Seawater desalination plant using nuclear heating reactor coupled with MED process

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Abstract A small size plant for seawater desalination using nuclear heating reactor coupled with MED process was developed by the Institute of Nuclear Energy Technology, Tsinghua University, China. This seawater desalination plant was designed to supply potable water demand to some coastal location or island where both fresh water and energy source are severely lacking. It is also recommended as a demonstration and training facility for seawater desalination using nuclear energy.

The design of small size of seawater desalination plant couples two proven technologies: Nuclear Heating Reactor (NHR) and Multi-Effect Destination (MED) process. The NHR design possesses intrinsic and passive safety features, which was demonstrated by the experiences of the project NHR-5. The intermediate circuit and steam circuit were designed as the safety barriers between the NHR reactor and MED desalination system. Within 10~200 MWt of the power range of the heating reactor, the desalination plant could provide 8000 to 150,000 m^3/d of high quality potable water. The design concept and parameters, safety features and coupling scheme are presented.

Keywords Nuclear desalination, Nuclear heating reactor, MED process, Direct thermo-coupling

CLC numbers $TL413^+.2$, $P747^+.15$

1 Introduction

Some coastal location, developing area and island with small or medium population, where both fresh water and energy source are severely lacking and there have not yet been adequate infrastructure and basic conditions for construction of a conventional nuclear power plant, show strong interest in potable water production by seawater desalination. For these cases, a small or medium size plant of sea water desalination by using heating reactor may be a suitable solution.

Such a small size for seawater desalination using nuclear heating reactor coupled with a demanded MED process was developed by the Institute of Nuclear Energy Technology, Tsinghua University, China. It was intended to supply potable water needed in some coastal area and islands, and to be recommended as a demonstration and training facility.

The design of small size seawater desalination plant couples two proven technologies : Nuclear Heating Reactor (NHR) with intrinsic, passive safety features and MED process. The secondary loop and a steam loop were designed as the safety barriers between reactor and MED desalination system. Within 10 to 200 MWt of the power range of the heating

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reactor, the desalination plant could provide 8000 to 150,000 m^3/d of high quality potable water.

The following comprehensive utilization of this desalination plant project were considered as the design objective:

—Potable water production:

—As a technical personnel training center;

—As a short term, full scope demonstration facility for sea water desalination using nuclear energy.

The design of the nuclear heating reactor used for a sea water desalination plant is based on the proven technology and experience of 5 MW prototype nuclear heating reactor project (NHR-5)[1], developed by Institute of Nuclear Energy Technology (INET), Tsinghua University, China. The NHR-5 has been successfully operated since 1989. The heat-electricity cogeneration with NHR-5[2] was also successfully carried out during 1991 to 1992. Very good operation characteristics and excellent safety features, such as high operation availability, inherent safety and self-regulation characteristics were practically demonstrated. Operating in cogeneration mode, the total complex (NHR-5 coupled with turbine generator and heat grid) is possessed of perfect operation stability, self-regulating performance and perfect load-following characteristics. The MED process is a commercially well established and proven technology and readily available.

In order to investigate the coupling scheme and technology, the nuclear sea water desalination experiment using NHR-5 coupled to a small MED unit was carried out and adopted as a limited scope demonstration. Based on the technology and experience of NHR-5 and the limited scope demonstration, a small size of NHR+MED project for sea water desalination could be successfully implemented in a short term and would also be logically as a full scope demonstration plant. A Morocco-China cooperation on performing a pre-project study on a demonstration plant for seawater desalination using a small nuclear heating reactor, within the framework of an IAEA Technical Co-operation project was smoothly implemented.[3]

2 Brief introduction of the NHR nuclear heating reactor

The nuclear heating reactor (NHR) is a vessel type of pressurized water reactor with integrated design of primary circuit in the pressure vessel. The reactor core is cooled by light water with natural circulation and the primary system is self- pressurized. The reactor structure is shown in Fig.1.

The reactor vessel is designed with 2.5 MPa of operating pressure. The core is located at the bottom of the vessel. There is a riser above the core outlet used for increasing driving force on natural circulation. There are several primary heat exchangers arranged in the annular space between the riser and the vessel. The heat carried over from the core is transferred to the intermediate circuit via the primary heat exchangers.

