

## Co-generation of Electricity and Desalted Water by Gas Turbine MHTGR

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**ABSTRACT:** The shortage of water resources and their imbalanced distribution have become one of the main bottleneck problems which inhibit China's sustainable development. Seawater desalination will be an effective measure to alleviate the shortage of water resource in coastal areas. Mass production of desalted water needs cheap energy. Nuclear energy may be a good selection for this purpose. The gas turbine Modular High Temperature Gas-cooled Reactor (MHTGR) system can be coupled with the seawater desalination system without affecting the electrical generation. The removal heat can be used to produce desalted water because its thermal parameters can meet the requirement for the low-temperature multi-effect distillation (LT-MED) of seawater desalination. The co-generation of electricity and seawater desalination by gas turbine MHTGR is an economical and feasible technique to alleviate the shortage of energy and water supply. This combined cycle can provide an effective technical support for China's sustainable development.

**KEYWORDS:** Brayton cycle, Gas turbine, LT-MED, MHTGR, Seawater desalination

### 1. INTRODUCTION

Energy supply by burning large quantities of fossil fuel, especially coal, has resulted in serious environmental problems in China. Over 30% of China's territory now experiences acid rain precipitation. Energy consumption on coal also results in transportation problems as well. In addition, excessive dependence on fossil fuels exerts a threat to the sustainable supply of energy resources and will cause China to confront the security of energy supply.

Nuclear energy seems to be one of the solutions to meet energy demand as well as curb the increasing air pollution and emission of greenhouse gases. In the past decades, NPPs have played a substantial role in the supply of electricity and produced about 17% of the world's electricity [1]. However, nuclear energy was not yet significant to China's energy supply. In 2005, nuclear power provided 52.3 billion kWh of electricity power, only 2.1 percent of the total generation [2]. Continued and expanded reliance on nuclear energy is one key to meeting increasing demand for electricity in China and is called for in the National Energy Policy. An ambitious nuclear power plan has been approved by the Chinese government, which presents a total NPPs capacity of 40 GWe by 2020. Nuclear power will play a more and more active role in China.

China is lacking of water resources, with one-fourths per capita of the world average. Shortage of water resources has become the main bottleneck problem inhibiting China's sustainable development. Seawater desalination will be an effective measure to alleviate water shortage in coastal areas. Mass production of desalted water needs cheap energy. Nuclear energy is a good selection for this purpose. The co-generation of electricity and desalted water by gas turbine MHTGR is an economical and feasible technique. The gas turbine MHTGR system can be coupled with the seawater desalination system without affecting the electrical generation because its removal heat can meet the requirement for LT-MED. This combined cycle can provide an effective technical support for China's sustainable development.

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This paper first describes the imbalanced distribution of China's water resources and the shortage situation of water supply, presents the prediction of demand for water resources in the future and provides the feasible solutions in Section 2. The techniques of seawater desalination and the research status of nuclear desalination are described in Section 3. China's research on nuclear seawater desalination is also presented. The technical features of gas turbine MHTGR with recuperated and inter-cooled Brayton Cycle are characterized while techniques for co-generating electricity and desalted water by coupling gas turbine MHTGR with LT-MED are investigated and discussed in Section 4. Section 5 gives a brief conclusion.

## 2. WATER SUPPLY STATUS IN CHINA

### 2.1 Distribution of China's Water Resources

Although possessing total water resources of 2800 billion m<sup>3</sup> and ranking the fourth in the world, the available water amount per capita in China is only one fourth of the world's average. Furthermore, the distribution of China's water resources is extremely imbalanced over different regions and seasons. Above 80% of the water resources concentrates on the southern area of China; the northern area possesses 65% arable land and supports about half the national total population with only insufficient 20% of the water resources. The rainfall in North China concentrates in the summer (June to August), of which a remarkable part forms the surface runoff. These characteristics determine that the water demand for North China must rely on the groundwater in a quite great degree, 72% for north cities and 66% for northwest cities. Excessive exploitation of groundwater for a long time has formed underground funnel and brought serious geological problems, such as the earth's surface settlements, building collapses, sea water seepage invasion in coastal area, and so on.

