27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

# COB-2023-0725
# HYBRID DCMD AND SWRO DESALINATION USING A SMALL PWR OF 75 MW(th) FOR COGENERATION OF WATER AND ELECTRICITY

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***Abstract.*** *A hybrid desalination strategy combining Direct Contact Membrane Distillation (DCMD) and Sea Water Reverse Osmosis (SWRO) is presented. A small PWR of 75 MW(th) provides the electrical power and the heat required by the SWRO and DCMD plants, respectively, besides generating electricity for the grid. Blending the water produced by SWRO with that produced by DCMD has two main advantages. One is the improvement of water quality, as compared to that obtained with the SWRO plant. The other is the reduction of the cost of water production, as compared to that attained by the DCMD plant alone. The SWRO plant uses the electricity generated on site by the small PWR. On the other hand, to provide heat to the DCMD plant, the steam produced in the steam generator is divided into two parallel Rankine cycles, a strategy devised to use all the power plant waste heat. The DE-TOP program, developed by the International Atomic Energy Agency (IAEA), is used for the simulation of PWR Rankine cycles, whilst the DESAL-PLANT program, developed at the Instituto de Engenharia Nuclear (IEN/CNEN), is employed to simulate the DCMD desalination plant with heat recovery. Estimates of water and electricity production are presented for the conditions of the Brazilian northeast.*

***Keywords:*** *small PWR, cogeneration, nuclear desalination*

## 1. INTRODUCTION

Cogeneration systems of electricity and water based on nuclear energy have recently gained renewed attention (Sadeghi *et al.*, 2020; da Silva *et al.*, 2022; De Sampaio *et al.*, 2022). In fact, such cogeneration systems can contribute towards the United Nations sustainable development goals such as "Clean Water and Sanitation", "Affordable and Clean Energy" and "Climate Action" (UN, 2022). Even though the global nuclear desalination accumulated experience exceeds 250 reactor years (IAEA, 2017), only a small fraction of the thermal energy generated by the nuclear reactors is used for producing freshwater through desalination in present day nuclear cogeneration plants.

Not surprisingly, the desalination technologies adopted in nuclear cogeneration plants worldwide are well established techniques such as Multistage Flashing (MSF), Multi-Effect Distillation (MED), and Sea Water Reverse Osmosis (SWRO). Among these, SWRO attains the lowest specific electricity consumption, approximately 3.5 to 4.5 $kW(e)h/m^3$, and has become the most widespread technology for desalination (Curto *et al.*, 2021). On the other hand, Membrane Distillation (MD) is an emerging desalination technology which is becoming increasingly attractive for its adequacy to use low-grade waste heat or renewable energy sources (Guan *et al.*, 2015; Dow *et al.*, 2016; Christie *et al.*, 2020; Cipollina *et al.*, 2012). In the Direct Contact Membrane Distillation (DCMD) concept, the feed and the permeate flows are separated by hydrophobic porous membranes. The driving force for mass transfer is the difference of vapour pressure between the hot and cold sides of the membrane (Schofield *et al.*, 1987; Alkhudhiri *et al.*, 2012). After evaporating at the feed side, water vapour crosses the membrane and condenses at the permeate side. There are also some specific advantages regarding the use of MD. Essentially, no additives are needed to prevent fouling of the MD module, in contrast to SWRO technology (Jansen *et al.*, 2013). Moreover, the environmental impact of a brine discharge directly to the sea can, in most cases, be considered low or negligible, as MD produces less than 10% of the feed stream as distillate in a single pass system (Jansen *et al.*, 2013).

Here we investigate a hybrid nuclear desalination strategy, using both Direct Contact Membrane Distillation (DCMD) and Sea Water Reverse Osmosis (SWRO), for cogeneration of water and electricity using a small PWR of 75 MW(th). Blending the water produced by SWRO with that produced by DCMD has two main advantages. One is the improvement of the quality of the water produced, as compared to that obtained with the SWRO plant. The other is the reduction of the cost of water production, as compared to that attained by the DCMD plant alone (Sadeghi *et al.*, 2020).

The SWRO plant uses the electricity generated on site by the small PWR. On the other hand, to provide heat to the DCMD plant, the steam produced in the steam generator is divided into two parallel Rankine cycles, a strategy devised to use all the power plant waste heat. Using this arrangement, a specific electricity consumption of 8.47 $kW(e)h/m^3$ has been obtained for the DCMD process.

The remainder of this work is organised as follows: The SWRO and the DCMD plants that constitute the hybrid desalination proposed are presented in section 2. Section 3 describes the computational tools employed, namely, the DE-TOP program, developed by the International Atomic Energy Agency (IAEA), which simulates the Rankine cycles of PWRs, and the DESAL-PLANT program, developed at IEN/CNEN, which models a DCMD desalination plant with heat recovery. Estimates of water and electricity production are presented in section 4, considering the mean seawater temperature of the Brazilian northeast. Finally, our concluding remarks are drawn in section 5.

## 2. HYBRID NUCLEAR DESALINATION

Sadeghi *et al.* (2020) analysed hybrid desalination schemes involving thermal and reverse osmosis desalination technologies, dividing them into two categories: the simple scheme and the integrated scheme. In this work we consider the simplest nuclear hybrid desalination solution, where the DCMD and the SWRO desalination plants operate independently. The small PWR provides the heat and the electrical power required by both desalination plants, besides generating electricity for either the grid or local use.

