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Comparing the efficiency of two different models of combined parallel flash binary cycles

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Abstract— **The main aim of this paper is a comparative study of two different geothermal power plant concepts, based on the exergy analysis. The cycles studied in this paper are the combination of single and double flash power plants with two different ORC cycles as regenerative ORC and regenerative ORC with an IHE, with R113 as working fluid. The main gain due to using combined flash-binary power plants with various types of ORCs is to achieve optimum and efficient energy utilization for Sabalan geothermal power plants.**

Index Terms—**ORC, IHE, R113**

I. INTRODUCTION

No one can deny that there is a dramatic increase in the oil prices and the environmental damages of conventional energy resources, so there is a growing tendency for all countries to focus on the development of renewable energy resources. Geothermal power is a comparatively pollution-free energy resource derived from naturally occurring reservoirs of hot water or steam that occur beneath the earth surface with temperature varying from 50 to 350 ℃ [H.D.M]. Amongst the renewable energy sources, geothermal energy is the most stable renewable energy source in which the operation of geothermal power plant is independent of the weather condition and fuel delivery.

Geothermal energy is used for the purpose of electricity production and direct uses. Depending on geothermal water temperature, different power plants concepts are suitable to generate electricity. Dry steam power plants use high temperature, vapor-dominant reservoirs. Flash steam power plants are used when a liquid-dominant fluid is produced at the wellhead of the hydrothermal reservoir. Binary power plants are the best energy conversion systems to exploit medium- and low-temperature systems.

In the recent years, much effort has been done to improve the efficiency of flash and binary power plants, distinctively and also there have been some attempts to explain criteria for the optimal design of flash and binary cycle power plants: Cerci [1] evaluated the performance of an existing single-flash geothermal power plant using exergy analysis. It was shown that the second law efficiency of the plant is 20.8 %. Also, an examination of the exergy destruction throughout the plant reveals that the largest exergy destruction occurs from the brine discharge to the river after flashing processes in the separators. According to that, two alternative designs were investigated to improve the efficiency of the existing power plant: double-flash design and a binary design added to a single flash cycle. Dagdas [] performed exergy and energy analysis of the Denizli Kizildere power plant in order to optimize the performance of the power plant. Due to the low efficiency of the existing power plant, a new flash-binary is proposed in this paper and it was shown that adding a binary system to the existing plant is suitable from an energy and economic point of view. Kanoglu [2] studied the exergy analysis of a dual-level binary geothermal power plant. DiPippo [3] proposed a heat recovery exchanger with a cascade of evaporators with both a high- and low-pressure turbine to increase binary plant efficiencies. Borsukiewicz-Gozdur and Nowak [4]have presented a different method of increasing the power of the geothermal power without an additional input of external energy. The method is based on increasing the flow of the geothermal water by returning the stream of geothermal energy medium from the outlet of the evaporator to the input line upstream of the evaporator. Gu and Sato [5] studied the use of supercritical cycles to raise the thermal efficiency and power output by optimizing cyclic parameters. Amiri et all [6] has determined optimum flashing pressure of single and double geothermal power plants to get maximum efficiency of flash-steam plants. Also, second law analyses of binary geothermal power plants using different organic Rankine cycles were performed by Yari [7]. A comparative study of the different geothermal power plants was done to clarify the best cycle configuration and it was shown that the maximum first-law efficiency is for the flash-binary cycle with R123 as working fluid and was calculated to be 11.81%. Luo et al [8]compared different types of geothermal power plant systems focusing on the operating parameters and thermal efficiency in China. The result shows that the binary cycle plant is favorable for power generation when water temperature is below 130 ℃, otherwise, flash steam power plant is a better choice.

Literature review shows that there has not been any performance analysis for different cycles of combined flash-binary geothermal power plants yet. In this paper, parallel flash-binary models with two different types of ORC cycles are studied gaining optimum operating pressure for the separator and surveying the effect of different ORC cycles on the efficiency of the geothermal power plant. Also, the effect of binary cycle working fluid on the performance of the different combined flash-binary power plants is investigated.