Statistics indicates that the total quantity of the water supply deficiency in China is about 40 billion m<sup>3</sup>, about 2 to 2.6 million square kilometers suffer from drought every year, which results in the grain yield reduction of 15 to 20 billion kilograms and industrial output reduction of 200 billion RMB. In addition, 70 million people suffer from deficiency of drinking water. Fig. 1 shows the water shortage situation in North China.

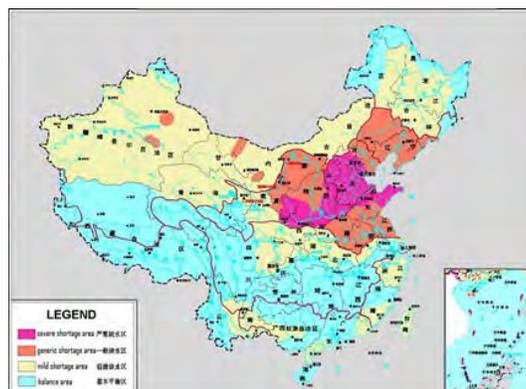


Fig. 1: Water shortage distribution in North China

### 2.2 Prediction of China's Water Demands

From 1980's, the water consumption per capita in China has stabilized in 430-450 tons. It is reasonable to estimate that the total quantity of water demands will increase with the increase of the national population and reach its peak in 2030 when the consumption is expected 700 billion m<sup>3</sup> [3]. With respect to the total quantity of water resources, China has the potential to supply 700 billion m<sup>3</sup> for supporting the economical activities and maintaining the living of its population. The challenge is how to solve the imbalanced distribution over different regions and to develop several kinds of water sources reasonably to meet the local area requirements.

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## **2.3 Feasible Solutions of Water Resources**

### **2.3.1 South to North Water Transfer**

The South to North water transfer (SNWT) is the largest water resources re-allocation to solve the serious water shortage problem in North China. Total scale of annual water transfer will be 44.8 billion m<sup>3</sup>, 14.8 billion m<sup>3</sup> by the east route along the Great Canal, 13 billion m<sup>3</sup> by the middle route from Danjiangkou Reservoir to Beijing, and 17 billion m<sup>3</sup> by the west route from Daduhe River, Yalongjiang and Tongtianhe River to the upriver of Yellow River.

Water transfer over long distances involves large financial outlays and long periods of construction. If the networks are open and/or unlined, they will incur substantial loss of water due to seepage and evaporation. Consequently, both desalination and water reuse are considered in such regions as long-term solutions for meeting increasing water needs.

### **2.3.2 Reuse of Urban Wastewater**

The treated sewage effluent can be reused directly or reused through groundwater recharge as an integral part of water and wastewater management [4]. The effluent recharged underground will be further purified by the soil through a serial of complex processes such as convection-dispersion, adsorption, bio-degradation etc. Because the quantity of urban wastewater is almost stable, the reuse of wastewater based on the regenerative cycle can provide a reliable water resource.

### **2.3.3 Seawater Desalination**

Seawater desalination is an important option for alleviating the current water shortage in coastal cities and satisfying future demands for fresh water in arid regions with close proximity to the sea. Separation of water from seawater is a thermodynamic process requiring an input of energy. Seawater desalination has been successfully practiced in several countries to meet industrial and domestic water requirements. The current number of desalination plants is about 13600 with a combined capacity of 25.91 million m<sup>3</sup> per day, which has been increasing yearly by 10% to 30% [5]. Desalination has become a very safe source of water and is comparable to conventional water supply schemes. The commercial seawater desalination processes which are proven and reliable for large scale freshwater production are multi-stage flash (MSF), multi-effect distillation (MED) for evaporative desalination and reverse osmosis (RO) for membrane desalination.

Compared with the conventional water supply, the seawater desalination is energy intensive in a limited scale, thus can only solve the local and temporary problem of water shortage. It is impossible to cosmically increase the amount of water resources by seawater desalination for solving the overall problem of water shortage in a large area.