### 2.1 The SWRO desalination plant

Sea Water Reverse Osmosis (SWRO) has the lowest specific eletric consumption, about 3.5 to 4.5 $\mathrm{kW(e)h/m^3}$, and is currently the most widespread technology for desalination (Kim *et al.*, 2019; Curto *et al.*, 2021). The coupling between the small PWR and the SWRO plant is exclusively through the electrical power generated and provided by the small PWR on site. Thus, all the electricity needed by the SWRO system, especially the power required to operate high pressure pumps, is provided by the nuclear power plant.

Figure 1 depicts a schematic representation of the SWRO desalination plant. The pre-treatment of seawater has been omitted in the simplified scheme shown in Fig. 1. The SWRO technology is based on the use of a semi-permeable membrane which allows water molecules to permeate while dissolved solids are blocked (Kim *et al.*, 2019). However, in order to overcome the the osmotic pressure across the semi-permeable membrane, the SWRO process requires the use of very high pressure on the feed side. Figure 1 shows that the feed (seawater) has its pressure elevated by the high pressure pump (HPP) before it enters the RO system, where the permeate (freshwater) and the brine are separated. It is important to remark that the brine leaving the RO system still has some considerable pressure that can be harnessed to save energy. This is done by energy recovery devices (ERD), shown in Fig. 1, which transfer pressure from the brine to the feed (seawater). However, as the pressure gained by the feed in the ERD is insufficient to match the required pressure at the entrance of the RO system, the feed stream pressure is supplemented by a booster pump (BP), as depicted in Fig. 1.

In our computations, to be presented in section 4, the electric power demand of the SWRO plant will be determined using the reference specific electricity consumption of 4 $\mathrm{kW(e)h/m^3}$, which is a value typical of a real-scale commercial SWRO plant, including pre-treatment and post-treatment processes (Kim *et al.*, 2019).

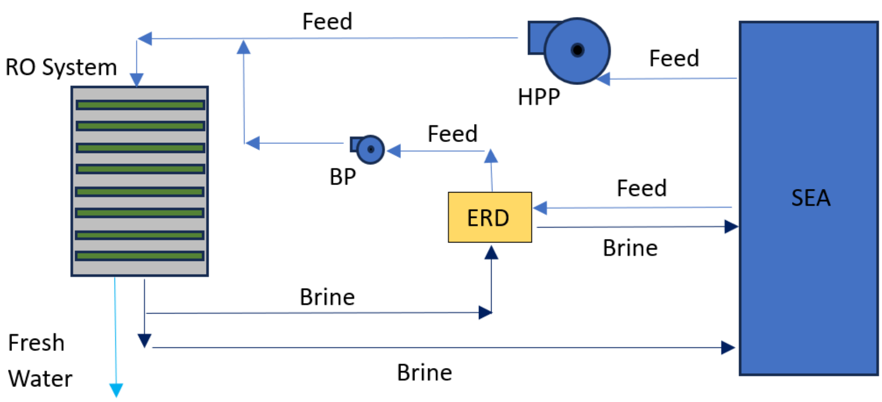



Figure 1. Schematic representation of the SWRO desalination plant.

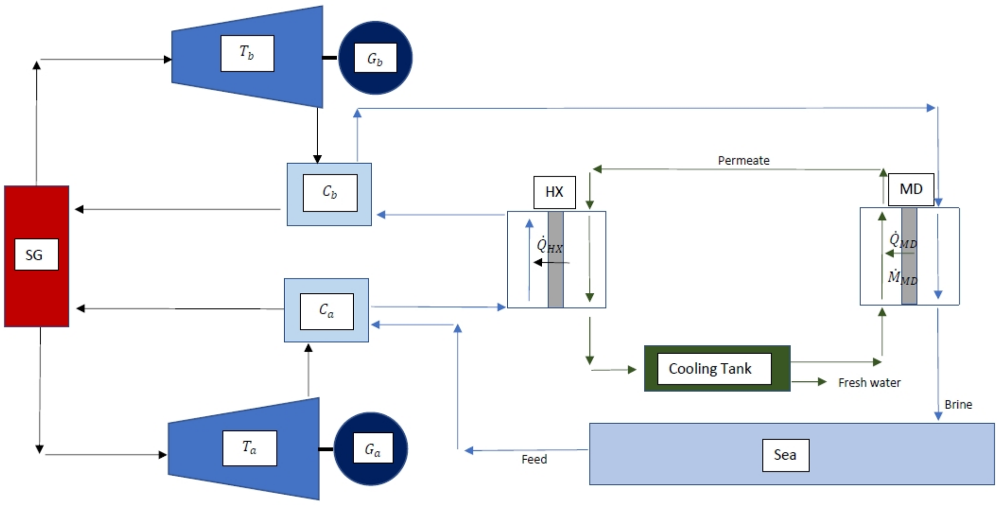
### 2.2 The DCMD plant with heat recovery

The coupling of the DCMD plant with heat recovery and the small PWR of 75 MW(th) is illustrated in Fig. 2, where the secondary loops of the small PWR are on the left and the DCMD plant is on the right. Referring to Fig. 2, note that the steam produced in the steam generator is divided into two parallel Rankine cycles.

