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COGENERATION OF ELECTRICITY AND WATER USING A SMALL PWR OF 75 MW(th) COUPLED TO A DCMD DESALINATION SYSTEM WITH HEAT RECOVERY

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Abstract. *Desalination technologies can help mitigating the water scarcity problem facing humankind. In this work we consider the use of a small PWR of 75 MW(th) for cogeneration of water and electricity. The nuclear power plant is coupled to a Direct Contact Membrane Distillation (DCMD) desalination plant with heat recovery. Part of the external heat used in the desalination process is waste heat from the power plant, as the desalination plant collects warm seawater from the power plant condenser instead of taking water directly from the sea. The program DE-TOP of the International Atomic Energy Agency (IAEA) is used to simulate the secondary system of the small PWR. Steam extractions, taken at the low pressure turbine, provide the additional heating required by the DCMD desalination plant. The performance of the desalination plant is simulated using the DESAL-PLANT program, developed at IEN/CNEN, which adopts a multiscale approach to model the mass and heat transfer from the feed to the permeate. It is shown that a 75 MW(th) nuclear plant can provide simultaneously 24.80 MW(e) of electricity and 1502.4 m³/day of fresh water, compared with the 25.41 MW(e) production of the reference nuclear power plant dedicated exclusively to electricity production.*

Keywords: *small PWR, cogeneration, nuclear desalination, direct contact membrane distillation*

1. INTRODUCTION

Fresh water scarcity is a concerning issue in a world facing rapidly growing population (UN, 2018). The development of desalination technologies can help to mitigate the problem by means of producing fresh water from seawater (Kucera, 2014). Multistage Flashing (MSF), Multi-Effect Distillation (MED) and Reverse Osmosis (RO) are the most employed technologies for desalination. 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; Alkudhiri *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 RO 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).

As far as the use of nuclear reactors for desalination is concerned, the global nuclear desalination accumulated experience exceeds 250 reactor years (IAEA, 2017). Not surprisingly, the desalination technologies adopted in nuclear cogeneration plants worldwide are the conventional techniques: Multistage Flashing (MSF), Multi-Effect Distillation (MED) and Reverse Osmosis (RO). It is also worth mentioning that, in general, only a small fraction of the thermal energy generated by the reactors is used for producing fresh water through desalination in present day nuclear cogeneration plants.

This work proposes to innovate in nuclear desalination by adopting MD technology. More specifically, we consider the use of a small PWR of 75 MW(th) for cogeneration of water and electricity, where the nuclear power plant is coupled to a Direct Contact Membrane Distillation (DCMD) desalination plant with heat recovery. Part of the external heat used in the desalination process is waste heat from the power plant, as the desalination plant collects warm seawater from the power

plant condenser instead of taking water directly from the sea. The program DE-TOP of the International Atomic Energy Agency (IAEA) is used to simulate the Rankine cycle of the small PWR (Sánchez-Cervera *et al.*, 2013). Furthermore, DE-TOP also allows the selection of the points of steam extraction from the nuclear power plant secondary system. These steam extractions, taken at the low pressure turbine, after the extracted steam has already done a substantial amount of mechanical work, provide the additional heating required by the DCMD desalination plant. On the other hand, the performance of the DCMD desalination plant is simulated using the DESAL-PLANT program developed at IEN/CNEN (De Sampaio, 2022) which determines the amount of fresh water produced.

The remainder of this work is organised as follows: The main features of the DESAL-PLANT program are discussed in section 2. In section 3 we present a brief description of the DE-TOP tool developed by the International Atomic Energy Agency (IAEA). The coupling of the small PWR of 75 MW(th) and the DCMD plant with heat recovery is presented in section 4. Finally, our concluding remarks are drawn in section 5.

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. A detailed presentation of the modelling and iterative solution methods employed in the DESAL-PLANT program can be seen in (De Sampaio, 2022). 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 computes the amount of fresh water produced by the desalination plant.

2.1 Modelling of the DCMD module

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 Γ 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 1 depicts the shell cross section and the equivalent channel.

DESAL-PLANT can deal both with cocurrent and countercurrent configurations for the feed and permeate flows. By default the permeate is assumed to occupy the interior of the hollow fibres (lumen) and the feed is assumed to flow in the shell. Nonetheless, the modelling also applies for the case of the hot feed flowing inside the fibres and the cold permeate flowing in the shell. In that case the heat and mass fluxes across the membranes will be negative.

