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Advanced Exergy Scrutiny of a Dual-loop Organic Rankine Cycle for Waste Heat Recovery of a Heavy-duty Stationary Diesel Engine

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ABSTRACT

In this paper, the normal exergy scrutiny (NES) and advanced exergy scrutiny (AES) of a waste heat recovery (WHR) system was performed. The proposed system contains a dual-loop organic Rankine cycle (DORC) which recovers the available waste heat of the intake air, exhaust gas, and coolant streams of a 12-cylinder heavy-duty stationary diesel engine. A well-known method of the AES called the thermodynamic cycle approach is utilized to determine each component exergy destruction parts namely exogenous/endogenous, unavoidable/avoidable, etc. Results showed that 59.04 kW from the 258.69 kW total exergy destruction rate of the system could be eliminated (22.82% of the total exergy destruction rate). The total avoidable exergy destruction part of the low-temperature loop accounts for 46.62 kW, which indicates that it requires more attention than that of the high-temperature loop by 12.42 kW. Furthermore, it is revealed that to enhance the overall productivity of the system, there is a relatively significant difference in priority order regarding the improvement of system components. The AES has proposed this ranking for improvement priority of components: condenser, expander 2, expander 1, respectively. While the NES has specified the priority as the evaporator 1, condenser, expander 2, respectively.

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NOMENCLATURE

E	Exergy rate (kW)	HT	High-temperature
H	Enthalpy	ICE	Internal combustion engine
N	Engine Speed (RPM)	LT	Low-temperature
P	Pressure (kPa)	AES	Advanced exergy scrutiny
S	Entropy	MFR	Mass flow rate
W	Power (kW)	NES	Normal exergy scrutiny
Abbreviations		ORC	Organic Rankine cycle
AV	Avoidable	**Subscripts**	
UN	Unavoidable	D	Destruction
WHR	Waste heat recovery	ex	Exergy
EN	Endogenous	th	Thermal
EX	Exogenous		

1. INTRODUCTION

With the growing human population, dependence on energy and its applications is increasing dramatically. Nonetheless, the world's non-renewable main energy resources are restricted. As a result, it is crucial to develop energy conversion systems and technologies to utilize the maximum capacity of existing resources optimally. In recent years, organic Rankine cycles (ORCs) have gained special attention due to their excellent reliability, low maintenance, and high productivity [1, 2]. Working fluid selection and developing the system configuration are two significant challenges in designing a well-productive ORC waste

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heat recovery (WHR) system[3, 4]. Developing a hydrogen production solid oxide electrolysis (SOEC) by marine engine ORC-WHR system was evaluated by Wang et al. [5]. The results revealed that the rate of hydrogen production and power production in the proposed system were 0.43 kg/s and 32387 kW, respectively. Also, the ORC efficiency and the integrated system achieved at 12.12% and 53.56%, respectively. An innovative hybrid-reversible ORC, ejector refrigeration cycle (ERC), and mobile air conditioning (MAC) system was investigated numerically and experimentally by Di Cairano et al. [6] for series hybrid electric vehicles (SHEV). Results revealed that in the ORC mode, the proposed hybrid system indicates a maximum calculated net efficiency of 3.9%, and in the ERC mode, the estimated fuel economy was 1.4%. Wang et al. [7] studied A novel analysis technique for selecting of operating fluid pairs utilized in the dual-loop ORC-engine WHR system. According to the results, toluene/R124 was found a great fluid couple for the proposed system. Di Battista et al. [8] evaluated the WHR capability of Ireland Custom Exhaust (ICE) exhaust gases through a combined supercritical CO_2-ORC cycle. As a comparison between the combined system and a single-based system, they determined that the overall efficiency of the combined system was around 3-4% greater. For a solid oxide fuel cell (SOFC), Emadi et al. [9] investigated the selection of operating fluids plus optimization of a cogeneration DORC-WHR system. The Thermodynamic and economic performance of the DORC system by 20 organic fluids was examined, which the combination of R601 for the topping cycle and ethane for the bottoming cycle was selected as the optimum. Also, the exergy efficiency of 52% and the power production of 969 kW were determined. A high-efficiency WHR system comprising SOFC, HCCI engine, and ORC is developed and examined by Ouyang et al. [10]. The effects of input variables on HCCI engine performance were determined, and the optimal zeotropic working fluid of ORC was observed in terms of exhaust gas stream temperature. They found that the combined system's exergy and energy efficiencies are more than 61.3% and 63.6%, respectively. These are about 17.95% and 18.76% higher than that of a simple cell.

In recent years, researchers have performed the advanced exergy examination approach for multiple works. This approach is also called advanced exergy scrutiny (AES). The AES is defined as the division of the exergy destruction rate for a given stream into four-parts of avoidable-unavoidable and endogenous-exogenous. This analysis is applied to provide more information regarding the inefficiencies due to interconnection between system components that the normal exergy scrutiny (NES) could not indicate. In addition, this approach can be employed to find the real ability of the system in order to further improvements and optimizations. Zhang et al. [11] investigated the performance of an integrated system containing an ORC and the transcritical CO_2 energy storage and using AES. R290 was selected as the organic operating fluid of ORC system. Results showed that the exergy efficiency of proposed system was determined around 35% under real conditions. For the unavoidable conditions it was near 42%. This exhibits the substantial improvement capacity of the system productivity. The AES of an ORC-based configuration for WHR of flue gases in processes of a coal-fired plant studied by Liao et al. [12]. Multiple configurations have been examined, and results showed that the exogenous exergy destruction part was fewer than the endogenous part in components. Also, results demonstrated that 25.65% part of the overall system exergy destruction is avoidable. Wang et al. [13] studied the AES and exergoeconomic analyzes of an integrated system containing CO_2 storage-capture plus WHR operations. The entire system exergy destruction rate was determined about 36 MW, of which the ORC process accounted for 32.35%, the CO_2 storage-capture process was 43.15%, and the absorption refrigeration cycle process determined near 25%. To achieve the actual potential of the system for improvement, the AES was performed for a recompression sCO_2-cycle by Mohammadi and co-workers [14]. The proposed system exergy efficiency was determined near 17.15% and 16.65% in terms of unavoidable and real conditions, respectively. The results revealed that the greatest potentiality for enhancement was calculated for 107 MW. Also, they found to enhance the system productivity, the priority ordering of system components obtained via the advanced exergy scrutiny differs from normal exergy scrutiny (NES). Moreover, many investigators studied this method for various new energy conversion systems and plants.

