Nuclear seawater desalination plant coupled with 200 MW heating reactor

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Abstract: A feasibility study on nuclear seawater desalination plant in which a 200 MW nuclear heating reactor (NHR-200) is coupled with MED processes has been completed, and the Chinese government has agreed to build a nuclear seawater desalination plant of this type in the Shandong Peninsula of China. Two different kinds of MED processes, high temperature stacked VTE-MED and low-temperature horizontal tube MED-TVC, have been investigated and compared, and their capacities for freshwater production are 160 000 m^3/d and 120 000 m^3/d, respectively. Based on the results of the feasibility study, the VTE-MED plant is more economical than the MED-TVC, but not on the technology maturity for a very large nuclear desalination plant. The two kinds of different nuclear desalination schemes and their primary economic results are presented in this paper.

Keywords: desalination plant; MED processes; China; freshwater production.

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1 Background

With its rapid economic and social development, China nowadays is also facing severe problems of freshwater shortage, particularly in north China. The Chinese government pays a lot of attention to these problems and has initiated very large water-transfer engineering projects, namely, transferring south China water to north China through three different canals located in eastern, middle and western China. In fact, the construction engineering of the middle route has been started and Beijing will be able to obtain some water from the canal during the 2008 Summer Olympic Games. Although the engineering is very grand and ambitious, it cannot solve all freshwater shortage problems in north China, not to mention the possible high price of the water.

Along the eastern coast of China, there are a lot of metropolitan and medium-sized cities, such as Tianjing and its neighbour city Beijing, Dalian in the Liaodong Peninsula, Yantai and Qingdao in the Shandong Peninsula. All of them have freshwater shortage problems and are eager to use desalination technology.

In addition, many Chinese coastal power plants want to use desalted seawater as power plant feed water. The Dagang power plant in Tianjing city has the longest history in China of using desalted seawater as its boiler feed water: its 3000 m^3/d MSF unit imported from the USA has been operated for over ten years. On 4 June 2004, a MED-TVC unit of 3000 m^3/d freshwater production capability made in China was tested in the Huangdao power plant. SIDEM built a four-effect MED-TVC desalination unit for a power plant in Hebei province. These thermal desalination projects, and the rapidly developing membrane desalination technology, are just a few representative projects for a booming desalination market in China.

Against the background of severe water shortage problems, the Shandong nuclear seawater desalination project has been agreed upon by the Chinese government as a new technology demonstration project. A feasibility study report on the project has been finished at INET, and the final report will be submitted to the Chinese government after a further optimum study. The comparative investigation of two cases, respectively, coupling the NHR-200 with a vertical tube evaporator VTE-MED or with a horizontal tube evaporator MED-TVC, has been carried out, and this paper summarises the two kinds of seawater desalination plants and compares the preliminary economic analysis results (INET, 2004).