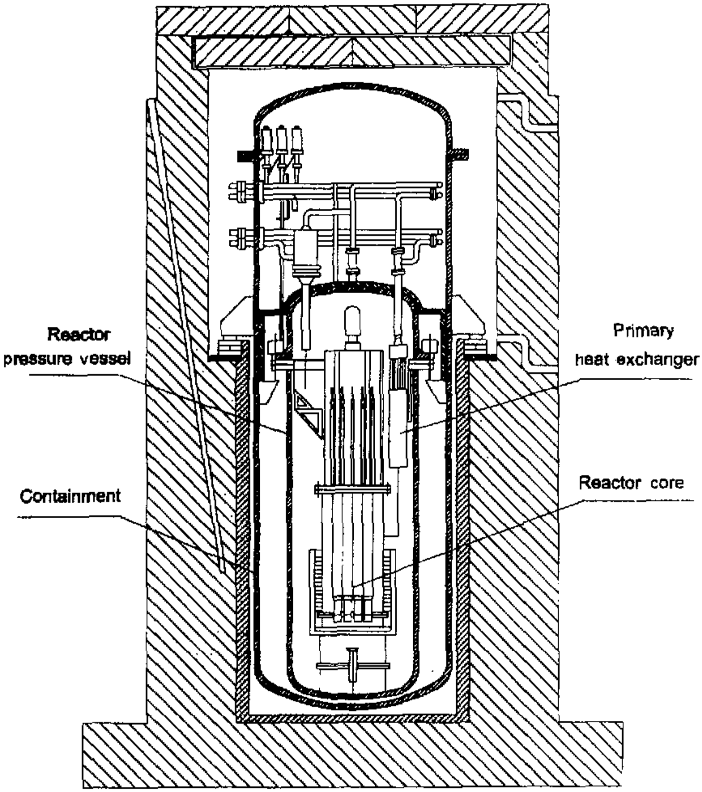

Fig.1 Nuclear heating reactor

The reactivity is controlled by a combination of fixed burnable poison, movable control rods and the negative temperature coefficient of reactivity. The control rods are driven with a specially designed hydraulic driving system, which consist of a hydraulic circuit located outside the containment, a hydraulic step-moving cylinder in the core and two control units. When reactor shutdown is needed, the control rods would drop down into the core driven by gravity (designed on "fail-safe" principle). A borate solution injection system is designed as the reserve shutdown system and initiated with pressurized gas source in the ATWS event.

The heat transfer system of NHR-10 is composed of three circuits including the integrated primary circuit in pressure vessel, the intermediate circuit and the steam circuit. The intermediate circuit, in between the primary circuit and the steam circuit, is set at the operating pressure higher than that in the primary circuit. Therefor, it would work as a barrier and protect the steam circuit from radioactive contamination.

A passive residual heat removal system connected with intermediate circuit is designed to safely disperse residual heat.

As a example the main design parameters of NHR-10 is shown in Table 1.

Table 1 Main design parameters of the NHR-10

Reactor rating power	10 MWt
Pressure in primary circuit	2.5 MPa
Core outlet temperature	210 °C
Core inlet temperature	170 °C
Number of fuel assembles	32
Enrichment of fuel	4.5%
Diameter of the fuel rod	10 mm
Average power density	~15 kW·L^{-1}

3 Safety concepts and features of NHR reactor

The NHR heating reactor is a new generation nuclear reactor. It's main design objectives are to possess the inherent and passive safety characteristics, and to improve availability by simplification of systems.

3.1 Integrated design and self-pressurization

Main components of primary circuit, such as reactor core, primary heat exchangers are integrated in the pressure vessel that could avoid the risk of large pipe break. An appropriate volume, filled with steam and inert gas, at the upper part in pressure vessel of NHR reactor is used for self-pressurization, keeping reactor at pressurized operation condition. The self pressurization is realized by the partial pressure principle of inert gas and steam. Therefor there are no separate pressurizer on the primary circuit.

3.2 Tightly arranged steel containment with higher design pressure (dual pressure vessel concept)

The core will never be uncovered by coolant, even in case of small break occurred at the bottom of the primary pressure vessel.

