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APPLICATION OF THE H&S MODEL FOR THE ADVANCED EXERGY ANALYSIS OF AN ORGANIC RANKINE CYCLE

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Abstract: In order to carry out the advanced exergy analysis of a system, an exergoeconomic-based approach is required. The Specific Exergy Costing method is chosen for this. Thus, there is a gap in the literature regarding the application of other approaches. An alternative is the H&S Model, which was originally proposed to solve the cost allocation problem in power cycles. Therefore, the objective of the present paper is to verify whether the H&S Model is able to be adapted for the purpose of performing advanced exergy analysis. The power cycle taken as a case study is an organic Rankine cycle, which is fed with waste heat and uses R-245fa as the working fluid. Both conventional and advanced exergy analyses are done for a base case. In addition, a parametric analysis is performed to check the consistency of the H&S Model. Regarding the results of the case study, the conventional exergy analysis indicated that the evaporator should be the priority to improve the cycle. On the other hand, the advanced exergy analysis showed that the greatest amount of the avoidable exergy destruction was also endogenous and associated with the expander. The results also showed that the adaptation of the H&S Model is possible when considering the base case. It has also been shown that such an adaptation is consistent when taking into account the parametric analysis.

Keywords: exergoeconomics; ORC; power cycle; thermoeconomics; waste heat.

1 INTRODUCTION

Exergy analysis is a powerful tool used to identify the true sources of thermodynamic inefficiency in energy conversion systems. It can be performed at the system component level and in detail. Applications are wide such as power plants, refrigeration and polygeneration systems, oil production and refining, combined sugar, ethanol and electricity production, aircraft engines, air conditioning processes, heating and drying systems, cryogenics and liquefaction, hydrogen production, and fuel cells. The concept of exergy can also be related to concepts associated with the environment such as renewability, life cycle assessment, and industrial ecology (DE OLIVEIRA JUNIOR, 2013; DINCER; ROSEN, 2021).

Conventional exergy analysis accounts for the respective exergy destructions that occur in each component of the system. In principle, by reducing such exergy destruction, the system would be improved from a thermodynamic point of view. However, due to technological limitations of the components, some exergy destruction is unavoidable and thus the rest is the avoidable part. In addition, a part may be due to exergy destruction in other components, which is called exogenous. The part due to the internal irreversibility of the component itself is called endogenous. Knowing the nature of the exergy destruction in the four mentioned parts, the procedure for improving the system is done in a more assertive way. Splitting the exergy destruction into its parts is called advanced exergy analysis (KELLY; TSATSARONIS; MOROSUK, 2009). There are several published case studies, such as those of power generation (ANETOR; OSAKUE; ODETUNDE, 2020; IDRISSA; BOULAMA, 2020), refrigeration (COLORADO-GARRIDO, 2019; ZENG; LI; PENG, 2022), and cogeneration (CAGLAYAN; CALISKAN, 2021; ECHEERI; MAALMI, 2022) systems.

To carry out the advanced exergy analysis of a system, an exergoeconomic-based approach is required because the fuel and product of each component of the system need to be defined. The Specific Exergy Costing (SPECO) method (LAZZARETTO; TSATSARONIS, 2006) is chosen for this. Thus, there is a gap in the literature regarding the application of other exergoeconomic approaches for the purpose of performing advanced exergy analysis.

An alternative exergoeconomic approach is the H&S Model, which splits the physical flow exergy into its enthalpic and entropic terms (SANTOS et al., 2009). By applying the H&S Model, dissipative components such as condensers can be well treated in exergoeconomic modeling. This means that both fuel and product can be well defined for such components. The H&S Model was applied for cost allocation in a gas turbine cogeneration system (DOS SANTOS et al., 2015), in addition to environmental burden allocation in steam turbine cogeneration (DOS SANTOS et al., 2016), gas turbine cogeneration (DOS SANTOS et al., 2016; DA SILVA et al., 2017), and combined cooling and power (TRINDADE et al., 2021) systems. This exergoeconomic approach was also used for the operational diagnosis of a steam power plant (LORENZONI et al., 2020). Recently, the H&S Model was applied to obtain the exergoeconomic variables (e.g. exergoeconomic factors) of an organic Rankine cycle (ORC) (LOURENÇO, 2021).