2 NHR-200 nuclear heating reactor

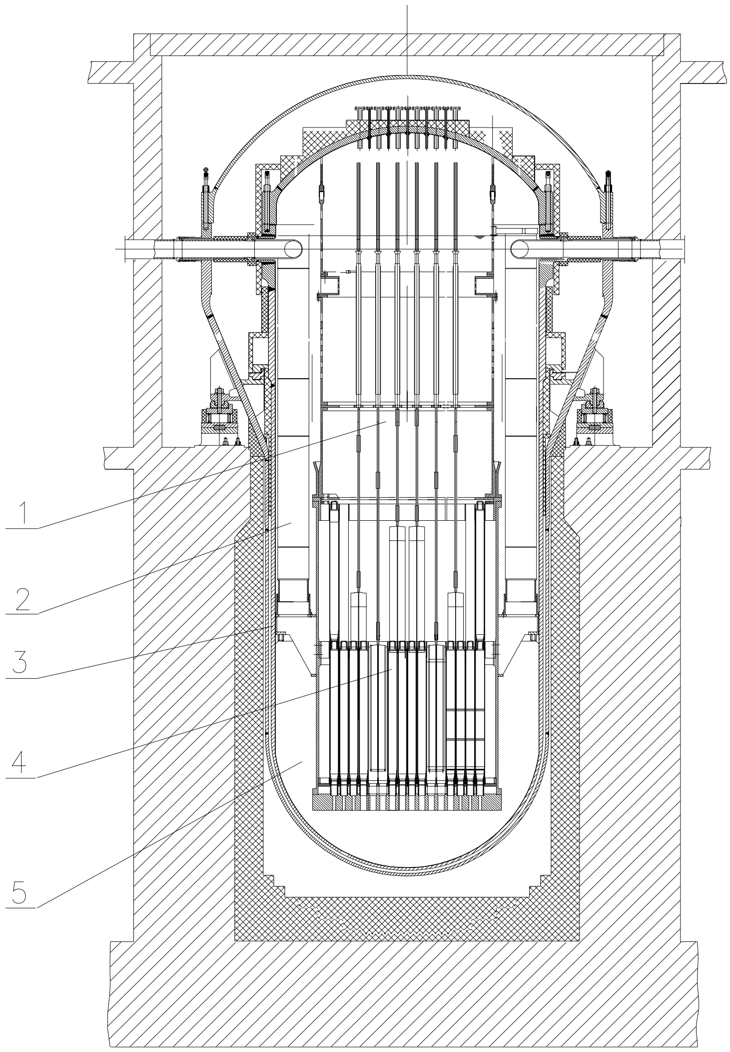
The 200 MW nuclear heating reactor was developed at INET of Tsinghua University in China after a 5 MW testing nuclear heating reactor was successfully constructed and safely operated at INET in 1989.

Both the tested 5 MW nuclear heating reactor and the 200 MW commercial demonstration heating reactor are water-cooled, integrated, full-power natural circulation reactors with passive safety features (Wang *et al.*, 1990; 1993). The double-layer steel pressure vessel and containment vessel and other very good safety characteristics guarantee no unplanned release of radioactive materials to the environment or to the equipment connected to it.

The main structure of the NHR-200 is shown in Figure 1. The reactor core and several similar main heat exchangers are arranged inside the pressure vessel; the core is located in the lower part and the main heat exchangers are set in the annular space between the pressure vessel and the riser on the upper part of the pressure vessel.

The NHR-200 is a heat-dedicated reactor, its main parameters are listed in Table 1. The pressure of the main loop is 2.5 MPa.

Figure 1 Cross-sectional view of NHR-200



Notes: 1 Riser.
2 Heat exchangers.
3 Vessels.
4 Reactor core.
5 Downcomer.

Table 1 Main design parameters of NHR-200

Parameter name	*Unit*	*NHR-200*
Thermal power	MW	200
Pressure	MPa	2.5
Core inlet/outlet temperature	°C	140/210
Intermediate circuit pressure	MPa	3.0
Intermediate circuit temperature	°C	95/145
Steam mass flow rate at exit of intermediate circuit steam generator	t/h	330
Steam pressure at exit of intermediate circuit steam generator	MPa	0.25
Steam temperature at exit of intermediate circuit steam generator	°C	127

As the main energy source of seawater desalination equipment, the motive steam used in desalination process will be obtained from steam generators in the intermediate circuits between reactor and final steam consumer, the parameters of the motive steam are as follows: the pressure is 0.25 MPa, the saturated temperature is 127°C, and the mass flow rate is 330 t/h. The heat transferring medium in the intermediate circuit is also water; its pressure is 3.0 MPa.

About 15 years of operation experience and some safety characteristics tests carried out on the 5 MW testing nuclear heating reactor show that it is safe and it is possible to construct the nuclear heating reactor near the civil living district as heating source or to use it as the power source for seawater desalination.

3 Coupling between NHR-200 and desalination systems

Because the NHR-200 is a heat-dedicated single-purpose reactor and is only operated in a heat mode, it cannot be used as the power source for Reverse Osmosis (RO) process. On the other hand, the high energy consumption rate of Multi-Stage Flash (MSF) process does not make it the best choice for the newly developing large-scale seawater desalination plant. Considering the potential huge advantage and rapid development and improvement in Multi-Effect Distillation (MED) technology (Al-Shammiri and Safar, 1999), such as low energy consumption rate, extensive experience in construction and operation, very good expression on corrosion, scaling and fouling, and higher operation flexibility in different loads, the MED processes were chosen as the desalination process in China's Shandong nuclear seawater desalination plant.

