Utilization of Waste Heat From Gas Cooled SMR in Water Desalination

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ABSTRACT

The Gas-Turbine Modular Helium Reactor (GT-MHR) incorporates two-stage compression with pre-cooling and intercooler in order to compress the helium to higher output pressures thereby achieving high-pressure ratios across the compressors. This minimizes the total work consumed by the compressors. Both the pre-cooler and the intercooler facilitate this process by reducing the inlet temperatures of the working fluid. In fact, they are specialized heat exchangers that use water to cool the helium before entering each of the compressors. At the optimum operating conditions of the GT_MHR, the coolers will then dissipate heat at a rate of about 318 MW_{th}. An energy analysis is conducted to utilize this waste heat for seawater desalination using Seawater Freezing Desalination (SFD) technology. This is achieved by connecting an Organic Rankine Cycle (ORC) to produce useful power. The power produced by the ORC turbine is supplied as electrical power to the compressor of a vapor-compression Refrigeration Cycle (RC) via an electric generator. The connection between the RC and the SFD cycle to maintain the desired temperature for the SFD unit is established through the evaporator of the RC. It was found that the efficiency of the combined GT-MHR/ORC cycle was higher than the simple GT-MHR and the proposed desalination system is capable of producing around 1.507 Million Cubic Meters (MCM) of freshwater annually.

Keywords: *Gas-Turbine Modular Helium Reactor (GT-MHR); Seawater Freezing Desalination (SFD); Thermal efficiency; Performance analysis.*

1 INTRODUCTION

Nuclear energy is used mainly for electricity generation as often viewed. However, new nuclear reactors design paved the way to expand the applications of nuclear energy well beyond electric power generation. In nuclear cogeneration, the heat produced in the nuclear reactor is not only used in electricity production but to meet other energy demands such as seawater desalination and district heating. Approximately 750 reactor operation years from 70 nuclear power plants with accumulated experience in nuclear desalination and district heating has proven that nuclear cogeneration is a vital option because it saves energy by opening new utilization of nuclear energy, saves the environment by reducing the CO_2 emissions, and saves money by reducing the need for fossil fuel. For these reasons, nuclear cogeneration can be extended to meet various demands such as hydrogen production and providing process steam for various industrial applications along with power production, especially when deployed for the recovery of waste heat. Currently, intensive efforts are made to develop the technology of the high temperature gas-cooled nuclear reactors (HTGRs) to achieve its potential improved economics, inherent safety, proliferation resistance, and better fuel utilization [1]. HTGRs are designed to provide a double solution; to produce electricity and utilize its waste heat in other applications. HTGRs have a high thermal efficiency of 45-50%, high fuel burns up (100 MWD/kg), and, lower radioactive waste quantities to meet Generation IV goals [2]. Gas-Turbine Modular Helium Reactor (GT-MHR) is a high-temperature gas cooled reactor with 600 MW thermal power and 48% cycle efficiency. GT-MHR is directly coupled to a closed Brayton cycle as a power conversion unit that uses helium as a working fluid with a maximum temperature of 850 °C at the reactor exit (turbine inlet). For better performance, GT-MHR employs two compressors with a pre-cooler and an inter-cooler which leads to the rejection of 308 MWth at the design operational conditions [3].

In nuclear desalination, heat and/or electricity generated by nuclear power plant are used to remove salt and minerals from saline water. Seawater desalination technologies can be classified into two types: membrane methods and thermal methods. In membrane methods, salt is removed from water using mechanical or electrical forces such as reverse osmosis (RO) and electro dialysis (ED) method. On the other hand, thermal methods separate salt through a phase-change process such as the seawater freezing desalination (SFD), multi-stage flash (MSF) and multi-effect distillation (MED). Nisan et al. [4] performed a comparative analysis of power and water costs using different types of nuclear reactors (900 MWe French PWR, Advanced PWR, AP-600, GT-MHR, and PBMR) operated in combined mode with multiple-effect distillation (MED) and reverse osmosis (RO). Comparisons were made with the cost of desalination from fossil energy, namely the 600 MWe gas turbine combined cycle power plant (CC-600). All nuclear desalination options were found to be more viable than CC-600 in terms of power generation costs. The GT-MHR and PBMR achieve the lowest costs in the MED systems by using waste heat. Moreover, the study showed that utilizing the waste heat from the nuclear power plant for seawater desalination is more profitable than using fossil fuel for this purpose.

In this work, utilization of waste heat from a GT-MHR for fresh water production has been investigated. A combined system that couples a GT-MHR with an organic Rankine cycle (ORC) and SFD system is proposed. Thermal performance of the proposed system has been studied and compared over a range of operating conditions.