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 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 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. Figure 2 illustrates the discretization adopted. It comprises N finite volumes and $N + 1$ nodes. The finite volumes are represented by $I = 1, N$

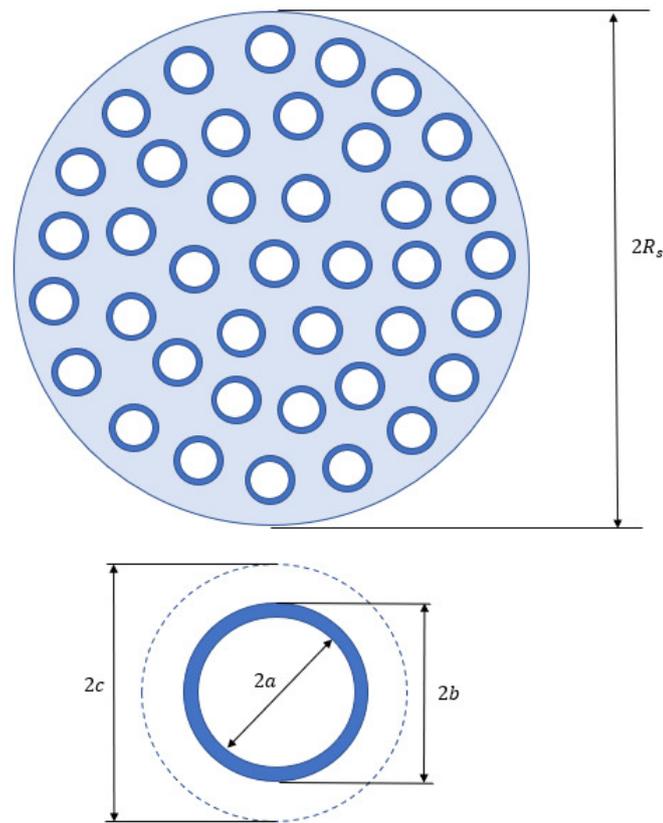


Figure 1. Shell cross section (top) and equivalent channel (bottom).

and the nodes by $i = 1, N + 1$. Finite volumes and nodes are numbered following the axial direction x . A general finite volume I has node i as its first node and node $i + 1$ as its second node. It is also important to locate where the variables are defined in the discretization. The radial mass fluxes, G_{ml} and G_{ms} , and the temperatures at the membrane walls, T_{ml} and T_{ms} , are cell centered i.e. defined at the center of each segment. On the other hand, the temperatures of the shell and lumen flows, T_s and T_l , and the axial mass fluxes, G_s and G_l , are defined on the nodes. These nodal values are used to set piecewise linear approximations for T_s , T_l , G_s and G_l (linear on each finite volume/segment). 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.

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.

2.2 DCMD desalination plant with heat recovery

A schematic representation of the DCMD desalination plant with heat recovery is shown in Fig. 3. Here we consider that the desalination plant is connected to a nuclear power plant and there is plenty of warm seawater, at temperature T_{SEA-in} , available from the nuclear power plant condenser (waste heat). As shown in Fig. 3, this warm seawater is used as feed for the desalination, thus reducing the energy required for the desalination process (Sadeghi *et al.*, 2020).

Referring to Fig. 3, the feed is preheated in the heat exchanger denoted as HX. The heating source in the HX is the hot permeate stream which gained heat in the desalination unit MD. The feed flowrate is \dot{M}_f . At the HX, heat is transferred from the permeate to the feed at the rate \dot{Q}_{HX} . The feed temperature rises from T_{SEA-in} , at the inlet, to T_{f-HX} , at the exit of the HX. The external heat source further heats the feed stream (with heating power \dot{Q}_H) up to T_{f-in} . Thus, the feed, with flowrate \dot{M}_f , enters the desalination unit MD at temperature T_{f-in} . Note that the external heating \dot{Q}_H is provided by the steam extracted from the secondary system of the nuclear power plant. However, in order to avoid the risk of radioactive contamination of the desalination process, an isolation loop is placed between the extracted steam and the desalination plant (Sánchez-Cervera *et al.*, 2013).

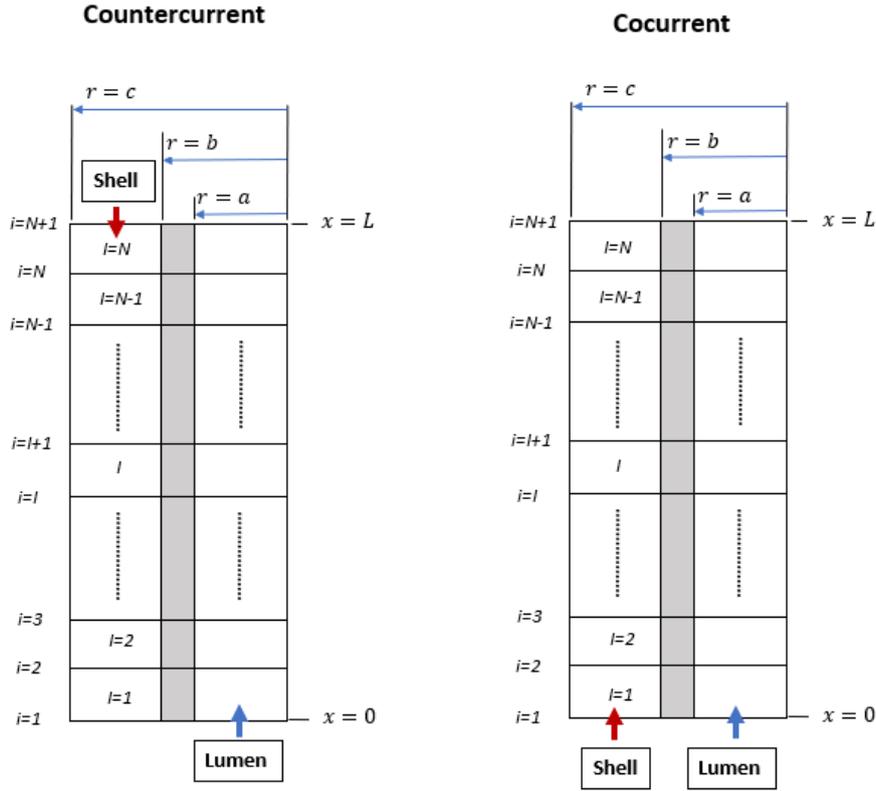


Figure 2. Discretisation: Finite volumes and nodes.

