PWR-TYPE SMALL MODULAR REACTOR FOR CO-GENERATION OF ELECTRICITY AND SEAWATER DESALINATION IN BRAZIL

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ABSTRACT

The growing demand for electricity, increasing fossil fuel prices, and global warming in Brazil, along with the lack of access to electricity in certain locations in the Northern Region, such as Rondônia, Pará, and Amazonas, are currently seeking solutions. In addition, Brazil has lost 15% of its water resources in 30 years, a loss of almost double the water surface of the entire Northeast. Researchers have conducted the feasibility of desalination technology coupled with a Small Modular Reactor (SMR). This paper analyzes the option of coupling Pressurized Water Reactor (PWR)-type SMR that have a power capacity of 52 MWth with desalinization technology in Brazil, considering the lack of electricity in residences and industries located in remote regions and for obtaining fresh water using seawater desalination. This study developed a computational model to simulate and sequentially optimize the performance of a nuclear desalination plant as a function of operating variables using Aspen Plus software. A chemical process flow diagram for this system is proposed and simulated using a CPS (Chemical Process Simulator) methodology. The Sankey diagram was used to represent the energy and mass balance flow. The Multi-Stage Flash (MSF) seawater desalination technology was adopted to couple with the SMR to produce fresh water. Thermodynamic analyses, including energy balances, exergy assessments, and efficiency, are performed in this work. The study concludes that the PWR-type SMRs offer energy-efficient solutions for the cogeneration of electricity and water in some special scenarios in Brazil. The comparison of the proposed desalination technology with the most practiced desalination plants shows that the optimum operating performance is obtained. It was verified that the proposed generic PWR-type SMR with 13,23 MWe can produce 14,69 kg/s of fresh water using MSF technology.

1. INTRODUCTION

According to the Brazilian National System for Water and Sanitation Data (in Portuguese, Sistema Nacional de Informações sobre Saneamento), SNIS 2022) [1], only 84.9% of the Brazilian population is currently supplied with drinking water. Brazil have the 12% of all fresh water in the world and it has not yet been possible to bring drinking water to the entire population, mainly in the North, which only has the worst percentage of 64,2 %. In the current Brazilian context, characterized by the urgent need to provide drinking water to the population and seek sustainable energy generation solutions, SMRs present themselves as a promising alternative.

The scientific literature contains numerous studies about the Nuclear Power Plant (NPP) coupled to desalinization plants, mainly in Kazakhstan, India, Japan, and the USA, but only a few studies can be found about the SMR coupled to desalinization [2]. Traditional desalinization requires fossil fuels or significant electricity from the grid. This contributes to a high carbon footprint, exacerbating climate change. It also contributes to local environmental impacts and carbon emissions. Desalinization with Small Modular Reactors (SMRs) has the potential to offer lower carbon emissions and provide a stable water supply immune to climatic fluctuations. In Brazil, the integration of a Pressurized Water Reactor (PWR)-type Small Modular Reactor (SMR) for co-generation offers a promising approach. This study explores the use of a PWR type microreactor to produce both electricity and desalinated water,

contributing to Brazil's energetic matrix diversification and addressing water scarcity issues, particularly in North regions.
SMR technology is well-suited to adapt their power output based on demand, which is crucial for combined power and desalination systems. In many coastal regions, the demand for electricity and water can fluctuate significantly throughout the day or between seasons. SMRs can adjust their power output dynamically to meet these varying needs. This technology effectively increases the total freshwater resources in coastal regions. Some of the SMR projects are being designed for seawater desalination [3], [4]. However, these studies require a thorough analysis of energy consumption, optimization of main components, exergy destruction rate, and efficiency.