## **3. NUCLEAR DESALINATION TECHNOLOGY**

### **3.1 Motivation for Nuclear Seawater Desalination**

Desalination plants require energy to separate salt from saline waters. The most efficient desalination technologies have a comparable energy requirement of 4–5 kW(e)·h/m<sup>3</sup>. Most of the large size plants are located near thermal power stations, which utilize fossil fuels - coal or oil fired boilers and gas turbines including combined cycles to supply both steam and electrical power for desalination. The use of fossil fuels to supply water needs has several drawbacks. The first is the emission of large amount greenhouse gases to the environment. The second is the fuel transportation. Fossil fuel sources are usually located at long distances from the prospective power and desalination plants. The third is that fossil fuels are non-renewable resources and their known reserves are projected to be exhausted in about 30 to 50 years (for oil and gas).

Interest in using nuclear energy for producing potable water has been growing worldwide for various reasons: economic competitiveness, energy supply diversification, conservation of fossil fuel resources and environmental protection.

The research on nuclear energy application in the seawater desalination began very early. From 1980s, the nuclear seawater desalination began to receive the widespread attention. The International Atomic Energy Agency (IAEA) has coordinated various feasibility studies on nuclear desalination of seawater with participation of interested Member States since 1989 and published the related technology and the economic analysis report. Many countries have been carrying out

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the long-term research plan on nuclear desalination to develop their own technical routes [1].

There are two general technical schemes for the nuclear seawater desalination. One scheme is the co-generation of electricity and desalted water. It possesses the competitive economic advantage with lower capital costs. The other scheme is to provide heat source for the seawater desalination by the special designed heating supply nuclear reactor. Technically, any reactor type can be used for nuclear desalination although several types are identified as the most practical and probable for potential use as an energy source for desalination. Several demonstration projects are currently in operation.

### **3.2 China's research on nuclear seawater desalination**

China's program on nuclear desalination currently involves two reactor types coupling with MED based seawater desalination plants. The first is a 200 MW(th) nuclear heating reactor (NHR-200) developed by INET of Tsinghua University from the experience of the 5 MW(th) nuclear testing reactor. NHR-200 adopts the integrated arrangement and the natural circulation cooling system [6]. A demonstration nuclear desalination plant coupling NHR-200 with a 150 000 m<sup>3</sup>/d MED plant has been approved and is planned for construction in Shandong Province. NHR-200 can also be applied to co-generation of electricity and water by coupling the steam turbine set with the MED installment. This scheme will have very high economic competitiveness.

The second type is a nuclear heating supply system (NHSS) designed by China National Nuclear Corporation. NHSS is a slightly pressurized low temperature reactor consisting of three loops. The primary loop is designed to operate at 0.5MPa with inlet/outlet temperatures of 82/100°C. NHSS will provide 200MW thermal power. The reactor has good inherent passive safety features. Because the vapor temperature is just 72°C, NHSS is only suitable to couple with LT-MED for the purpose of seawater desalination. The design capacity of fresh water production is 8×10,000m<sup>3</sup>/d.

Recently, Chinese Institute of Atomic Energy proposed a concept reactor design using the spent fuel of NPPs for seawater desalination. The spent fuel elements of NPPs already achieved designed burn-up can not be used for NPPs. However, such spent fuel elements still contain certain quantity of fissionable material, which is possible to go a deep burn-up. If a special reactor core is designed based on the spent fuel elements for supplying heat under lower parameters, they can still meet the requirement for maintaining neutron chain reactions and continue to operate for a quite long period. These lower parameters of heat can satisfy what the seawater desalination of LT-MED requires.

## **4. COUPLING OF GAS TURBINE MHTGR WITH SEAWATER DESALINATION**

### **4.1 Prospects of Gas Turbine MHTGR**

#### **4.1.1 Development of MHTGR technologies**

The MHTGR concept originated in Germany in 1979 is based primarily on the passive safety concept without the need for active systems by limiting thermal power and allowing sufficient heat losses from the reactor vessel [7, 8]. Its safety attributes of passive heat transfer lead to plant simplification and associated economic advantages, and has the potential for being located at industrial sites. Substantial high efficiency can be achieved through the direct coupling of a gas turbine to a MHTGR. Although MHTGR was preferred to generate electricity, an ever increasing interest was the development of cogeneration and industrial applications afforded by its capability to achieve high core outlet temperatures.