The desalination unit MD comprises n_m identical modules, each with n_f hollow fibres. The DCMD modules operate in countercurrent mode for, in such case, less membrane area is required for the same duty than in cocurrent mode. As shown in Fig. 3, the permeate enters the MD with flowrate \dot{M}_p and temperature T_{p-in} . Mass and energy are transferred from the feed to the permeate, through the membranes of the MD unit, at rates \dot{M}_{MD} and \dot{Q}_{MD} , respectively. The feed stream leaves the MD unit as brine with flowrate $\dot{M}_f - \dot{M}_{MD}$ and temperature T_{f-out} . Depending on its temperature and salinity, the brine can be directly discharged to the sea. With a single pass of the feed through the MD unit, as considered here, the resulting brine concentration will not be high. Indeed, with a maximum expected single pass recovery rate of 0.07, and seawater salinity of 35 g/Kg, the brine concentration will be limited to 38 g/Kg and its direct discharge to the sea is not likely to harm the environment. However, the temperature of the feed should be decreased enough inside the MD unit, so that T_{f-out} is sufficiently low, both for environmental and thermal efficiency reasons.

The permeate leaves the MD unit at temperature T_{p-out} and flowrate $\dot{M}_p + \dot{M}_{MD}$. From there it goes to the heat exchanger HX where, as previously mentioned, it will preheat the feed stream. After transferring heat to the feed, the permeate leaves the HX at the temperature T_{p-HX} . The temperature T_{p-HX} , always higher than T_{SEA-in} , should be as low as feasibly possible in order to maximize the preheating of the feed stream. Ideally, it should be just above the temperature of the permeate inside the cooling tank depicted in Fig. 3 and also close to T_{p-in} , the temperature of the feed as it enters the MD unit. If that is the case, there will be no need for active cooling of the cooling tank, as it will naturally lose the excess heat \dot{Q}_C to the environment.

2.3 Metrics for evaluating the desalination plant performance

The heat transferred across the membranes is \dot{Q}_{MD} . However, only part of this heat is associated with the distillation process. The remaining part crosses the membranes through heat conduction and it is considered as energy loss. The thermal efficiency η_{th} is defined as the fraction of \dot{Q}_{MD} which is effectively used for producing the distillate at the rate \dot{M}_{MD} . Thus, it is written as

$$\eta_{th} = \dot{M}_{MD} \bar{H}_{LV} / \dot{Q}_{MD} \quad (1)$$

where \bar{H}_{LV} is the mean latent heat of evaporation of the desalination unit MD. It is evaluated at the mean MD unit temperature $T_{mean} = (T_{f-in} + T_{p-in})/2$.

Another important metric is the gained output ratio (GOR). It is the ratio between the heating used for the distillation

