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Thermal coupling of HTGRs and MED desalination plants, and its performance and cost analysis for nuclear desalination

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HIGHLIGHTS

- ► The new HTGR + MED coupling scheme was proposed.
- ► KAIST coupling scheme uses PCHE without any intermediate loop.
- ► KAIST coupling scheme has independent structure between MED and heat sink.
- ► Water production capacity increases by 258% compared to previous researcher's results.
- ► Water cost is reduced by 9.0% compared to previous researcher's results.

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ABSTRACT

The nuclear desalination based on the high temperature gas-cooled reactor (HTGR) with gas turbomachinery and multi-effect distillation (MED) has been drawing attention, because it can utilize waste heat for desalination. In this paper, research objectives are as follows: (a) proposing an optimal design of HTGR + MED systems and (b) performance and cost analysis for the HTGR + MED system. In the first step, the KAIST coupling scheme was proposed. It uses printed circuit heat exchangers (PCHE) instead of conventional heat exchangers without any intermediate loop and has the independent structure between MED plants and heat sink. In the second step, the KAIST version of DEEP (K-DEEP) code was developed for more practical cost and performance analysis of the KAIST HTGR + MED system. The desalination performance and cost analysis with the K-DEEP code were performed for the Gas Turbine-Modular Helium cooled Reactor (GT-MHR) + MED system. The maximum desalted water production capacity increases by 258% compared to the production capacity using the previous coupling scheme. The desalted water cost could be reduced by 9.0%. Finally, from the comparison of various nuclear MED desalination systems we confirmed the potential of the KAIST HTGR + MED system that may be one of the best desalination options in mass production of desalted water.

1. Introduction

Water crisis is one of the most serious problems that humans are facing. Desalination technologies are attractive and sustainable solutions for water crisis. Desalination processes can be divided by two categories: distillation processes and membrane processes. Recently a multi-effect distillation (MED) process in distillation processes and a reverse osmosis (RO) process in membrane processes are in the limelight because these processes can be improved further and their desalted water costs are commonly lower than water costs of other processes [1]. Desalination processes need energy sources: heat or electricity. Nuclear energy, fossil energy, renewable energy can be candidates. If we consider global warming, low cost, and sustainability, nuclear can be one of the best energy options. Researches on nuclear desalination systems are very active because nuclear power plants can provide low cost, carbon free, and sustainable energy to desalination plants. Since the 1960s IAEA and several countries have carried out technical and economic feasibility studies for desalination technologies utilizing the nuclear energy and demonstration programs of nuclear desalination are in progress in several countries [2–4].

There are various options in nuclear power plants and in desalination processes. Specially, we pay close attention to coupling MED plants and high temperature gas-cooled reactors (HTGRs) with gas turbomachinery. Because of thermodynamic reasons, there is unavoidable waste heat in all nuclear power plant systems, so researchers have tried to utilize the waste heat for other purposes. Desalination is one of the options. In the case of light water reactors (LWRs), the temperature ranges of the waste heat are too low to utilize for desalination, so in order to get enough temperature ranges of the waste heat, modification of thermodynamic conditions and a significant decrease of electrical power are inevitable [8]. Fortunately, however, in the case of HTGRs, the temperature ranges of the waste heat are ideal for desalination,

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and so modification of the existing thermodynamic conditions is not needed and there is no penalty. Free heat can be utilized for desalination processes.

From literature survey, we could find a Desalination Economic Evaluation Program (DEEP) developed by the International Atomic Energy Agency (IAEA) [5–7]. The DEEP is the software linked Microsoft Excel spreadsheets and for estimating the desalination performances and costs for various alternative energy and desalination process configurations.

Dardour et al. [10] selected the coupling scheme of HTGR + MED systems used in both EURODESAL and TUNDESAL projects [8, 9]. At that time, actual versions of DEEP did not have models for HTGR + MED systems, and so they developed the models from basic thermodynamic considerations and integrated them in the new, CEA version of the DEEP code. However utilization of waste heat from HTGRs is limited to only 23% due to characteristics of their HTGR + MED coupling scheme.

KAIST is conducting the research on the WHEN (Water-Hydrogen-Electricity Nuclear gas-cooled reactor) system that is an integrated system based on the nuclear power system coupled with desalination and hydrogen generation systems. The WHEN system is based on high temperature gas-cooled reactors (HTGRs) which have passive safety features and generates power through gas turbomachinery. The WHEN system utilizes electricity and waste heat from a power conversion system for producing fresh water through a desalination system. A hydrogen production system produces hydrogen by receiving the high temperature heat produced by HTGRs and/or the electricity produced by an electric generator. This study focused on the thermal coupling of HTGRs and thermal desalination systems which utilize the waste heat.

Research objectives are as follows:

1) Proposing an optimal design of HTGR + MED systems
2) Safety, performance, and cost analysis for the HTGR + MED systems

There are three steps for achieving the research objectives. The first step is a design step of HTGR + MED systems based on understanding for each of them: HTGRs and MED desalination plants. In this step, the previous design for HTGR + MED systems was improved in the aspects of safety, performance, and cost.

