The Turbine Heat Waste of RDE for Desalination Laboratory Plant

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Abstract. Reaktor Daya Eksperimental (RDE) is currently being developed by Batan. This reactor uses HTGR technology as the basis for its development. It has an indirect cycle power conversion with primary coolant is helium and its secondary is water. The RDE will be operated not only for an electrical generation but also for cogeneration purposes. One process can be supported in the cogeneration scheme is seawater desalination. Water is the main source of life and its availability must be maintained on earth. Therefore, to overcome the scarcity of freshwater at the remote islands in Indonesia, it needs nuclear cogeneration by coupling of RDE and desalination. With this technology, it can simultaneously produce electricity and freshwater. A variety of desalting technologies has been developed over the years, including primarily thermal and membrane processes. This paper discusses the simulation of RDE for desalination purposes. The methodology used in this research is modeled and simulation by using ChemCAD. The desalination plant is simulated by the heat exchanger unit operation. The RDE primary mass flow rate is 4.3 kg/s, 700°C of temperature and 30 bars of pressure. The secondary coolant mass flow rate is 3.8 kg/s, 60 bars, and 350°C respectively. Depending upon the specific designs the temperature ranges of the waters in this exchanger could be between 80-130°C. The extraction point of the desalination process is at turbine output, with 300.16°C, 8 bars and 3.7 kg/s of mass flow rate. The total amount of freshwater will generate is 4.09 m³/h equal to 98.16 m³/day.

Keywords: turbine heat waste, RDE, desalination

1. Introduction

BATAN has been developed as an experimental power reactor with the name of Reaktor Daya Eksperimental (RDE) [1] [2]. RDE is made base and refers to HTGR technology, helium as primary fluid and water as a secondary coolant [3]. RDE uses pebble fuels with an isotropic carbon-coated kernel in it. HTGR is a Gen-IV reactor type due to its good passive inheritance safety features. RDE is
a very good power reactor to take its advantage for co-generation purposes [4]. RDE is built as a prototype reactor for the next Indonesian commercial power plant to fulfill huge electrical and energy demand [2]. The ball fuel type is good in terms of any kind different fuel for the metal fuel of U (Uranium), Th (Thorium) or Pu (Plutonium) cycle [5]. RDE as shown in Figure 1, will be used to produce the electricity and dry high-temperature steam for supporting cogeneration purposes. The thermal power of RDE is 10MWth equal to 3 MWel [3].

Besides electricity, the heat from secondary coolant generated will be used for supporting the coupling processes such as hydrogen production, coal gasification, etc. RDE has an indirect cycle, steam drives the turbine and will generate the electricity through the generator electrical component. Steam out from the turbine will be congealed and flow back into the steam generator system through a condenser [1].

Water is a very important resource for human life. It is availability indicates environmental sustainability. However, most of the water on the earth's surface is contain much salt and is not suitable for human use for daily life. Most water (90%) is found in the ocean with a very high salt concentration larger than 30,000 mg/L [3].

Indonesia is an archipelago country that has many small islands and its location is difficult to reach far from large islands. Water sources in Indonesia fluctuate according to monsoon and are spread out differences between these areas. Naturally, rainfall varies greatly depending on location and change in seasons (rainy and dry seasons). Some areas in Indonesia have different rainfall deposits. Around sixty percent (60%) of the inhabited area receives annual deposits of 2,000 to 3,500 mm, a few regions have less than 1,000 mm and some are more than 5,000 mm. In addition to this heavy rainfall, Indonesia has no less than 5,590 rivers flowing with a total distance equal to 5,500 km³ per year or more than 5,500 billion tons of water per year.

For some remote islands, there will be no river and has a long dry season duration. Therefore this small island requires has its energy and water sources [6]. The RDE can support electricity and also for desalination. Especially in Java island the densest population island in Indonesia. During the dry season, it is difficult to have water. Therefore the desalination plant is suitable for those kind conditions [7].