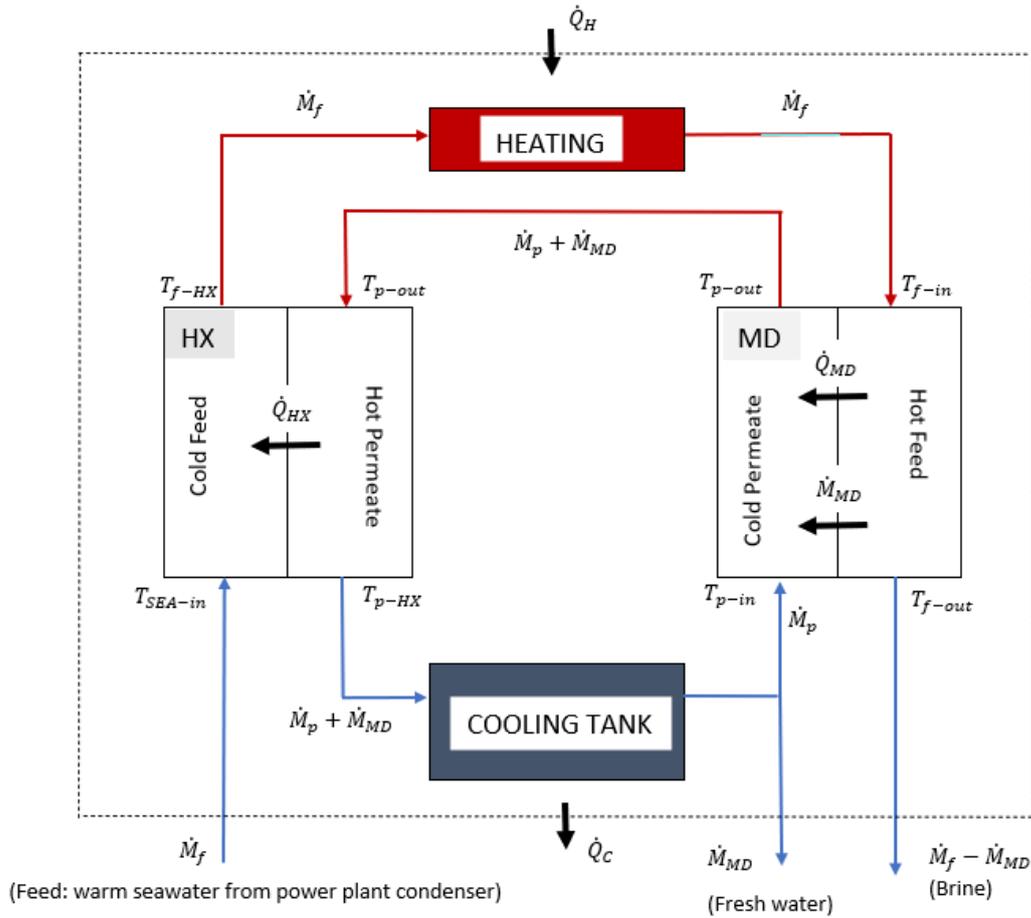


Figure 3. DCMD desalination plant with heat recovery.

and the external heating power \dot{Q}_H . The gained output ratio is given by

$$GOR = \dot{M}_{MD} \bar{H}_{LV} / \dot{Q}_H = \eta_{th} \dot{Q}_{MD} / \dot{Q}_H \quad (2)$$

The specific thermal energy consumption (SEC_{th}) represents the thermal energy consumed to produce a unit mass of distillate. It is defined as

$$SEC_{th} = \dot{Q}_H / \dot{M}_{MD} = \bar{H}_{LV} / GOR \quad (3)$$

Another useful parameter is the mass recovery rate R_{rec} . It expresses the fraction of the feed flowrate \dot{M}_f which is distilled and transferred to the permeate side,

$$R_{rec} = \dot{M}_{MD} / \dot{M}_f \quad (4)$$

References (Guan *et al.*, 2015; Christie *et al.*, 2020; Lin *et al.*, 2014) have identified the ratio between the permeate and feed mass flowrates, $\alpha = \dot{m}_p / \dot{m}_f$, as the most influential operational factor affecting GOR . If the permeate mass flowrate is too low with respect to the feed mass flowrate, the permeate quickly warms up inside the DCMD module, eventually cancelling the driving force for mass transfer, which depends on having the permeate sufficiently cooler than the feed. This is called *Permeate Limiting Regime* (PLR) operation (Lin *et al.*, 2014). Conversely, if the feed mass flowrate is too low with respect to the permeate mass flowrate, the feed quickly cools down inside the DCMD module. In such case, the driving force for mass transfer shrinks as the feed temperature quickly approximates the temperature of the permeate. This is the *Feed Limiting Regime* (FLR) operation (Lin *et al.*, 2014).

In (De Sampaio, 2022) it is shown that there is an optimal ratio α^* between the permeate and feed mass flowrates for which the mass recovery ratio R_{rec} is maximised. The optimal ratio α^* depends on the specific heats of both feed and permeate, on the latent heat of vaporisation and on the thermal efficiency of the heat transfer across the membrane η_{th} .

3. 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 according to fundamental thermodynamic models (El-Wakil, 2002; Teyssedou *et al.*, 2010; Medina-Flores and Picon-Nunez, 2010). The thermodynamic properties of water and steam used in DE-TOP are based on the IAPWS-IF97 industrial formulation. Besides modelling the thermodynamic cycle, DE-TOP also models the coupling of the secondary loop of the PWR with a desalination plant. The desalination technologies included in DE-TOP are Multistage Flashing (MSF) and Multi-Effect Distillation (MED). Although in this work we focus on desalination, it is important to mention that DE-TOP can also be applied to District Heating.

DE-TOP has an intuitive graphical user interface and flexible system configuration. 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. The user is also able to select different coupling arrangements between power plant and the non-electric application (single steam extraction, multiple steam extraction, backpressure operation, etc.).

Figure 4 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. Referring to Fig. 4, note that steam produced by the steam generator is expanded in the high pressure (HP) turbine. Partial flows are extracted and delivered to feed the high pressure regenerative heater and the 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. Closing the cycle, the 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 heater. Note that, as shown in Fig. 4, DE-TOP presents pressure, temperature, enthalpy and mass flowrate at various points along the loop.

In the example shown in Fig. 4, we used the default values of DE-TOP for the following parameters: HP turbine efficiency 0.85, LP 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).