2 SEAWATER FREEZING DESALINATION (SFD) TECHNOLOGY

When compared to other desalination systems such as Multi-Stage Flash (MSH) and Multi-Effect Distillation (MED) which require a lot of energy to vaporize the seawater, Seawater Freezing Desalination (SFD) has a superiority in producing a source of fresh water with low energy input. SFD consumes less energy because its latent heat of fusion is only one-seventh of the latent heat of vaporization, which helps in saving energy when producing fresh water. SFD processes are classified into main types, indirect contact freezing, and direct contact freezing. In the direct contact freezing method, an immiscible refrigerant is injected into an ice generator filled with seawater. SFD employs a refrigerant cycle which uses n-butane that cools seawater to -2 °C. As a result, the seawater will be separated into brine and crystallized freshwater in the ice generator. Figure 1 depicts the design of the ice generator. The design adopts a jacketed cylinder to improve heat transfer. It consists of an inner nozzle, outlet nozzle, and air diffuser. The cold refrigerant is injected into the seawater through the inlet nozzle. The refrigerant is atomized into many micro-droplets. Due to the temperature gradient between the two fluids, heat exchange takes place between water molecules and the refrigerant micro-droplets, therefore a layer of ice forms on the surface of the droplets. As several forces act on it, the ice layer is detached. After heat exchange, the refrigerant falls to the bottom of the ice generator due to its higher density, and to maintain efficient heat exchange with fresh refrigerant, the exhausted refrigerant drops from the outer nozzle. Meanwhile, the air diffuser pushes ice crystals to leave the mixture and float on top of the ice generator to form the ice slurry. Then, the ice slurry is pumped into the centrifuge and the ice washer and then ice melter [5].

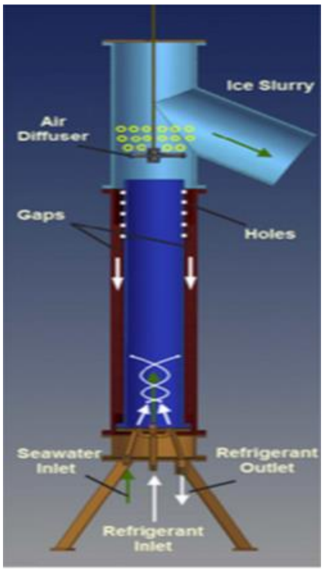

Figure 1: Design of Direct Contact Ice Generator [6].

3 MODEL DESCRIPTION

At optimum operation conditions of GT-MHR, the pre-cooler and inter-cooler reject around 318 MW of low-grade thermal energy. Since Organic Rankin Cycle (ORC) is a favorable cycle for converting low- and medium-temperature thermal energy into electricity [7], it’s employed in this work to power the refrigeration cycle compressor of the SFD system and hence producing fresh water, the thing that will improve the overall thermal efficiency of the proposed system that is illustrated in figure 2. Moreover, the evaporator of the RC acts as a heat sink for the SFD cycle thus maintaining the desired operating temperatures of the SFD process to produce fresh water.

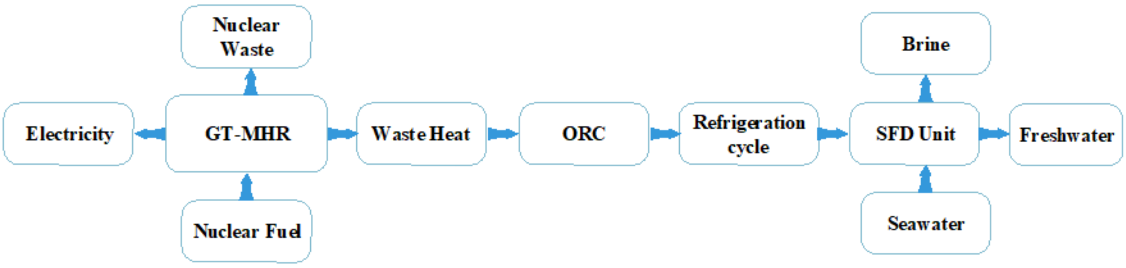

Figure 2: General Scheme of the Proposed System.

3.1 Thermodynamic Analysis

Energy and mass analysis is performed with Engineering Equations Solver (EES) for GT-MHR and GT-MHR/ORC in conjunction with an SFD unit to investigate the effect of GT-MHR waste heat utilization to produce fresh water in improving the performance of the proposed cycle.