The potable water requires salt content below 1000 mg/L for daily life people consumptions [6]. The seawater potential availability is unlimited. People struggle to develop a feasible and inexpensive salt reducing concentration (desalting) technology to get fresh water for human life. Meanwhile, most of the primary energy demand in Indonesia is accomplish with conventional energy sources such as petroleum, natural gas, coal and so on. Base on the data of 2016, almost 41% of Indonesia's energy consumption was based on petroleum, 24% on natural gas, and 29% on carbon coal. The other renewable energy such as hydro, solar, wind and geothermal contributes about 6% of the national demand. Biomass and bioenergy share about 21-29% for daily life cooking, lighting and so on. At present, nuclear energy is an important component of world electricity supply [7].

Reactors all over the world are connected to the grids and it supports about 16% of the electricity consumed worldwide and almost one-quarter in OECD countries [8]. In Indonesia was reported that fossil fuel consumption at 65.56 % in 2014, according to the World Bank collection of development indicators. [6][9].

Nuclear energy is clean energy that can be used for cogeneration through coupling between NPP and industry that requires process heat (nuclear cogeneration)[8], [10]. By nuclear cogeneration can generate electricity and process heat for the industry simultaneously so that the use of fossil energy that should be used for electricity production and industrial process heat can be reduced and the contribution of renewable energy to energy mix In Indonesia can be reached. Therefore, to overcome the scarcity of freshwater and deficit energy in several big cities in Indonesia, it needed nuclear cogeneration by coupling of RDE reactor and desalination installation, so it is simultaneously produced electricity and fresh/drinking water[11].

At present, around thirty per cent of the earth's main energy is used for electricity generation, and about two-thirds of this energy is discharged as heat waste [12]. Therefore, the direct use of
thermal energy from power plants is more desirable comparing to electrical. For optimizing nuclear heat, the non-electrical application is needed. Those experiences were used in some countries such as Russia, Slovakia, Bulgaria, Canada, China, Hungary, Ukraine, and Kazakhstan [3].

There are many desalination technologies have been installed and introduced over the years including membrane and thermal method. Some membrane methods are Nano filtration (NF), electro dialysis (ED) and reverse osmosis (RO). The RO and MSF technologies are most widely used in the world sharing about eighty-eight percent (88%) of the total have been built capacity. Seawater and brackish with different salt content treated in some desalination plants [13]. For seawater reducing salt concentration various thermal and RO, desalination is used, but for brackish water, the RO and ED method is suitable for this kind of desalination treatment. [13].

This paper discusses the desalination model and simulation in RDE by using ChemCAD. The coupling extraction point is in the first stage of the turbine output of 216 °C, 8 bars and 3.5 kg/s of mass flow rate. The simulation is done by simulating the various inlet temperature, mass flow rate and pressure of desalination plants. The total amount of potable water production is investigated.

2. Theory

2.1. General Description of RDE.

The RDE has an indirect cycle power conversion, it uses pebble ball fuel. The reactor thermal power is around 10 Mega-Watt (MW) and it is similar to 3 MW for generating electrical power [14]. RDE is designed and will be used for mainly electricity generation, nuclear reactor (thermal-hydraulics and neutronics) researches and also support the heat for coal gasification/liquefaction, hydrogen generation research, desalination, waste treatment and also the other research facilities. The power conversion system of RDE showed in Figure 1 [1] [15].

![Figure 1. The power conversion system of RDE [11]](image-url)

In the indirect cycle, the heat is moved from primary to secondary coolant via steam generator (SG). The secondary coolant is good quality water usually demineralized water. The dry steam in the secondary coolant is moving to the turbine and electrical generator to produce electricity. A condenser is installed to condense the steam from the turbine outlet and return it to the secondary cooling. Cooling towers take the heat from the secondary coolant heat as the tertiary cooling system, and it
discharged to the environment. The tertiary coolant uses Cisadane river water after mechanical cleaning and chemically treatment.