To the best of the author’s knowledge, there is no application of the H&S Model for the advanced exergy analysis of a system. The H&S Model was proposed to model power cycles. Thus, the case study system consists of a power cycle. The objective of the present paper is to verify whether this exergoeconomic approach is able to be adapted for the purpose of performing advanced exergy analysis.

2 METHODOLOGY

The power cycle taken as a case study is an ORC. Figure 1 shows the flow sheet of the cycle. All the flows shown are energetic (first law-based) flows. The net power produced by the cycle is sent to its surroundings. The ORC is fed with waste heat and rejects heat to the reference environment. According to Quoilin et al. (2013), a working fluid commonly used under this condition is R-245fa. Thus, this is the working fluid adopted in this work.

The H&S Model was originally proposed to solve the cost allocation problem. In this paper, this approach is applied to perform the advanced exergy analysis of an ORC. The H&S Model disaggregates physical flow exergy into its enthalpic and entropic terms. Mathematically, $\dot{H}_{i:j} = \dot{m}\,(h_i - h_j)$ and $\dot{S}_{i:j} = \dot{m}\,T_0\,(s_i - s_j)$, where i and j are subscripts associated with physical flows. If the reader wants to understand the application of the H&S Model in detail, reading the paper published by Santos et al. (2009) is recommended.

Figure 2 depicts the productive diagram of the ORC. The productive diagram represents the cost formation process of the cycle. The external fuel consumed by the system is the waste heat exergy added to the evaporator. The functional product is the net power generated by the cycle. Rectangles are real units that represent the actual equipment (i.e., components) of the cycle. Diamonds and circles are fictitious units called junctions and bifurcations, respectively. Each productive unit has inlet and outlet arrows that represent its fuel and product, respectively. Each productive flow is defined based on physical flows (LOURENÇO, 2021).

Figure 1: Flow sheet of the ORC

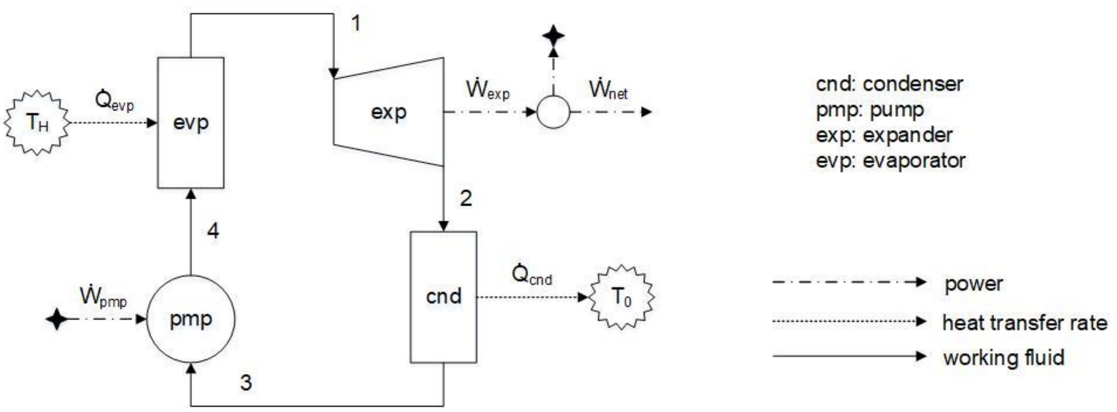
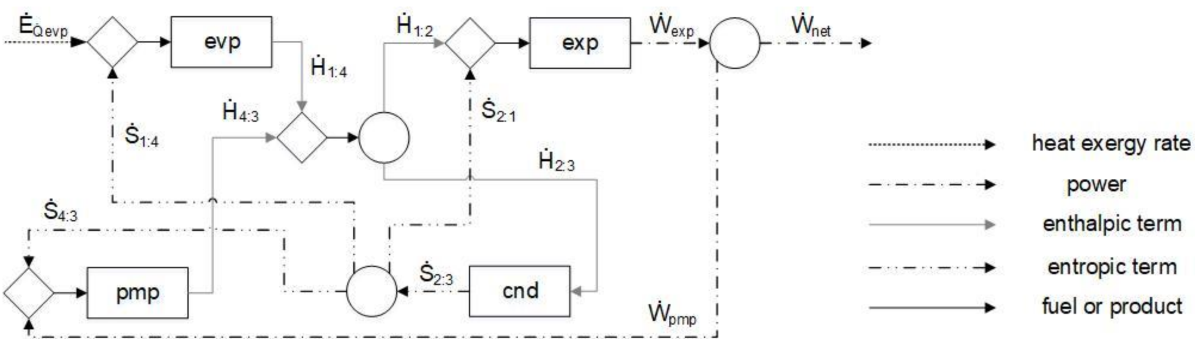