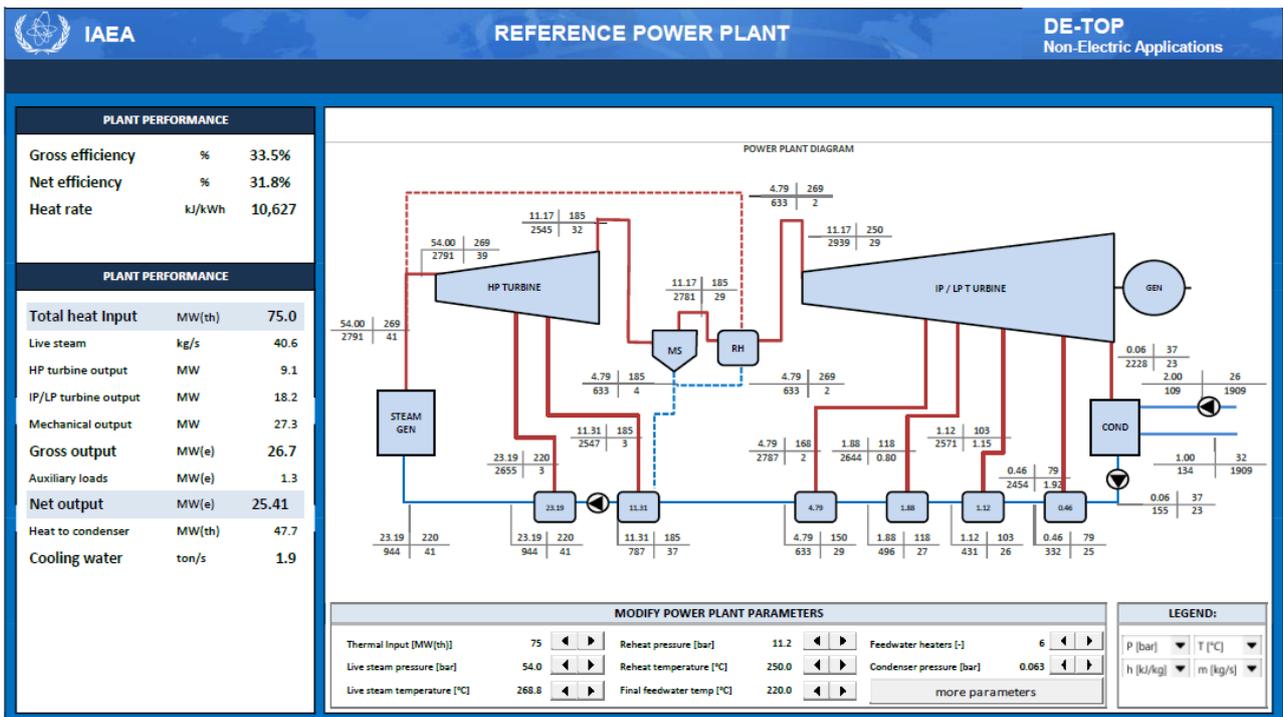


Figure 4. Reference plant with 75 MW(th) (regenerative Rankine cycle with reheat).

4. COUPLING OF THE SMALL PWR AND THE DCMD DESALINATION PLANT

Even though Membrane Distillation (MD) is not a desalination technology currently available in DE-TOP, it is possible to combine DE-TOP and DESAL-PLANT to model the coupling of the small PWR and the DCMD desalination plant. Indeed, DE-TOP can be used to select the points of steam extraction from the nuclear power plant secondary system. The external heating power required by the DCMD desalination plant (see Fig. 3) is provided by the extracted steam. It is important to remark that, in order to avoid the risk of radioactive contamination of the desalination process, an isolation loop is placed between the extracted steam and the desalination plant. Because of the isolation loop, the temperature at which heat is delivered to the desalination plant is lower than the temperature of the extracted steam. Here we set the minimum temperature difference between the steam and the desalination plant at 10.5 C, the same value used in DE-TOP applications involving MSF and MED technologies. Note that given the DCMD module characteristics and operation conditions, the DESAL-PLANT program can be used to determine the number of DCMD modules required to meet the available external heating power and the total production of fresh water of the DCMD desalination plant.

Regarding the desalination plant, the feed (seawater) at the inlet of the DCMD modules is set as $T_{f-in} = 92$ C. Thus, considering the minimum 10.5 C temperature drop in the isolation loop, the temperature of the extracted steam must be higher than 102.5 C. Figure 5 depicts the two extraction points considered for this application. The first extraction is 1.15 kg/s of steam at 1.12 bar and 103 C. The second extraction is 0.80 kg/s of steam at 1.88 bar and 118 C. As a result of the steam extractions, the electric power generated by the nuclear power plant is reduced to 24.80 MW(e) as compared with the 25.41 MW(e) generated by the reference nuclear power plant. The steam extractions, after delivering their latent heat to the isolation loop, return as condensate to the PWR secondary system at the points shown in blue in Fig. 5. In the present case, the heating power transferred to the isolation loop is 4.18 MW(th), which is also the heating power transferred to the desalination plant (assuming that heat losses at the isolation loop are negligible).