I. FORMULATION OF GEOTHERMAL POWER PLANT SYSTEM

Flash steam plants are the most common type of geothermal power plants. Single flash steam technology is used where the hydrothermal resources are liquid. In flash power plants, high-pressure hot water rushes from the production wells into a separator, where a pressure reduction process vaporizes some of the fluid, rapidly. The double flash steam power plant is an improvement of single flash plant which can produce 15

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to 25 % more power output from a same inlet condition of geofluid. Binary power plants are used when the hydrothermal resources are not hot enough to produce steam for a single flash power plant or where the resource contains many chemical impurities. The hot liquid of the separator of a flash cycle can be utilized as the inlet of a binary cycle as well as the directional injection of the geofluid into the binary power plant. Hence, the combination of a flash power plant with a binary cycle can be suitable to decrease the wastage of the energy and produce more energy and electricity. One of the combinations of flash cycles with binary power plants is parallel flash-binary power plants, in which binary power plant works with the liquid that extracted from the flash cycle separator. In this study, the considered binary cycles are regenerative ORC and regenerative ORC with an IHE which R113 is the working fluid.

Fig. 1 shows the schematic diagram of two combined flash-binary power plant. Fig .1 (a) has been selected as a sample to explain the procedures that happen in the combined power plant. As can be observed from Fig. 1(a) the geofluid goes into the separator, causing some of it to vaporize rapidly. After the flashing process, produced steam passes through the flash cycle turbine, and also the remained liquid from flashing process goes through the evaporator to exchange the water heat to the working fluid of the binary cycle and then the geothermal fluid would injected to the injection well. Some complicate processes would be accomplished on the working fluid at evaporator which contain preheating, evaporating and superheating of the organic working fluid. The superheated vapor generates mechanical work by passing through an expander. The expanded vapor is pre-cooled in an IHE. The precooled vapor is condensed in a condenser then, the pump pumps it to the IHE. After that, the vapor extracted from the turbine mixes with the feed-water exiting from IHE, and also the saturated liquid leaves open feed-organic heater at the heater pressure, and it goes to the evaporator again.

II. ANALYSIS

The performance evaluation of the four flash-binary systems is considered by determining the first- and second-law efficiency of the power plant. For each component, the first and second-laws of thermodynamic are applied to find the work output and the system irreversibility. The mass and energy balance equation can be expressed as:

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \tag{1}$$

$$\sum_{in} \dot{m}_{in} h_{in} + \dot{Q} - \sum_{out} \dot{m}_{out} h_{out} - \dot{W} = 0 \tag{2}$$

The irreversibility rate for power plant components with steady state condition without chemical reaction is:

$$\dot{I} = T_0 \left[\left(\sum \dot{m}_e s_e - \sum \dot{m}_i s_i \right) - \frac{\dot{Q}_{c.v}}{T_j} \right] \tag{3}$$

III. ANALYSIS OF COMPONENTS

As discussed before a combination of flash cycle with the binary system of regenerative ORC with an IHE has been chosen to describe the different components of the power plant. The reason for this selection is that this combination has all the necessary components of the other cycles.

Separator: as the name of this component implies, its duty is separation of the steam from the liquid phase of the brine. The geofluid, which goes to the separator, comes out as two distinct parts of steam and liquid because only steam should enter the turbine. Separators always work with a pressure decrement process. Increasing the pressure drop in separator increases mass flow of vapor, but decreases its enthalpy. Therefore, there is an optimum pressure getting the maximum possible efficiency in combined flash-binary geothermal power plants. The flashing process is modeled as an isenthalpic process, because it occurs steadily, adiabatically with no work involvement, so mass and energy equations in flashing chamber can be expressed by:

$$\dot{m}_2 = \dot{m}_3 + \dot{m}_4 \tag{4}$$

$$\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_4 h_4 \tag{5}$$

The temperature and the pressure lost of the separator unit have been considered to zero. Regarding this issue, the temperature and the pressure of the steam and liquid extracted from the separator are the same as the temperature and pressure of the geothermal fluid that comes into the separator:

$$T_2 = T_3 = T_4 = T_{sat}(P_{flash}) \tag{6}$$

$$P_{flash} = P_2 = P_3 = P_4 \tag{7}$$

The enthalpy of the steam, h_2 , and the enthalpy of the tubrine, h_3 , are determined as saturated steam enthalpy and saturated liquid enthalpy at the flashing pressure. The entropy of the steam and the brine can be calculated from pressure and enthalpy.

