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DE-TOP: A new IAEA tool for the thermodynamic evaluation of nuclear desalination

I.G. Sánchez-Cervera, K.C. Kavvadias, I. Khamis *

International Atomic Energy Agency (IAEA), Wagramer Strasse 5, P.O. Box 100, A-1400, Vienna, Austria

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ABSTRACT

The IAEA Desalination Thermodynamic Optimization Program DE-TOP, a newly developed tool for thermodynamic analysis of coupled nuclear power and seawater desalination plants, was released early this year. This software is capable of analyzing different coupling options including power generation systems coupled to desalination systems through various alternatives of steam extractions. The advantages and disadvantages of each coupling on the overall power cycle can be analyzed based on detailed models in DE-TOP. General description of DE-TOP structure is made and main features are highlighted. Benchmarking of DE-TOP with cases found in literature demonstrated satisfactory results.

1. Introduction

Nuclear power contributed about 14% of the global electricity production in 2009, with rising growth projections to energy source worldwide. Recent studies show that global nuclear power capacity will rise to 511 GW (e) in 2030, compared to a capacity of 370 GW(e) at the end of 2009 [1]. Yet, nuclear power is mostly used for electrical generation. The use of nuclear energy for cogeneration i.e. for electricity and process heat for various applications such as district heating, seawater desalination, or hydrogen production, allows significant economic advantages and primary fuel savings [2]. Among heat applications, nuclear desalination is gaining more and more interest in the last decade.

Nuclear desalination is defined as the production of potable water from sea water in an integrated and co-located facility in which a nuclear reactor is used as the source of electrical and/or thermal energy for the desalination process [3]. It is a demonstrated option, with more than 200 reactor-years of operating experience worldwide, which could help meet the expected energy and water demand increase in the future.

For more than two decades ago, the International Atomic Energy Agency (IAEA) continues to support nuclear desalination and has addressed the main considerations involving this technology. The IAEA has published several works on the economics [4–6], safety [7] and technical aspects [8,3,9,10] of nuclear desalination. A key outcome of this experience was the development of DEEP (Desalination Economic Evaluation Program) a software under continuous development that has been recently reviewed and verified [11] for the release of the new version in February 2011. DEEP is used for economic evaluation and comparison of various desalination and energy source options. DEEP calculates the water and power cost broken down to their components, by solving a detailed economic model of the power and sea water desalination plant [5]. Its model considers the power plant as a black box and shortcut energy balances are used as an input for the economic models. However, a complimentary detailed thermodynamic analysis for the coupled plant was still needed, since the coupling configuration between desalination and nuclear power plant not only entails technical and safety considerations but has a strong influence on the overall economics of the system [12].

Addressing this issue, the IAEA recently released the Desalination Thermodynamic Optimization Program (DE-TOP), an excel based powerful tool that simulates in detail the water/steam cycle of generic water cooled reactors and its coupling with seawater desalination plants. DE-TOP analyzes different coupling options and compares their performance from a thermodynamic point of view. Along with DEEP, DE-TOP provides a wider overview of nuclear desalination of both thermodynamic and economic aspects. This paper describes structure and salient features of DE-TOP, and evaluates its validity and reliability through benchmarking with literature data. The benefits and main goals of DE-TOP will be demonstrated through a case study to be presented in this paper.

2. DE-TOP models

As modeled in DE-TOP, both nuclear power plant and seawater desalination plant are described. The dual purpose power plant provides electrical power and steam required for the seawater desalination process. In DE-TOP, thermal desalination technologies such as Multi Effect Distillation (MED) or Multi Stage flash (MSF) are suitable.

* Corresponding author. Tel.: +43 1 2600 22822/22815; fax: +43 1 2600 29598.
E-mail address: i.khamis@iaea.org (I. Khamis).

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2.1. Power plant model

DE-TOP models the secondary loop of a generic water cooled nuclear power plant (Fig. 1) according to fundamental thermodynamic models [13–15]. Each model has been formulated with limited input to be requested from the user. Such input will be sufficient to calculate the regenerative Rankine cycle with reheat. In order to simulate various types of power plants, other important input parameters can be modified by the user including: thermal capacity, live steam conditions, reheat pressure ratio, feedwater preheating conditions and efficiencies. Site-specific data such as cooling water temperature is also modeled as an input necessary to show the impact of ambient temperature to the performance of the dual-purpose plant. All input data required along with 4 generic predefined cases modeled in DE-TOP are presented in Table 1. DE-TOP uses the input data to simulate the thermodynamic model of the power plant, solving all mass and energy flows using thermophysical properties which will be calculated based on a built-in databank, such as temperature, pressure, specific enthalpy and entropy.

A brief description of the theoretical thermodynamic process considered in DE-TOP involves the heat generated (from nuclear reactor or conventional boiler) and transferred to the secondary side, via a steam generator. The generated steam is expanded in the high pressure (HP) turbine where partial flows are extracted and delivered to feed high pressure heaters and deaerator. The remaining steam is directed to the moisture separator and reheater where moisture content is removed and the remaining dry steam is superheated by a portion of live steam to decrease steam moisture in the last low pressure (LP) turbine stages. In the LP turbine, steam is expanded to the condenser pressure. The working steam passes through the condenser where condensation takes place, and condensate is pumped through the LP regenerative heaters to the deaerator, from which the water is delivered by the main feedwater pumps back into the steam generator through the HP heaters.