Cycle (a) operates at pressures and temperatures that are typical of a Rankine cycle optimized for electricity generation. Condenser $C_a$ operates at the pressure of 0.063 bar, with steam condensation at 37 °C. We consider that the feed (seawater) enters the condenser $C_a$ at 26 °C, which is the mean seawater temperature at the Brazilian northeast (IBGE, 2011). The feed, as it cools condenser $C_a$, is heated up to 32 °C. Because the desalination plant collects warm seawater from the power plant condenser $C_a$, instead of colder water directly from the sea, a large amount of power plant waste heat is used to pre-heat the feed (Sadeghi *et al.*, 2020).

On the other hand, in cycle (b) steam expansion in the turbine $T_b$ is shortened to a pressure just below the atmospheric pressure. Indeed, condenser $C_b$ operates at 0.911 bar and, at such pressure, steam condenses at 97 °C. We consider a margin of 5 °C between the steam condensation temperature and the temperature of the feed at the condenser exit. Thus, in condenser $C_b$ the feed temperature can be elevated up to 92 °C before the feed enters the DCMD desalination unit, indicated as MD in Fig. 2. Inside the MD unit, mass and heat are transferred from the feed to the permeate at rates $\dot{M}_{MD}$ and $\dot{Q}_{MD}$, respectively. Figure 2 also shows the recovery heat exchanger HX, where part of the heat that had been transferred to the permeate in the MD unit is reused, at rate $\dot{Q}_{HX}$, to help rising the temperature of the feed.

It is important to remark that the external heating required for the desalination process comes exclusively from cooling the two Rankine cycle condensers. Because both condensers operate at pressures that are lower than the atmospheric pressure, there is no risk of radioactive contamination of the seawater with water leaking from the PWR secondary loop. Thus, there is no need to introduce isolation loops between the secondary loops of the PWR and the desalination plant. Indeed, in the power industry the concern is quite the opposite: the contamination of the secondary loop with the seawater used for cooling the condensers (EPRI, 1977).




SG – Steam Generator; T_a – Turbines of cycle a; C_a – Condenser of cycle a; G_a – Eletric Generator of cycle a; T_b – Turbines of cycle b; C_b – Condenser of cycle b; G_b – Eletric Generator of cycle b; HX – Heat Exchanger used for heat recovery of the DCMD process; MD – DCMD desalination unit.

Figure 2. Schematic representation of the coupling using two parallel Rankine cycles.

## 3. THE COMPUTATIONAL TOOLS

The coupling of the DCMD plant with heat recovery with the small PWR of 75 MW(th) is modelled using two computational programs, namely, the DESAL-PLANT program and the DE-TOP program. The amount of desalinated water produced by the DCMD plant is computed using the DESAL-PLANT program developed at IEN/CNEN (De Sampaio, 2022). On the other hand, the program DE-TOP of the International Atomic Energy Agency (IAEA) is used to simulate the Rankine cycles of the small PWR (Sánchez-Cervera *et al.*, 2013).

### 3.1 The DE-TOP program

The DE-TOP program, developed by the International Atomic Energy Agency (IAEA), models the secondary loop of a generic Pressurised Water Reactor (PWR). More precisely, it models the regenerative Rankine cycle with reheat (El-Wakil, 2002; Teyssedou *et al.*, 2010; Medina-Flores and Picon-Nunez, 2010). The IAPWS-IF97 industrial formulation is used to represent the thermodynamic properties of water and steam. Besides the thermodynamic cycle, DE-TOP also models the coupling of the PWR secondary loop with a desalination plant. The desalination technologies included in DE-TOP are MSF and MED, but not the DCMD technology adopted in this work. Nonetheless, DE-TOP can be used to compute the electricity output of a cogeneration system containing a DCMD desalination plant.

DE-TOP has a flexible system configuration. Indeed, the user can choose the number of regenerative heaters, including the deaerator, and the deaerator position along the feedwater line. By default, DE-TOP automatically sets the operating pressures of each regenerative heater, but users can redefine these heater pressures according to their own requirements.

Figure 3 illustrates the use of DE-TOP to model a small PWR of 75 MW(th), which is the reference nuclear power plant considered in this work. The steam generator pressure was set to 54 bar. We decided to use 6 regenerative heaters, with the deaerator occupying position 5 along the feedwater line, and accepted the heater pressures suggested by the program. Note that, as shown in Fig. 3, DE-TOP presents pressure, temperature, enthalpy and mass flowrate at various points along the PWR secondary loop. For the reference power plant considered here, we used the default values of DE-TOP for the following parameters: high-pressure turbine efficiency 0.85, low-pressure turbine efficiency 0.83, pump efficiency 0.85, generator efficiency 0.98. Using DE-TOP with these values, the PWR reference plant of 75 MW(th) yields a net electric output of 25.41 MW(e).