This study presents a methodology for integrating a SMR with the Multi-Stage Flash (MSF) desalination process using the Aspen Plus software. The thermodynamic cycle of the PWR-type SMR is simulated to evaluate heat generation, steam production, and electricity output. The parameters of reactor such as core thermal power, steam pressure, and temperature are modeled to establish the thermal energy available for the desalination process. Utilizing Aspen Plus software, the thermodynamic performance of the reactor is simulated to evaluate its capability in producing energy efficiently. A fraction of the thermal energy generated by the SMR is extracted at the appropriate stage of the steam cycle for use in the MSF desalination process. It is necessary to ensure efficient energy transfer while maintaining sufficient steam for electricity generation.
The MSF desalination system is modeled in Aspen Plus, including the flash evaporation stages, condensers and mixers. The extracted thermal energy from the SMR is applied to heat seawater, causing it to evaporate and condense in successive stages, producing potable water. After that, the SMR and MSF models are integrated into a co-generation system within Aspen Plus. The system simulates the combined production of electricity and desalinated water, with energy flows balanced between power generation and thermal desalination processes.
Process Flow Diagrams (PFDs) is a methodology used to represent chemical processes graphically, which can be supported and modeled by Aspen Plus. The Aspen Plus provides the ability to model the equipment, streams, and interactions, and the results can be represented by PFDs. PFDs are simplified graphical representations of a process, showing the flow of materials and energy between the various units (nuclear reactors, heat exchangers, pumps, etc.) [5-9].
Lastly, simulation scenarios are run to optimize the system's performance. The analysis focuses on maximizing desalinated water output while maintaining efficient electricity production. The parameters such as steam extraction rate, water recovery, and overall system efficiency are evaluated under varying operating conditions.

This work focuses on the co-generation model's operational efficiency, examining its potential to provide both sustainable electricity and a reliable source of clean water in water-scarce regions of Brazil. The coupling of SMR and MSF Systems offers a viable and sustainable solution to meet Brazil's growing industrial and population demands.

2. METHODOLOGY

There are several technologies for the seawater desalination. In Brazil, the Fresh Water Program (in Portuguese, Programa de Água Doce, PAD) of the Ministry of the Environment (MMA) invests in desalination systems to provide quality water to low-income populations in semi-arid communities. The PAD serves the entire Northeast and north of Minas Gerais, where water availability is low, and groundwater salinity is high [10]. Multi-stage flash (MSF) distillation involves heating seawater and then directing it into a flash chamber. In this chamber, the pressure is kept lower than the vapor pressure of the heated seawater, causing the water to quickly turn into steam. This steam is then cooled down and condensed to produce the desired freshwater.

2.1 Desalinization technology

In a Multi-Stage Flash (MSF) system, seawater undergoes a process where it transforms into vapor through multiple stages operating at progressively lower pressures and temperatures, based on steam thermodynamics. Seawater is first preheated using heat exchangers. These heat exchangers typically use vapor extracted from turbine to warm the seawater to a temperature close to its boiling point and directing it through multi-stages flash evaporator with progressively lower pressures causing a portion of the water to flash (evaporate) into vapor. Subsequently, the produced vapor is collected and condensed on the exterior of seawater tubes within each stage, cooling to form fresh water (distilled water). The distilled water is efficiently collected through dedicated tubes for storage. As a result, the seawater entering the system undergoes gradual heating as it passes through tubes positioned across the upper sections of all evaporation stages. This process repeats until the brine reaches the designated operating temperature, known as the Maximum Brine Temperature (MBT), within the Brine Heater (see Fig. 2). Here, vapor extracted from one or more turbine stages is typically employed to further heat the seawater up to the MBT. Additionally, part of the discharged brine can be reintroduced by the Heat Rejection Stages into the incoming seawater stream for desalination, ensuring that only the remaining portion is discharged through the Brine Discharge line.

2.2 Nuclear reactor description

The operational parameters of PWR-type SMR are illustrated in Tab. 1.

Tab. 1. Operational parameters of an SMR power plant [8]

Parameter	**Value**
Thermal power	52 MWt
Electrical power	11 MWe
Primary pressure	13,10 MPa
Hot Leg temperature	558,08 K
Cold Leg temperature	537,95 K
Feed water flow rate	9,45 kg/s
Steam pressure	3,77 MPa
Steam temperature	519,15 K

The initial thermal power of nuclear reactor was optimized to 52 MWt. The model optimization process adopted the initial parameters of an SMR power plant.
The thermal energy output of the nuclear reactor serves as the primary energy source for the desalination process.