Figure 2: Productive diagram of the ORC



To apply advanced exergy analysis, it is necessary to define both fuel and product of each component of the cycle. This information is obtained graphically from Figure 2. The input arrows make up the fuel and the output arrows make up the product. For example, the fuel is the sum of $\dot{H}_{1:2}$ and $\dot{S}_{2:1}$, and the product is $\dot{W}_{exp}$ for the expander. In general, when there is an increase in the enthalpic term and/or a decrease in the entropic term, these terms make up the product. When the opposite happens, these terms make up the fuel. Furthermore, the difference of fuel and product is equal to the exergy destruction. For the kth component, this is shown by Equation 1. Exergy destruction can be obtained by conventional exergy analysis as well.

$$\dot{E}_{F,k} - \dot{E}_{P,k} = \dot{E}_{D,k} \qquad 1$$

The next step is to split the exergy destruction of the kth component into its endogenous and exogenous parts. In parallel, the exergy destruction must also be split into its avoidable and unavoidable parts. According to Wang et al. (2021), these steps can be called first-level splitting. Equations 2 and 3 show the exergy destruction and its parts for the kth component.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX} \quad 2$$

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{AV} + \dot{E}_{D,k}^{UN} \quad 3$$

Some approaches to split the exergy destruction have been proposed, which can be read in the paper by Kelly et al. (2009). The thermodynamic cycle approach is the most suitable for analyzing ORCs. Therefore, this is the approach used in this work. For systems that do not operate according to thermodynamic cycles, other approaches are indicated, such as the engineering approach.

In the thermodynamic cycle approach, ORC data in real, unavoidable, and ideal conditions are needed. To obtain the unavoidable part of the exergy destruction of all the components, the cycle must be simulated in the unavoidable condition. One must calculate the ratio of the exergy destruction to the product of the kth component in such a condition. After that, this ratio must be multiplied by the product of the kth component obtained in the real condition. Equation 4 expresses the unavoidable part of the exergy destruction.

$$\dot{E}_{D,k}^{UN} = \dot{E}_{P,k} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{UN} \quad 4$$

The endogenous part of the exergy destruction of the kth component must be obtained in a simulation such that the kth component operates in the ideal condition and the remaining components in the real condition. This is known as the hybrid cycle condition and must be done for each component of the cycle. A corresponding hybrid cycle must be built for each component when multiple components exist in the system (WANG et al., 2021).

According to Wang et al. (2021), the second-level splitting is a combination of two first-level splitting methods. The endogenous-avoidable part is associated with the internal irreversibility of the component and it can be reduced or eliminated by improving the component itself. The exogenous-avoidable part is related to the thermodynamic imperfection of the other components and it can be reduced or eliminated by improving these components. Equations 5-8 present the relationships between the parts obtained by the first-level and second-level splitting methods for the kth component.

$$\dot{E}_{D,k}^{EN} = \dot{E}_{D,k}^{EN,AV} + \dot{E}_{D,k}^{EN,UN} \quad 5$$

$$\dot{E}_{D,k}^{EX} = \dot{E}_{D,k}^{EX,AV} + \dot{E}_{D,k}^{EX,UN} \quad 6$$

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k}^{EN,AV} + \dot{E}_{D,k}^{EX,AV} \quad 7$$

$$\dot{E}_{D,k}^{UN} = \dot{E}_{D,k}^{EN,UN} + \dot{E}_{D,k}^{EX,UN} \quad 8$$

To obtain the endogenous-unavoidable part of the exergy destruction, the ratio of the exergy destruction to the product of the kth component in the unavoidable condition must be multiplied by the product of the kth component obtained in the hybrid condition. Equation 9 expresses the endogenous-unavoidable part of the exergy destruction.

$$\dot{E}_{D,k}^{EN,UN} = \dot{E}_{P,k}^{EN} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{UN} \quad 9$$

For more details on the application of advanced exergy analysis of ORC-based systems, reading the papers by Liao et al. (2020) and Wang et al. (2021) is recommended.