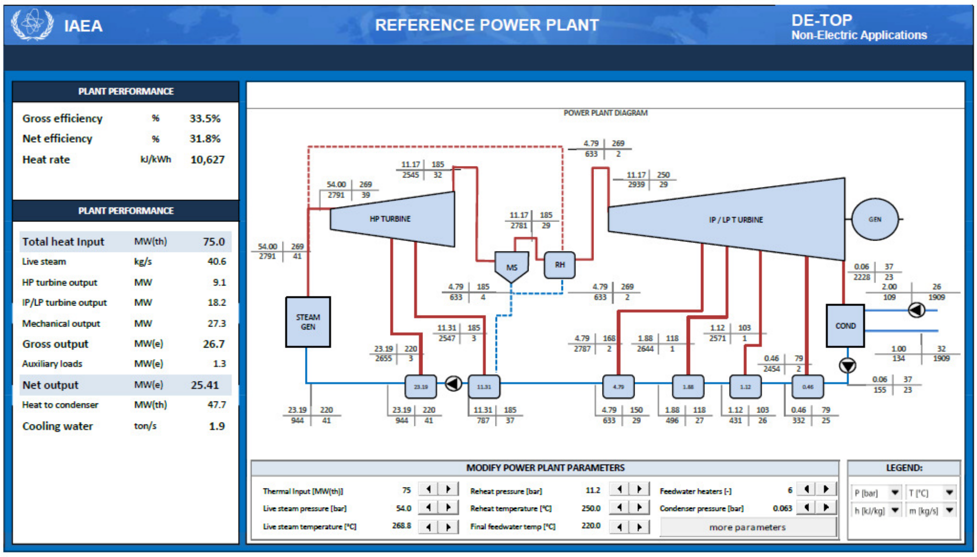



Figure 3. DE-TOP schematic representation of the reference 75 MW(th) PWR (regenerative Rankine cycle with reheat).

### 3.2 The DESAL-PLANT program

The DESAL-PLANT program was developed to model a Direct Contact Membrane Distillation (DCMD) desalination plant with heat recovery. The desalination unit comprises several DCMD modules, each of a shell and hollow fibre tube bundle type (Schofield, 1989). DESAL-PLANT includes modelling of the vapour flux through the micro/nano porous membrane, models for the mass and energy conservation at the scale of the DCMD module, and modelling at the scale of the desalination plant itself, involving several identical DCMD modules, the external heat source and the heat exchanger used for heat recovery.

As the desalination plant comprises several identical DCMD modules, the modelling of a single representative DCMD module is the cornerstone of DESAL-PLANT. The DCMD module considered is a cylindrical shell, with internal radius $R_s$, which is occupied by $n_f$ hollow fibres aligned with the shell axis. The hollow fibres internal and external radii are $a$ and $b$, respectively. Note that a detailed 3D modelling of the flow inside the shell would render the analysis cumbersome and computationally expensive. DESAL-PLANT adopts a simplified one-dimensional model based on defining an equivalent channel for the shell flow surrounding a single representative hollow fibre. The equivalent channel is chosen as the annulus, with internal radius $b$ and external radius $c$, having the same equivalent diameter as the original configuration i.e. the shell filled with $n_f$ hollow fibres. We recall that the equivalent diameter is defined as $4A/\Gamma$, where $A$ is the cross-sectional area of the flow and $\Gamma$ is the part of the perimeter of the cross-section where mass and heat transfer take place. Thus, it is easy to verify that, in order to preserve the same equivalent diameter of the shell side flow, the external radius of the equivalent channel is $c = R_s/\sqrt{n_f}$. Figure 4 depicts the shell cross section and the equivalent channel.

Appropriate one-dimensional mass and energy conservation equations, along the module length, are written for both feed and permeate flows (De Sampaio, 2022). However, these conservation equations depend on closure models that describe mass and heat transfer across the membranes. The Dusty Gas Model is used to describe the vapour diffusion through the micro/nano membrane pores (Evans III *et al.*, 1961; Fernández-Pineda *et al.*, 2002). The models in DESAL-PLANT also account for the relevant heat transfer processes between the feed and permeate sides of the membranes. These include convective heat transfer (based on appropriate Nusselt number correlations), latent heat transport by the vapour crossing the membrane pores, and conductive heat transfer through the membrane matrix.

The dependent variables in DESAL-PLANT are temperatures and mass fluxes. The temperatures in the lumen (hollow fibre interior) and shell sides are denoted by $T_l$ and $T_s$, respectively. The axial mass fluxes for lumen and shell are $G_l$ and $G_s$. They represent the lumen and shell mass flowrates divided by their respective cross-section areas. Other

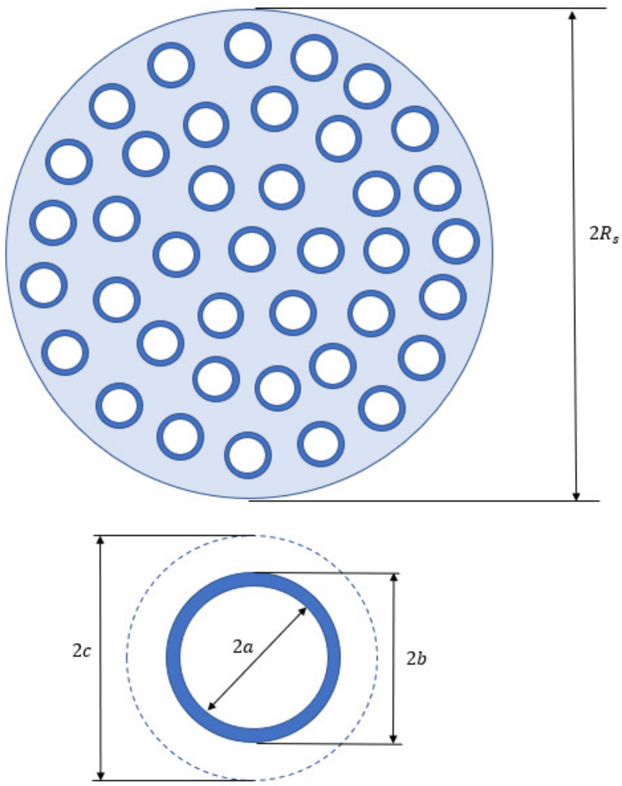



Figure 4. Shell cross section (top) and equivalent channel (bottom).

important variables are the radial mass and heat fluxes crossing the membrane. The subscripts $ms$ and $ml$ are used to indicate variables at the shell-membrane and lumen-membrane interfaces, respectively. Thus, the radial mass fluxes at the membrane surfaces are denoted by $G_{ml}$ and $G_{ms}$ and the radial heat fluxes at the membrane surfaces are represented by $q''_{ml}$ and $q''_{ms}$.