International interest in modular MHTGR technology has been increasing in recent years due to a growing recognition of the potential of MHTGR designs to provide high efficiency, cost effective electricity generation appropriate for the conditions in developing countries, and in the longer term to provide a source of high temperature process heat. A series national / international projects based on such technology are being carried out in dozen of countries including China, Netherlands, Russia, South Africa, UK, US, and also Japan.

#### **4.1.2 Gas turbine MHTGR**

Most of the existing NPPs operate under sub-critical steam conditions of Rankine cycle. This makes their efficiency relatively lower than the supercritical FPPs. Only the MHTGR technology has the potential to achieve higher thermal efficiency. The Gen-III AP1000 can achieve a thermal efficiency of 35%. As comparisons, supercritical steam turbine MHTGR can achieve a net efficiency of 45% [9] while the gas turbine MHTGR can achieve up to 50%. Fig. 2 is the schematic diagram of MHTGR coupled with gas turbine cycle that is a closed, recuperated and inter-cooled Brayton cycle.

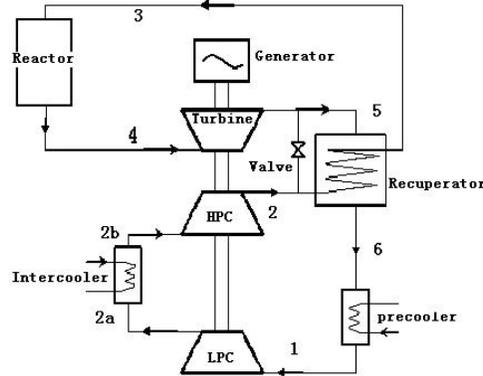


Fig. 2: Schematic diagram of MHTGR coupled with gas turbine cycle

During the past decades, technological developments provided the key components to realize this cycle. The possibilities presented by the gas turbine MHTGR for substantial improvement NPP efficiency coupled with the potential for lowering capital and operating costs due to plant simplification have brought about an increasing interest by international research organizations and plant developers.

#### 4.1.3 The Testing Gas Turbine Project HTR-10GT

Based on the successful operation of the testing steam turbine HTR-10, a testing gas turbine plant utilizing the reactor HTR-10 is now under construction at INET. This project uses a direct gas turbine cycle to convert the nuclear energy into electricity. Such a plant possesses only the primary loop including the reactor, the turbo-machinery and auxiliary heat exchangers. The turbo-machinery consists of turbine, LPC, HPC and generator, all of which will be installed in the PCU pressure vessel. At the full power condition, the temperatures at inlet and outlet are designed to be 330°C and 750°C respectively while the core pressure is designed to be 1.56 MPa with a helium flow rate of 4.56 kg/s. The design of turbo-compressor is based on above described conditions. The compromise of material strength and the turbo-compressor features gives a rotary speed of 15,000 rpm. All other features of the PCU components are based on these basic parameters.

HTR-10GT is currently in the progress and estimated to realize the coupling of gas turbine to HTR-10 in 2009. Through HTR-10GT, a series of techniques and accumulated abundant experience on construction, operation and maintenance will be achieved. The gas turbine MHTGR can be as one option of reactor types for China's NPP market.

## 4.2 Seawater Desalination Coupled with Gas Turbine MHTGR

### 4.2.1 Suitable Seawater Desalination Process

Several gas turbine MHTGR projects including the South Africa's PBMR and China's HTR-10GT are planned to construct. Because the HTR-10GT project is a testing installation, its thermodynamic parameters are limited to the HTR-10. Thus, its performance can not reach the commercial level. It is unsuitable to take HTR-10GT as the representative of gas turbine MHTGR for seawater desalination. Currently, PBMR is the representative of the commercial gas turbine MHTGR plant. Its main parameters are listed in Table 1.

Table 1: Main designed parameters of PBMR

Parameter	Unit	Value
Reactor power	MW	400
Electricity power	MW	165
Core pressure	MPa	9.0
Core temperature In/Out	°C	500/900
Pre-Cooler temperature In/Out	°C	143.8/33.2
Inter-Cooler temperature In/Out	°C	135/31.6

The removal heat from the pre-cooler and inter-cooler of the gas turbine MHTGR can be re-used for the seawater desalination. To avoid corrosion and sediments of coolers, an isolation loop between pre-cooler / inter-cooler and the desalination installment should be required. Considering the effective heat transfer, the available removal heat from the isolation loop will be equivalent to that of the NHSS. It is only suitable to use LT-MED process for seawater desalination.