2.2. Cogeneration models

Dual-purpose plants are modeled in DE-TOP in a similar way to the single purpose power plant. The main difference for cogeneration systems is the use of heat in the form of steam from the power plant to drive the thermal desalination process. Steam has to be extracted from the power plant cycle in the same way that is extracted for the feedwater heaters, but with additional safety measures to prevent any potential carryover of the radioactivity from the water/steam cycle to

Table 1
Main parameters for the power plant predefined cases in DE-TOP V1.0.

Reactor type		PWR	BWR	PHWR	SMR
Thermal capacity	MW(th)	3 002	3 926	2 156	330
Live steam pressure	MPa	6.65	6.79	4.64	3.00
Live steam temperature	°C	285	284	260	274
Turbine internal efficiency	[-]	0.85	0.85	0.85	0.80
Pump efficiency	[-]	0.85	0.85	0.85	0.85
Generator efficiency	[-]	0.98	0.98	0.98	0.98
Reheat pressure ratio	[-]	0.15	0.15	0.15	0.15
Reheat steam temperature	°C	260	256	240	250
Condenser temperature	°C	42.7	49.0	24.5	40.3
Pressure head cooling water	MPa	0.2	0.2	0.2	0.5
Cooling water inlet temperature	°C	23.7	30.0	11.5	29.3
Cooling water temp rise in condenser	°C	14.0	14.0	8.0	6.0
Final feedwater temperature	°C	218.0	215.2	186.9	180.0
Number of preheating stages	[-]	5.0	8.0	8.0	5.0

the desalination process. In such a case, an isolation loop is placed between extracted steam and desalination plant, acting as a third physical barrier against possible radioactive contamination. Once the steam from the power plant has released its latent heat by condensation, it is returned to the power plant and injected in an appropriate location.

Possible steam extraction points are limited by two main constraints: the size of the desalination plant, which defines the amount of steam to be extracted and the desalination technology, which defines the quality of the heat needed. Thus, steam has to be withdrawn from a point in the power plant where its saturation temperature is above the desalination max brine temperature, considering an additional temperature drop due to the intermediate loop and minimum temperature approach in heat exchangers (Table 2) [17]. Technical constraints from the power plant side, such as maximal extraction flows in turbine bleed points, or specific layout in the plant may limit the feasible extraction locations and have to be considered.

DE-TOP simulates the following configurations for the coupled nuclear power and sea water desalination plant (Fig. 2):

a) *Extraction from low pressure turbine*: steam is tabbed directly from the low pressure turbine at the exact required conditions for the desalination plant. This option is favored for new design dual purpose plants with variable power to water ratios. Retrofitting existing power plants with this option may not be feasible because of constraints in current design, available space, etc.

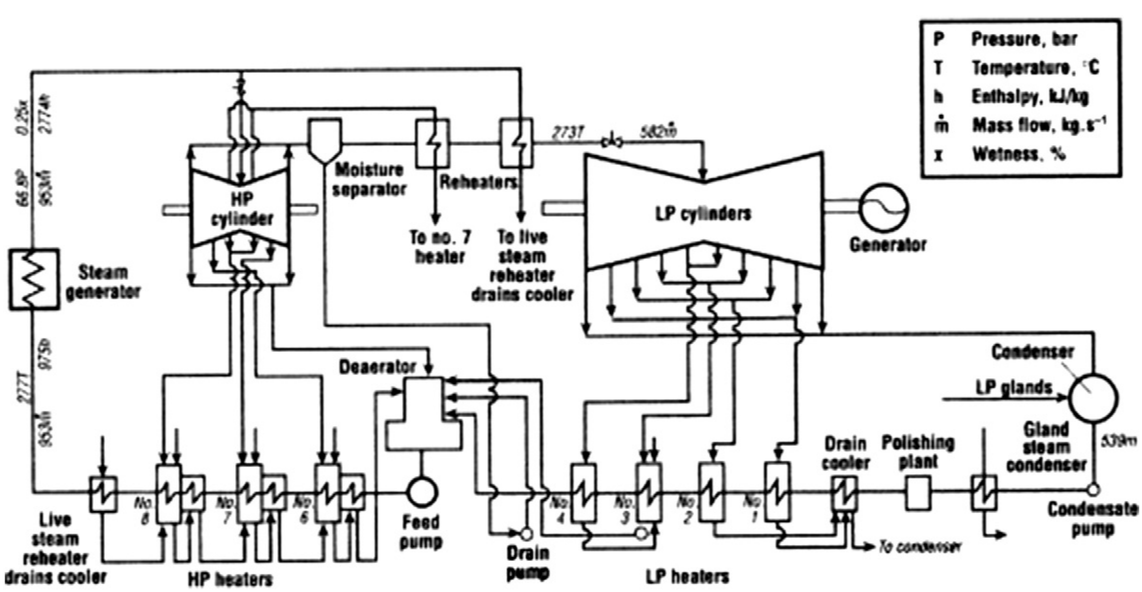

Fig. 1. Schematic diagram of a large nuclear power unit secondary cycle (16).