As shown in (De Sampaio, 2022), analytical solutions of the mass and heat transfer across the membrane are combined with finite volume discretized equations describing heat and mass conservation for the feed and permeate streams. Both countercurrent and cocurrent configurations of the feed and permeate streams are considered. All variables characterizing the DCMD operation are connected, either directly or indirectly. The radial mass fluxes across the membrane depend on the temperatures at the membrane walls, $T_{ml}$ and $T_{ms}$. These, in their turn, and together with the heat fluxes $q''_{ml}$ and $q''_{ms}$, depend on the radial mass fluxes and on the temperatures in both lumen and shell. Finally, the temperatures $T_l$ and $T_s$, together with the axial mass fluxes $G_l$ and $G_s$, depend on the radial mass and heat fluxes. In order to tackle this coupled and non linear problem, DESAL-PLANT employs an iterative solution strategy for updating all relevant variables, starting from a initial guessed solution.

A detailed presentation of the modelling and iterative solution methods employed in the DESAL-PLANT program can be seen in (De Sampaio, 2022). DESAL-PLANT was tested in order to compare its predictions with the experimental results presented in (Schofield, 1989) and in (Wang *et al.*, 2008). As shown in (De Sampaio, 2022), good agreement was obtained for both sets of data.

Given the characteristics of the DCMD module (dimensions, materials, number of hollow fibres) and the DCMD module operational conditions (temperatures, flowrates), DESAL-PLANT determines the number of DCMD modules required to meet the external heating available and the amount of freshwater produced by the desalination plant. The DESAL-PLANT program also determines the pressure drop for both lumen and shell and, from there, the pumping power needed for circulating both feed and permeate inside the DCMD modules.

## 4. PERFORMANCE OF THE COGENERATION SYSTEM

In this section we evaluate the performance of the cogeneration system comprising the small PWR of 75 MW(th) and the hybrid desalination arrangement involving the SWRO and the DCMD desalination plants. As mentioned previously, the simplest hybrid configuration is considered, where the DCMD and the SWRO plants operate independently.

We deal first with the DCMD plant with heat recovery and the coupling strategy described in section 2.1. Employing DE-TOP and DESAL-PLANT, we obtain the freshwater production of the DCMD plant ($m^3/day$) and also the electric power loss due to pumping and due to the coupling between the DCMD plant and the small PWR. After obtaining the electric power loss and the freshwater production, the specific electricity consumption of the DCMD plant (kW(e)h/m$^3$) can be determined.

Here we consider a blend of equal parts of the freshwater produced by the DCMD and the SWRO plants. Thus, the SWRO plant is dimensioned in such a way that its freshwater production equals that of the DCMD plant. The electric power demand of the SWRO plant is obtained using the specific electricity consumption of 4 kW(e)h/m$^3$, which is a value typical of a real-scale commercial SWRO plant, including pre and post-treatment processes (Kim *et al.*, 2019).

### 4.1 Performance of the DCMD plant

As mentioned in section 2.2, cycle (a), shown in Fig. 2, operates at pressures and temperatures that are typical of a Rankine cycle optimized for electricity generation. Thus, pressures and temperatures of cycle (a) are chosen to be the same as those of the reference small PWR of 75 MW(th) presented in Fig. 3. In particular, condenser $C_a$ operates at the pressure of 0.063 bar (steam condensation at 37 °C). The feed enters condenser $C_a$ at 26 °C, the mean temperature of the seawater at the Brazilian northeast, and is heated up to $T_{f-HX-in}$ = 32 °C, an increase of $\Delta T_a$ = 6 °C, before it enters the recovery heat exchanger HX.

Using DESAL-PLANT, the DCMD desalination plant is dimensioned such that the temperature of the feed leaving HX will be 87.9 °C. Note that this is also the temperature of the feed as it enters condenser $C_b$, where its temperature is elevated to 92 °C, an increase of $\Delta T_b$ = 4.1 °C, before the feed finally enters the DCMD modules. Note, though, that as we have risen the pressure of condenser $C_b$ to 0.911 bar, we must adjust the pressures of the regenerative heaters accordingly. This is accomplished using the DE-TOP program to set the pressures of regenerative heaters numbers #1,#2 and #3 to 1.40 bar, 2.20 bar and 3.25 bar, respectively.

A question now arises on how to split the total thermal power available in the steam generator (SG) between the Rankine cycles (a) and (b) i.e., how much steam from the SG should go to each parallel Rankine cycle? Here we pursue a strategy aimed to use all the power plant waste heat.

