- Recovery ratio of 35% of product water;
- Product-water salinity of 625 mg/l of chloride, equivalent to a TDS of 1,250 mg/l.

RO MSF hybrid systems were performed by Doha Desalination Research Plant (DRP) in Kuwait using two RO units linked with the nearby MSF via one common feed water header and pretreatment unit [10]. The RO units are of the spiral-wound and the hollow-fiber twin seawater RO membrane configurations, each of 300 m^3/d. Up to a 43% increase in the RO product water recovery was found under hybrid operation. The average change in RO product water recovery was almost linearly related to the change in feed water temperature.

3. Nuclear energy options

Nuclear reactors are used mainly for the production of either heat or power. In the nuclear heating reactors (NHR), heat can be extracted at various temperature levels, both in the form of hot gas or steam. The low pressure and temperature steam may be used for supplying the necessary energy to derive the MSF. In the nuclear power reactor (NPR), electricity can be generated to derive the high-pressure pumps of the RO desalination plants. Developing the most appropriate plant configuration of nuclear reactor (NHR or NPR) and desalination process (distillation or membrane) is indeed the most crucial factor that will determine the feasibility of nuclear desalination.

Steam and electricity can be produced easily by nuclear reactors. Nuclear reactors may be coupled with desalination plants. This integrated plant will be capable of producing power and water at reasonable cost. Maintenance and operating cost will drop significantly.

Nuclear power reactors (NPRs) belong to one of the following three major groupings based on the cooling medium:

1) Water cooled reactors (WCR):

Most of the operating NPRs today are water-cooled reactors. Water-cooled reactors are either light water cooled reactors (LWR) of both the pressurized (PWR) and pool type, or pressurized heavy water cooled reactors (PHWR). Pressurized water reactors use enriched uranium as fuel, whereas pressurized heavy water reactors use natural uranium as fuel.

2) Gas cooled reactors (GCR):

High temperatures GCRs use helium as a coolant and graphite as a moderator. In order to attain the capability of retaining fission products at temperature of 1600°C and more a ceramic cladding of the fuel is used. If high temperature gas cooled reactors are used for heating or desalination, which require low power and low operating temperature, the safety factor of the operation will be highly enhanced.

3) Liquid-metal fast reactors (LMFR):

Since light materials have to be avoided as moderators in fast reactors, liquid metals such as sodium are used as coolants in fast reactors. Most of the development work on LMFRs has concentrated on developing a configuration that will produce electricity competitive with LWRs. The BN-350 LMFR at the Aktau complex in Kazakhstan is the only LMFR used for seawater desalination.

The status of nuclear technology fall into three major categories:

1. Reactors proven and commercially available for export: (PWRs, BWRs and PHWRs).

2. Reactors proven but not available for export: (GCRs, AGRs and LWGRs).

3. Reactors developed to the stage of industrial prototypes: (FBRs, HTGRs, HWGCRs, HWLWRs and SGHWRs)

Table 1 shows the nuclear power plants in commercial operation in year 2000. Small and medium sized nuclear reactors (SMRs) are suitable for desalination, often with cogeneration of electricity using low-pressure steam from the turbine and hot seawater feed from the final cooling system. Currently SMRs are defined as power reactors that have power outputs in the range of 100–400 MWe. The development of cost competitive small and medium size nuclear power reactors are more suitable for grid sizes in developing countries as well as for coupling with desalination plants of 10,000 m^3/d (2.64 mgd) to 100,000 m^3/d (26.4 mgd) capacities. About one-third of the SMRs under construction are expected to supply heat or electricity or both to integrated seawater desalination plants.

In the Middle East countries, it was found that the Canadian deuterium uranium pressurized heavy water reactor (CANDU PHWR) is the most suitable type of reactor for desalination and power generation [3,11–14]. Atomic Energy of Canada developed CANDU heavy water reactor. Natural uranium dioxide is used in the reactor vessel as well as the pressured heavy water as a coolant and cool heavy water as moderator. Producing heavy water is basically simpler than enriching uranium. Commercial heavy water plants have been built in smaller size than would be possible for uranium enrichment plants.

CANDU PHWR reactor is also considered appropriate based on a technical and economic comparison of major commercial nuclear power reactor systems. CANDU PHWR has marginal economic advantages compared with other reactor types. It uses natural uranium as fuel. Natural

Table 1
Nuclear power plants in commercial operation

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	US, France, Japan, Russia	260	243	enriched UO_2	water	water
Boiling water reactor (BWR)	US, Japan, Sweden	92	83	enriched UO_2	water	water
Gas-cooled reactor (Magnox, AGR)	UK	32	12	natural U (metal), enriched UO_2	CO_2	graphite
Pressurized heavy water reactor (PHWR), CANDU	Canada	34	18	natural UO_2	heavy water	heavy water
Light water graphite reactor (RBMK)	Russia	13	14	enriched UO_2	water	graphite
Fast neutron reactor (FBR)	Japan, France, Russia	4	1.3	PuO_2 and UO_2	liquid sodium	none
Other	Russia, Japan	5	0.2			
	Total	440	371			

Source: Nuclear Engineering International Handbook 2002, http://www.uic.com.au/ne3.htm.

uranium can be relatively easily supplied from international market. Several developing countries have operated and built CANDU PHWR indigenously [15].