The following simplifying assumptions are employed to analyze the ORC (WANG et al., 2021):

- steady state
- kinetic and potential energy effects are not considered
- pressure drops are not taken into account
- heat losses are not considered

- saturated liquid leaves the condenser
- saturated vapor enters the expander.

Table 1 presents the ORC operating parameters under real, unavoidable, and ideal conditions. For the condenser, the parameter adopted is the temperature difference of the working fluid and the thermal reservoir. For the evaporator, the same temperatures are taken, but vice versa. Considering both expander and pump, the parameter is the isentropic efficiency. All the values are retrieved from Wang et al. (2021).

For the real condition, the net power produced by the ORC is 100 kW (set value). Quoilin et al. (2013) found that ORCs using R-245fa and powered by waste heat produce net power in the range of 50 kW to 325 kW. In their review paper, the authors also found that 80°C ≤ T_1 ≤ 150°C and 25°C ≤ T_3 ≤ 30°C. In the present paper, T_H = 105°C and T_0 = 25°C (set values). Thus, T_1 = 100°C and T_3 = 30°C. Further information was obtained from the review paper: the maximum pressure of ORCs does not exceed 3000 kPa and their thermal efficiency does not exceed 24%. In the present case study, the evaporator pressure is 1264 kPa and the thermal efficiency of the ORC is 12.7%. For example, Kong et al. (2019) obtained a thermal efficiency of approximately 12% with T_1 = 110°C, $\eta_{exp} = \eta_{pmp}$ = 0.85, and T_3 = 40°C. Therefore, all the values used in the simulations are valid.

Table 1: ORC operating parameters under real, unavoidable, and ideal conditions

Component	Parameter	Real value	Ideal value	Unavoidable value
Condenser	$\Delta T_{cnd} = T_3 - T_0$	5°C	0°C	0.5°C
Evaporator	$\Delta T_{evp} = T_H - T_1$	5°C	0°C	0.5°C
Expander	η_{exp}	85%	100%	95%
Pump	η_{pmp}	80%	100%	95%

All the simulations are carried out using Engineering Equation Solver (F-CHART SOFTWARE, 2022).

3 RESULTS AND DISCUSSION

Table 2 presents the thermodynamic data of the ORC in the real, unavoidable, and ideal conditions. Data for the four hybrid cycles are also presented. As in the works by Liao et al. (2020) and Wang et al. (2021), the mass flow rate of the working fluid changes according to the cycle condition. Furthermore, the thermodynamic properties of the working fluid can change in each of the four states depending on the parameters used in a given simulation.

Table 3 shows the results from the conventional exergy analysis for the base case (real condition). The highest rate of exergy destruction is associated with the evaporator, followed by the expander, the condenser, and finally the pump. Thus, in light of the conventional exergy analysis, this is the order that should be followed for the purpose of thermodynamic improvement of the cycle. In other words, primarily improve the process that takes place in the evaporator for a greater thermodynamic gain in the exergetic efficiency of the cycle, followed by the expander and so on. Wang et al. (2021) also found that the highest rate of exergy destruction was associated with the evaporator.

Table 4 presents the results from the advanced exergy analysis for the base case. There are the results obtained from the first-level splitting, whose discussion must be done in two stages. There are also the results from the second-level splitting, which must be addressed in a third stage. The percentage numbers, which are in parentheses, indicate the values related to the total exergy destruction.

Considering the split of the exergy destruction into its endogenous and exogenous parts, the endogenous part is dominant for all the components of the cycle. This means that the interdependence among such components is weak from an exergetic point of view. Thus, each component can be improved if their respective internal irreversibilities are reduced. The same information was obtained by Liao et al. (2020) and Wang et al. (2021). For the expander, the exogenous part is negative. This indicates that if the other components were improved, the exergy destruction of the expander would increase. On the other hand, this is a low value, that is, with little overall influence on the cycle.