In simple GT-MHR plant; a helium coolant is heated in the reactor core and then enters the power conversion system, which includes a gas turbine that drive an electric generator, two compressors connected to the same vertically orientated shaft, recuperator, precooler, and intercooler heat exchangers. The thermal efficiency of GT-MHR is calculated by dividing the net power output over the input heat energy from the nuclear reactor core as follows:

$$\eta_{\text{th, GT-MHR}} = \frac{W_{\text{net, GT-MHR}}}{\dot{Q}_{\text{Core}}} \quad (1)$$

$$W_{\text{net, GT-MHR}} = W_{\text{T}} - W_{\text{C}} \quad (2)$$

For combined GT-MHR/ORC, the efficiency is calculated by dividing the net work output (works produced and consumed through the turbine and pump) by the heat input from the core as:

$$\eta_{\text{th, GT-MHR/ORC}} = \frac{W_{\text{net, GT-MHR/ORC}}}{\dot{Q}_{\text{Core}}} \quad (3)$$

$$W_{\text{net, GT-MHR/ORC}} = \left(W_{\text{T}} + W_{\text{T,ORC}}\right) - \left(W_{\text{C}} + W_{\text{P,ORC}}\right) \quad (4)$$

For the refrigeration cycle of SFD, the coefficient of performance (COP) is defined as the ratio of the output energy from the refrigeration cycle evaporator over the input work in the compressor (electric power from ORC electric generator):

$$\text{COP} = \frac{\dot{Q}_{\text{Evaporator}}}{W_{\text{T,ORC}}} \quad (5)$$

In the analysis of the SFD unit, the energy conservation equation is applied on the different components of the unit that includes: the evaporator, the ice generator, the SFD heat exchanger, and the ice melter as follows:

$$\dot{Q}_{\text{Evaporator}} = \dot{m}_r c_r \Delta T_{Evaporator} \quad (6)$$

$$\dot{Q}_{\text{ig}} = \dot{m}_r c_r \Delta T_{ig} \quad (7)$$

$$\dot{Q}_{\text{hex}} = \dot{m}_r c_r \Delta T_{hex} \quad (8)$$

$$\dot{Q}_{\text{im}} = \dot{m}_s c_s \Delta T_{im} \quad (9)$$

4 RESULTS AND DISCUSSION

Figure 3 represents the mass flow rate of produced freshwater as a function of the coefficient of performance (COP) of the refrigeration cycle. Recall that a higher COP means that the ability of the refrigeration cycle to draw more energy from the refrigerant of the SFD unit will increase. Thus, the mass flow rate of the refrigerant can be increased (assuming a constant refrigerant temperature drop) and its ability to generate ice in the ice generator will increase; finally leading to an increase in fresh water production. The connection between the refrigeration cycle and the SFD unit is established via the evaporator of the refrigeration cycle. Moreover, the ORC turbine work output and the heat addition in the refrigeration cycle evaporator are directly related using the definition of the COP.

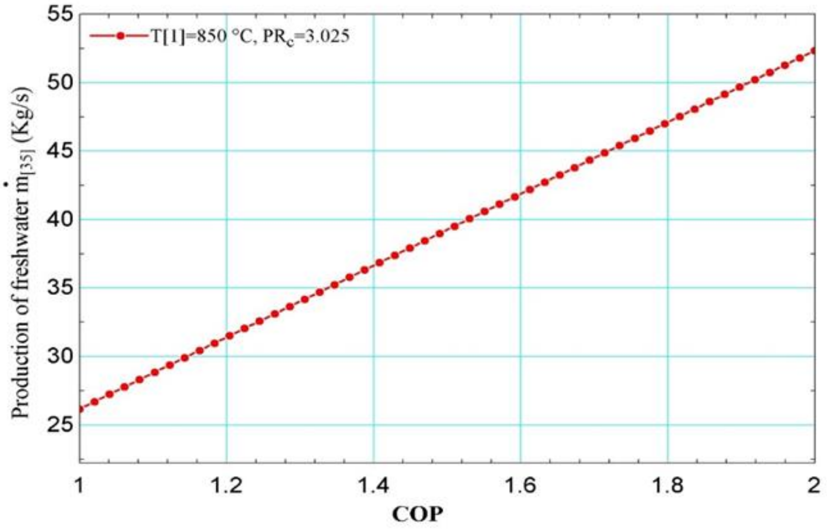

Figure 3: The Mass Flow Rate of Produced Freshwater as a Function of the Coefficient of Performance COP.