4. Coupling schemes

Power reactors are suitable for desalination processes that require energy in the form of electricity such as RO. The power is supplied from a dedicated plant/electric grid to drive the high-pressure pump for RO process. Electrical coupling of the nuclear power plant with a RO desalination plant is simple requiring only an electrical connection. There is little interdependence between the power plant generating electricity and the desalination plant producing desalted water. It allows flexibility with respect to sitting and plant size.

Waste heat from the power reactor can be used to improve the efficiency of the RO plant. The increase of operating temperature leads to a higher RO membrane flux and produces more desalted water from the same membrane area. By using appropriate feed pre-treatment, system design and optimization techniques, overall improvements in efficiency and cost can be achieved.

In nuclear power reactors, the steam is generated at high temperature and pressure, whereas heating reactors need only to produce low temperature steam or hot water for thermal desalination processes. Thermal desalination processes have an upper temperature limit to prevent excessive scaling. Heating reactors, which are designed to supply steam at 130°C or lower, have the best potential for coupling to desalination plants. Steam at 2.0–3.7 bar (120–140°C) can be used in MSF desalination plants to give a high GOR. In order to avoid scale formation, the maximum brine temperature is limited to about 121°C for recycle type MSF and 135°C for once-through MSF.

In the case of nuclear plants that co-generate heat and electric power, the steam can be bled-off at suitable points in the secondary circuit of the power plant for use by the desalination plant. However, protective barriers must be included in all co-generation modes to prevent potential carry over of radioactivity.

It can be advantageous to use a part of the electricity generated by the nuclear co-generation plant to operate RO desalination plants in addition to thermal desalination plants. The hybrid system at the same location can play an important role in bringing down the water cost as well as making multiple product water qualities available.

Nuclear dual purpose plants for power and desalination using pressurized water reactor are examined by Drude and Rohl [15,16]. The possible coupling schemes of heat and power are pure back pressure cycle, the extraction scheme and the combination of back pressure and condensing turbines cycle.

The choice of the suitable nuclear reactor and desalination process depends on several factors. In case of coupling between NHR and distillation process, it will be necessary for the two plants to be on the same site to cut down the cost of transporting heat over long distances and avoid unnecessary losses. While for coupling NPR and RO, there will be no special arrangements other than an electrical connection between the two plants.

Coupling of a nuclear power plant to hybrid desalination system consists of an MSF plant followed by an RO plant, which may take reject cooling water from the last effect of the MSF system as feedwater to the RO system. Normally, the nuclear power plant is designed for optimum production of electricity. However, there is a large amount of low-grade thermal energy available in the form of waste heat discharged from the nuclear plant through the condenser cooling system. Heat in the form of steam can be supplied by the nuclear reactor through one or more intermediate circuits to the MSF desalination system. Heat may also be supplied in the form of hot water, depending on the temperature and pressure conditions specific to the desalination plant design. Also part or all of the feedwater to the RO MSF system can be drawn from the condenser cooling water discharge stream. The RO system, which uses electricity as its primary energy input, may draw either from the electrical grid or by direct connection to the nuclear plant with an auxiliary connection to the grid. Fig. 2 shows a schematic coupling arrangement for a hybrid RO MSF plant.

Coupling RO and MSF with nuclear steam supply system (NSSS) will yield some economical and technical advantages. A comparison between NSSS-MSF and NSSS-RO desalination plants is illustrated in Table 2 [17].

Fujairah seawater desalination project in the United Arab Emirates consists of 284,000 m^3/d (75 mgd) of multi-stage flash distillation and 170,000 m^3/d (45 mgd) of seawater reverse osmosis. The hybrid system will permit the plant to