Table 2: Thermodynamic data of the ORC

Condition	ṁ [kg/s]	Stream	x [-]	T [°C]	P [kPa]	h [kJ/kg]	s [kJ/(kgK)]
Real	3.358	1	1	100	1269	474.1	1.791
		2	-	47.42	177.2	443.3	1.808
		3	0	30	177.2	239.1	1.135
		4	-	30.55	1269	240.1	1.136
Ideal	2.459	1	1	105	1416	477.0	1.793
		2	-	38.18	147.8	435.3	1.793
		3	0	25	147.8	232.5	1.113
		4	-	25.43	1416	233.4	1.113
Hybrid: real condenser	2.677	1	1	105	1416	477.0	1.793
		2	-	42.61	177.2	438.7	1.793
		3	0	30	177.2	239.1	1.135
		4	-	30.44	1416	240.0	1.135
Hybrid: real evaporator	2.581	1	1	100	1269	474.1	1.791
		2	-	37.37	147.8	434.6	1.791
		3	0	25	147.8	232.5	1.113
		4	-	25.38	1269	233.3	1.113
Hybrid: real expander	2.904	1	1	105	1416	477.0	1.793
		2	-	44.74	147.8	441.6	1.813
		3	0	25	147.8	232.5	1.113
		4	-	25.43	1416	233.4	1.113
Hybrid: real pump	2.473	1	1	105	1416	477.0	1.793
		2	-	38.18	147.8	435.3	1.793
		3	0	25	147.8	232.5	1.113
		4	-	25.61	1416	233.6	1.114
Unavoidable	2.628	1	1	104.5	1400	476.7	1.793
		2	-	40.7	150.5	437.7	1.799
		3	0	25.5	150.5	233.1	1.116
		4	-	25.97	1400	234.1	1.116

With respect to the avoidable and unavoidable parts of the exergy destruction, the unavoidable part is dominant only in the process associated with the evaporator. Liao et al. (2020) obtained the same result. The other components of the cycle have more than 69% of the exergy destruction related to the avoidable part. This means that there is good scope to improve them.

From the second-level splitting results, the endogenous-unavoidable part is dominant in the evaporator. In addition, the endogenous-avoidable part is the most significant in the other components of the cycle. This is in agreement with the result presented by Liao et al. (2020). Therefore, advanced exergy analysis shows that the expander should be the priority component when improving the cycle. Second, efforts

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must be directed towards the condenser. For the evaporator and expander, the exogenous-avoidable part is negative. This means that there is scope to improve the other components and such an improvement would increase the exergy destroyed in the two mentioned components. However, these are low values, which would not significantly influence the cycle in terms of its improvement.

The results obtained from the conventional exergy analysis are inconsistent with those by the advanced exergy analysis for the base case. The first approach indicates that the evaporator should be the priority for cycle improvement. On the other hand, the second approach points out that the priority should be the expander. This is in line with Liao et al. (2020) and Wang et al. (2021). In other words, an analyst who masters conventional exergy analysis would interpret that the greatest margin for reducing exergy destruction in the cycle would be associated with the evaporator. However, advanced exergy analysis clearly shows that the greatest potential for reducing exergy destruction in the cycle is associated with the expander. This is because, according to the parameters adopted for the unavoidable and real cycles, the evaporator is already operating in a condition relatively close to unavoidable. In turn, the expander is operating in a condition farther than unavoidable.

Table 3: Results from the conventional exergy analysis

Items	Value [kW]	Relative value [%]
Input		
Heat source exergy	166.22	100
Output		
Net power	100.00	60.16
Exergy destruction		
Condenser	12.65	7.61
Evaporator	35.76	21.51
Expander	17.13	10.31
Pump	0.68	0.41