2.3 Proposed nuclear desalination plant

MSF technology is selected in this work because it is one of the most reliable thermal seawater desalination plants in the world. It is the only evaporator technology that strictly separates heat transfer and evaporation, minimizing the risk of scaling and greatly reducing maintenance costs. The integration between the nuclear reactor and desalination plant is performed using thermodynamic analyses through the Rankine cycle.

2.3.1 Computational model

Fig. 1 illustrates the integration of the seawater desalination process with a PWR type reactor power module. The energy generated by the Rankine cycle is delivered to the grid process while the MSF desalination is integrated using an intermediate heat exchanger before condenser. The turbine steam flow goes to a heat exchanger before the condenser, preheating the water before the desalination process.

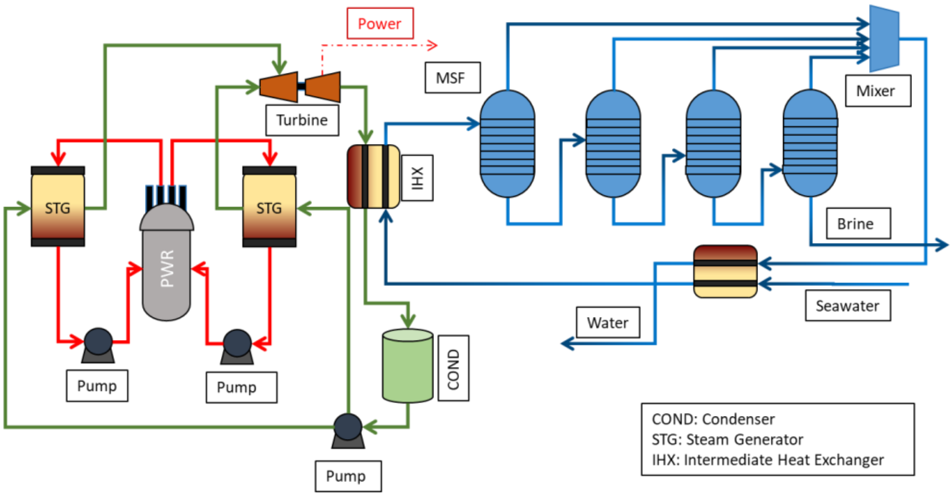

Fig. 1. Schematic representation of the coupling between PWR-type SMR of 52 MWth and the MSF technology.

The computational model presented in Fig. 2 was created in a Chemical Process Simulator (CPS) with SI Cycle [12] where some operation parameters optimization can be performed as well as the sizing of energy requirements for the main components of the flowsheet.

The desalination plant consists of 4 unit of Evaporator (FLASH), 1 Mixer and 2 Intermediate Heat Exchanger (IHX). The different stages of heating and condensation help to separate the water from the salt.

IHXs are used to transfer heat between different streams in the system. The mixer helps to adjust the temperature of the brine before it enters the evaporator stages. Proper mixing ensures that the brine reaches the desired temperature for efficient flashing. The number of flash stage is 4.

Combining the unit operations involved in the process and linking the material and energy streams a process flow diagram is developed, see Fig. 3.