Turbine: The turbine has an isentropic efficiency. The isentropic efficiency of the turbine is considered 80% and defined as:

$$\eta_t = \frac{h_3 - h_5}{h_3 - h_{5s}} \tag{8}$$

Where h_{5s} is the turbine outlet enthalpy in ideal condition which is a function of a condenser pressure. Using Eq. (9), the actual enthalpy of the geofluid at the turbine outlet is calculated.

The flash-turbine power is given by:

$$\dot{W}_{flash-turbine} = \dot{m}_3 (h_3 - h_5) \tag{9}$$

Flash Cycle Condenser: The condenser is considered as an air-cooled type [9]. The heat transfer in condenser is calculated by:

$$\dot{Q}_{flash-condesnser} = \dot{m}_3 \left(h_5 - h_6 \right) = \dot{m}_{air1} \left(h_{air,out} - h_{air,in} \right) \tag{10}$$

where the $h_{air,out}$ and $h_{air,in}$ are the enthalpies of cooling air in the air cooled condenser at $T = 35°C$ and $T = 25°C$,respectively . $\dot{m}_{air,1}$ is the mass flow rate of the air flows in the condenser to cool the fluid.

Evaporator of the binary cycle: The evaporator heats the working fluid to the turbine inlet condition, which is saturated vapor. An energy balance in the evaporator between geofliud and working fluid can be written as:

$$\dot{m}_4 \left(h_4 - h_{pp} \right) = \dot{m}_9 \left(h_9 - h_{f,binary} \right) \tag{11}$$

$$\dot{m}_4 \left(h_{pp} - h_7 \right) = \dot{m}_9 \left(h_{f,binary} - h_{17} \right) \tag{12}$$

where $h_{f,binary}$ is the saturated liquid enthalpy of the working fluid at the vaporization temperature and h_{pp} is the enthalpy of the geofluid at the pinch-point temperature of the geothermal fluid. The pinch-point difference is considered as 10 °C in this paper. Solving these equations the enthalpy of geofluid reinjected to the wellhead is calculated.

Open feed organic heater (OFOH): In OFOH heat is transferred from the extracted vapor to the feed organic fluid, and ideally, the working fluid leaves the heater as a saturated liquid at the heater pressure.

The fraction of the working fluid that goes into the open feed-organic heater is achieved by applying energy balance in the feed-organic heater:

$$y = \frac{h_{16} - h_{15}}{h_{10} - h_{15}} \tag{13}$$

where h_{16} is the enthalpy of saturated liquid of working fluid at the extraction pressure.

Internal heat exchanger (IHE): The IHE heats the working fluid from the pump outlet to the open feed organic heater inlet condition and cools the saturated vapor of working fluid from outlet condition of the turbine to the condenser inlet condition.

The IHE effectiveness can be expressed as:

$$\varepsilon = \frac{T_{11} - T_{12}}{T_{11} - T_{14}} \tag{14}$$

Binary cycle turbine: Ideally, the entropy of the working fluid after the turbine is the same as the entropy of the working fluid before the turbine. In this paper, isentropic efficiency is considered for turbines. The isentropic efficiency of the binary cycle turbine is considered as 85% [20] and defined as:

$$\eta_t = \frac{h_9 - h_{10}}{h_9 - h_{10s}} = \frac{h_{10} - h_{11}}{h_{10} - h_{11s}} \tag{15}$$

where h_{10s} and h_{11s} are the enthalpies of the working fluid at the exit of the turbine for the ideal case.

The saturated vapor of working fluid passes through the turbine to generate mechanical work. The turbine power is:

$$\dot{W}_{binary-turbine} = \dot{m}_9 \left[y\,(h_9 - h_{10}) + (1 - y)\,(h_9 - h_{11}) \right] \tag{16}$$

Condenser in the binary cycle: The working fluid leaving the IHE goes through a condenser and saturated liquid is exited.