Table 4: Results from the advanced exergy analysis

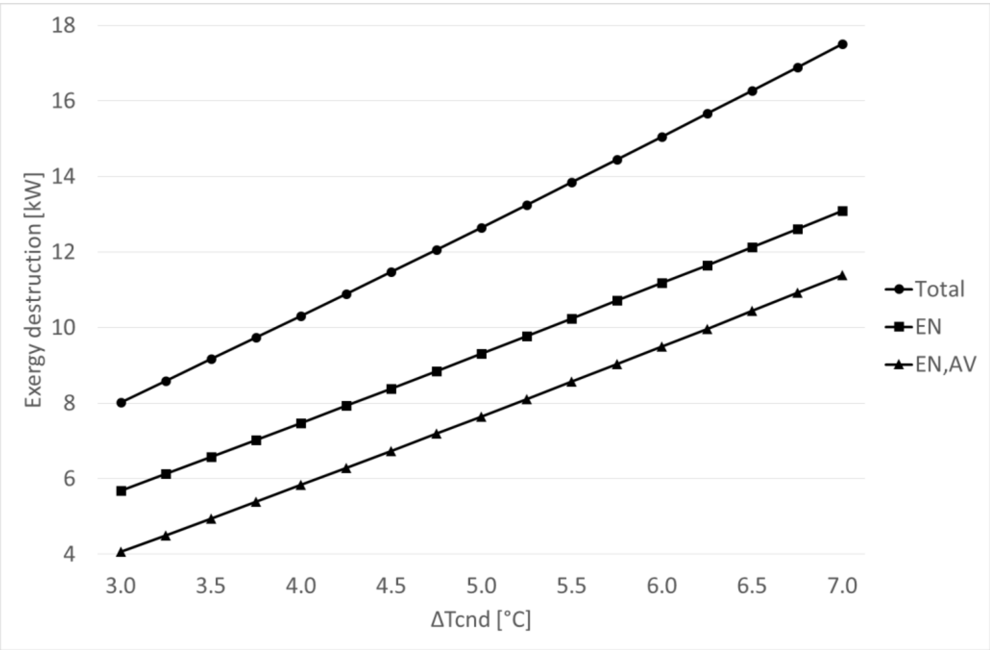
k	$\dot{E}_{D,k}$ [kW]	First-level splitting				Second-level splitting			
		EN [kW]	EX [kW]	UN [kW]	AV [kW]	EN,UN [kW]	EN,AV [kW]	EX,UN [kW]	EX,AV [kW]
cnd	12.65	9.307 (73.57%)	3.343 (26.43%)	2.128 (16.82%)	10.522 (83.18%)	1.660 (13.12%)	7.647 (60.45%)	0.468 (3.70%)	2.875 (22.73%)
evp	35.76	31.05 (86.83%)	4.71 (13.17%)	34.41 (96.23%)	1.35 (3.78%)	27.224 (76.13%)	3.826 (10.70%)	7.182 (20.08%)	-2.472 (-6.91%)
exp	17.13	17.18 (100.29%)	-0.05 (-0.29%)	5.193 (30.32%)	11.937 (69.69%)	5.152 (30.08%)	12.028 (70.22%)	0.040 (0.23%)	-0.090 (-0.53%)
pmp	0.6787	0.5839 (86.03%)	0.0948 (13.97%)	0.1722 (25.37%)	0.5065 (74.63%)	0.146 (21.51%)	0.438 (64.54%)	0.026 (3.83%)	0.068 (10.02%)

In order to better assess the consistency of the H&S Model, a parametric analysis is now proposed. The operating parameters of each component are taken within a range around the base case value. The outputs are the total exergy destruction (conventional analysis), and its endogenous (first-level splitting) and endogenous-avoidable (second-level splitting) parts. The changed parameters are those of the real cycle condition. The values for the unavoidable and ideal conditions remain constant.

Figures 3-6 depict the results from the parametric analysis. For both heat exchangers, the greater the temperature difference of the working fluid and the thermal reservoir, the greater the values shown in Figures 3 and 4. Considering the expander and the pump, the result is the opposite: the higher the isentropic efficiency, the lower the exergy destruction rates shown in Figures 5 and 6. It is well known that the lower the entropy generation, the lower the total exergy destruction. For the endogenous part, an identical rationale must be applied, as it is the part of exergy destruction associated with the internal irreversibility of the component. Regarding the endogenous-avoidable part, in addition to the rationale already presented, the increase in the difference of the parameters in the real and unavoidable conditions causes this part to increase. Therefore, the consistency of the H&S Model for advanced exergy analysis is confirmed.

The H&S Model was able to determine a product for the condenser, which is a dissipative component. On the other hand, if the SPECO method had been applied, a product for such a component could not have been defined. Thus, the advanced exergy analysis could not have been done comprehensively. It should be noted that this impediment would be due to the boundary of the condenser taken at T_0 (thermal reservoir model). In broader terms, the disaggregation of exergy obtained by the H&S Model solves the problem of determining the product of some dissipative components in other systems. Dissipative components are those that consume flow exergy but do not produce useful exergy effects. Examples are condensers and cooling towers. These components are present in systems such as thermoelectric power plants based on the Rankine cycle. Such components also appear in steam turbine cogeneration systems.

Figure 3: Results from the parametric analysis of the condenser



The versatility of the H&S Model is evidenced by the results presented. As stated in the Introduction, SPECO is commonly chosen for advanced exergy analysis, but cannot be applied to evaluate exergetic costs of systems, since SPECO only deals with exergo-economic costs and was later adapted to deal with exergo-environmental costs. On the other hand, the H&S Model can tackle both problems.