High efficiency and safety are the main factors when the optimal coupling between the NHR-200 and desalination equipment is taken into account, thus the following basic requirements must be satisfied:

- the nuclear energy should be transferred to the desalination equipment with high efficiency
- the product water of the desalination equipment should not be contaminated by radioactive materials released possibly from the reactor
- the desalination equipment should not induce additional safety measures on the reactor.

The steam generators installed in the intermediate circuit contributes a lot for the above-mentioned basic coupling requirements. The reactor primary heat exchangers and the steam generators supply two steel barriers between the reactor and desalination equipment to prevent radioactive contamination of product water. The first effect of the MED desalination equipment is also a safety barrier because either the motive steam supply circuit is a closed loop (in VTE-MED case) or the product water condensed in the first effect will not be added to the next effect (in MED-TVC case). In the VTE-MED case, all the condensate in first effect will be pumped back to the steam generator as its feed water. In the MED-TVC case, part of the condensate will be pumped back to the steam generator and the excess condensate will be accumulated and not used as the potable water.

In addition, the pressures in the intermediate circuit is higher than the primary circuit pressure, thus even in the case of breaking heat transfer tubes or tube sheet of the primary heat exchangers, the contaminated reactor coolant would not leak into the intermediate circuit and motive steam circuit.

The real changing load tests done on 5 MW testing nuclear heating reactor has shown that even under the loss of the steam load, the nuclear heating reactor had very good safety characteristics and its power level could be decreased automatically in a short time (Wang *et al*., 1994; Zhang *et al.*, 1990; 1999). This result shows that the desalination plant would not result in heating reactor safety problem even in the event that the desalination equipment results in the rapid valve closing action of motive steam supply system of the desalination equipment.

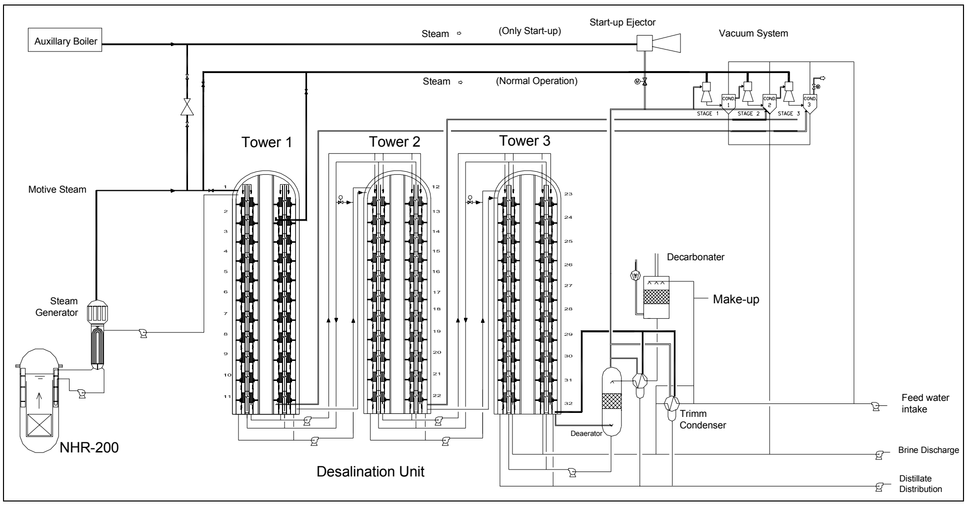
4 VTE-MED desalination plant

One scheme of the Shandong nuclear seawater desalination plant is the high temperature VTE-MED desalination units coupled with NHR-200; the schematic diagram of the coupling scheme, NHR-200 and VTE-MED process are shown in Figure 2. The rated fresh water production capacity of the total desalination plant would be 160 000 m^3/d. In the design there are two units, and every one has a fresh water production capacity of 80 000 m^3/d. The two units share one feed water supply system and brine outflow system.