Let $\dot{Q}_{SG}$ be the total thermal power available in the SG and $\dot{Q}_a$ and $\dot{Q}_b$ represent the thermal power delivered to cycles (a) and (b), respectively. We can also define the parameters $\gamma_a = \dot{Q}_a/\dot{Q}_{SG}$ and $\gamma_b = \dot{Q}_b/\dot{Q}_{SG}$ denoting the fractions of the total thermal power that go to the respective cycles. Note that because $\dot{Q}_{SG} = \dot{Q}_a + \dot{Q}_b$ we have $\gamma_a + \gamma_b = 1$. We can also represent the heat rejected in condensers $C_a$ and $C_b$ as $\dot{Q}_{ca}$ and $\dot{Q}_{cb}$, respectively. These are fractions of the heat received from the SG by each Rankine cycle and can be written as $\dot{Q}_{ca} = r_a\dot{Q}_a$ and $\dot{Q}_{cb} = r_b\dot{Q}_b$, where $r_a < 1$ and $r_b < 1$. Note that $r_a$ and $r_b$ depend only on the thermodynamic conditions of each respective cycle. In our application, for instance, we have $r_a < r_b$. This is because cycle (a), which is optimised for electricity generation, has a higher thermodynamic efficiency than cycle (b). Thus, proportionally less heat is rejected in condenser $C_a$ than in condenser $C_b$, which we set to operate at a higher pressure to provide heat at a higher temperature to the feed. On the other hand, referring to Fig. 2 and considering that the feed flowrate is $\dot{M}_f$, the heat transferred to the feed in condenser $C_a$ can also be written as $\dot{Q}_{ca} = \dot{M}_f c_{ps}\Delta T_a$, where $c_{ps}$ is the specific heat at constant pressure of the seawater and $\Delta T_a$ is the temperature rise of the seawater in condenser $C_a$. Similarly, the heat transferred to the feed in condenser $C_b$ can also be written as $\dot{Q}_{cb} = \dot{M}_f c_{ps}\Delta T_b$, where $\Delta T_b$ is the temperature rise of the seawater in condenser $C_b$. Thus, in view of the discussion above, we can write

$$\dot{Q}_{ca} = r_a\dot{Q}_a = \dot{M}_f c_{ps}\Delta T_a \tag{1}$$

and

$$\dot{Q}_{cb} = r_b\dot{Q}_b = \dot{M}_f c_{ps}\Delta T_b \tag{2}$$

Using Eq. (1) and Eq. (2) we can write the following ratio

$$\frac{\dot{Q}_a}{\dot{Q}_b} = \frac{\gamma_a}{\gamma_b} = \frac{r_b\Delta T_a}{r_a\Delta T_b} \tag{3}$$

Thus, using Eq. (3) and the fact that $\gamma_a + \gamma_b = 1$, we obtain $\gamma_a = r_b\Delta T_a/(r_a\Delta T_b + r_b\Delta T_a)$ and $\gamma_b = r_a\Delta T_b/(r_a\Delta T_b + r_b\Delta T_a)$. For the Rankine cycles considered here we have $r_a$ = 0.6363, $r_b$ = 0.7333, $\Delta T_a$ = 6 °C and $\Delta T_b$ = 4.1 °C. Therefore, using these data, we calculate $\gamma_a$ = 0.62779 and $\gamma_b$ = 0.37221. As the total thermal power is 75 MW(th), cycles (a) and (b) will receive $\dot{Q}_a$ = 47.08 MW(th) and $\dot{Q}_b$ =27.92 MW(th), respectively. The heat delivered to the desalination plant by condensers $C_a$ and $C_b$ are obtained using Eq. (1) and Eq. (2), respectively. They are $\dot{Q}_{ca}$ = 29.95 MW(th) and $\dot{Q}_{cb}$ = 20.48 MW(th). These values of $\dot{Q}_{ca}$ and $\dot{Q}_{cb}$ are used in DE-TOP to simulate Rankine cycles (a) and (b), respectively.

Table 1 summarises the most relevant data concerning the two parallel Rankine cycles and Figure 5 exemplifies the DE-TOP simulation results for cycle (b). The attentive reader will notice a small difference between the condenser cooling mass flowrate shown in Fig. 5 and the value of 1.25 ton/s presented in Tab. 1. This is because, when calculating the feed

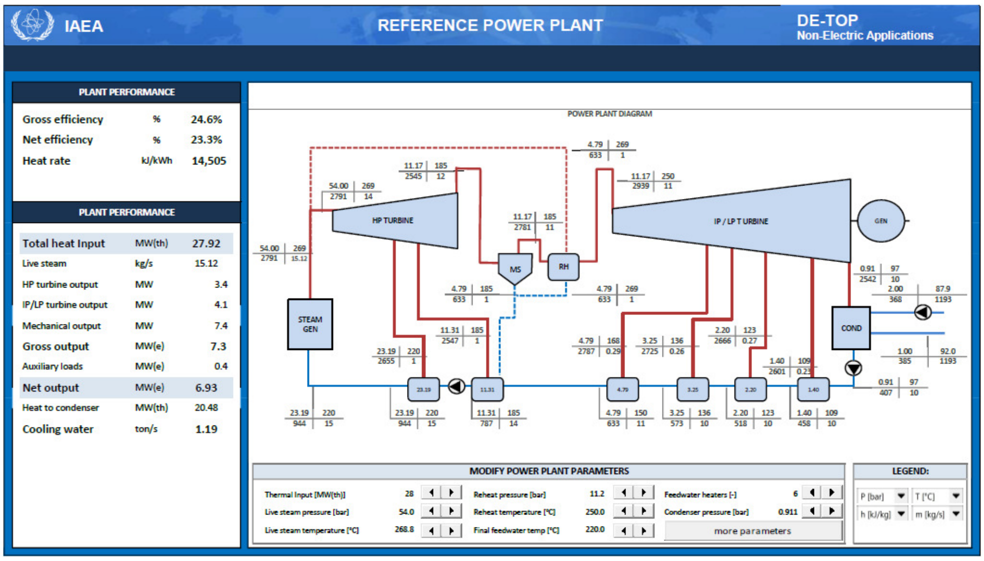



Figure 5. DE-TOP schematic representation of cycle (b) with 27.92 MW(th).