The main component in a desalination plant is evaporators. Evaporator serves to evaporate seawater into freshwater. The amount of evaporated water is 48,000 m$^3$ (2000 tons/hour) depend on the heat consumed. The other equipment is: pumps, ejector, condenser, flash tank, heat exchanger, utility, switch cooler, condensate tank, filter and settling pool. There are three coupling schemes for nuclear distillation process:

1. Using steam from the low-pressure turbine steam.
   In this condition, the steam outlet from the extraction point is split to the feed water pre-heater and intermediate loop pre-heaters. The extracted steam to the input line of condenser, drive its latent heat to the intermediate loop coolant. The condensate is then sent back to the power station condensate line and mixed with condensate from the condenser.

2. Using steam from the crossover pipe.
   The Low Pressure (LP) steam is divulged at the crossover pipe at the reheat stream after high pressure (HP) turbine outlet. The water moisture content is clean up through a moisture/dew separator. Steam is channeled to the intermediate loop heat exchanger (IHX) to produce much steam process for brine heaters of a desalination plant.

3. Using steam from the backpressure turbine.
   In this case, all of the steam extraction from the LP turbine is used for the desalination process.

3. Methodology
The power conversion system of RDE has been modelled using ChemCAD as seen in Figure 2. The primary system is helium and secondary is water. The primary mass flow rate is 4.3 kg/s, 700°C of temperature and 30 bars of pressure. The outlet reactor temperature is 700 °C. The RDE with high outlet coolant temperature can be utilized for electricity and otherwise for cogeneration.

The heat is transfer to the secondary coolant system through the steam generator. The mass flow rate of secondary coolant is 3.8 kg/s, 60 bars and 350 °C. The purpose of cogeneration i.e. heat generated other than used for electricity production is also utilized for freshwater production by desalination process MED-RO with process temperature about 70°C process. MED desalination unit has the function to evaporate seawater (30 °C, atmospheric pressure) into freshwater using evaporative principles.

Figure 2. The ChemCAD simulation of the power conversion system of RDE
MED uses spray evaporator tool type with operating conditions: temperature is below 70 °C and pressure are below 0.3 atm. The RDE technical specification is explained in Table 1.

Table 1. RDE technical specification [15]

| Parameter                              | Value   | units |
|----------------------------------------|---------|-------|
| Reactor Core                           |         |       |
| Height (active)                        | ~ 2     | m     |
| Diameter                               | ~ 1.8   | m     |
| Heat transfer area                     | 305.4   | m²    |
| Thermal power output                   | ~10     | MW    |
| Fuel type                              | Pebble  |       |
| Electrical power (gross)               | ~3      | MWₑ   |
| Electrical power (net)                 | ~2.9    | MWₑ   |
| Primary coolant system                 |         |       |
| Primary fluid                          | Helium  |       |
| Primary mass flow rate                 | 4.4     | kg.s⁻¹|
| Primary pressure                       | 30      | bar   |
| Reactor core inlet temperature         | 250     | °C    |
| Reactor core outlet temperature        | 700     | °C    |
| Average core temperature               | 450     | °C    |
| Secondary coolant system               |         |       |
| Nominal steam mass flow rate           | ~4.0    | kg.s⁻¹|
| Nominal helium mass flow rate          | ~4.4    | kg.s⁻¹|
| Nominal feed mass flow rate            | ~4.0    | kg.s⁻¹|
| Steam/vapor temperature                | ~530    | °C    |
| Steam/vapor pressure                   | ~60     | bar   |
| Feed-water temperature                 | ~160    | °C    |
| Secondary pump power                   | 223     | liter per minute |
| Primary Compressor                     |         |       |
| Total static head                      | approx. 1.5 | bar |
| Nominal delivery                       | approx. 4.3 | kg.s⁻¹|
| Outlet pressure                        | approx. 30.3 | bar |
| Outlet temperature                     | 250°    | °C    |