For every unit under rated design condition, the raw seawater at 20°C is screened and divided into two parts: one part is introduced to the trim condenser in order to condense excess vapour in summer, while the other part is used as feed water of the desalination unit. The feed water is mixed with sulphuric acid to release carbon dioxide in a decarbonation co1umn and then passed through final condenser. In the final condenser the seawater is warmed to about 28°C, and the warmed feed water will spray into a vacuum deaerator in order to fully release the oxygen; the deaerator is connected with the vacuum ejectors of the desalination system. Finally, the feed water becomes make-up water to the evaporators in the concrete towers.

The vacuum system under normal operation condition of the desalination plant is composed of multistage steam ejectors with interstage and after-stage condensers, the multistage ejectors will use steam from steam generator of the NHR-200 as their motive steam. During start-up of the desalination plant, a middle-pressure steam ejector will be used for initial evacuation. The middle-pressure steam with 1.0 MPa pressure is from auxiliary boilers, which are also the energy source of the desalination plant during the refuelling period of the NHR-200.

Figure 2 Schematic diagrams of the coupling scheme between NHR200 and the VTE-MED process



The waste brine from the last effect of the VTE-MED plant will have a salt concentration about three times that of seawater, a temperature of about 35°C, and a flow rate of about 90 000 m^3/d. However, the temperature and salinity of brine will lower greatly after it is blended with the trim condenser cooling flow and vacuum system cooling water, thus its heat and high salinity impact on environment can be decreased substantially. The Total Dissolved Solid (TDS) of the distillate from the desalination plant will be less than 20 ppm, so it will be blended with other high-salinity potable water before it is distributed into a potable water system. The simple posttreatments include adding oxygen and chlorine and contact distillate with lime.

Because the thermal parameter coupling between the high-temperature VTE-MED process and the NHR-200 is very good, it leads to a high efficiency of energy utilisation and the high performance ratio (GOR) of 22 in the desalination plant.

The main part of the VTE-MED desalination unit is three concrete towers and evaporator–preheater tube bundles in towers. The towers are used as evaporator shells and each tower is constituted by dual cylinders and connecting floors. The inner diameter of the outside cylinder is 20 m and the outer diameter of the inner cylinder is 10 m. The total height of the tower is about 90 m. Each concrete tower is separated into 10–11 floors and there are holes on floors, the annular spaces formed by two floors and cylinder walls are the volumes to install evaporator–preheater tube bundles, which are installed vertically in floor holes in lines. There are 32 effects for every unit and seven bundles in parallel for every effect, and each effect is 7 m in height.

The heat transfer tubes of evaporators are double-fluted stainless steal tubes (flutes along axial direction) with 50 cm in average diameter and 4.8 m in length. The smaller diameter smooth tubes in the central region of evaporator–preheater bundles constitute the preheater bundles.

The top sheet and watertight skirt around its perimeters form a receiving pond for brine and vapour leaving from the effect above, and it is also a feed water reservoir for the tubes below because the floor of the pond is the top of the tube bundle below. There is a multihole orifice plate in the bottom of the pond, which is the key part to control the brine flow into the tubes below according to the required pressure and static head difference between the effects.

The treated warm make-up leaving from the deaerator is pumped upward into a series of make-up preheater bundles joined one by one in the three towers, the temperature will be increased to the designed value 115°C when make-up arrives to the top of tower 1. The make-up is then distributed to the tubes of the top effect, where the make-up absorbs the heat from the motive steam on the other side of the tubes and forms rapidly moving vapour in the centre of the tube. As mentioned before, the motive steam with 125°C of temperature and 0.24 MPa pressure is from the intermediate steam generator of the nuclear heating reactor. The condensate collected in the first effect is returned to the steam generator as its feed water.