Figure 4: Results from the parametric analysis of the evaporator

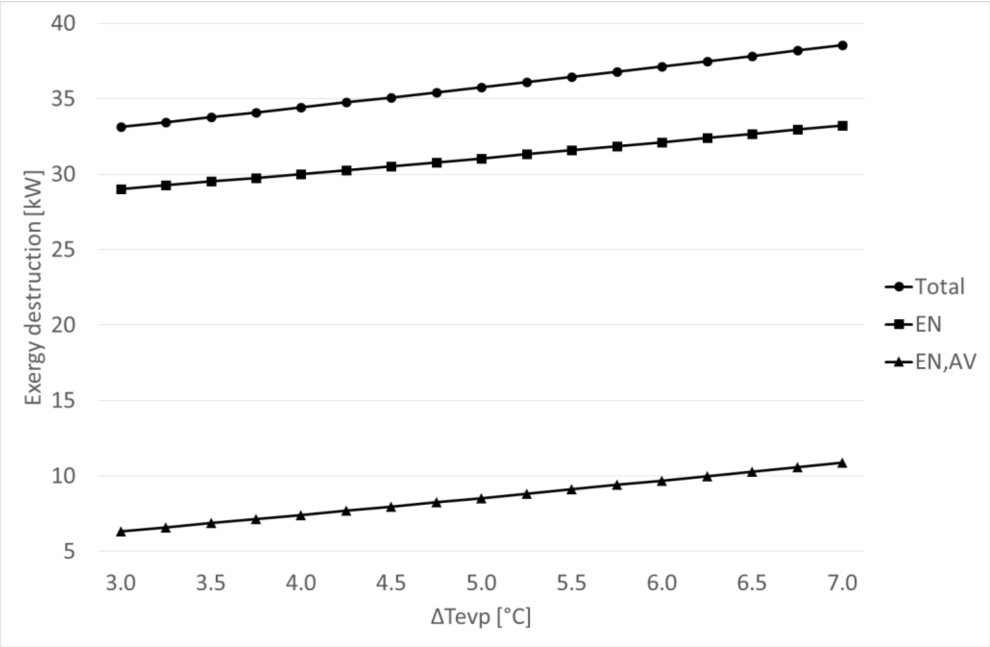


Figure 5: Results from the parametric analysis of the expander

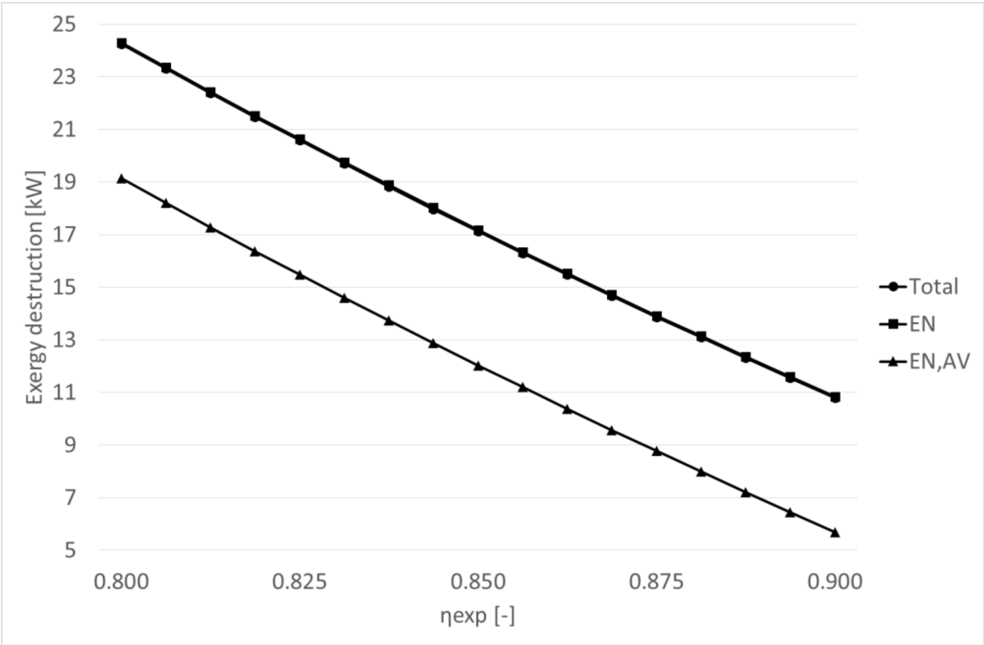
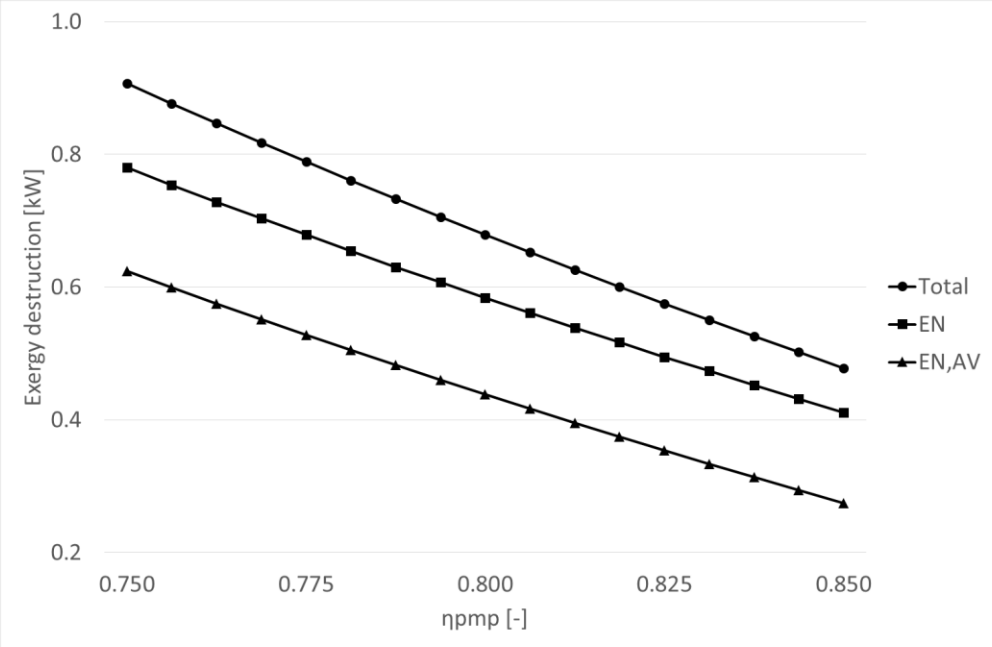


Figure 6: Results from the parametric analysis of the pump



4 CONCLUSIONS

In this paper, the H&S Model was applied for the advanced exergy analysis of power cycles. The case study was an ORC. The objective was to verify whether this exergoeconomic approach was able to be adapted for this purpose. The results showed that this adaptation is possible when considering the base case. It was also shown that such an adaptation is consistent when taking into account the parametric analysis.

Regarding the results of the case study, the conventional exergy analysis indicated that the evaporator should be the priority to improve the cycle. On the other hand, the advanced exergy analysis showed that the greatest amount of the avoidable exergy destruction was also endogenous and associated with the expander.

The thermodynamic cycle approach was used to split the exergy destruction. For an ORC, this approach worked well. However, other approaches must be applied to systems that do not operate according to a thermodynamic cycle. For