Figure 4 depicts the mass flow rate of produced freshwater, the ORC turbine work output $W_{\mathrm{T.ORC}}$, and the thermal efficiency η as functions of the GT-MHR compressor inlet temperature. It can be deduced that increasing the compressor inlet temperature has a negative effect on all of the aforementioned variables. This is expected since an increase in temperature will also increase the energy input required to drive the compressor and eventually leads to a reduction in the main turbine output and ultimately, the efficiency will decrease. More required compressor input work W_{C} means less energy content available from the working fluid helium to be utilized in the production of extra electric power from the ORC turbine; consequently, leading to less freshwater production.

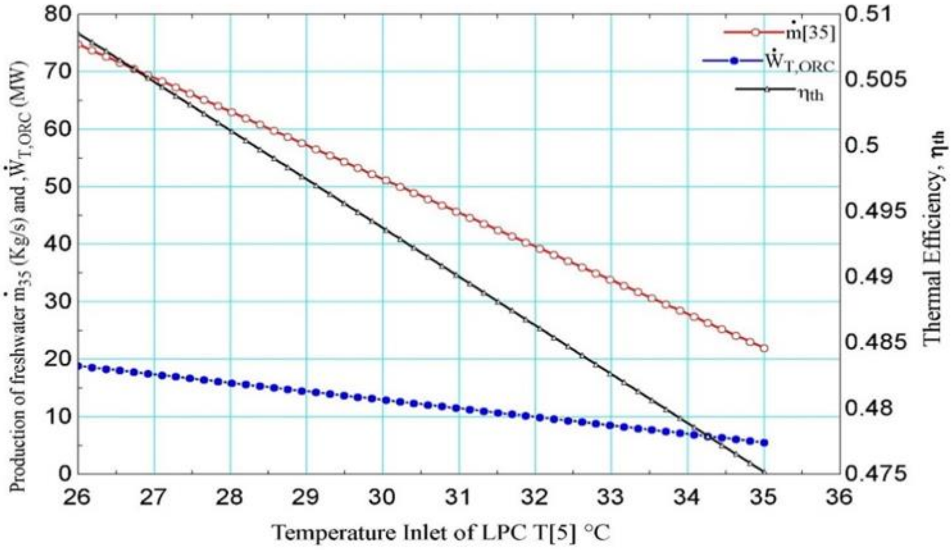

Figure 4: The Mass Flow Rate of Produced Freshwater, the ORC Turbine Work Output, and the Thermal Efficiency as Functions of the Compressor Inlet Temperature.

5 CONCLUSION

In the present study, an energy analysis for GT-MHR and GT-MHR/ORC connected with the SFD unit was carried out in order to improve the overall efficiency of the cycle. This is achieved by connecting an ORC to utilize the waste heat from simple GT-MHR in the direct-contact-type ice generator through refrigeration cycle to produce freshwater by using seawater as raw material. Analysis is performed using EES. It was observed that the efficiency of the cycle increases when reducing the inlet temperature of GT-MHR compressor and further enhance the amount of freshwater produced. Moreover, the proposed system is found to be capable of producing 52.36 kg/s of freshwater at the optimum operating conditions of the GT-MHR/ORC-SFD system.

NOMENCLATURE

Symbol	**Description**
GT-MHR	Gas Turbine Modular Helium Reactor
HPC	High pressure compressor
C_p	Specific heat at average temperature (kJ/kg.).
MED	Multiple-Effect Distillation
PBMR	Pebble Bed Modular Reactor
$\dot{m}$	Mass flow rate (kg/s)
ORC	Organic Rankine cycle
P	Pressure (kPa)
PR	Pressure ratio
Q	Thermal energy (MW).
T	Temperature (°C)
W	Work (MW)
SFD	Seawater freezing desalination
RC	Refrigeration Cycle
MSF	Multi-stage flash
EES	Engineering Equation Solver
COP	Coefficient of performance
c_r	Specific heat for refrigerant (kJ/kg.)
c_s	Specific heat for seawater (kJ/kg.)
c_{fw}	Specific heat for freshwater (kJ/kg.).
HTGR	High Temperature Gas-cooled Reactor
ΔT	Temperature difference (°C).

Greek symbols	
η	First law efficiency (%)

Subscripts	
Core	Reactor Core
C	Compressor
T	Turbine
He	Helium
th	Thermal
P	Pump
E	Evaporator
IC	Intercooler
Pre	Pre-cooler
HX	Heat exchanger
HP	High pressure
LP	Low pressure
Rec	Recuperator
ig	Ice generator
r	Refrigerant
im	Ice Melter

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