LT-MED is a low temperature (up to 70°C) version of MED with horizontal tube thin film evaporator, which is gaining ground for low and medium capacity desalination plants. In the LT-MED process, the seawater feed is heated by the steam in the first effect, resulting in evaporation of a fraction of the water content. The seawater feed is sprayed on the outer surface of the tubes and vapor flows inside the horizontal tubes, where it condenses to give product water. The concentrated brine is sent to the second effect maintained at slightly lower pressure than the previous effect. The vapor produced in the first effect condenses on the heat transfer tubes in the second effect, giving up its latent heat and generating an almost equal amount of vapor from the brine. The process is repeated from effect to effect at successively lower pressures. The condensate is collected as product water. Fig. 3 is the LT-MED seawater desalination.

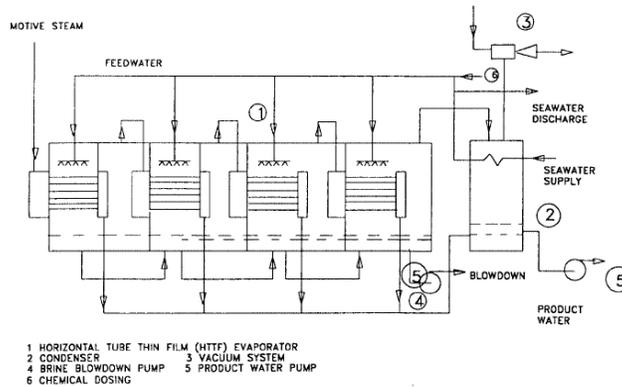


Fig. 3 Schematic flow diagram of the LT-MED desalination process [1]

The energy efficiency of the LT-MED plant can be increased by increasing the number of effects. The GOR is theoretically equal to the number of effects, but practically somewhat less because of heat losses.

China's first demonstration seawater desalination plant based on LT-MED was set up at Huang Dao thermal power plant and has been in operation for some time. Its designed capacity is 3000 m<sup>3</sup>/d by 10 effects with a GOR of 9.6 and energy consumption of 1.5 kW(e)-h/m<sup>3</sup>, which reach the advanced level.

#### 4.2.2 Co-generation Installment

As mentioned above, heat transfer tubes will suffer from problems of corrosion and scaling deposition during the desalination process. An isolation loop is required to separate the primary loop of gas turbine MHTGR from the LT-MED installment, as show in Fig. 4.

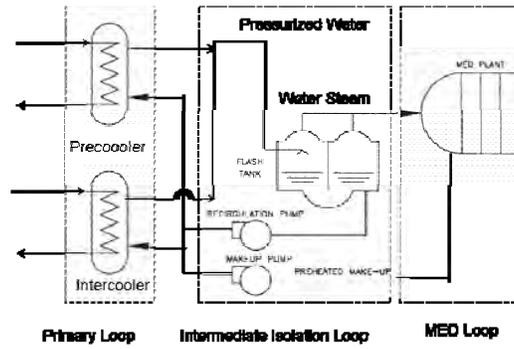


Fig. 4: The coupling of gas turbine MHTGR with seawater desalination

The removal heat from the pre-cooler and inter-cooler is transfer to the water in the isolation loop. The water gets heated, a fraction of it evaporates while the rest is used to pre-heat the seawater feed, gets cooled itself and is pumped to the pre-cooler and inter-cooler again for the continuing circulation. The evaporation generated in the isolation loop is sent to the first effect of the LT-MED, heats the seawater feed in the tubes of fist effect and gets condensed. The condensate is first used to pre-heat the seawater feed and then pumped to the pre-cooler and inter-cooler again for the continuing circulation.