To the authors' knowledge, there are very few studies which investigated a waste heat recovery system consisting of a DORC and a stationary heavy-duty Diesel (HDD) engine by means of the advanced exergy scrutiny (AES) which could enhance the value of the conclusions obtained from a normal exergy scrutiny (NES) by demonstrating the real potential for performance improvement of system components. Hence, in this investigation, the DORC-HDD engine system is numerically modeled, and energy plus exergy characteristics of the system has been studied. In addition, the AES is utilized to reveal a detailed information regarding the components inefficiency on each other as well as the real potential of system for enhancement. The results achieved by both the exergy scrutiny approaches are compared, and the improvement priority of components in terms of each method has been provided. The structure of this study is as follows: the proposed system, HDD engine descriptions as well as exergy analysis are introduced in section 2. Section 3 contains the result and discussion. Eventually, the conclusion is provided in section 4.

2. SYSTEM DESCRIPTION

2. 1. Engine Modeling

The engine exhaust gas, intake air, and coolant streams drive the bottoming DORC system. Thus, the 1-D numerical configuration of the 12-cylinder stationary HDD engine is simulated using the GT-Power [15] software. By employing the GT-Power, the heat transfer and flow processes through each component of the engine are modeled 1-dimensionally. The engine configuration model and the main technical specifications are provided in Figure 1 and Table 1. Moreover, it should be noted that the experimental validation of engine performance is provided in our previous work [16].

2. 2. Dual-loop Organic Rankine Cycle (DORC)

The DORC system, the high-temperature (HT) loop comprises pump1, evaporator1, expander1, preheater, and reservoir1, recovering the HDD engine exhaust gases available waste heat. The low-temperature (LT) loop recovers the remaining unconsumed thermal energy of the HT loop plus the dissipated energy of intake air and coolant streams. The LT loop has involved pump2, intercooler, evaporator2, expander2, condenser, and reservoir2. The proposed DORC system is illustrated in Figure 2.

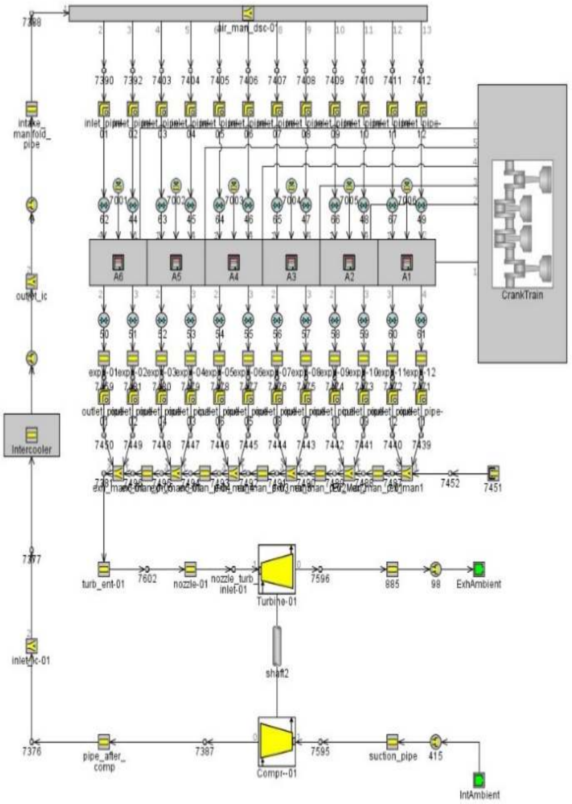

Figure 1. Configuration of the HDD engine model in GT-Power

Due to its appropriate thermodynamic properties, R245fa is one of the most common organic operating fluids applied in medium-high temperature ORC-WHR systems [17]. So, the fluid of R245fa is considered as the operating fluid of the HT loop. Because of the low temperature of the waste heats utilized, there is no matter regarding the de-composition of the LT loop working

TABLE 1. HDD engine specifications

Parameter	Value
Engine type	Turbocharged Heavy-duty Diesel, water-cooled
Rated speed	1500 RPM
Rated power	1000 kW
Displacement	38 L
Number of cylinders	12
Compression ratio	15:1
Bore × Stroke	150 mm × 180 mm
Exhaust gases temperature	530 °C
Exhaust gases mass flow rate	1.4 kg/s
Coolant temperature	84 °C

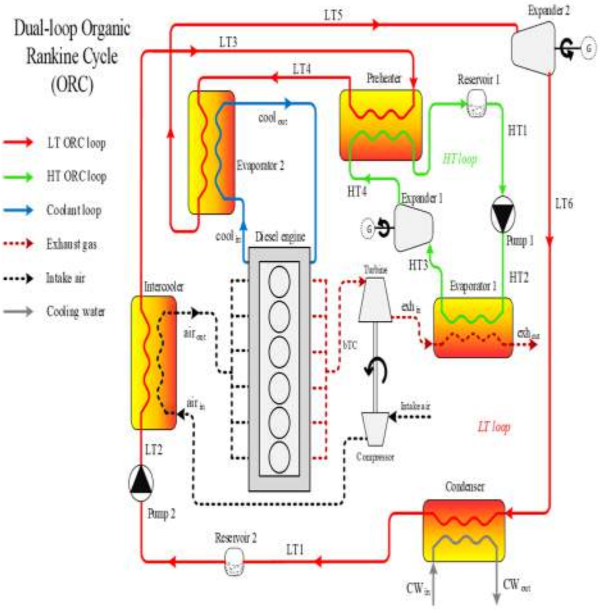

Figure 2. Construction of the proposed dual-loop ORC-WHR system

fluid. Therefore, because of its desirable thermal attributes, the R134a has been considered in the role of operating fluid for the LT loop. Thermo-environmental attributes of the organic fluids of loops are displayed in Table 2 [18-20].