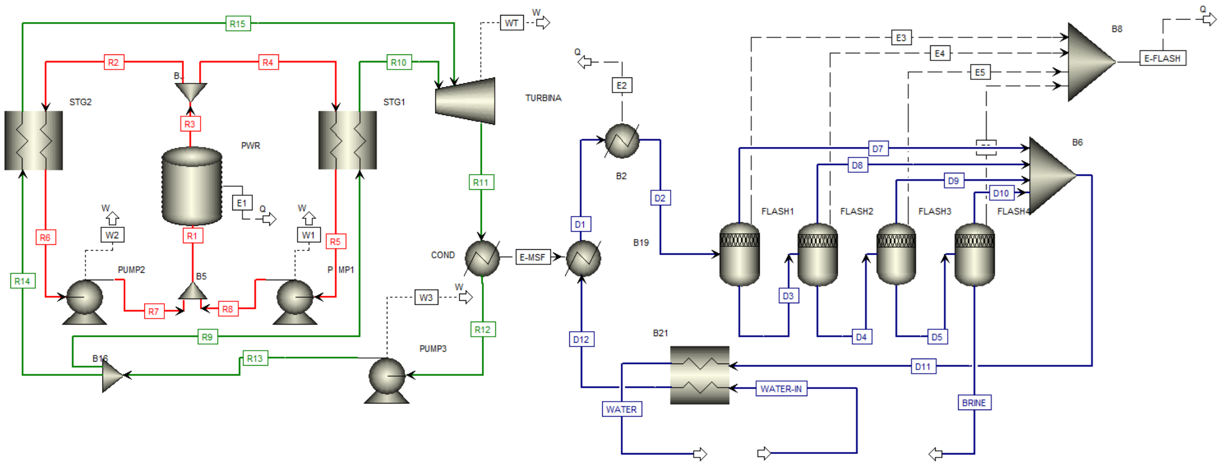

Fig. 3. Desalination process flow diagram developed in Aspen Plus [9] for integration of the MSF with PWR-type SMR through a Rankine cycle for power production.

2.4 Thermodynamic Analysis

Energy balances for chemical process units are performed to quantify the thermal energy requirements and utilization efficiency within the desalination process. This includes tracking heat inputs and outputs at each stage of the desalination cycle, and:

- Calculate Exergy Flows and Destruction;
- Calculate the exergy of the heat input from the nuclear reactor;
- Track the exergy losses at each stage of the desalination process (e.g., preheating, evaporation, condensation);

- Identify exergy destruction, which occurs due to irreversibilities such as friction, heat transfer across finite temperature differences, and mixing;
- Exergy Balance;
- Calculate exergy efficiencies to quantify how effectively the system converts nuclear energy into useful work (freshwater).
- Assess Exergy Efficiency;
- Examine each component's exergetic efficiency (ratio of useful exergy output to exergy input);
- Identify areas of high exergy destruction and inefficiency, suggesting potential improvements.

In order to calculate the overall efficiency of the proposed system, the mass, energy, and exergy balances are performed using the following expressions:

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \quad (1.1)$$

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \sum_{out} \dot{m}(h_{PT} - h_0 + h_f) - \sum_{in} \dot{m}(h_{PT} - h_0 + h_f) \quad (1.2)$$

$$\dot{E}x_{\dot{Q}_{in}} - \dot{E}x_{\dot{Q}_{out}} + \dot{E}x_{\dot{W}_{in}} - \dot{E}x_{\dot{W}_{out}} = \sum_{out} \dot{m}ex_{ou} - \sum_{in} \dot{m}ex_{in} + \dot{E}x_d \quad (1.3)$$

where $\dot{m}$ is used to denoted the mass flow rates, $\dot{W}$ the work rate, $\dot{Q}$ the heat transfer rate, $\dot{E}x_d$ the exergy destruction rate, ex the specific exergy, $\dot{E}x_{Q_{in}}$ exergy content of the heat transfer rate that can be calculated as $Ex_Q = \left(1 - {T_0}/{T_f}\right)\dot{Q}$ according to Al-Zareer et. al. [10] and h is the specific enthalpy.

A thermodynamic model is developed to calculate the energy and exergy efficiencies and evaluate this proposal's viability. To determine the properties of all the material and energy streams involved in the computational model, a thermodynamic model must be used. This model has to be determined as a function of the process characteristics. For this proposal, the thermodynamic model of Peng-Robinson is enough to calculate the state equation of the components and stream simulated. The Peng-Robinson model is ideal for calculating non-ideal systems such as the SI cycle by solving two or three-phase systems using a mixture of the alpha function developed by Boston-Mathias [14]. The Peng-Robinson model is composed by:

$$P = \frac{RT}{V_m - b} - \frac{a}{V_m(V_m + b) + b(V_m - b)} \quad (1.4)$$

This model solves the interactions of the phases whenever the operating conditions are temperatures and pressures less than 100, 00 kPa. For the calculations of the enthalpy and entropy of the unit operations of the system using the expressions:

$$\frac{H - H^{ID}}{RT} = \frac{PV}{RT} - 1 - \frac{1}{2^{1.5} bRT}\left[a - T\frac{da}{dT}\right]\ln\left[\frac{V + (2^{0.5} + 1)b}{V - (2^{0.5} - 1)b}\right] \quad (1.5)$$

$$\frac{S - S_o^{ID}}{R} = \ln\left(\frac{PV}{RT} - \frac{bP}{RT}\right) - \ln\frac{P}{p^0} - \frac{A}{2^{1.5} bRT}\left[\frac{T}{a}\frac{da}{dT}\right]\ln\left[\frac{V + (2^{0.5} + 1)b}{V - (2^{0.5} - 1)b}\right] \quad (1.6)$$

Combining the equation of state for the thermodynamic variables of pressure, temperature, and volume and equations for calculating the enthalpy and entropy of each component of the system, a complete thermodynamic description of the process can be obtained through this model.

The number of assumptions that were made through using the Aspen Plus software [12] are listed below:

1. The flow diagram is in steady-state conditions;
2. The start-up period of the NPP and the MSF plant is not considered;
3. The gases involved are considered ideal gases;

4. Changes in kinetic energy are neglected;
5. Feed water temperature and pressure are 25 °C and 1 atm.

3. RESULTS

The PWR-type SMR system used two steam generators for a single turbine as presented in Fig 2. The objective of this proposal is to evaluate the viability of seawater desalination in co-generation with power production using the PWR type plant. In this proposal the thermal energy requirements for the MSF system are supplied by an intermediate heat exchanger after the turbine in the Rankine cycle. The main objective of this component is to raise the seawater temperature to the appropriate value for the first flash stage separation. Tab. 2 lists the main properties and characteristics of the proposed system.

Tab. 2. Main properties and characteristics of the proposed system for the PWR type SMR-MSF system coupling for electrical energy and seawater desalination production

Parameter	**Value**
Number of steam generators (STG)	2
Number of turbines	1
Power conversion cycle	Rankine
Thermal Power	52,00 MWth
Mass flow of water for steam generator	2 x 9,45 kg/s
Electrical power produced	13,32 MW
Thermal energy for MSF system	19,34 MWth
Rankine efficiency	24,85 %

The thermal efficiency of the Rankine cycle can be determined using the ratio between the power produced by the steam turbine, the energy consumed in the primary and secondary circuit pumps, and the thermal energy produced in the PWR. This efficiency value is expected considering the values of inlet and outlet temperature for this PWR project. Using the computational model proposed, the exergy efficiency and exergy destruction rate of each component of the Rankine cycle can be determined.

The amount of thermal energy available for the MSF process determined using the energy balance before the condenser represented in the E-MSF energy stream. This value is used as a target to determine the amount of water that the proposed system can process. Performing an energy balance in the MSF process and knowing the temperature of the first flash separator is 95 ^{o}C, the water capacity of this system is determined in 15,22 kg/s consuming (19,08 MWth) (98,7%) of the energy available in the E-MSF energy stream. The Tab. 3 presents the parameters of Multi-Stage Flash desalination system.

Tab. 3. Multi-Stage Flash desalination system flow diagram parameters

Parameter	**Value**
Seawater inlet mass flow	15,22 kg/s
Seawater salinity	5000 ppm
Seawater inlet temperature	25 ^{o}C
Energy efficiency	77,14 %
Exergy efficiency	47,98 %
Brine mass flow	0,5242 kg/s
Freshwater mass flow	14,69 kg/s

Given the main parameters of the process flow diagram, the exergy efficiency (η) and exergy destruction rate (ψ) for the computational model's components can be determined (See Tab. 4).