4. Results and Discussion
The steam extraction point for the desalination process is the bypass outlet flow from the first turbine stage (stream no. 10). This stream is the flow to be fed back to the steam generator (SG) after going through the de-aerator. It has a temperature of 306.5 °C, a pressure of 8 bars and a mass flow rate of 0.62 kg per second. The bypass volume is depending on the temperature that must be kept at 170 °C (HE outlet, stream no 16). The main function of the de-aerator is to maintain the inlet temperature of SG at 150 °C. Therefore the maximum heat that can be taken is still high enough for desalination. The desalination evaporator will convert seawater at a mass flow rate of 1.1 kg/s, 1 bar of pressure and 30 °C of temperature (stream no 17) to certain outlet temperature at 70-140 °C (stream no. 18). The amount of potable water produced in this simulation is seen in Table 2.
Table 2. The amount of drinking water produced by turbine heat waste

| Temperature evaporator (°C) | Water produced (m³/h) | Total capacity (m³/day) |
|-----------------------------|-----------------------|------------------------|
| 70                          | 4.09                  | 98.16                  |
| 80                          | 3.29                  | 78.96                  |
| 90                          | 2.76                  | 66.24                  |
| 100                         | 2.38                  | 57.12                  |
| 110                         | 2.09                  | 59.16                  |

Usually, in evaporation systems to condense of seawater need high temperature. Seawater boiling temperature can be reduced to as low as possible by a vacuum system. By using heat waste from a steam turbine at the first stage, a simulation was conducted to observe the appropriateness of a vacuum desalination process for water treatment. This simulation was conducted using a condenser. The model is built to minimize the heat requirements, and water production is still optimum. At first, the inlet seawater is varied to wet steam in a saturated vapor heater. This vapor heater gets heat from the superheated steam from the HP turbine which is due to condensation. The dry component of wet vapor is heated until the superheated condition by the steam generator is achieved. Superheated vapor is used to recover seawater that enters the wet steam and then it condensed as potable water for daily life consumption.

The observation shows that desalination using a vacuum system at HP turbine output waste steam is enabled and it has many profits. In this system, seawater bait can be seethed even in the low temperature and it can reduce energy requirement needs, due to simulation result, water effervesces at 45–100°C at the referring vacuum pressure of 0.1–1.0 bar, respectively. The calorific/heat needed from the waste stream is low because the superheated steam is used to reheat the influent/feed seawater. Almost all of the heat waste that needed to compensates for the heat loss in the system. The energy efficiency of the system depends on releasing heat loss from the system. It possibly uses non-conventional energy such as low-temperature vapor heat waste for vacuum desalination.

De-aerator is one component removes dissolved oxygen and another impurities gas in the water or vapor. Dissolved oxygen can initiate corrosion to the boiler or steam generator and its product adheres to the component surface as a corrosion oxide. Dissolved carbon dioxide (CO₂) mixed with water to form carbonated water or carbonic acid with the chemical formula H₂CO₃ (equivalently: OC(OH)₂) which impacts/initiates to corrosion. Most de-aerators are designed to remove oxygen up to the level of 7 ppb by weight (0.005 cm³ / L) or less and remove carbon dioxide. De-aeration depends on the principle that the solubility of gases in water decreases when the temperature of the water rises and approaches a saturation point. In a de-aerator, water is heated to near saturation temperature with a minimum pressure drop and minimum ventilation. Aeration is done by spraying feed water to provide a large surface area and may involve flow over several layers of the tray. This scrubbing (or stripping) steam is fed to the bottom of the aeration. When the steam touches the feed water, it heats it until the temperature is saturated and the dissolved gas is released from the feed water and is removed from the de-aerator through ventilation. A waterfall is treated into a storage tank under the de-aerator.