The second step is developing a KAIST Desalination Economical Evaluation Program (K-DEEP) code reflecting the coupling scheme proposed in the first step and evaluating the performance and cost of desalted water production. In this step, on-design performance value of HTGRs is used as HTGRs performance input data of the K-DEEP code.

The third step is to analyze the safety and performance of HTGRs due to failures or accidents of desalination plants coupled with the HTGRs. For transient analysis, the GAMMA-T (GAs Multidimensional Multicomponent mixture Analysis–Turbomachinery) code is used, which was developed for transient analysis of an HTGR with an emphasis on a gas turbine through a two-dimensional approach [12, 13]. This paper is focused on the first and second research steps.

2. Design of HTGR + MED system

Mainly; there are two kinds of safety issues in design of nuclear desalination systems:

1) Potential for release or transfer of radioactive materials in a normal operating condition and accident conditions.
2) Reactor safety in transient conditions such as failures of desalination plants

In the case of the first issue, because of high integrity of tri-structural isotropic (TRISO) fuel, possibility of release of radioactive materials from nuclear fuel is very low. Tritium permeation is the important safety issue in normal operating condition. In the case of the tritium permeation, KAIST research team has been studying.

A new HTGR + MED coupling scheme can be compared with the previous one, which Dardour et al. [10] used, in three aspects: 1) existence of an intermediate loop and types of a heat exchanger, 2) dependency of a MED plant and a heat sink (Fig. 1; Fig. 2), and 3) the number of MED plants. The first aspect is related with the first safety issue, and the second and the third aspects are related with the second safety issue.

2.1. Intermediate loop vs. no intermediate loop + PCHE

Nuclear power plants can be divided into two kinds of cycles. The first one is a direct cycle, in which a working fluid of a reactor side is used in a power conversion system (PCS). Another one is an indirect cycle, in which the working fluid of the reactor side cannot be used in the PCS, and so thermal energy of the reactor is transferred to the PCS through a heat exchanger and a secondary working fluid. Therefore, the two kinds of the system cycles are different in the potential for the transfer of radioactive materials.

2.1.1. Direct cycle

As HTGRs with direct cycle, boiling water reactors (BWRs) also are nuclear power plants with the indirect cycle, but two reactor types are different in pressure distribution. In the case of BWRs, although a cooling pipe in a condenser breaks, radioactive materials do not leak out to the environment, because the internal pressure of cooling pipes is higher than condenser pressure. In the case of HTGRs with the direct cycle, however, if the pipe in a precooler or an intercooler breaks, the radioactive materials in the reactor side can leak out to outside. The reason is that the pressure of the reactor side is higher than that of the cooling water side. If HTGRs are coupled with MED plants, there is a possibility that desalted water will be contaminated by radioactive materials in accidents. The reason is that pressure continuously drops from the reactor side to the MED plants. Therefore any solution is needed for the potential of the transfer of radioactive materials to the environment.

Dardour et al.'s [10] reference plants are only HTGRs with the direct cycle: a gas turbine–modular helium cooled reactor (GT-MHR) and a pebble bed modular reactor (PBMR). Therefore, they introduced the intermediate water loop that can provide a pressure barrier between HTGRs and MED plants to solve the abovementioned problem (Fig. 1). Because of the intermediate loop, however, thermal energy utilization decreases and desalination performance decreases.

In order to get enough safety and higher desalination performance, we propose replacing conventional shell and tube type heat exchangers with printed circuit heat exchangers (PCHEs) which have high effectiveness and removing the intermediate water loop (Fig. 2). PCHEs can have much higher effectiveness value than conventional shell and tube type heat exchangers [14, 15]. It means that more waste heat can be utilized for desalination process. In the case of helium, choked flow occurs when the pressure ratio between the high pressure side and the low pressure side in the precooler or the intercooler is higher than about 2. For example, in the case of GT-MHRs and PBMRs the pressure ratios between the two sides in the precooler and the intercooler are about 4–7 [10], and so surely the choked flow occurs. The mass flow rate of the choked flow is proportional to the cross section of a discharge hole. The diameter of the conventional heat exchangers is usually in several centimeter orders, but the diameter of the PCHEs is generally in several millimeter orders [14, 15]. As the diameter of the PCHE is about 1/10 times smaller than the diameter of the conventional one, the cross section of the discharge hole in the PCHE is about 1/100 times smaller than that in the conventional one. In other words, even if leakage of radioactive materials occurs in the precooler or the intercooler, leakage in the PCHEs is 1/100 times less than that in the conventional heat exchangers. In addition, the PCHEs have lower potential for leakage of radioactive materials than the conventional shell and tube type heat exchangers do because the PCHEs have higher structural ntegrity than the conventional heat exchangers do.