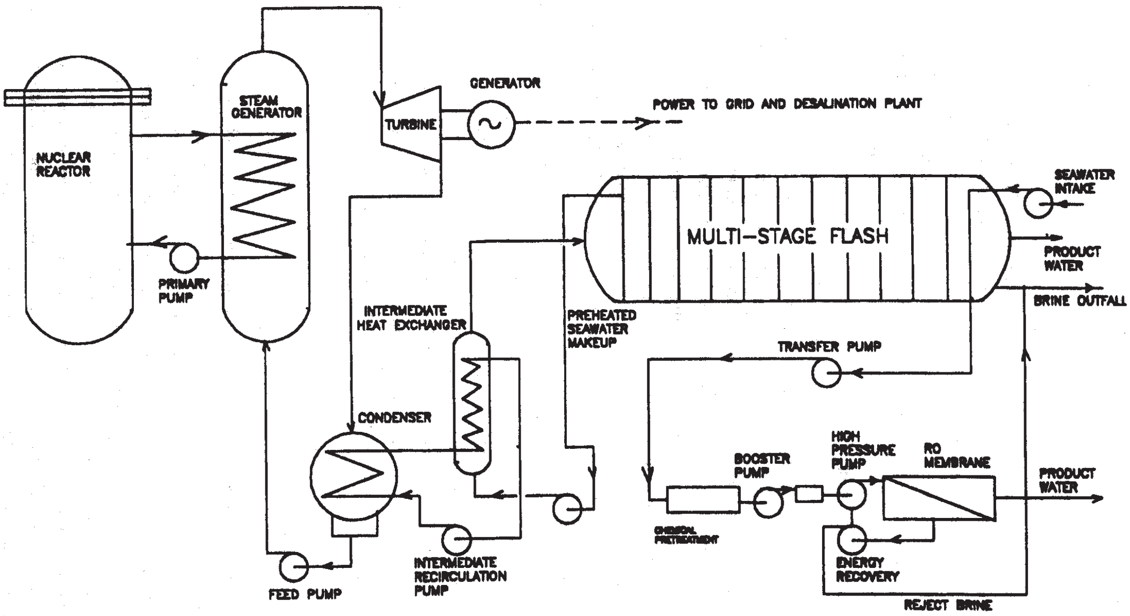

Fig. 2. Schematic diagram of a nuclear power reactor coupled to RO MSF plant [1].

Table 2
Comparisons between NSSS-MSF and NSSS-RO desalination plants

Item	NSSS-MSF	NSSS-RO
Availability	0.9	0.89
Product salinity, kg/m^3	0–1	0.5–1.5
Capital cost	High	Low
Operation interface	Yes	No
Energy consumption	Steam and power	Power only
Safety consideration	Radiation contamination	Nuclear plant only
Load regulation	Flexible	No load regulation
Coupling	Require extensive care	Direct coupling
Thermal pollution	High	Medium
Manpower	Highly qualified	Qualified in nuclear
Plant site	On the same site	RO near the city
Transportation cost	Required	Not required

maximize and balance the use of power, water consumption and water quality to produce the best performance at the lowest operating costs. The plant scheduled for start-up in June 2003.

In Kalpakkam on the east cost of India, a hybrid RO MSF nuclear desalination is being considered [18]. This will include MSF plant producing 1,800 m^3/d (0.47 mgd) and RO units producing 4,500 m^3/d (1.19 mgd). The desalination facilities will be coupled with 2×170 MWe nuclear power station. MSF plant requires about 21 t/h steam at around 3.5 bar and 400 kg/h steam for ejectors at 7 bar. Steam will be tapped at 3.5 bar from a suitable point in the turbine for heating the brine in the MSF plant.

According to previous studies [3,11–14], CANDU PHWR is the appropriate type of nuclear reactor for coupling with desalination plants specially RO MSF types. Hybrid RO MSF CANDU PHWR is the candidate system for the application of dual purpose nuclear desalination plants. The electrical and thermal power produced from CANDU reactor may be utilized to derive the desalination plans. This makes such option more favorable to meet the increasing demand of power and water. The possible coupling schemes of heat and power are pure back pressure cycle, the extraction scheme and the combination of back pressure and condensing turbines cycle.

PHWR provides a safer steam generation due to an additional barrier. It uses heavy water (D_2O) as primary coolant and de-mineralized water as the secondary coolant. The steam required for MSF is extracted by coupling to the low pressure turbine. The steam is tapped from a suitable point on the low pressure turbine for heating the brine in the MSF plant. The selection of tapping point depends on the maximum brine temperature selected. The arrangement is also made to tap the steam from both the reactor systems for MSF to ensure the continuous operation of the desalination plant.

Part of the power generated in the nuclear power station is used for operating seawater RO plant by coupling it thermally and electrically with the power plant. The thermal coupling gives higher throughput due to higher feed seawater temperature up to 40°C. The remaining power is used for distribution.

For a preventive coupling scheme, the vapor extracted from the specified turbine stage is fed to a heat exchanger (acting as a barrier). The incoming water temperature is raised to an appropriate level. The hot water then passes through a flash tank (a second barrier) where it is partially evaporated. This vapor then serves as the heating source in the MSF brine heater. This is called a flash loop. The flash loop is the optimum coupling scheme for PWRs, which provides maximum quantity of fresh water at the lower cost, without unacceptable reduction of the electrical power produced and without undue health hazard for population.

5. Conclusions

Desalination plants require significant amounts of energy in the form of heat and/or electricity (power). This energy can be supplied by nuclear reactors since nuclear reactors are used mainly for the production of either heat or power. Coupling desalination plants with nuclear reactors gives many economical and technical advantages. The hybrid RO MSF desalination plant coupled to a nuclear power plant gives high overall availability factor.

CANDU PHWR is the appropriate type of nuclear reactor for coupling with hybrid RO MSF desalination plants. This hybrid system has potential advantages of a low power demand, improved water quality and possible lower running cost.

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