The working process of the DORC system is as follows: the waste heat of the HDD engine exhaust gas stream is conveyed to the operating fluid of the HT loop, R245fa (process exhin-exh¬out). This makes the R245fa fluid evaporate and reach to the saturated vapor state (state HT3). Then, by operation HT3 to HT4, the expansion procedure occurs, and the useful power is produced. After that, the working fluid remains at the superheated vapor state. Then, the condensation operation proceeds by transferring the heat to the working fluid of the LT loop. Consequently, at HT1, the R245fa converts to the saturated liquid state. Eventually, the pumping happens and via the process HT1-HT2, R245fa is conveyed from reservoir 1 to pump 1. Meantime, by crossing into reservoir 2, the R134a is pumping over process LT1-LT2. Then, via passing into the intercooler, the working fluid is heated through the available dissipated energy of engine intake charge air (LT2-LT3). After that, over the LT3-LT4 process, the working fluid obtains some heat through the pre-heater and converts to the saturated two-phase of liquid-gas state. Then, to make sure there is no liquid that survives during the expansion process, the superheating is essential. Thus, via LT5 and through evaporator 2, the engine coolant stream is heating the R134a and converts it to the superheated state. Following the expansion process (LT5-LT6), the working fluid still experiences a superheated state. So, the condensation process is performed, and the R134a returns to the saturated liquid state (LT1).

2. 3. Exergy Scrutiny In order to facilitate the thermodynamic modeling process and simplifying the exergy scrutiny, some assumptions are required to make for the DORC system:

1) The changes in kinetic energy are neglected, and the entire system works at steady-state condition [21].
2) Pressure loss over the heat exchangers and pipes is ignored [22].
3) The pinch-point temperature difference is evaluated for each heat exchanger.
4) The ambient temperature and atmospheric pressure are defined as 20 °C and 101.325 kPa, respectively.
5) To avoid acid corrosion happening, the temperature of the exhaust gases after the recovery process should be over 100 °C [23].

TABLE 2. Properties of the DORC working fluids

Loop	Working fluid	Critical pressure (kPa)	Critical temperature (K)	GWP (100 year)	ODP
HT loop	R245fa	3640	427.3	1030	0
LT loop	R134a	4060	374.2	1430	0

2. 3. 1. Normal Exergy Scrutiny (NES) According to the presumptions of the last section, the thermodynamic balance equations for each DORC system component is defined as follows [24]:

$$E_Q + \sum m_i e_i = W + \sum m_e e_e + E_D \tag{1}$$

$$Q + \sum m_i h_i = W + \sum m_e h_e \tag{2}$$

$$\sum m_e - \sum m_i = 0 \tag{3}$$

$$E = me \tag{4}$$

where, E_Q is considered as the exergy related to the heat transfer, $\sum m_i e_i$ is defined as the input exergy, $\sum m_e e_e$ is the rate of output work, denotes the rate of output exergy flow, E_D is the exergy destruction rate, represents the stream MFR, Q is the heat transfer rate, $\sum m_i h_i$ and $\sum m_e h_e$ indicate the rate of input enthalpy and output enthalpy, respectively. Also, the rate of exergy transferred by thermal energy at the given temperature of T can be examined by :

$$E_Q = Q\,(1 - \frac{T_0}{T}) \tag{5}$$

here, the ambient temperature is characterized by T_0. To calculate the overall productivity of the DORC-WHR system, the exergy efficiency equation is required:

$$\eta = \left(\frac{exergy\ of\ products}{total\ exergy\ inputs} \right) \tag{6}$$

For the *kth* system component, the primary equations required for the NES are [25, 26]:

$$E_{F,k} = E_{P,k} + E_D \tag{7}$$

$$\varepsilon_k = \frac{E_{P,k}}{E_{F,k}} \times 100\% = \left(1 - \frac{E_D}{E_{F,k}} \right) \times 100\% \tag{8}$$

$$y_k^* = \frac{E_D}{E_{D,tot}} \times 100\% \tag{9}$$

$$y_k = \frac{E_D}{E_{F,k}} \times 100\% \quad (10)$$

here, $E_{F,k}$ is the fuel exergy rate, $E_{P,k}$ is the product exergy rate, ε_k denotes the exergy efficiency, y_k^* represents the relative exergy destruction, and y_k is the ratio of exergy destruction.

In Table 3, the balance equations of each component in terms of the energy and exergy analysis is provided [27].

2. 4. 1. Advanced Exergy Scrutiny (AES) As mentioned before, the rate of exergy destruction for every component is split in four parts of avoidable-unavoidable as well as endogenous-exogenous. This dividing technique is called advanced exergy scrutiny (AES). It is implemented to exhibit the accurate information related to inefficiencies of interconnection within the system components, and in order to determine the system's actual capability for extra enhancement.

In a system, the exergy destruction rate of each component is divided into two parts of the exogenous exergy destruction $E_{D,k}^{EX}$, and the endogenous exergy destruction $E_{D,k}^{EN}$ [28]:

$$E_{D,k} = E_{D,k}^{EX} + E_{D,k}^{EN} \quad (11)$$

Here, $E_{D,k}^{EX}$ presents the irreversible process within a component, and the irreversible process within other components is defined by $E_{D,k}^{EN}$. Defining the concept of dual exogenous-endogenous rate of exergy destruction helps to investigate various irreversibility in the proposed system. Applying this approach leads to identify whether the system modification must be assigned to the *kth* component or others [29, 30]. The exergy destruction rate can also be divided in unavoidable exergy destruction $E_{D,k}^{UN}$ part and avoidable exergy destruction $E_{D,k}^{AV}$ part [31, 32]:

$$E_{D,k} = E_{D,k}^{UN} + E_{D,k}^{AV} \quad (12)$$

here, $E_{D,k}^{UN}$ defines the certain exergy destruction part that could not be decreased because of engineering constraints. $E_{D,k}^{AV}$ is specified as other part of the exergy destruction that could be diminished through suitable modification techniques. In a certain system, the mentioned dividing approach can demonstrate the possible improvement of components.