The heat transfer rate for the condenser is shown in Eq. (17):

$$\dot{Q}_{binary-condesnser} = \dot{m}_9 (1 - y)\left(h_{13} - h_{12}\right) = \dot{m}_{air2}\left(h_{air,out} - h_{air,in}\right) \tag{17}$$

Pumps: isentropic condition is considered for the pump. The isentropic efficiencies of the pumps are considered 90%and it can be expressed as:

$$\eta_{pump} = \frac{v_{13}\left(P_{14} - P_{13}\right)}{h_{14} - h_{13}} = \frac{v_{16}\left(P_{17} - P_{16}\right)}{h_{17} - h_{16}} \tag{18}$$

The pumps power can be determined as:

$$\dot{W}_{pump,1} = \dot{m}_9 (1 - y)(h_{13} - h_{14}) \tag{19}$$

$$\dot{W}_{pump,2} = \dot{m}_9 \left(h_{16} - h_{17}\right) \tag{20}$$

An understanding analysis of a geothermal power plant includes both energy and exergy analysis in order to obtain a more complete picture of the system behavior. Exergy analysis is a powerful tool like an energy analysis, because it helps identify the causes of losses to improve the overall system and its components [2, 10].

For a combined flash-binary cycle, the thermal and exergy efficiency can be expressed as:

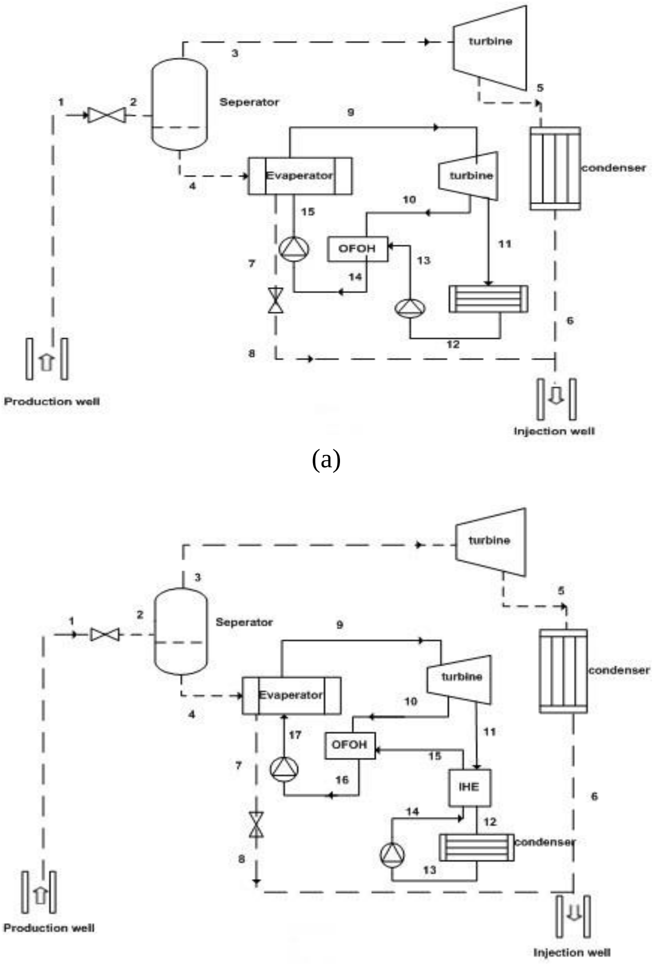
$$\eta_{thermal} = \frac{\dot{W}_{net}}{(\dot{m}_2 h_2 - \dot{m}_4 h_4) + (\dot{m}_4 h_4 - \dot{m}_7 h_7)} \tag{21}$$

$$\eta_{exergy} = \frac{\dot{W}_{net}}{(\dot{m}_2 ex_2 - \dot{m}_4 ex_4) + (\dot{m}_4 ex_4 - \dot{m}_7 ex_7)} \tag{22}$$

where ex is the specific flow exergy of the fluid and calculated with Eq. (23):

$$ex_i = (h_i - h_0) - T_0 (s_i - s_0) \tag{23}$$

The dead state condition is represented by subscript 0.



(a)

(b)

Figure 1: Simplified scheme of parallel flash-binary geothermal power plants, (a) regenerative ORC, (b) regenerative ORC with IHE.

IV. RESULTS AND DISCUSSIONS

In this article performance evaluation of different flash-binary geothermal power plants using various organic Rankine cycles as a binary cycle is considered and compared based on the first and second laws of thermodynamics. Also, the influence of the some key parameters such as flashing pressure, working fluid selection, extraction pressure on the flash-binary geothermal power plants is investigated.