Table 1. Parallel Rankine cycles data.

| | Cycle (a) | Cycle (b) |
|---|---|---|
| Thermal power (MW(th)) | 47.08 | 27.92 |
| Net electric power (MW(e)) | 15.95 | 6.93 |
| Heat to condenser (MW(th)) | 29.95 | 20.48 |
| Feed temperature rise in condenser (°C) | 6.0 | 4.1 |
| Feed mass flowrate (ton/s) | 1.25 | 1.25 |

mass flowrate from Eq. (1) or Eq. (2), we used $c_{ps} = 3.997$ kJ/Kg.K, to ensure compatibility with the seawater properties employed in DESAL-PLANT. On the other hand, DE-TOP models the condenser cooling fluid as pure water.

Now that we have determined the heating power delivered to the desalination plant by condenser $C_b$ i.e., $\dot{Q}_{cb} = 20.48$ MW(th), we can run DESAL-PLANT to determine the number of parallel DCMD modules and the freshwater production of the DCMD plant. The performance of the DCMD plant with heat recovery depends on operational factors, such as temperatures and flowrates of both feed (seawater) and permeate, and also on the DCMD module characteristics such as dimensions, number of hollow fibres per module, membrane material, porosity, etc.

The membrane material considered here is Polyvinylidene Fluoride (PVDF). We consider that the feed and the permeate are in countercurrent flow and that the feed runs in the shell side. Figure 6 presents the input data used in DESAL-PLANT. The discretisation adopted comprises 20 finite volumes. This number of finite volumes proved adequate as no appreciable changes in the numerical results were observed using more refinement. The computation with the data shown in Fig. 6 took just a few seconds to converge running in a notebook with processor Intel(R) Core(TM) i7.

The results of the simulation using DESAL-PLANT are shown in Figure 7. In particular, the temperature of the feed leaving the recovery heat exchanger HX reaches 87.9 °C, as required. It is important to note that most of the heat transferred from the feed to the permeate in the DCMD modules is reused to pre-heat the feed in HX, the recovery heat exchanger. Indeed, as shown in Figure 7, the pre-heating in the HX per module is 38.16 kW whilst the heat transferred from the feed to permeate is 42.40 kW per module, thus a heat recovery index of 90 %. The mass recovery rate i.e., the fraction of the feed flowrate that is distilled across the membranes, is 7 %.

A total of 7289 DCMD modules is required to meet the available heating power of 20.48 MW(th). The freshwater production is 315.7 $m^3/h$ or 7577 $m^3/day$. The main price paid for this freshwater output was the reduction of electricity production from 25.41 MW(e) (reference plant) to 22.88 MW(e) (15.95 MW(e) from cycle (a) plus 6.93 MW(e) from cycle (b)), thus a loss of 2.53 MW(e). The pumping power required to circulate both feed and permeate inside the DCMD modules should also be added to the electricity cost. As shown in Fig. 6, the pumping power computed by DESAL-PLANT (assuming a pump efficiency of 0.85) is 0.14431 MW(e), and thus the net electricity production drops to 22.74 MW(e). Therefore, we have a specific electricity consumption of 8.01 kW(e)h/$m^3$ due to the loss of electricity production plus 0.46 kW(e)h/$m^3$ due to pumping, totalling 8.47 kW(e)h/$m^3$.

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THE INPUT DATA:

Heat Rate Input from Power Plant (MW)          =     20.48000
HX_Permeate_out_temperature (C)                =     34.00000
Sea_water_temperature (C)                      =     32.00000
************************************
Data for desalination_module
************************************
No. of fibers per module  =        2150
Shell (ID) (cm)           =     5.00000
Length of fibers (cm)     =   500.00000
Fiber(ID) (micro_m)       =   600.00000
Fiber(OD) (micro_m)       =   820.00000
Pore diameter (micro_m)   =     0.16500
Membrane porosity         =     0.73800
Inlet feed flow (l/min)   =    10.00000
Inlet perm. flow (l/min)  =     9.15600
Inlet feed temp. (C)      =    92.00000
Inlet perm. temp. (C)     =    30.00000
Countercurrent?  (yes=1)  =           1
Feed in Shell?   (yes=1)  =           1
Feed Water (Sea Water=1, Fresh Water=2)        =            1
Membrane Material (PTFE=1,PVDF=2,PP=3,UFRJ=4) =            2
************************************
Data for Numerical Model
************************************
Number of Finite Volumes  =          20
Relaxation Parameter      =     0.50000
```

Figure 6. Data input for DESAL-PLANT.