TABLE 3. Balance equations of each component

Component	Energy balance equation	Exergy balance equation
Evap.1	$m_{HT2}\left(h_{HT3} - h_{HT2}\right) =$ $m_{exh,out}\left(h_{exh,in} - h_{exh,out}\right)$	$E_{HT2} + E_{exh,in} =$ $E_{HT3} + E_{exh,out} + E_{D,eva1}$
Exp.1	$W_{\exp 1} = m_{HT3}\left(h_{HT3} - h_{HT4}\right)$	$E_{HT3} = E_{HT4} + W_{\exp 1} + E_{D,\exp 1}$
Preh.	$m_{HT4}\left(h_{HT4} - h_{HT1}\right) =$ $m_{LT4}\left(h_{LT4} - h_{LT3}\right)$	$E_{HT4} + E_{LT3} =$ $E_{HT1} + E_{LT4} + E_{D,pre}$
Pump1	$W_{pump1} = m_{HT1}\left(h_{HT2} - h_{HT1}\right)$	$E_{HT1} + W_{pump1} = E_{HT2} + E_{D,pump1}$
Evap.2	$m_{cool,in}\left(h_{cool,in} - h_{cool,out}\right) =$ $m_{LT5}\left(h_{LT5} - h_{LT4}\right)$	$E_{LT4} + E_{cool,in} =$ $E_{LT5} + E_{cool,out} + E_{D,eva2}$
Exp.2	$W_{\exp 2} = m_{LT5}\left(h_{LT5} - h_{LT6}\right)$	$E_{LT5} = E_{lT6} + W_{\exp 2} + E_{D,\exp 2}$
Cond.	$m_{LT6}\left(h_{LT6} - h_{LT1}\right) =$ $m_{CW,out}\left(h_{CW,out} - h_{CW,in}\right)$	$E_{LT6} + E_{CW,in} =$ $E_{LT1} + E_{CW,out} + E_{D,cond}$
Pump2	$W_{pump2} = m_{LT1}\left(h_{LT2} - h_{LT1}\right)$	$E_{LT1} + W_{pump2} = E_{LT2} + E_{D,pump2}$
Interc.	$m_{air,in}\left(h_{air,in} - h_{air,out}\right) =$ $m_{LT3}\left(h_{LT3} - h_{LT3}\right)$	$E_{LT2} + E_{air,in} =$ $E_{LT3} + E_{air,out} + E_{D,\mathrm{int}er}$

Four parts of the exergy destruction rate are not influenced by each other. Hence, various equations for exogenous-endogenous and unavoidable-avoidable exergy destruction parts is provided as follows [33]:

$$E_{D,k}^{EX} = E_{D,k}^{EX,UN} + E_{D,k}^{EX,AV} \tag{13}$$

$$E_{D,k}^{EN} = E_{D,k}^{EN,UN} + E_{D,k}^{EN,AV} \tag{14}$$

$$E_{D,k}^{UN} = E_{D,k}^{EX,UN} + E_{D,k}^{EN,UN} \tag{15}$$

$$E_{D,k}^{AV} = E_{D,k}^{EN,AV} + E_{D,k}^{EX,AV} \tag{16}$$

in presented equations, $E_{D,k}^{EX,UN}$ is defined as the exogenous unavoidable part of exergy destruction rate, $E_{D,k}^{EX,AV}$ indicates the exogenous avoidable part, $E_{D,k}^{EN,UN}$ specifies the endogenous unavoidable exergy destruction rate, and $E_{D,k}^{EN,AV}$ denotes the endogenous avoidable part. The $E_{D,k}^{UN}$ is divided into exogenous and endogenous exergy destruction parts as represented by $E_{D,k}^{EX,UN}$ and $E_{D,k}^{EN,UN}$, respectively. Likewise, the $E_{D,k}^{AV}$ has an exact definition and is divided into $E_{D,k}^{EX,AV}$ and $E_{D,k}^{EN,AV}$ parts.

Equation (17) is an essential relationship that represents the combination of avoidable-unavoidable and endogenous-exogenous exergy destruction parts for the certain component of *k*:

$$E_{D,k} = E_{D,k}^{EN,AV} + E_{D,k}^{EN,UN} + E_{D,k}^{EX,AV} + E_{D,k}^{EX,UN} \tag{17}$$

Usually, through the engineering improvement of the *kth* component, the $E_{D,k}^{EN,AV}$ can be reduced. However, due to the technological restrictions of the component, the $E_{D,k}^{EN,UN}$ is irreducible. To reduce the $E_{D,k}^{EX,AV}$ of the *k*th component, increasing the *k*th component's efficiency as well as improving the efficiency of the related components is effective. Furthermore, due to the technical limitations related to the components of the system, the $E_{D,k}^{EX,UN}$ of the *k*th component cannot be modified.

In recent years, multiple approaches have been recommended for determining parts of the exergy destruction rate using the AES: 1. The structural theory approach, 2. Engineering approach, 3. Exergy balance approach, 4. Thermodynamic cycle approach, etc. [28, 34]. In this research, the thermodynamic cycle approach is implemented to estimate the components' exergy destruction in avoidable-unavoidable and exogenous-endogenous divisions. For relatively complex thermodynamic cycles, the high prediction accuracy is an essential requirement. So, the thermodynamic cycle approach is considered the most suitable approach for these cycles [14].

Based on the thermodynamic cycle approach, to determine the exergy destruction parts it is required to identify the differences between the hybrid, real, and unavoidable cycles. The unavoidable cycle is defined in this way: the whole thermodynamic processes of the cycle are performed as ideal processes, while the technological limitations of the components are considered. The real cycle is: considering the whole thermodynamic processes of the system as irreversible processes under real conditions. The hybrid cycle is defined as: the thermodynamic process related to the kth component is examined as irreversible, while the other system components are operating as ideal process [35].

The unavoidable exergy destruction is calculated when the whole cycle operates under unavoidable conditions [36]:

$$E_{D,k}^{UN} = E_{P,k}^{real} \times \left(\frac{E_{D,k}}{E_{P,k}} \right)^{UN} \tag{18}$$

Via considering the hybrid cycle for the *k*th component, the endogenous part of the exergy destruction rate is computed:

$$E_{D,k}^{EN} = E_{P,k}^{real} \times \left(\frac{E_{D,k}}{E_{P,k}} \right)^{EN} \tag{19}$$

The endogenous unavoidable part of the exergy destruction rate can be determined as the given component runs under unavoidable conditions, while the other cycle components operate under reversible conditions:

$$E_{D,k}^{EN,UN} = E_{P,k}^{EN} \times \left(\frac{E_{D,k}}{E_{P,k}} \right)^{UN} \tag{20}$$

3. RESULTS AND DISCUSSIONS

The comprehensive examination of advanced exergy method for the DORC-HDD system is accomplished by solving the numerical model of the system under various conditions of hybrid, unavoidable, and real. The numerical model is developed in MATLAB [37] environment, and REFPROP [38] is utilized as the thermodynamic reference to specify the characteristics of the operating fluids. In Tables 4 and 5, the simulation presumptions as well as main designing variables for the ideal, unavoidable, and real conditions are outlined.