In the first step of evaluation, various types of flash-binary cycles will be evaluated using R113 as working fluid and then in the second stage of optimization, different working fluids would be used to study the effects of common working fluids on the efficiency of combined geothermal power plants.

Figure 2 shows the variation of the thermal efficiency with the flashing pressure of the flash-binary power plants. The evaporator temperature and condensers temperature were kept constant at 120 ℃ and 40 ℃, respectively. As shown in this figure, thermal efficiency has a maximum value in the optimum flashing pressure for each cycle of flash-binary power plant. Also, it can be observed that the regenerative ORC with an IHE shows the best thermal efficiency amongst the others. The optimum thermal efficiency of the flash-binary power plants of regenerative ORC with IHE, regenerative ORC is 18.99%, 18.49% respectively.

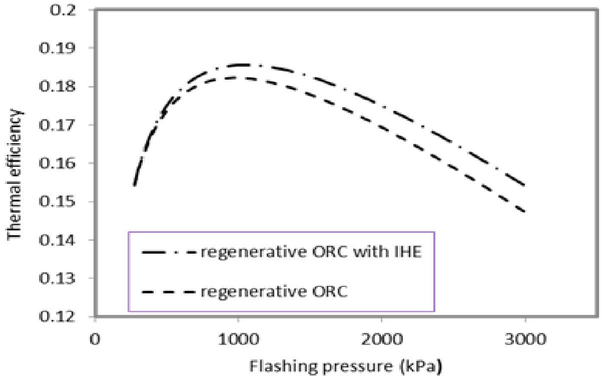


Figure 2: Thermal efficiency of different parallel flash-binary geothermal power plants

Figure 3 shows the variation of total exergy destruction with the flashing pressure. It can be observed that the total system irreversibility also has optimum flashing pressure. The trend observed in this figure is consistent with the result shown in Figure 3, where the regenerative ORC with an IHE has the minimum exergy destruction and maximum thermal efficiency.

The remarkable thing is that both views of thermodynamic lows approximately show almost the same optimum flashing pressure for various configurations. The optimum flashing pressure for the flash-binary power plant using regenerative ORC based on the first- and second-laws of thermodynamic is 970.3 kpa. The optimum flashing pressure for the regenerative ORC with IHE based on the first- and second-laws of thermodynamic is 1081 kPa.

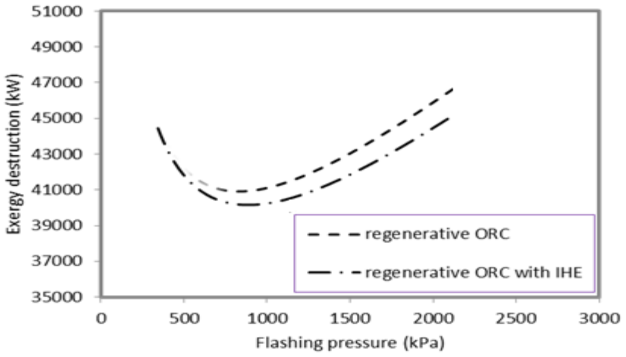


Figure 3: Total exergy destruction of different parallel flash-binary geothermal power plants

Exergy destruction of major components of regenerative ORC is calculated and shown in Fig.4. In this configuration, the largest exergy destruction is occurred during the turbines. The rate of exergy destruction for flashing losses, evaporator decrease compared with the regenerative ORC with IHE. Due to open feed organic heater, the irreversibility of the boiler is decreased by using the heat of the steam of organic fluid during the expansion to preheat the liquid.

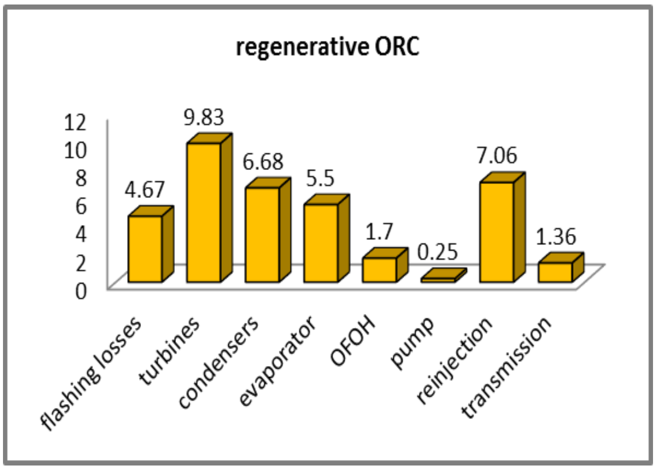


Figure 4: The exergy destruction of component of parallel flash-binary geothermal power plant using regenerative ORC.