3.3 Natural circulation in primary circuit

Reactor core is cooled by water with natural circulation. A riser is set on the top the core to increase driving force on natural circulation. Use of natural circulation can avoid the primary circulation pump on the primary circuit and lead to both increasing in reactor operation reliability and excluding the big pipe penetration through the RPV.

3.4 Low power density and large water inventory in pressure vessel

The core power density of the NHR-10 is about 15 kW/L, about 1/5~1/8 of that in PWR plant design. The water inventory in pressure vessel is quite large. The ratio of water volume to core power is more than 1 m^3/MW which is about 20 times of that in PWR design. With the water inventory in primary system of NHR heating reactor being much larger than that of PWR and the operaton pressure as well as the temperature of NHR heating reactor being much lower, the heating reactor has good behavior and less serious consequence even in the case of LOCA.

3.5 Hydraulic control rod driving system with passive safety

A specially designed hydraulic control rod driving system is adopted in NHR heating reactor. It is enclosed in the pressure vessel without penetration at the head of pressure vessel, therefore the accident of control rod ejection can be avoided. The hydraulic control rod driving system has been successfully operated at NHR-5 for several years. Operation results show that it is safe, reliable and simple in structure.

3.6 Passive residual heat removal system

The passive residual heat removal system is adopted in NHR heating reactor design. The residual heat can be dissipated out from the core to atmosphere by natural circulation.

3.7 Intermediate circuits

Intermediate circuits are set up to protect the steam circuit and desalination system from radiation contamination.

3.8 Emergeney cooling and water making up systems

It is not needed to set up emergency cooling system and emergency water making up system due to above mentioned inherent and passive safety features, that leads to simplified systems and lower cost.

4 NHR desalination plant

The NHR desalination plant coupled a heating reactor to a MED desalination process with higher temperature and higher energy efficiency. The MED process has lower energy consumption, lower investment cost and appears to be less sensitive to corrosion, scaling and fouling. Its operation flexibility in partial load is higher. Therefor the MED process was adopted in the design. The NHR reactor is used as the heat source and operated in a heat only mode. A steam generator is installed in the intermediate circuit for supplying steam to the desalination process. Steam generated in the steam generator is totally supplied to the first effect of the MED process. In the desalinaton system, seawater is heated up to 120°C and then evaporated and condensed in a series of successive stages (named as 'effect'). As a example The schematic diagram of the small desalination plant with directly thermo- coupling scheme is shown in Fig.2. The main parameters is listed in Table.2. With the heat only operation mode, the 10 MW NHR desalination plant could supply 8000 m^3/d of potable water.

Table 2 Main parameters of the desalination plant with NHR-10

Reactor rating power	10 MWt
Core outlet temperature	210°C
Core inlet temperature	170°C
Outlet temperature at intermediate circuit	170°C
Inlet temperature at intermediate circuit	135°C
Steam temperature at outlet of steam generator	130°C
Steam temperature at the first effect of MED	125°C
Top brine temperature	120°C
Capacity of MED desalination unit	$4000 m^3 \cdot d^{-1}$
Number of the unit	2
Number of effect	27
GOR	20
Maximum water production	$8000 m^3 \cdot d^{-1}$