3. 1. Normal Exergy Scrutiny Results

The DORC system is simulated numerically using the conservation equations of the energy, exergy, and mass balance for

TABLE 4. Main parameters applied in the simulation

Parameter	Unit	Value
Inlet pressure of pump1	kPa	690
Inlet pressure of expander1	kPa	3300
Inlet pressure of expander 2	kPa	2250
Inlet temperature of expander1	°C	148
Inlet temperature of pump2	°C	T_0+10
ΔT_{PP} for evaporator1	°C	28
ΔT_{PP} for other heat exchangers used in the cycle	°C	5-15
Isentropic pumps efficiency	-	85%
Isentropic expanders efficiency	-	80%

TABLE 5. Assumptions for components under ideal, real, and unavoidable conditions

Component	Parameter	Ideal	Real	Unavoidable
Evaporator 1	ΔT_{PP}	0	28	15
	ΔP	0	3%	1%
Preheater	ΔT_{PP}	0	5	3
	ΔP	0	3%	1%
Evaporator 2	ΔT_{PP}	0	5	3
	ΔP	0	3%	1%
Intercooler	ΔT_{PP}	0	18	10
	ΔP	0	3%	1%
Condenser	ΔT_{PP}	0	8	4
	ΔP	0	3%	1%
Expander 1	η_{Exp1}	1	0.85	0.95
Pump 1	η_{P1}	1	0.85	0.95
Expander 2	η_{Exp2}	1	0.85	0.95
Pump 2	η_{P2}	1	0.85	0.95

various components of the system working as an individual control volume under a steady-state conditions. The main thermodynamic characteristics of the system are computed in terms of ideal, real, and unavoidable conditions. The results are represented in Tables 6-8. Also, in Tables 9-11, the main results of exergy scrutiny for the components of the system in terms of the ideal, real, and unavoidable conditions are specified.

Figures 3 and 4 demonstrate the exergy efficiency and exergy destruction rate of various components of the DORC system under real conditions, respectively. Also, Figure 5 indicates the relative exergy destruction of components in terms of the real conditions. As demonstrated in Figure 3, evaporator 2 plus turbomachines (pumps and expanders) have a relatively high exergy efficiency (>85%). In heat exchangers, higher temperature differences between the flowing streams within the components require higher energy consumption to perform the heat transfer process. This leads to increased exergy destruction as well as decreased exergy efficiency and vice versa. Hence, in evaporator 2, there is no phase change process which means the component requires little heat transfer. So, evaporator 2 has the maximum exergy efficiency between the heat exchangers and the whole system. In pumps and expanders, the greater the isentropic efficiency of the component, the greater value of exergy efficiency (Figure 3) as well as, the lower value of the exergy destruction (Figure 4) and vice versa.

Considering Figure 4, it is indicated that to perform the phase transition process in evaporator 1, the high-temperature difference between the exhaust gas and R245fa streams lead to the highest rate of the system exergy destruction (>95 kW). Considering Figure 5, it is demonstrated that 68.03% of the total exergy destruction rate of the system, is shared by evaporator 1 (36.69%) and condenser (28.34%). Also, pump 1 (0.38%) and pump 2 (0.76%) have the minimum relative exergy destructions of the system followed by evaporator 2 and expander 1.

TABLE 6. Thermodynamic properties and mass flow rates at different state points of the DORC system under real conditions at various state points

State	***m*** (kg/s)	T (K)	P (kPa)	H (kJ/kg)	S (kJ/kg.K)	***E*** (kW)
HT1	2.81	346.6	669.3	299.74	1.321	27.80
HT2	2.81	348.4	3300	302.32	1.322	34.15
HT3	2.81	419.9	3201	486.18	1.785	169.15
HT4	2.81	353.8	690	465.15	1.796	101.22
LT1	8.29	307.5	873	248.17	1.164	328.25
LT2	8.29	308.8	2550	249.85	1.165	340.20
LT3	8.29	316.6	2473.5	261.43	1.202	345.70
LT4	8.29	341.6	2399.2	317.60	1.372	398.25
LT5	8.29	358.1	2327.3	445.58	1.738	568.98
LT6	8.29	319.0	900	428.57	1.748	405.06

TABLE 7. Thermodynamic properties and mass flow rates of the DORC system under ideal conditions at various state points

State	*m* (kg/s)	T (K)	P (kPa)	H (kJ/kg)	S (kJ/kg. K)	*E* (kW)
HT1	2.85	347.86	690	301.45	1.325	29.02
HT2	2.85	349.36	3300	303.64	1.325	35.27
HT3	2.85	421.58	3300	484.76	1.781	171.19
HT4	2.85	349.35	690	459.95	1.781	100.28
LT1	7.81	308.67	900	249.78	1.169	310.15
LT2	7.81	309.73	2550	251.19	1.169	321.18
LT3	7.81	316.69	2550	261.42	1.202	326.30
LT4	7.81	342.86	2550	319.39	1.377	378.08
LT5	7.81	358.16	2550	440.22	1.718	540.15
LT6	7.81	310.39	900	419.32	1.720	376.82

TABLE 8. Thermodynamic properties and mass flow rates of the DORC system under unavoidable conditions at various state points

State	*m* (kg/s)	T (K)	P (kPa)	h (kJ/kg)	s (kJ/kg.K)	*E* (kW)
HT1	2.84	347.4	683.10	300.88	1.324	28.60
HT2	2.84	349.0	3300	303.19	1.324	34.88
HT3	2.84	421.0	3267	485.29	1.783	170.50
HT4	2.84	350.8	690	461.73	1.786	100.57
LT1	7.96	308.3	891	249.25	1.167	316.04
LT2	7.96	309.4	2550	250.74	1.168	327.36
LT3	7.96	316.6	2524.5	261.42	1.202	332.61
LT4	7.96	342.4	2499.3	318.80	1.375	384.66
LT5	7.96	358.1	2474.3	442.15	1.725	549.87
LT6	7.96	313.3	900	422.53	1.729	385.84