```
------------------------------------------------
HEAT EXCHANGER TEMPERATURES
THX_FEED_IN  (C) =    32.00000
THX_FEED_OUT (C) =    87.88541
THX_PERM_IN  (C) =    89.72542
THX_PERM_OUT (C) =    34.00000
------------------------------------------------
Distilled water production per module (l/h)  =     43.31150
Membrane area(facing feed) per module (m2)   =     27.69314
Heat transferred in DCMD per module   (kW)   =     42.40014
Pre_Heating in HX per module          (kW)   =     38.15972
Heating from Power Plant per module   (kW)   =      2.80953
Pumping Power per module              (kW)   =      0.01980
Energy consumption per m3           (kWh/m3) =     64.86791
Specific Thermal Energy Consumption (kJ/kg)  =    234.93408
Thermal Efficiency                    ( - )  =      0.66416
Gained Output Ratio (GOR)             ( - )  =     10.02315
Mechanical Gained Output Ratio (MGOR) ( - )  =   1422.34452
Feed Recovery Fraction                ( % )  =      7.00026
Maximum Feed Recovery Fraction        ( % )  =      7.23415
Maximum Max Feed Recovery Fraction    ( % )  =     11.08852

****************************************************************
NUMBER OF MODULES =         7289
TOTAL MEMBRANE AREA (FACING FEED)(m2)    = 201855.29193
TOTAL FEED FLOWRATE               (ton/s)=      1.24520
TOTAL DISTILLED WATER PRODUCTION (m3/h) =     315.69751
TOTAL PRE HEATING IN HX          (MW)   =     278.14623
TOTAL HEATING FROM POWER PLANT   (MW)   =      20.47864
PUMPING POWER FOR ALL MODULES    (MW)   =       0.14431
****************************************************************

Number of Iterations:       33145
Convergence Residual: 0.99968E-12
```

Figure 7. DESAL-PLANT output.

### 4.2 Freshwater and electric power outputs of the cogeneration system

In this work we consider a blend of equal parts of the freshwater produced by the DCMD and the SWRO plants. Therefore, as the DCMD plant produces 7577 $m^3/day$ of freshwater, the SWRO plant must match that output, and the overall freshwater production of the hybrid desalination arrangement will reach 15154 $m^3/day$.

The electric power needed by the SWRO plant to produce the required 7577 $m^3/day$ i.e., 315.7 $m^3/h$, is estimated using the specific electricity consumption of 4 $kW(e)h/m^3$, which is a value typical of a real-scale commercial SWRO plant, including pre and post-treatment processes (Kim *et al.*, 2019). Therefore, the SWRO plant will consume 1.2628 MW(e) that must be provided by the nuclear power plant. As a result, the electricity output of the cogeneration system drops from 22.74 MW(e) (when we have DCMD only) to 21.48 MW(e). Thus, compared to the reference power plant shown in Fig. 3, which produces 25.41 MW(e), we have a total loss of 3.93 MW(e). This is the cost paid by the cogeneration system to produce 15154 $m^3/day$ (631.4 $m^3/h$). Table 2 summarises the electric power and freshwater outputs of the cogeneration system comprising a small PWR of 75 MW(th) and the DCMD and SWRO desalination plants. The overall specific electricity consumption of the hybrid DCMD + SWRO arrangement is 6.235 $kW(e)h/m^3$.

Table 2. Cogeneration system electric power and freshwater production

| | |
|---|---|
| Electric power output | 21.48 MW(e) |
| DCMD freshwater output | 7577 $m^3/day$ |
| SWRO freshwater output | 7577 $m^3/day$ |
| Hybrid (DCMD+SWRO) freshwater output | 15154 $m^3/day$ |

## 5. CONCLUDING REMARKS

In this work we studied a nuclear cogeneration system for the production of electricity and freshwater through desalination. The system comprises a small PWR of 75 MW(th) and a hybrid desalination arrangement involving a Direct Contact Membrane Distillation (DCMD) plant with heat recovery and a Sea Water Reverse Osmosis (SWRO) desalination plant. The small PWR provides the heat and the electrical power required by both desalination plants, besides generating electricity for either the grid or local use.

We consider the simplest nuclear hybrid desalination solution, where the DCMD and the SWRO desalination plants operate independently. It is important to stress that blending the water produced by SWRO with that produced by DCMD has two main advantages. One is the improvement of the quality of the water produced, as compared to that obtained with the SWRO plant. The other is the reduction of the cost of water production, as compared to that attained by the DCMD plant alone (Sadeghi *et al.*, 2020).

The coupling between the small PWR and the SWRO plant is exclusively through the electrical power generated and provided by the small PWR on site. Thus, all the electricity needed by the SWRO system, especially the power required to operate high pressure pumps, is provided by the nuclear power plant. On the other hand, to provide heat to the DCMD plant, the steam produced in the steam generator is divided into two parallel Rankine cycles, a strategy devised to use all the power plant waste heat.

The DCMD plant with heat recovery presented here attained a heat recovery ratio of 90 % and the specific electricity consumption as low as 8.47 $kW(e)h/m^3$, which is a quite good performance for a thermal desalination process. We consider a blend of equal parts of the freshwater produced by the DCMD and the SWRO plants. In order to determine the electricity demand of the SWRO plant we assumed a specific electricity consumption of 4 $kW(e)h/m^3$, which is a value typical of a real-scale commercial SWRO plant, including pre and post-treatment processes (Kim *et al.*, 2019).

In our computer simulations, using the programs DE-TOP and DESAL-PLANT, we assumed the seawater temperature of 26°C, which is the mean temperature of the seawater at the Brazilian northeast. These simulations indicate that the cogeneration system studied here can deliver 21.48 MW(e) of electricity, simultaneously with 15154 $m^3/day$ of freshwater, with a specific electricity consumption of 6.235 $kW(e)h/m^3$.

## 6. ACKNOWLEDGEMENTS

This work has the support of FINEP No. 000298/16 and CAPES-PROCAD-DEFESA No. 88887.387824/2019-00.

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