The potable water will be achieved from the desalination process by RDE is about 98.18 m³/day by using a multi-effect desalination (MED) method. This technology is a low thermal method to obtained freshwater/potable water by restoring the vapour of boiling sea/brackish water in a sequence of desalination component (vessels), (called effects) in a lower temperature of each vessel than the last one. The seawater boiling point decrease linearly with pressure, the vapour boiled outlet in one vessel can be used again to reheat the next stage vessel, and only the first one (at the highest pressure) requires an external source of heat. The heat is supplied from the first stage turbine outlet steam. The relation between water pressure and the boiling point temperature of seawater is represented in Table 3. The temperature is maintained below 65°C avoiding unnecessary heating and it can control scaling problem in the each vessel.
Vacuum desalination when some seawater is evaporated at the lower temperature during experiencing vacuum pressure. The energy requirement for desalination can be brought down by decreasing the boiling water temperature.

Table 3. Correlation between pressure and boiling point temperature of the water

| Pressure (bar) | Boiling point (°C) |
|---------------|--------------------|
| 1.0           | 100                |
| 0.47          | 80                 |
| 0.32          | 70                 |
| 0.25          | 65                 |
| 0.1           | 45                 |

Figure 3. The amount of freshwater generates by using MED desalination technology

The desalination process cost depends on some factors such as plant location, site conditions, the size and type of desalination plant, source and quality of feed water, qualified labor, energy costs and plant lifetime. The lower salt content in the seawater feed requires less power consumption and reduce the overall cost of desalination. The chemical added to treat the scaling also decreases when the water salinity is very low. The bigger plant production capacity reduces the desalination/unit cost due to the economics scale. Some technologies of desalination were introduced in the world including primary membrane and thermal methods.

In this simulation, the amount of clean water produced is little because the turbine output temperature and mass flow rate is very low. However, for a laboratory scale, the amount of clean water produced does not affect. This modeling and simulation proved that RDE can be used for seawater desalination. The larger capacity of the desalination plant or commercial plant can be increased by increasing temperature outlet and mass flow rate of the bypass flow.

For long term lifetime, what type of desalination process, what type of energy source and how much required output are factors that affect the cost. In general, the MSF method has specific higher unit costs compare with the MED, MED/VC and RO (for EC or WHO standard) as 1800, 1440-1680, 1650 and 1125 US$/m³/d, respectively. The amount of output volume per day for MSF and MED is similar (48,000 m³/d). MED/VC and RO processes have a lower output volume of 24,000 m³/d. Every desalination method has a different kind of energized energy, electrical/mechanical or thermal. All of them could be produced by fossil or nuclear plants. For a single purpose plant, the
nuclear power plant has a higher cost construction, operation-maintenance and electrical production cost compare with fossil plants. However, the fuel cost in US $/MW.h for NPP is lower than fossil plants, and both of them have a similar water cost production around the US $ 0.7-2.0 per m$^3$. Considering the lack of electricity and water availability in some parts of Indonesia, and high cost in some cost aspect for NPP, so it is suggested to use NPP coupling with desalination in dual purpose. However, for economic benefit, while using dual-purpose plants, coupling with desalination plants applies only to thermal (destination) processes such as MSF or MED. Therefore, electricity is the main product and not more than 10% of the thermal output for the desalination process.

**Conclusion**

The ChemCAD simulation for the desalination process in RDE has been done. The steam extraction point for this process is on the bypass outlet flow from the first turbine stage of RDE. It has a temperature of 306.5 °C, a pressure of 8 bars and a mass flow rate of 0.62 kg/s. The desalination process is simulated by heat exchangers. Desalination methods in this simulation depend on temperature ranges of the waters in the HE could be between 70-130 °C. The pure water resulted from the simulation is 4.09 m$^3$/h equal to 98.16 m$^3$/day.

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**Author Contributions**

All authors contributed equally to this research. All authors discussed at all stages during the writing, results analysis and conclusions.

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