TABLE 9. Results of exergy scrutiny for DORC system under real

Component	E_F (kW)	E_P (kW)	E_D (kW)	ε (%)	y^* (%)	y (%)
Evaporator1	228.2	131.6	96.6	57.6	39.69	11.54
Expander1	67.9	58.9	9.0	86.7	3.70	1.08
Preheater	73.4	52.4	21.0	71.3	8.64	2.51
Pump 1	7.2	6.33	0.9	87.0	0.39	0.11
Evaporator2	187.5	178.8	8.6	95.3	3.56	1.03
Expander 2	163.9	140.5	23.3	85.7	9.60	2.79
Condenser	76.8	7.8	69.0	10.1	28.35	8.24
Pump 2	13.9	12.0	1.8	86.5	0.77	0.22
Intercooler	18.2	5.3	12.9	29.2	5.31	1.54
HT loop	376.8	249.2	127.5	22.7	-	-
LT loop	460.4	344.6	115.8	45.4	-	-
DORC syst.	837.3	593.9	243.4	41.2	100.0	29.07

TABLE 10. Results of exergy scrutiny for DORC system under ideal conditions

Component	E_F (kW)	E_P (kW)	E_D (kW)	ε (%)	y^* (%)	y (%)
Evaporator1	229.9	137.9	91.9	60.0	57.90	11.37
Expander1	71.9	71.9	0.0	100	0.00	0.00
Preheater	72.3	52.5	19.7	72.6	12.45	2.44
Pump 1	6.3	6.3	0.0	100	0.00	0.00
Evaporator2	169.4	164.5	4.8	97.1	3.08	0.60
Expander2	165.7	165.7	0.0	100	0.00	0.00
Condenser	67.6	34.7	32.9	51.3	20.72	4.07
Pump2	11.1	11.1	0.0	100	0.00	0.00
Intercooler	14.4	5.2	9.29	35.8	5.85	1.15
HT loop	380.5	268.8	111.7	28.55	-	-
LT loop	428.5	381.4	47.0	60.34	-	-
DORC syst.	809.1	650.2	158.8	53.2	100	19.63

3. 2. Advanced Exergy Scrutiny Results

As presented in Table 5, performing the AES needs more hypothesis for conditions of ideal, unavoidable, and real. The main result achieved by AES for the DORC is provided in Table A1 in Appendix. According to Table A1, it is inferred the endogenous part of the exergy destruction is larger than the exogenous part for each system component. Accordingly, the main portion of the components' exergy destruction rate originates through the internal irreversibility of each component itself.

Hence, it can be evolved that the interconnection between components is insignificant. It means the most essential consideration for system optimization should be given to improvement of system components. The greatest exogenous part of the exergy destruction rate is discovered in the condenser, intercooler, and evaporator 1. This indicate that modifications in other components' efficiency make a reduction in the value of exergy destruction for mentioned components, and consequently increment of the whole system productivity. The endogenous part of the exergy destruction for several components is greater than its exergy destruction. In the thermodynamic cycle, the interconnections among various components lead to the production of extra irreversibility. As an increase in entropy production of the system outweighs the reduction in the MFR. Thus, decreasing the rate of exergy destruction for these components can yield the increment in amount of this parameter in related components of the system. This demonstrates that the interconnection between the system components is not relatively simple.

Furthermore, by looking at the avoidable column of Table A1, it is inferred that 59.04 kW of the 258.69 kW total system exergy destruction could be eliminated. Thus, 22.82% of the DORC system exergy destruction rate can be decreased. Between the system components, the avoidable part of the exergy destruction rate for expander 2 is the most significant (16.43 kW), followed by expander 1, pump 2, and pump 1 (6.41 kW, 1.27 kW, 0.66 kW). Expander and pumps are holding 41.95% of the entire system avoidable part of the exergy destruction rate. This implies that these components possess an excellent capacity for boosting by applying engineering modifications and modern technologies. Accordingly, decreasing the exergy destruction rate of pumps and expanders is possible, and this is directly relevant to enhancing the whole cycle performance. The LT loop avoidable part of the exergy destruction is calculated to be 46.62 kW (78.96%), which indicates that it requires more attention than that of the HT loop by near 12.42 kW (21.03%).

TABLE 11. Results of exergy scrutiny for DORC system under unavoidable conditions

Component	E_F (kW)	E_P (kW)	E_D (kW)	ε (%)	y^* (%)	y (%)
Evaporator1	228.2	135.6	92.60	59.4	47.16	11.41
Expander 1	69.9	66.9	2.9	95.7	1.50	0.36
Preheater	71.9	52.0	19.9	72.3	10.14	2.45
Pump 1	6.5	6.2	0.2	95.8	0.14	0.03
Evaporator2	173.7	165.2	8.5	95.0	4.34	1.05
Expander 2	164.0	156.3	7.7	95.3	3.93	0.95
Condenser	69.8	16.2	53.5	23.2	27.29	6.60
Pump 2	11.8	11.3	0.5	95.2	0.29	0.07
Intercooler	15.4	5.2	10.2	33.9	5.21	1.26
HT loop	376.6	260.9	115.7	26.4	-	-
LT loop	434.9	354.3	80.6	55.3	-	-
DORC syst.	811.6	615.2	196.3	49.0	100.00	24.19

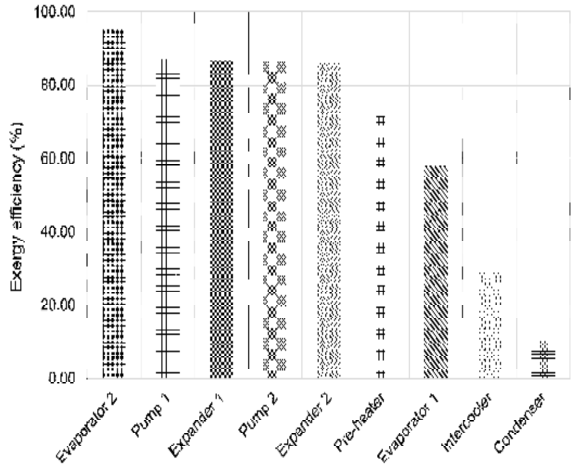

Figure 3. Exergy efficiency of each component in DORC-WHR system

The avoidable-exogenous part as well as the avoidable-endogenous part of the exergy destruction rate can be decreased via enhancing the efficiency of components. Therefore, to boost the cycle productivity, improving performance of those components with larger avoidable endogenous part must be the prime concern. By a proper modification to the *kth* system component, the endogenous avoidable exergy destruction part which related to this component can be lessened. Moreover, the exogenous avoidable exergy destruction rate of the *kth* component can also be decreased by modifying the whole structure of the system, as well as improving the efficiency of each component including the *kth* component. According to Table A1, it represents that the avoidable endogenous parts of exergy destruction rate for all expanders and pumps are greater than the unavoidable endogenous part associated with these components. It means, through appropriate technological modifications, the performance of mentioned components as well as productivity of the entire cycle can be raised.