**4.2.3 Potential Capacity of Desalination**

(1) Co-generation based on PBMR. With respect to PBMR, the pre-cooler will discharge 114.1 MW removal heat while the inter-cooler will release 103.8 MW. In addition to its 165MW electricity, a co-generation plant coupling the LT-MED can provide about 218 MW removal heat to produce desalted water, greater than the power of NHSS. Therefore, the desalted water production will be greater than that ( $8 \times 10,000 \text{m}^3/\text{d}$ ) of a desalination plant based on NHSS.

(2) Co-generation based on a 250 MW MHTGR. It is evaluated that 250 MW is the optimal power level for a pebble bed MHTGR. MIT and INEEL have utilized the reference design from the PBMR and selected a 250 MW(t) MPBR design with a significantly different balance of plant [7]. A pebble bed reactor module with the same power level may be selected by INET for its demonstration MHTGR plant, which is currently designed to couple with a sub-critical steam turbine. After the demonstration steam turbine plant, a prospective gas turbine MHTGR plant based on this reactor module will be carried out, which will achieve an efficiency of 47% by adopting one shaft arrangement and support of electro-magnetic bearings. The prospective gas turbine MHTGR plant can also be coupled with LT-MED for co-generation of electricity and desalted water. By using the same thermodynamic parameters of PBMR as reference, the removal heat will be about 130 MW and can generate  $5.2 \times 10,000 \text{m}^3/\text{d}$  desalted water.

**4.3 Comparisons among Nuclear Desalination Installments**

There exist no difficulties for using nuclear energy to produce desalted water. The current techniques may guarantee that the desalted water will not suffer from radioactive contamination. The only uncertainty is the economic competitiveness. Using nuclear energy to co-generate electricity and fresh water will achieve a high thermal efficiency. Certainly, the nuclear reactor should have suitable scale to assure the competitiveness for both electricity and the desalted water at low capital cost per unit. The comparisons among different nuclear desalination systems are presented in Table 2.

Table 2: Comparisons among nuclear seawater desalination systems

Reactor Type	NHR—200	NHSS	Spent fuel Reactor	Gas turbine MHTGR
Desalination processes	LT-MED, RO+MED	LT-MED	LT-MED	LT-MED
Heat sources	Reactor	Reactor	Reactor	Removal
Investment cost	Reactor, Desalination	Reactor, Desalination	Reactor, Desalination	Desalination
Operation cost	Reactor, Desalination	Reactor, Desalination	Reactor, Desalination	Desalination

It can be seen from above comparisons that desalination installment based on gas turbine MHTGR has obvious advantages. First, it uses the removal heat of the gas turbine MHTGR, does not need to build a special nuclear reactor for providing heat source. The desalination does not affect the electricity generation of the plant and only needs the additional investment for the seawater desalination. The investment for gas turbine MHTGR plant and the operation cost for electricity generation should not be included into the cost of desalted water. Beside all the costs needed by the seawater desalination installment, the only added cost is for the redesign and optimal construction of the pre-cooler and inter-cooler. By using the removal heat of gas turbine MHTGR, the operation cost only involves the power consumption for seawater desalination approximately 0.9~1.2kWh/m<sup>3</sup>.

## 5. CONCLUSIONS

The cost of desalted water has been a constraint to large scale adoption of desalination plants in many parts of the world. Combined cycle based power stations are now proven to be more economic for co-generation plants producing power and water. The co-generation of electricity and desalted water by coupling the gas turbine MHTGR with LT-MED seawater desalination has the incomparable advantages that other NPPs and nuclear desalination installments don't have.

For the electricity generation, gas turbine MHTGR can achieve a theoretical efficiency of about 50%, very higher than those of other NPPs (PWR 33%, BWR 32%, CANDU 29%, and AP1000 35%). For the seawater desalination, the co-generation of electricity and desalted water based on gas turbine MHTGR uses the removal heat to produce desalted water, will have a relatively lower investment and operation cost than other nuclear desalinations and has evident economic competitiveness. With respect to the thermodynamic process, the desalination system has no influence on the operation of the electricity generation. The co-generation only involves the cost increases of desalination installment and the power consumption for driving the desalination circulation. The co-generation of electricity and desalted water coupled gas turbine MHTGR with seawater desalination will provide a technical support for China's sustainable development. In order to put the co-generation project into implementation, it needs us to take further investigations on the theoretical and technical affairs and to carry out engineering verification.

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