Once the two coupled processes are analyzed, we can calculate the overall efficiency of the proposed model, as shown in Fig. 2. To calculate the overall efficiency, we must consider integrating the power conversion cycle through a Rankine cycle and the seawater desalination system. Performing a mass and energy balance, we can calculate the energy and exergy efficiency of the power conversion cycle.

Tab. 4 presents the parameters of Power Conversion System (PCS).

Tab. 4. Power conversion system parameters

Parameter	Value
Rankine cycle	
Power electricity	13,32 MWe
Efficiency	24,85 %
PWR-type SMR + MSF system	
Energy efficiency	25,24 %
Exergy efficiency	55,34 %

3.1 Comparison of plant integration options

Tab. 5 shows the comparison between different technology of desalination and different source of power.

Tab. 5. Summary of comparison of plant integration options

Parameter	Geothermal system + MED desalination [12]	Nuclear system + MSF desalination	
		HTR [4]	PWR [this work]
$\eta_{Rankine}$	9,00 %	37,34 %	25,24 %
$\psi_{Rankine}$	34,15 %	58,70 %	55,34 %
Steam pressure	3,9 MPa	-	3,77 MPa
Main steam temperature	383,15 K	-	519,15 K
Feed water flow rate	107,4 kg/s	33,09 kg/s	9,45 Kg/s

We must clarify that these efficiency values do not consider seawater desalination. These values can be compared with those obtained by Farsi and Rosen (2022) [15] and González et al. (2023) [4].

The High Temperature Reactor (HTR) is thermodynamically more efficient than PWR because operate at high temperature. We must notice that the exergy efficiency of the two small nuclear reactor systems (PWR and HTR) is similar. This result is very important because it allows us to affirm that this proposal of the Rankine cycle can meet the energy requirement with competitive efficiency values.

Using the computational model developed for the integration between the PWR-type reactor and the MSF desalination system, the exergy efficiency can be obtained for all the components simulated in the process flow diagram distribution, as shown in Fig. 3.

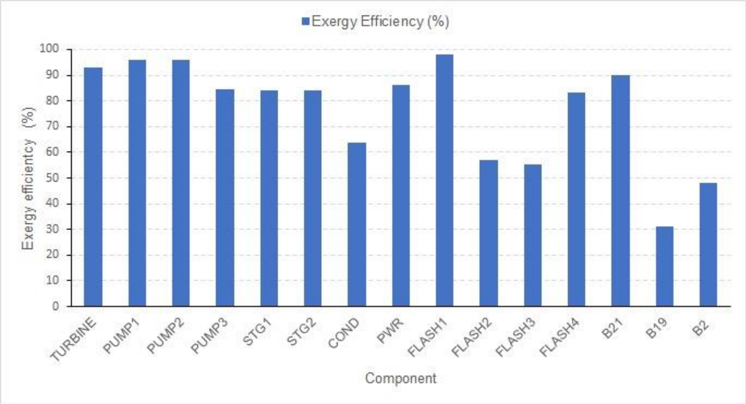

Fig. 3. Exergy efficiencies distribution of the main components of the MSF process coupled to the PWR-type reactor obtained with Aspen Plus software.

B2 and B19 are heat exchangers and B21 is a heater for the temperature control at the MSF inlet.

These results identify the higher values of exergy efficiency in the primary and secondary pumps. Typical values of exergy efficiency are obtained for the turbine and the PWR-type reactor. The lowest values of exergy efficiency are reported in the second and third steps of the MSF process. In this case, this is justified by the high values of exergy destruction rate occurring in these components, as can be seen in Fig. 3. The flash separation involves a variation of pressure and temperature, which has an influence on the stream-specific exergy. Also, the second and third steps are where most seawater is processed at a higher temperature, which is the reason why the exergy efficiency is lower than the first flash separator. Fig. 4 also, reports the sustainability index of the components in the computational model development with Aspen Plus software [12].

