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Comparative assessment of CANDU 6 and Sodium-cooled Fast Reactors for nuclear desalination

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HIGHLIGHTS

- Two integrated systems for power production and desalination are proposed.
- Exergy analysis is used in the present study and assessment.
- Exergy efficiencies are determined comparatively for both systems.
- A parametric study is undertaken to investigate how changing operating conditions and state properties affect the system performance.

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ABSTRACT

A comparative assessment is reported of two systems for nuclear desalination. The systems use Reverse Osmosis (RO) for desalination and are coupled with either a CANDU 6 nuclear reactor or a Sodium-cooled Fast Reactor (SFR). Exergy analysis is used to assess the performance of the electric power generation and desalination processes, and overall system, for each of the systems, as well as the effects of varying significant design and operating parameters on the exergy efficiencies of the power generation process, desalination process and overall system. The cogeneration exergy efficiencies of the CANDU 6-based and SFR-based systems are found to be 32.8% and 36.8%, respectively, while the exergy efficiencies of the RO process for the CANDU 6-based and SFR-based systems are found to be 49.2% and 63.3%, respectively.

1. Introduction

As clean ground water and surface water sources decline, many regions are increasingly turning to water desalination as a means to satisfy clean water demands. Although distillation of seawater is the most common large-scale desalination process, accounting for approximately 60% of global desalination capacity, desalination of brackish ground water and surface water now accounts for nearly 35% of the desalination [1,2]. Reverse osmosis (RO) is a promising seawater desalination technology appropriate for moderate production rates.

Fossil fuels have in the past been the main source of electrical and thermal energy for desalination plants. With the gradual depletion of conveniently available fossil fuel reserves and increasing environmental concerns, countries and people are seeking alternative energy sources that are sustainable and environmentally benign, like renewable energy. The main renewable energy sources in use today are solar, geothermal, wind, biomass and hydro [3]. However, their intermittency creates reliability challenges for industrial processes such as desalination. Hence, nuclear technology, which also avoids many of the concerns associated with fossil fuels, is also considered a feasible option for driving desalination plants [4].

There are mainly three methods of seawater desalination employed commonly, based on the type of energy used, such as electricity, thermal and both electricity and thermal (see Fig. 1). The thermal based desalination techniques, namely multistage flash and thermal vapor compression, require extensive amount energy input and different reactor coupling while the ones, using electricity, e.g., reverse osmosis (RO), require less amount of energy, resulting in a lower cost of desalination [5]. The reverse osmosis plants are then easily coupled with any type of nuclear plants since they only require electricity. Nuclear power reactors are suitable for desalination processes that require energy in the form of electrical power, including reverse osmosis (RO) and mechanical vapor compression (MVC) systems as well as others (see Fig. 1). Desalination plants can be coupled with single purpose or cogeneration plants. In the case

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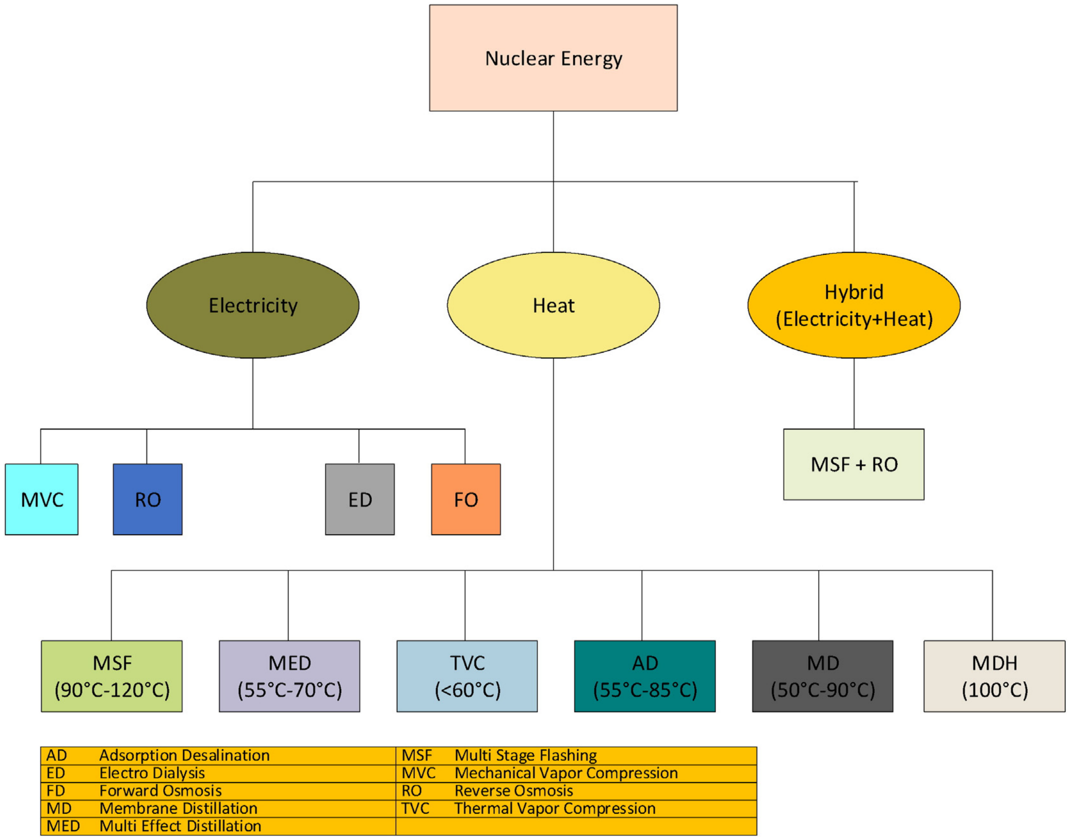