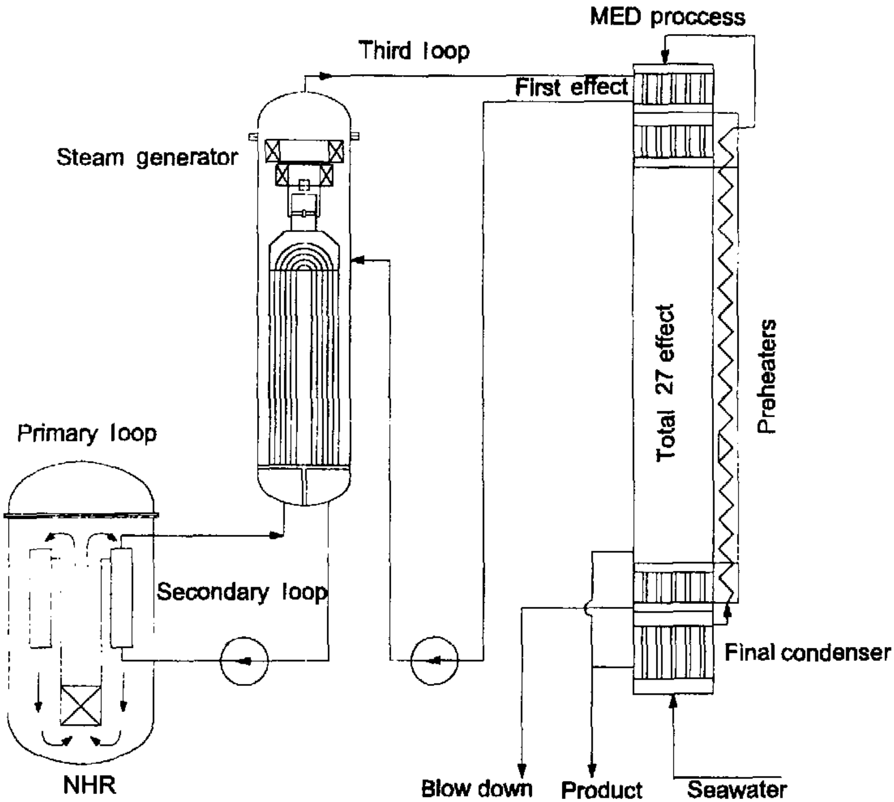

Fig.2 Coupling scheme of NHR desalination plant

5 Selection criteria of optimum coupling scheme

Special considerations for selection criteria of optimum coupling scheme between desalination process and Nuclear Heating Reactor are as follows:

(1) *Reliablity*: Reliable connection between the reactor system and desalination system. The desalination system and the nuclear reactor system are mechanically and thermally connected via the main steam pipe and the main feed water pipe in the steam supply circuit (in-between short distance, at a common site). Thermo-energy required by desalination process is efficiently transferred by steam from the steam generator to the first effect of the desalination system;

(2) *Safety*: Multi-barriers isolation. Between nuclear reactor and desalination system, there are three layers of steel wall boundaries, (i.e. heat transfer tubes of the primary heat exchanger, steam generator and the first effect of evaporator of desalination system) and two circuits (Intermediate circuit and Steam supply circuit) working as barriers to effectively prevent the desalination system from radioactive contamination.

(3) *Inherent safety*: Appropriate pressure barrier.

Pressure in the primary circuit and the secondary circuit are 25×10^5 Pa and 30×10^5 Pa separately. Even in case of rare failure of heat transfer tube or its welding on the tube plate of the primary heat exchanger, the coolant in the primary circuit would not leak into the intermediate circuit;

(4) *Efficiency*: Perfect match of parameters. Coupling of a high temperature MED process with the nuclear heating reactor leads to a high energy efficiency of the integrated desalination plant.

(5) *Operability*: Suitability of operation performance. Both of the heating reactor and the desalination system have excellent self- regulation capability. When the load fluctuates within the range of 70% to 100%, no matter the active perturbation happens in either side, operation of the integrated plant would be very smooth and with perfect self-regulation performance. Adjustment within load range of 40% to 100% is also easy and simple to perform.

(6) *Simplicity*: Simplicity and maintainability of the integrated system.

(7) *Ecolomical*: The integrated desalination plant with the selected coupling scheme would produce drinking water with optimum water cost and high quality. The optimization will eventually be economical optimization.

6 Conclusions

The NHR type of heating reactor could be built near the city for supply heat to seawater desalination and very close to the final users, therefor, the water transport cost could be dramatically reduced due to its perfect safety features.

The design parameters of NHR nuclear heating reactor perfectly match the requirement of MED process. The heat produced from NHR heating reactor could be connected through the third circuit to the MED desalination plant with a top brine temperature of 120°C.

The interaction between desalination process and reactor could be minimized with the proper load following according to the characteristics of NHR heating reactor.

A small and medium sized sea water desalination plant using nuclear heating reactor coupled with MED process would be a suitable solution to supply potable water demanded in some coastal district, island or country with small or medium population due to its perfect inherent safety, simplification in structure, proven technology, acceptable investment cost and water cost.

References

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