In the effects below, the brine entered the double-fluted tubes will move down inside the walls in thin film, the process that happened in the first effect will repeat again and again. The two-phase flow mixture falls into brine ponds below each bundle, vapour will be separated from the pond and flow to the outside of the tube bundles after passing through demisters installed along the upper rim of the pond, and the separated vapour becomes the heating steam for the bundle below.

In each effect, the condensate collected on the lower tube sheet becomes the fresh water product of the effect and is passed through a trap to the lower-pressure effect below and releases some flashing heat there.

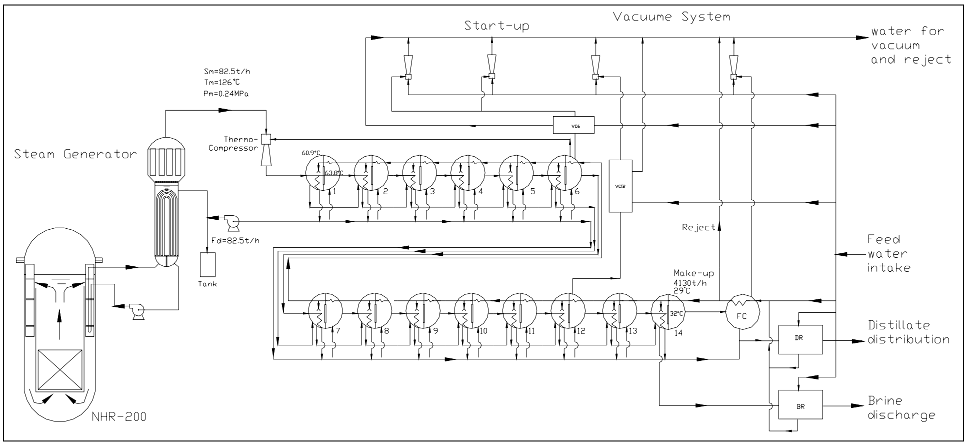
The process described above will repeat in each effect and the brine leaves the final condenser and will be pumped to the plant outflow system. The combined distillate at about 30°C is pumped to a posttreatment facility.

5 MED-TVC desalination plant

Another scheme of the Shandong nuclear seawater desalination plant is the NHR-200 coupling low temperature MED with thermo-compressor. The schematic diagram of the coupling scheme, NHR-200 and the MED-TVC process is shown in Figure 3. In this scheme, taking account of the maturity of low-temperature horizontal tube MED process in which top brine temperature usually is less than 65°C, the NHR-200 will couple with four similar MED-TVC units. The production capacity of each unit is 30 000 m^3/d, and the total capacity is 120 000 m^3/d.

Each unit consists of 14 effects, a final condenser and preheaters. The first six effects will work with thermo-compressor, which absorbs about 65 t/h of vapour produced in the sixth effect. The saturated motive steam of thermo-compressor has 82.5 t/h of mass low rate and 0.24 MPa pressure, which is from the steam generator in the intermediate circuit of the NHR-200. The blended middle pressure steam then will be pressed into the first effect. After releasing heat and condensed into the distillate, part of the condensate in the first effect is pumped back to the steam generator of the NHR-200 as its feed water, and excess distillate will be pumped to other place in order to avoid the possible contamination of potable water from the NHR-200.

Figure 3 Schematic diagrams of the coupling scheme between NHR200 and the MED-TVC process



The four units share one feed water supply system and one brine outflow system. Under rated design conditions, the raw seawater at about 20°C is screened and mixed with antiscale additive and then make-up passes through the final condenser; in the final condenser it is warmed to about 29°C. Finally, the make-up is sprayed on evaporator heat transfer tube bundles in every effect. Corresponding to the different effect temperature, the make-up needs to be preheated to different temperatures by means of different number of preheaters, before it is sprayed on tube bundles.

In winter the feed water will not only pass through the final condenser but also flow through distillate and brine heat recover exchangers in order to be warmed to the required make-up temperature. On the other hand, in summer when the seawater temperature is higher than the rated design value, the feed water flow rate is larger than make-up flow rate and part of it will be discharged as rejecter after it passes through the final condenser and condenses the excess vapour produced in the 14th effect.