Fig. 1. Routes for desalination using nuclear energy.

of a single purpose nuclear desalination plant, the energy produced by the nuclear plant is exclusively used for the desalination process, and the desalinated water is the only product. That is, the nuclear reactor is fully dedicated to supplying energy for desalination. In case of a cogeneration plant, only a part of the energy from the nuclear plant is utilised for desalination. Table 1 lists some existing nuclear power plants in various countries. The nuclear power plant in India is a cogeneration plant used for electricity and pure water while in Japan the High Temperature Nuclear Reactor is used for high temperature process heating. Currently, there are 11% (third largest group) of CANDU nuclear reactors, working in the world and an integration of the RO seawater desalination system with CANDU 6 as discussed in the CANDESAL [7]. The essential feature of the CANDESAL plant was that the heat from the condenser was utilised to preheat the seawater as a feed for RO desalination plant. The main drawback associated with these types of nuclear reactors is the poor performance compared to advanced thermal reactors. To improve the thermal efficiency and better utilisation of the fuel, the Generation IV nuclear reactors were proposed. Among these reactors, the sodium cooled fast reactors (SFR) has gained increasing attention as they feature a fast spectrum reactor and better resource utilisation [8].

Much research has been reported on coupling of desalination plants with nuclear reactors. Recently, Park and Kim [9] examined the integration of very high temperature reactor and forward osmosis desalination system and found that it is five times more efficient than the integration of multistage flash distillation and a very high temperature reactor. Adak and Tiwari [10] studied the feasibility of integrating a desalination plant with heavy water nuclear reactors, considering the technical feasibility of coupling a multi-effect distillation and thermal vapor compression desalination plant with a heavy water reactor. Jung et al. [11] assessed the feasibility of having a small nuclear reactor dedicated to desalination, and found that coupling a small reactor with a thermal desalination plant is beneficial from economic and safety viewpoints. Kim and No [12] describe the feasibility of coupling a high temperature gas reactor and a multi-effect distillation desalination plant, and determined that the production of fresh water increases by 258% compared to a previous design scheme. Alonso et al. [13] discuss alternatives for sea water desalination using nuclear power, mainly considering five desalination processes: reverse osmosis, multistage flash distillation, multi-effect distillation, hybrid multistage flash distillation-reverse osmosis, and hybrid multi-effect distillation-reverse osmosis.

Table 1
Selected major nuclear plants in several countries.

Country	Plant Type	Outputs
India	PHWR	Electricity, pure water
Russia	ATEC-200	Electricity, domestic heating
China	NHR-200	Domestic heating
Japan	HTTR	High temperature process heat

Source [6].

Nissan and Dadour [14] determine the electric power and desalination costs for four types of nuclear power plants coupled to multi-effect distillation and reverse osmosis desalination systems, and identify the cost associated with reverse osmosis to be the lowest. Misra [15] discusses the challenges and prospects of nuclear energy for desalination plants and concludes that it is one of the feasible options for the production of fresh water. All the above mentioned studies conclude that an integration of desalination process with the nuclear reactor is feasible and can be greatly beneficial to the economy in achieving better sustainability. The other interesting feature of the above studies is that none of them has included any sort of exergy analyses in their studies.

In the present study, we analyze and compare two types of nuclear reactors in an integration fashion for the combined production of electricity and fresh water to provide more efficient, effective and environmentally benign and sustainable option. The specific objectives are listed as follows: (a) to develop two integrated systems for power production and desalination, (b) to analyze them using a exergy analysis as