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A comprehensive approach in optimization of a dual nuclear power and desalination system

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ABSTRACT

A typical 1000 MW Pressurized Water Reactor (*PWR*) nuclear power plant coupled to a multi effect distillation desalination system with a thermo-vapor compressor (MED–TVC) is considered for optimization. The thermodynamic modeling is performed based on the energy and exergy analyses, while an economic model is developed according to the *Total Revenue Requirement* (*TRR*) method. The objective functions based on the thermodynamic and thermoeconomic analyses are obtained. The proposed hybrid plant with ten decision variables for power plant and six decision variables for the desalination plant is optimized in a multi-objective optimization process. This approach is applied to minimize either the cost of the system product (including the cost of generated electricity and fresh water) and/or maximize the exergetic efficiency of the system. Three optimization scenarios including thermodynamic single objective, thermoeconomic single objective and multi-objective optimizations are performed using the Genetic Algorithm (GA). In multi-objective optimization, both thermodynamics and thermoeconomic objectives are considered, simultaneously. A series of optimum solutions namely Pareto frontier is obtained. In the case of multi-objective optimization, an example of decision-making process for selection of the final optimal solution from the available optimal points on the Pareto frontier is introduced. The results obtained using the various optimization scenarios are compared and discussed.

Contents

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Nomenclature

BL	book life
c	unit cost of the exergy rate ($^{\$}/_{kJ}$)
CC	carrying charge
$\dot{C}_{P,tot}$	the cost rate of the dual system product (electricity and distilled water) ,$^{\$}/_{s}$
c_Q	cost of the nuclear fuel per thermal exergy of the reactor, $^{\$}/_{kJ}$
CRF	capital recovery factor
D_i	distillate flow rate of the effect i^{th}, $^{kg}/_{s}$
Dr_n	entrained vapor from the effect n^{th}, $^{kg}/_{s}$
D_t	total flow rate of the fresh water, $^{kg}/_{s}$
$\dot{E}$	exergy rate, kW
$\dot{E}_D$	exergy destruction rate, kW
$\dot{E}_{D,tot}$	total rate of the exergy destruction for the dual cycle, kW
$\dot{E}_L$	exergy loss rate, kW
$H.P$	high pressure
$H.P.T$	high pressure turbine
i_{eff}	interest rate (the cost of money), %
j	j^{th} year of the system operation
$L.P$	low pressure
$L.P.T$	low pressure turbine
MED	multi effect distillation
N	number of effects
n	vapor return effect
P	pressure, kPa
PEC	purchase equipment cost, $
P_i	pressure in the effect i^{th}, kPa
ppm	parts per million
PWR	pressurized water reactor
$\dot{Q}_{fiss}$	thermal capacity of the nuclear reactor, kW
Rej	rejected flow rate of the cooling seawater stream for the condenser of the desalination plant, $^{kg}/_{s}$
T	temperature, °C or K
T_{f1}	feed water temperature enters to the first effect, °C or K
T_N	outlet brine temperature from the condenser of the desalination plant, °C or K
T_s	outlet steam temperature from the de-superheater of the desalination plant, °C or K
TDS	total dissolved solids
TRR	total revenue requirement
TVC	thermo-vapor compressor
$\dot{Z}_k^{CI}$	capital investment cost rate apportioned to the component k^{th}, $^{\$}/_{s}$
$\dot{Z}_k^{OM}$	operating and maintenance cost rate apportioned to the component k^{th}, $^{\$}/_{s}$

Greek letters

τ	annual number of operating hours (hr)
ΔT_i	pinch temperature difference of the effect i^{th}, °C
ΔT_{mincon}	pinch temperature difference of the condenser, °C
Ψ	overall exergetic efficiency of plant

Subscripts

distillate	distillate (fresh) water
D	destruction
elec	electricity
fiss	fission
k	component k^{th}
L	levelized
L	loss
overall	overall
tot	total

1. Introduction

About 23 million m^3/day of desalted water is currently produced by 12,500 plants set up in various parts of the world. These plants largely use fossil energy sources. Interest in using nuclear energy for producing potable water has been growing worldwide in the past decade. This has been motivated by a wide variety of reasons, from economic competitiveness of nuclear energy to energy supply diversification; from conservation of limited fossil fuel resources to environmental protection; and to the spin-off effects of nuclear technology in industrial development [1].

Review on the history of the nuclear desalination and its future prospects can be found by *Megahed* [2] and *Misra* [3]. Most of the analyses performed on nuclear desalination systems are only based on economic evaluations. Economic evaluation of some types of nuclear desalination systems including PWR–MED is discussed by Nisan et al. [4]. Nuclear desalination involves three technologies: nuclear, desalination and their coupling system.

On the other hand, for a comprehensive analysis and optimization of a complex energy system, a powerful tool that deals with energetic and economic aspects of the energy system is highly required. In this regard, the combination of the second law of thermodynamics with the principle of engineering economics provides such powerful tool for systematic study and optimization of these complex energy systems. This powerful universal tool is called "*Thermoeconomics*". The principles and methodologies of thermoeconomics are well-established by Bejan et al. [5].

A comprehensive study to establish methodologies for allocating costs into the final products of co-production plants based on thermodynamic criteria and providing capability for economic ranking of co-production plant alternatives is carried out by *International Atomic Energy Agency* (*IAEA*) [1]. Thermoeconomic analysis of a hybrid conventional power plant and desalination system was conducted by Hamed et al. [6]; however they did not attempt to perform any optimization on this system. Instead, thermoeconomic optimization of a dual purposed conventional power plant and desalination system was performed by Uche et al. [7]. In another work, authors performed an thermoeconomic optimization of the hybrid nuclear desalination system [8], where the nuclear power plant was pressurized light water reactor (PWR) and the desalination system was a multi effects distillation desalination system with a thermal vapor compressor (MED–TVC desalination system).

An integrated design optimization approach would be preferred to be able to deal with various aspects in real and complex energy systems. A multi-objective optimization problem requires the simultaneous satisfaction of number of different and often conflicting objectives. Multi-objective optimization problems generally show a possibly uncountable set of solutions namely as Pareto frontier, whose evaluated vectors represent the best possible trade-offs in the objective function space [9,10].

In this paper a comprehensive optimization with the aim of comparison of the various optimization approaches is performed for a hybrid PWR–MED plant. A typical 1000 MW Pressurized Water Reactor (PWR) nuclear power plant is coupled to a typical multi effect distillation (MED) desalination system with thermo-vapor compressor. The thermodynamic modeling is performed based on the energy and exergy analyses, while an economic model is developed according to the *Total Revenue Requirement* (*TRR*) method [5,11]. The objective functions based on the thermodynamic and thermoeconomic analyses are obtained. The optimization using thermodynamics and thermoeconomics is conducted separately. In the multi-objective optimization, both objectives are considered simultaneously. All optimization processes are performed with implementing of a stochastic/deterministic approach namely as Genetic Algorithm. In the case of multi-objective optimization, an example of decision-making process is presented and the final optimum solution is compared with the corresponding results obtained in single objective optimization.