The exogenous avoidable part for almost any component of the system is calculated with a negative value. This shows decreasing the value of exergy destruction rate for most components can raise the exergy destruction rate of remaining components. However, the real value regarding the exogenous avoidable part of the condenser, evaporator 1, and intercooler is relatively higher. This is denoting that the exergy destruction rate of the mentioned components had a more prominent effect on relevant components of the system. Applying improvements in productivity of the condenser, evaporator 1, and intercooler can directly add the rate of the exergy destruction for the entire cycle. Considering Table A1 once more, shows results regarding the entire cycle endogenous avoidable part as well as endogenous unavoidable part. As it is seen, the system overall endogenous unavoidable part is larger than the endogenous avoidable part, which denotes that the potential of the DORC system for improvement is not significant. In Figures 6-8, the relative exergy destruction rate of DORC system regarding endogenous avoidable, avoidable, and unavoidable parts is provided.

3. 3. Comparison Between Results of the AES and NES

Considering Figures 5 and 7, a comparison between results obtained by normal and advanced exergy scrutiny approaches is provided in Table 13. By observing at this table, it can be concluded that there is an important disparity amid the outcomes of these two methods. For instance, based on the NES, evaporator 1 has the highest priority for improvement due to the irreversibility of high-temperature differences between the exhaust gas and R245fa streams. On the other hand, according to the AES, evaporator 1 ranked in sixth position. This indicates that there is a great proportion of exergy destruction rate which is not avoidable.

Possessing the greatest avoidable exergy destruction part associated with component *kth* demonstrates that this component has an excellent capability to increase the productivity of the whole cycle. Hence, referring to results of the AES in Table 13 reveals that the condenser has the highest priority for optimization, which it can make a significant advantage for the DORC system. Likewise, expander 1 is ranked in the sixth position in terms of NES, while it held in third place according to the AES results. The results also display that the AES does not recommend any improvement for the preheater, while according to the NES, a relatively significant amount of total exergy destruction rate is assigned to the preheater. The priority of each component for improvement based on the two approaches is plainly provided. This helps the designer to optimize the system with a clearer view.

Although the priority for improvement of system components based on two approaches is contrasting, but the optimizing techniques are identical. For instance, the primary exergy destruction rate produced by a pump/expander is because of the isentropic efficiency defined for the compression/expansion process. Therefore, to enhance the isentropic efficiency, it is recommended that effective design parameters of the pump/expander to be optimized. As stated before, a large part of the exergy destruction rate in heat exchangers is produced by relatively high temperature difference of heat transfer process. So, reduction of the temperature differences is essential to increase the efficiency of the heat exchanger as well as the power production of the system. Thus, various optimization algorithms such as GA, PSO, RSM, etc. were employed for optimization of the effective parameters at the inlet and outlet of the heat exchangers.

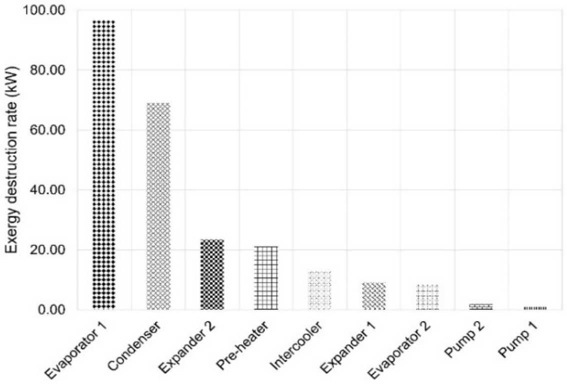

Figure 4. Exergy destruction rate of each component in DORC-WHR system

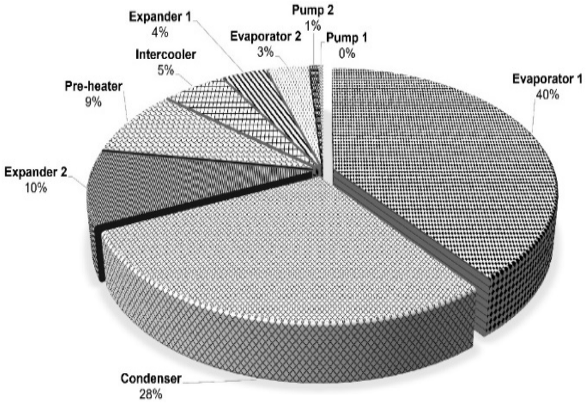

Figure 5. Relative exergy destruction of DORC system components under real condition

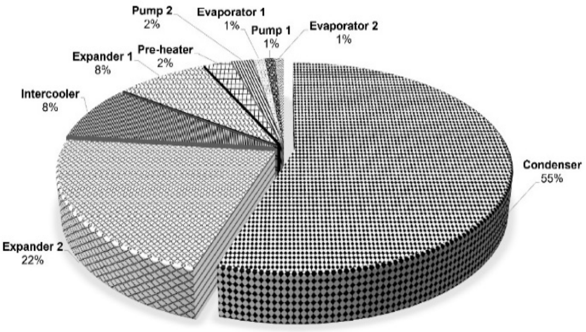

Figure 6. Relative endogenous avoidable exergy destruction rate of DORC system components

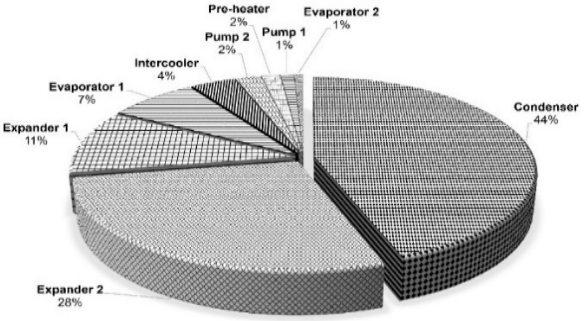

Figure 7. Relative avoidable exergy destruction rate of DORC system components

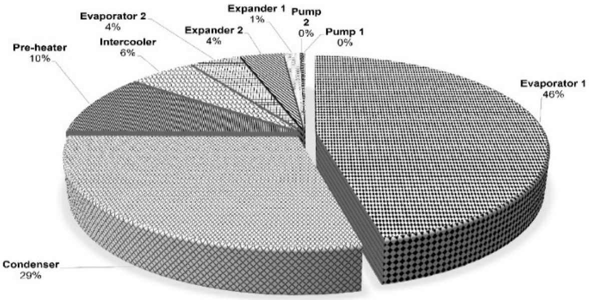

Figure 8. Relative unavoidable exergy destruction rate of DORC system components

TABLE 13. Improvement priority of the DORC system components in respect of two different approaches of exergy scrutiny