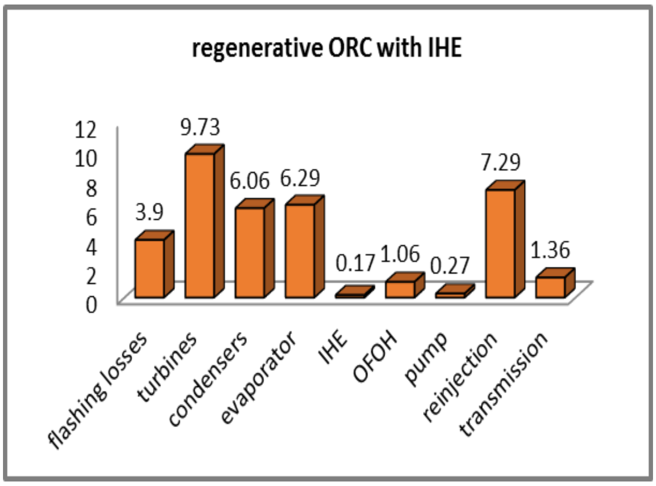


Figure 5: The exergy destruction of component of parallel flash-binary geothermal power plant using regenerative ORC with IHE

Figure 5 illustrates the exergy destruction at major components of regenerative ORC with an IHE. As it is observed, the turbine makes the highest contribution to the total exergy destruction, 9.73 % of the total exergy. Other exergy destruction and locations are: 1.36% for the transmission of the geofluid from the reservoir to the wellhead, 6.29 % for the evaporator, 6.06 % for the condensers, 1.06% for the OFOH, 0.17 % for the IHE, 0.27 % for the pumps and 7.29 % for the waste fluid reinjected to the wellhead. It can be seen that the rate of the exergy destruction during turbine losses and flashing process decrease significantly compared with the regenerative ORC. The utilization of OFOH and IHE cause the decrease of exergy destruction of these components as explained before but it increases the exergy destruction of the waste water during reinjection processes. Also the diagram shows that the remaining of the total exergy is converted to power which is higher than regenerative ORC.

Table 1: THE EFFICIENCY PERFORMANCE OF SINGLE AND DOUBLE FLASH-BINARY GEOTHERMAL POWER PLANTS USING DIFFERENT ORCs COMPARED WITH THE FLASH STEAM CYCLES IN THE REFERENCE

Type plant		Net power output (MW)	Thermal efficiency (%)	Exergy efficiency
Flash-binary using Regenerative ORC	Single flash	51.8	18.49	63.05
	Double flash	53.89	19.18	69.59
Flash-binary using Regenerative ORC with IHE	Single flash	52.06	18.99	63.62
	Double flash	57.44	20.78	72.69

V. CONCLUSION

This paper investigates the effects of two various types of binary cycles on the thermal and exergy efficiency of the flash-binary power plants which the working fluid is R113. Two different ORC cycles (regenerative ORC and ORC with IHE) have been evaluated analytically. Flashing pressure and extraction pressure optimization of these cycles was performed. According to this study, the best cycle, which gives maximum thermal and exergy efficiency to a flash-binary power plant is a regenerative ORC with IHE which is on average higher than regenerative ORC. Also, the optimum flashing pressure for single and double flash-binary power plants have been surveyed, which illustrates a higher optimum flashing pressure of the double flash plants to the single flash power plants.

VI. APPENDIX

Nomenclature

h	Specific enthalpy (kJ/kg)
IHE	Internal heat exchanger
m	Mass flow rate (kg/s)
OFOH	Open feed organic heater
S	Specific entropy (kJ/kg k)
Q	Heat transfer (kW)
W	Power output (kW)
I	Irreversibility (kW)
T	Temperature (°C)
P	Pressure (kPa)
y	Mass fraction
ex	exergy
$\dot{W}_{net}$	Net power output (kW)

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