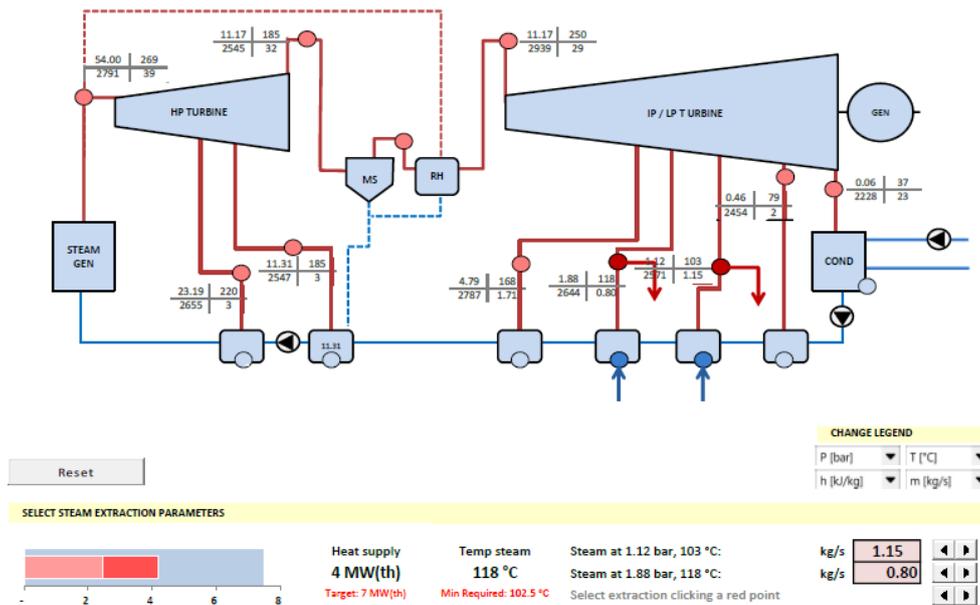


Figure 5. Steam extractions to provide heating for the DCMD desalination plant.

In this work we assume that seawater is at 26 C. However, the seawater used in the desalination plant is not taken directly from the sea. Rather, the feed in the desalination plant is taken from the warm seawater available at the exit of the nuclear power plant condenser, as shown in Fig. 3. As can be seen in Fig. 4, the warm seawater that leaves the condenser is at 32 C. Thus, regarding Fig. 3, we have $T_{SEA-in} = 32$ C. Still referring to Fig. 3, other relevant temperatures for the analysis of the desalination plant are the temperature of the permeate leaving the recovery heat exchanger, T_{p-HX} , and the temperature of the permeate as it enters the DCMD modules, T_{p-in} . Here we set $T_{p-HX} = 34$ C and $T_{p-in} = 30$ C.

Figure 6 shows the input data for DESAL-PLANT. Characteristics of the DCMD module such as number of hollow fibres, shell internal diameter, hollow fibres internal and external diameters and hollow fibres length can be seen in Fig. 6 which also indicates the membrane material and membrane properties such as porosity and mean pore diameter. In the present case the membrane material is Polyvinylidene fluoride (PVDF). The input data also specifies the countercurrent operation mode and that the feed (seawater) flows inside the shell. The volumetric flow rates of feed and permeate per module are specified in the input data presented in Fig. 6. They satisfy the optimal ratio between the permeate and feed mass flowrates defined in (De Sampaio, 2022). Completing the input data, the number of finite volumes and the relaxation parameter for the iterative solution procedure are specified.

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*****
Heat Rate Input from Power Plant (MW) = 4.18000 (1x,f12.5)
HX_Permeate_out_temperature (C) = 34.00000 (1x,f12.5)
Sea_water_temperature (C) = 32.00000 (1x,f12.5)
*****
Data for desalination_module
*****
No. of fibers per module = 2150 (1x,i12)
Shell (ID) (cm) = 5.00000 (1x,f12.5)
Length of fibers (cm) = 500.00000 (1x,f12.5)
Fiber(ID) (micro_m) = 600.00000 (1x,f12.5)
Fiber(OD) (micro_m) = 820.00000 (1x,f12.5)
Pore diameter (micro_m) = 0.16500 (1x,f12.5)
Membrane porosity = 0.73800 (1x,f12.5)
Inlet feed flow (l/min) = 10.00000 (1x,f12.5)
Inlet perm. flow (l/min) = 9.10400 (1x,f12.5)
Inlet feed temp. (C) = 92.00000 (1x,f12.5)
Inlet perm. temp. (C) = 30.00000 (1x,f12.5)
Countercurrent? (yes=1) = 1 (1x,i12)
Feed in Shell? (yes=1) = 1 (1x,i12)
Feed Water (Sea Water=1, Fresh Water=2) = 1 (1x,i12)
Membrane Material (PTFE=1,PVDF=2,PP=3,UFRJ=4) = 2 (1x,i12)
*****
Data for Numerical Model
*****
Number of Finite Volumes = 40 (1x,i12)
Relaxation Parameter = 0.50000 (1x,f12.5)

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Figure 6. Data input for DESAL-PLANT.

The discretisation used in the present analysis comprises 40 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 flows of feed and permeate are both laminar, with the feed Reynolds number varying between 150 and 396 along the length, and the permeate Reynolds number varying between 186 and 502 along the length. The heat transfer coefficients along the length are nearly the same on both sides of the membrane, varying between 4500 and 4900 W/m²K.