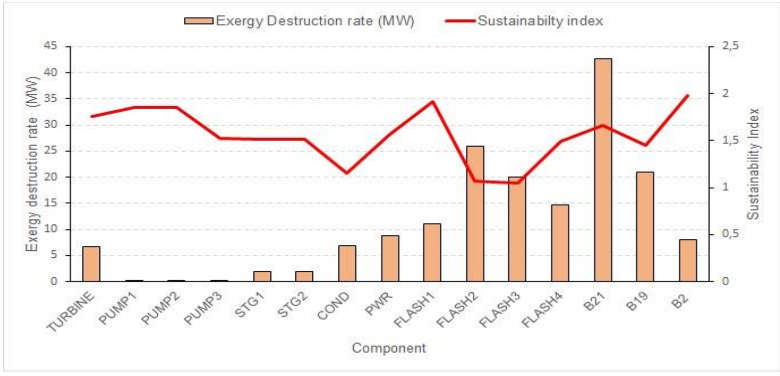

Fig. 4. Exergy destruction rate and sustainability index of the main components of the MSF process coupled to the PWR-type reactor.

The proposed model can be used to determine the exergy destruction shares for equipment, as shown in Fig. 5.

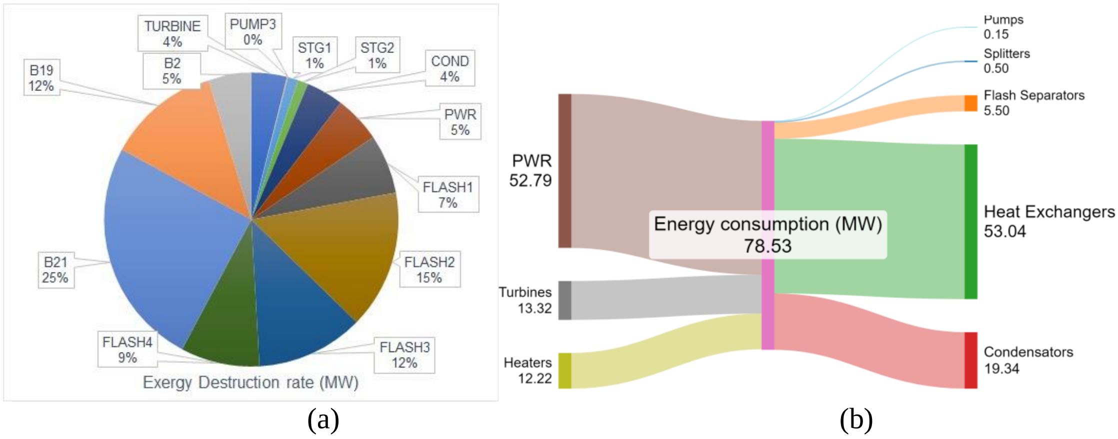

Fig. 5. Pie chart of the exergy destruction rate share of the main components of the MSF process coupled to the PWR-type reactor (a) and Sankey diagram for the energy consumption (b).

Additionally, the Sankey diagram of enthalpy/exergy streams generated with Aspen Plus software [12] is presented for the proposed model, as shown in Figure 6 (b). This diagram can identify the quantity of mass flow that input, output, and exergy destruction of each type of component used in the computational model.

This PWR-type SMR can be used in an Floating Nuclear Power Plant (FNPP) for co-generation of electricity and water desalination in Brazil as mentioned by Maritza. R. Gual et. al. [16-17].

4. CONCLUSIONS

A computational model development with Aspen Plus software for the process flow diagram of the integration is developed to study the coupling of these systems. A power conversion cycle is proposed using a Rankine cycle for power production, and a Multi-Stage Flash (MSF) system is coupled to residual heat for seawater heating.

In this work, the applications of the proposed novel solution for co-generation of electricity and fresh water using a PWR-type SMR with 52 MWt have been technically investigated.

This work involved a comprehensive technical analysis, focusing on various thermodynamic evaluations, such as energy balances, exergy assessments, and overall system efficiency. These analyses provided key insights into the operational performance and potential areas for optimization of the combined PWR-type Small Modular Reactor (SMR) and Multi-Stage Flash (MSF) desalination technology. However, in Brazil to gain a full understanding of the feasibility of this integration, an economic analysis is also essential.

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