In order to avoid a middle-pressure fossil fuel auxiliary boiler, water eject pumps are used as the vacuum pumps both in the start-up period and also during the normal operation conditions. The water eject pumps are divided into four groups: the first group has two water eject pumps and are only used during the start-up, while the other three groups of water eject pumps are used to deaerate the non-condensable gas from the 6th effect, 14th effect and the final condenser during the normal operation.

Because the motive steam temperature from the steam generator is 127°C and much higher than the required heating steam temperature in the first effect (about 65°C), thermal parameter coupling between the MED-TVC process and the NHR-200 is not the best; moreover, there are less number of effects in the MED-TVC scheme than in the VTE-MED scheme. All these result in lower efficiency of energy use and the lower GOR of 15 in the MED-TVC desalination plant.

6 Technical scheme and economic comparison

A technical and economic analysis of the Shandong nuclear seawater desalination plant was finished recently, and two schemes coupling NHR-200 with the VTE-MED or MED-TVC desalination systems were evaluated. The VTE-MED process is similar to the one for Southern California in many aspects (Hammond *et al.*, 1994), the MED-TVC process will be a commercially mature technology.

All manufacturing and construction work of the NHR-200 can be done based on local Chinese technology. Based on the quotations from Chinese vendors, including the original nuclear fuel, the direct capital cost is about USD65 million. NHR-200 will contribute 30% to 35% of the total water price.

The engineering construction schemes for the two kinds of desalination plants are different. For the VTE-MED case, only the double-fluted tubes will be imported from the international market, and other major works, such as fabricating of evaporator–preheater bundles, construction of the concrete towers, erection of the plant, civil work, seawater intake and brine outflow engineering, will be based in a Chinese company and finished in China. For the MED-TVC case, taking account of the experiences and maturity of the foreign suppliers, all main desalination equipment will be imported as a lump sum from foreign market; only site preparation work, civil work, seawater intake and outflow engineering work will depend on Chinese companies.

Direct capital costs for the two schemes are different: the VTE-MED scheme is more expensive than the MED-TVC scheme. Indirect capital costs are calculated based on certain proportion of the direct capital costs. Taking account of different impact factors, the cost price range of product water of the Shandong nuclear seawater desalination plants is USD 0.65 to 0.85/m^3 for above two schemes, and the water price of the VTE-MED scheme is a little cheaper than that of the MED-TVC scheme.

The effect analysis of several sensitivity parameters on water prices has shown that the total desalination plant investment is the most sensitive parameter on the water cost, because the bank loan is not the main part of the investment.

7 Conclusions

The feasibility study on China’s Shandong nuclear seawater desalination plant, which couples a 200 MW nuclear heating reactor with the VTE-MED or MED-TVC processes has been finished at INET of Tsinghua University.

NHR-200 is a single-purpose thermal-dedicated integrated reactor developed at INET. The heat produced from NHR-200 will be transmitted to the desalination units through three circuits, which provide sufficient safety barriers to the produced water.

The VTE-MED scheme and the MED-TVC scheme can supply 160 000 m^3/d and 120 000 m^3/d desalted water, respectively. For the VTE-MED case, only the double-fluted stainless steel tubes will be imported from the international market, and other construction work will depend on a local Chinese company and finished in China. For the MED-TVC case, all desalination equipment needs to be imported as a lump sum from the foreign market, and only the site preparation work, civil work, seawater intake and outflow engineering work will rely on Chinese companies.

Taking account of different engineering schemes and other factors, the cost of product water is USD 0.65 to 0.85/m^3 for the above two schemes, and the water price of the VTE-MED scheme is a little cheaper than that of the MED-TVC scheme.

Although the VTE-MED scheme shows economic and production capability advantage compared with the MED-TVC scheme, the fact that there has been no experience of such a large-scale desalination plant of this type anywhere in the world up to now makes it necessary to do further studies and assessments. However, no matter which scheme will be used, the nuclear seawater desalination technology coupling NHR-200 with the MED process has shown its huge advantages both in producing fresh water with a competitive cost and in decreasing environmental pollution and greenhouse gas emissions.

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