Figure 7 presents results of the analysis using DESAL-PLANT. Note that the mass recovery rate is 6.98 %. The number of DCMD modules required to meet the available external heating power of 4.18 MW(th) is $n_m = 1449$. The fresh water output amounts to 62.60 m³/h or 1502.40 m³/day. The price paid for this fresh water output was the reduction of electricity production from 25.41 MW(e) (reference plant) to 24.80 MW(e) (cogeneration plant). This is equivalent to a specific electricity consumption of 9.79 kW(e)h/m³ (electricity consumed in kW(e)h per m³ of produced fresh water).

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Distilled water production per module (l/h) = 43.20396
Membrane area(facing feed) per module (m2) = 27.69314
Heat transferred in DCMD per module (kW) = 42.30551
Pre_Heating in HX per module (kW) = 38.08375
Heating from Power Plant per module (kW) = 2.88550
Energy consumption per m3 (kWh/m3) = 66.78796
Specific Thermal Energy Consumption (kJ/kg) = 241.88799
Thermal Efficiency ( - ) = 0.66399
Gained Output Ratio (GOR) ( - ) = 9.73500
Feed Recovery Fraction ( % ) = 6.98288
Maximum Feed Recovery Fraction ( % ) = 7.23227
Maximum Max Feed Recovery Fraction ( % ) = 11.08852
*****
NUMBER OF MODULES = 1449
TOTAL MEMBRANE AREA (FACING FEED)(m2) = 40127.35876
TOTAL FEED FLOWRATE (kg/s) = 247.53750
TOTAL DISTILLED WATER PRODUCTION (m3/h) = 62.60254
TOTAL PRE HEATING IN HX (MW) = 55.18335
TOTAL HEATING FROM POWER PLANT (MW) = 4.18110
*****
Number of Iterations: 36937
Convergence Residual: 0.99996E-12

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Figure 7. DESAL-PLANT output.

It is interesting to compare the results from the DCMD desalination plant, obtained above, with analogous results from cogeneration with the same nuclear power plant but considering the alternative technologies of Multi-Effect Distillation (MED) and Multistage Flashing (MSF). As these desalination technologies are already available in DE-TOP the analysis using DE-TOP is straightforward. However, it should be noted that each technology has its own limitations on the maximum feed temperature. For MED the maximum feed temperature is in the range of 60 C to 75 C and for MSF this range is from 110 C to 115 C (Sánchez-Cervera *et al.*, 2013).

We recall that an isolation loop is used to avoid the risk of radioactive contamination of the desalination plant. Accounting for the temperature drop of 10.5 C in the isolation loop and considering the maximum feed temperature of 65 C, the minimum steam temperature required for the MED desalination plant is 75.5 C. Thus, the same steam extractions used in the MD example can be used for the MED desalination plant (see Fig. 5). Running DE-TOP we obtained a fresh water output of 56.58 m³/h or 1358 m³/day. The net electricity production of the cogeneration plant, with the same steam extractions as in the MD case, remains at 24.80 MW(e) as compared to the 25.41 MW(e) of the reference nuclear power plant. Therefore, for the MED desalination plant, the specific electricity consumption is 10.78 kW(e)h/m³.

For the MSF desalination plant we take the maximum feed temperature at 115 C. Thus, accounting for the isolation loop, the minimum steam temperature is 125.5 C and we cannot use the steam extractions shown in Fig. 5. For the MSF desalination plant we take a single steam extraction of 1.71 kg/s of steam at 4.79 bar and 168 C. The thermal energy transferred to the isolation loop and to the MSF desalination plant amounts to 3.78 MW(th). As a result of the steam extraction, the nuclear power plant electricity production drops to 24.63 MW(e) as compared to the 25.41 MW(e) of the reference nuclear power plant. Running DE-TOP we obtained for the MSF desalination plant a fresh water output of 60.75 m³/h or 1458 m³/day. Thus, the specific electricity consumption of the MSF desalination plant is 12.84 kW(e)h/m³.

Table 1 presents a comparison of the different desalination technologies considered in the present study. In particular, we observe that a DCMD desalination plant with heat recovery, and using waste heat from the nuclear power plant, can be a viable alternative to the conventional Multi-Effect Distillation (MED) and Multistage Flashing (MSF) technologies.

Table 1. Comparison of the desalination technologies.

DESALINATION TECHNOLOGY	FEED MAX. TEMP. (C)	SPEC. ELECTR. CONSUMP. (kW(e)h/m ³)
DCMD using Power Plant Waste Heat	92	9.79
Multi-Effect Distillation (MED)	65	10.78
Multistage Flashing (MSF)	115	12.84

5. CONCLUDING REMARKS

This work investigates the innovative coupling of a DCMD desalination plant with heat recovery with a small PWR of 75 MW(th) for cogeneration of water and electricity. Part of the external heat used in the desalination process is waste heat from the nuclear power plant, as the DCMD desalination plant collects warm seawater from the nuclear power plant condenser instead of taking water directly from the sea. The program DE-TOP of the International Atomic Energy Agency (IAEA) is used to simulate the regenerative Rankine cycle with reheat of the secondary system of the small PWR (Sánchez-Cervera *et al.*, 2013). Steam extractions, taken at the low pressure turbine, provide the additional heating required by the DCMD desalination plant. The performance of the DCMD desalination plant with heat recovery is simulated using the DESAL-PLANT program, developed at IEN/CNEN, which adopts a multiscale approach to model the mass and heat transfer from the feed to the permeate (De Sampaio, 2022). Our analysis indicates that a DCMD desalination plant with heat recovery, and using waste heat from the nuclear power plant, can be a viable alternative to the conventional Multi-Effect Distillation (MED) and Multistage Flashing (MSF) desalination technologies.