example, the engineering approach could be applied to analyze a combustion-driven gas turbine. An investigation into the application of the H&S Model under these conditions may be carried out in the future.

One of the subsequent steps to advanced exergy analysis is its combination with exergoeconomic analysis. This combination is called advanced exergoeconomic analysis. In the future, the H&S Model may be applied in order to verify its feasibility for this purpose. The case study could be the same ORC.

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NOTATION

Symbols:

h	specific enthalpy, [kJ/kg]
$\dot{m}$	mass flow rate, [kg/s]
s	specific entropy, [kJ/(kgK)]
x	quality, [-]
$\dot{E}$	exergy rate, [kW]
$\dot{H}$	enthalpic term, [kW]

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P	pressure, [kPa]
$\dot{Q}$	heat transfer rate, [kW]
$\dot{S}$	entropic term, [kW]
T	temperature, [°C]
$\dot{W}$	power, [kW]
η	isentropic efficiency, [-]

Subscripts and superscripts:

0	reference state
cnd	condenser
evp	evaporator
exp	expander
k	kth component
net	net power
pmp	pump
AV	avoidable
D	destruction
EN	endogenous
EX	exogenous
F	fuel
H	heat source
ORC	organic Rankine cycle
P	product
SPECO	Specific Exergy Costing
UN	unavoidable

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