Priority	Advanced exergy scrutiny	Normal exergy scrutiny
1	Condenser	Evaporator 1
2	Expander 2	Condenser
3	Expander 1	Expander 2
4	Evaporator 1	Preheater
5	Intercooler	Intercooler
6	Pump 2	Expander 1
7	Preheater	Evaporator 2
8	Pump 1	Pump 2
9	Evaporator 2	Pump 1

4. CONCLUSIONS

In the present investigation, a WHR system containing a dual-loop ORC and an HDD engine was simulated and analyzed from viewpoints of two methods, normal and advanced exergy scrutiny. The exergy destruction rates of all system components based on these two approaches were achieved, and the significant differences between these methods were specified. The significant conclusions and the valuable outcomes of this study are presented below:

- According to the overall unavoidable and avoidable parts of the exergy destruction rate for the DORC system, the whole system exergy destruction rate can be decreased by around 23%. Pumps and expanders accounted for 41.95% of the total avoidable exergy destruction.
- For improving the entire system productivity, the advanced exergy scrutiny recommends the main consideration must assign to the condenser, expander 2, expander 1, and evaporator 1, respectively. However, the normal exergy scrutiny designates the arrangement of improvement priority as follows: evaporator 1, condenser, expander 2, and preheater, respectively.
- As a comparison between loops, the total avoidable exergy destruction part of the LT loop is 46.62 kW (78.96%), which indicates that it requires more attention than that of the HT loop by 12.42 kW (21.03%).
- The endogenous unavoidable exergy destruction rate in some components is calculated fewer than the endogenous avoidable parts of these components. This demonstrates that by proper technological modifications, the productivity of these components and eventually the whole cycle could be raised.
- The highest exogenous part of the exergy destruction rate is determined in the condenser, intercooler, and evaporator 1. This represents that modification in other components' efficiency can improve the performance of the mentioned components.

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Appendix A

TABLE A1. Results of the advanced exergy scrutiny for the DORC system

Component	E_D **(kW)**	**Splitting the exergy destruction**				**Combined two splitting approaches**			
		$E_{D,k}^{EN}$ **(kW)**	$E_{D,k}^{EX}$ **(kW)**	$E_{D,k}^{AV}$ **(kW)**	$E_{D,k}^{UN}$ **(kW)**	$E_{D,k}^{EN,AV}$ **(kW)**	$E_{D,k}^{EN,UN}$ **(kW)**	$E_{D,k}^{EX,AV}$ **(kW)**	$E_{D,k}^{EX,UN}$ **(kW)**
Evaporator1	96.61	94.59	2.02	4.44	92.17	0.77	93.82	3.67	-1.65
Expander1	9.02	8.73	0.29	6.41	2.61	6.04	2.69	0.37	-0.09
Pre-heater	21.02	21.47	-0.45	0.91	20.11	1.78	19.69	-0.87	0.42
Pump1	0.94	0.91	0.03	0.66	0.28	0.63	0.29	0.03	-0.01
Evaporator2	8.66	9.04	-0.38	0.44	8.21	0.60	8.44	-0.15	-0.23
Expander2	23.37	23.38	-0.01	16.43	6.95	16.43	6.95	-0.01	0.00
Condenser	84.28	93.65	-9.37	26.27	58.01	41.45	52.20	-15.18	5.81
Pump2	1.87	1.98	-0.11	1.27	0.59	1.41	0.56	-0.14	0.03
Intercooler	12.91	15.41	-2.50	2.20	10.71	6.24	9.18	-4.04	1.54
HT loop	127.59	125.70	1.88	12.42	115.17	9.21	116.49	3.21	-1.33
LT loop	131.10	143.47	-12.3	46.62	84.48	66.14	77.33	-19.52	7.16
DORC	258.69	269.17	-10.4	59.04	199.65	75.35	193.82	-16.32	5.83

Persian Abstract

چکیده

در این مقاله، بررسی اگزرژی معمولی (NES) و بررسی اگزرژی پیشرفته (AES) یک سیستم بازیابی گرمای اتلافی (WHR) انجام شده است. سیستم پیشنهادی شامل یک چرخه دو حلقه‌ای رنکین آلی (DORC) است که گرمای اتلافی موجود در هوای ورودی، گازهای خروجی و جریان خنک کننده یک موتور دیزل سنگین ۱۲ سیلندر را بازیابی می کند. یک روش شناخته شده از AES به نام دیدگاه چرخه ترمودینامیکی برای تعیین هر یک از اجزای تخریب اگزرژی یعنی اجزای برون‌زا/درون زا و اجزای اجتناب-پذیر/اجتناب‌ناپذیر استفاده می شود. ۵۹/۰٤ کیلووات از ۲۵۸/٦۹ کیلووات مجموع تخریب اگزرژی کل سیستم را می توان از بین برد (۲۲/۸۲٪ از تخریب اگزژی کل سیستم). کل تخریب اکسرژی اجتناب‌ناپذیر حلقه دماپایین برابر ٤۲/٦۲ کیلووات است، که نشان می دهد این حلقه نیاز به توجه بیشتری نسبت به حلقه دمابالا با مقدار ۱۲/٤۲ کیلووات دارد. علاوه بر این، مشخص شده است که برای افزایش بهره‌وری کلی سیستم، تفاوت نسبتا چشمگیری در ترتیب اولویت بهبود اجزای سیستم وجود دارد. بر همین اساس، AES این رتبه‌بندی را برای اولویت بهبود اجزاء ارائه داده است: کندانسور، منبسط‌کننده ۲ و منبسط‌کننده ۱. در حالی که NES اولویت بهبود را به ترتیب اواپراتور ۱، کندانسور و منبسط‌کننده ۲ تعیین کرده است.