6. REFERENCES

- Alkudhiri, A., Darwish, N. and Hilal, N., 2012. "Membrane distillation: A comprehensive review". *Desalination*, Vol. 287, pp. 2–18.
- Christie, K.S.S., Horseman, T. and Lin, S., 2020. "Energy efficiency of membrane distillation: Simplified analysis, heat recovery, and the use of waste-heat". *Environment International*, Vol. 138, 105588.
- Cipollina, A., Sparti, M.G.D., Tamburini, A. and Micale, G., 2012. "Development of a Membrane Distillation module for solar energy seawater desalination". *Chemical Engineering Research and Design*, Vol. 90, pp. 2101–2121.
- De Sampaio, P.A.B., 2022. "Computational model and simulation of DCMD desalination systems with heat recovery". *Desalination*, Vol. 533, 115769.
- Dow, N., Gray, S., Li, J.D., Zhang, J., Ostarcevic, E., Liubinas, A., Atherton, P., Roeszler, G., Gibbs, A. and Duke, M., 2016. "Pilot trial of membrane distillation driven by low grade waste heat: membrane fouling and energy assessment".

- Desalination*, Vol. 391, pp. 30–42.
- El-Wakil, M.M., 2002. *Powerplant Technology*. McGraw-Hill Science.
- Evans III, R.B., Watson, G.M. and Mason, E.A., 1961. “Gaseous diffusion in porous media at uniform pressure”. *The Journal of Chemical Physics*, Vol. 35, No. 6, pp. 2076–2083.
- Fernández-Pineda, C., Izquierdo-Gil, M.A. and García-Payo, M.C., 2002. “Gas permeation and direct contact membrane distillation experiments and their analysis using different models”. *Journal of Membrane Science*, Vol. 198, pp. 33–49.
- Guan, G., Yang, X., Wang, R. and Fane, A.G., 2015. “Evaluation of heat utilization in membrane distillation desalination system integrated with heat recovery”. *Desalination*, Vol. 366, pp. 80–93.
- IAEA, 2017. *Opportunities for Cogeneration with Nuclear Energy*. Number NP-T-4.1 in Nuclear Energy Series. International Atomic Energy Agency, Vienna.
- Jansen, A.E., Assink, J.W., Hanemaaijer, J.H. and van Sonsbeek, E., 2013. “Development and pilot testing of full-scale membrane distillation modules for deployment of waste heat”. *Desalination*, Vol. 323, pp. 55–65.
- Kucera, J., ed., 2014. *Desalination*. John Wiley & Sons, Inc., New Jersey, USA.
- Lin, S., Yip, N.Y. and Elimelech, M., 2014. “Direct contact membrane distillation with heat recovery: Thermodynamic insights from module scale modeling”. *Journal of Membrane Science*, Vol. 453, pp. 498–515.
- Medina-Flores, J.M. and Picon-Nunez, M., 2010. “Modelling the power production of single and multiple extraction steam turbines”. *Chemical Engineering Science*, Vol. 65, p. 2811–2820.
- Sadeghi, K., Ghazaie, S.H., Sokolova, E., Fedorovich, E. and Shirani, A., 2020. “Comprehensive techno-economic analysis of integrated nuclear power plant equipped with various hybrid desalination systems”. *Desalination*, Vol. 493, 114623.
- Schofield, R.W., 1989. *Membrane Distillation*. Ph.D. thesis, University of New South Wales.
- Schofield, R.W., Fane, A.G. and Fell, C.J.D., 1987. “Heat and Mass Transfer in Membrane Distillation”. *Journal of Membrane Science*, Vol. 33, pp. 299–313.
- Sánchez-Cervera, I.G., Kavvadias, K.C. and Khamis, I., 2013. “DE-TOP: A new IAEA tool for the thermodynamic evaluation of nuclear desalination”. *Desalination*, Vol. 321, pp. 103–109.
- Teyssedou, A., Dipama, J., Hounkonnou, W. and Aube, F., 2010. “Modelling and optimization of a nuclear power plant secondary loop”. *Nuclear Engineering and Design*, Vol. 240, p. 1403–1416.
- UN, 2018. *Sustainable Development Goal 6 Synthesis Report 2018 on Water and Sanitation*. United Nations, New York.
- Wang, K.Y., Chung-Gil, T.S. and Gryta, M., 2008. “Hydrophobic PVDF hollow-fiber membranes with narrowpore size distribution and ultra-thin skin for the freshwater production through membrane distillation”. *Chemical Engineering Science*, Vol. 63, pp. 2587–2594.

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