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Thermodynamic evaluation of shell and tube heat exchanger through advanced exergy analysis

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ABSTRACT

Shell and tube heat exchanger is a pivotal equipment used in industries for heat transfer. Any effort to minimize the irreversibility in the heat exchanger will enhance the performance and leads to energy optimization and cost savings. In the current study, a water to water, segmental baffled shell and tube heat exchanger was considered for an investigation and designed using the Kern method. Exergy analysis and advanced exergy analysis was carried out to understand the performance of the heat exchanger and to determine the possibility of reducing irreversibilities. The results of the exergy analysis showed that the system has 684.6 kW of exergy destruction. Advanced exergy analysis was carried out through endogenous and exogenous modes and subsequently performed for avoidable and unavoidable components. Majority of the exergy destruction in the heat exchanger is avoidable. The results showed that 97.5 % of the total exergy destruction is of endogenous avoidable type. The system can be improved by changing the system configuration, design variables, mass flow rates, materials, and many other parameters. Subsequently, the exergy destruction in the pumps is unavoidable and no further design improvements are required.

1. Introduction

One of the biggest challenges facings industries nowadays is the move towards greener and more sustainable technology, as carbon emissions are the biggest threat to the world. Industrial development is increasing rapidly, and so energy demands are rising, too [1–3] but moving towards green technology is not possible for every industry immediately. A clean and sustainable energy system can help in transition, but it can be a complex model [4]. A solution can be to improve systems to use minimum energy and provide maximum work. Observing the performance, efficiency, and irreversibility associated with each component is very important in optimizing a system under consideration [5,6]. Exergy analyses allow us to analyze all three parameters of any component and an entire system [7]. Mahammadpour et al. [8] carried out energy and exergy analysis to understand the irreversibilities in biogas fired regenerative gas turbine cycle. Exergy, exergoeconomic and sustainability analysis was performed on a diesel engine operated using biodiesel fuel blends containing nanoparticles by Dogan et al. [9]. It was observed that the total exergy losses in fuel blends decreases with the nanoparticles additives.

Subsequent analysis of the system can lead to an advanced exergy analysis. Performing advanced exergy analysis on any system provides the potential improvement available for each component and helps to identify the focus of improvement that should be laid on any specific component.

One of the most common pieces of equipment in any system used in industries is a heat exchanger; specifically, a widely used heat exchanger is a shell and tube heat exchanger [10,11]. Substantial research has been conducted to identify the irreversibility of heat exchangers and to reduce energy consumption by performing exergy analyses on the system. Ahmad Hajatzadeh et al. [12] reduced the energy consumption of various heat exchangers using nanofluids. The results also showed a decreased water use in heat exchangers and reduced industrial waste. D Colorado et al. [13] performed an advanced exergy analysis on a single-state absorption heat transformer to analyze the quality of exergy destruction available. The results showed that 15 % of the irreversibility associated with the system could have been avoided by optimizing the

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Nomenclature

A	heat transfer area, m^2
B_c	Baffle cut, %
B_s	Baffle spacing, m
D_s	Shell Diameter, m
D_t	Tube outside diameter, m
Ex	exergy, kW
h	heat transfer coefficient, W k/m^2
i	inlet
$\dot{m}$	mass flow rate, kg/s
N_P	Number of tube pass
P	Pump
ΔP	pressure drop, kPa
T	tube side
U	overall heat transfer coefficient, W k/m^2
PP	pumping power, kW
W	work done
S	shell side
o	outlet
$\dot{m}$	mass flow
w	water
Re	Reynolds number

Greek Symbols

η_{HE}	heat exchangers efficiency
η_P	Pump efficiency
η_{ex}	exergetic efficiency
Φ	tube layout

Abbreviations

E_D^{AV}	Avoidable Part of exergy destruction, kW
$E_{D,k}^{EX}$	Exogenous Part Exergy destruction, kW
$E_{D,k}^{UN}$	Unavoidable Part of exergy destruction, kW
$E_{D,k}^{EN}$	Endogenous Part of exergy destruction, kW
GA	Genetic Algorithm
HE	Heat Exchanger
STHE	Shell and tube heat exchanger
UN	Unavoidable part of exergy destruction, kW
XD	Total Exergy Destruction, kW

system design. Harun et al. [14] considered an actual geothermal power plant as a test case and performed advanced exergy analysis to identify the source of exergy destruction. The Bereket geothermal power plant in Turkey was the test case, and on performing advanced exergy analysis, it was found that the exergy efficiency could have been increased by 5.9 % by improving the system. Except for turbines, all the other components had avoidable exergy destruction greater than unavoidable exergy destruction, and heat exchangers had the highest improvement potential. Benfeng Yuan et al. [15] aimed to reduce the energy consumption of a steam cracking furnace by reducing the exergy destruction occurring in the system. The exergy efficiency for the system was calculated to be 43 %, showing that the exergy is not being utilized properly. The radiation section had the highest exergy destruction, whereas tube reactors were responsible for the maximum exergy loss. The advanced exergy analysis showed that the combustion process was the highest unavoidable part of exergy destruction, while the radiation section had the highest avoidable part. Kumar Dhillon et al. [16] considered a reverse Brayton cryocooler with a 10 kW capacity at 65 K temperature. The study was based on performing and analysing the results of exergy and advanced exergy analysis on the various components of the system considered and finding the improvement potential available in them by splitting up the exergy destruction. The results showed that 61 % of the total exergy destruction was avoidable, showing much improvement potential.

Tatiana Morosuk et al. [17] performed an advanced exergy analysis on an absorption refrigeration system to observe the division of exergy destruction. They calculated the exogenous, endogenous, avoidable, and unavoidable exergy destruction at various values of the input parameters. Jamil et al. [18] designed a shell and tube heat exchanger with the Kern, Bell-Delaware, and Wills-Johnston methods and compared the results for the thermo-economic parameters. The optimization was performed using a genetic algorithm by considering the minimization of overall heat exchanger cost as the objective function. The results showed a reduction in heat transfer area by 26 %, capital cost by 20 %, and operational cost by 22 %. D Colorado et al. [19] presented an advanced exergy analysis on a compression-absorption cascade refrigeration system. The improvement potential available for the overall system was 55 %. To investigate the scopes of enhancement and the interaction between waste heat recover subsystems, the advanced exergy analysis of the combined systems was conducted by Ref. [20]. Advanced exergy analysis of a mechanical subcooled vapor refrigeration system was carried out by Solanki et al. [21]. The results showed that 38.9 % endogenous irreversible losses can be avoided.

All the research mentioned above shows the importance of advanced exergy analysis for optimizing and saving energy, which ultimately targets the economy and sustainable development. It also depicts the applications and need for various industries to conduct exergy and advanced exergy analyses. It is also observed that all the analyses are done on the overall system, not targeting just a specific component. Shell and tube heat exchanger being the important component of the system it demands special attention to address the problems of irreversibilities. This study presents the exergy and advanced exergy analyses on a shell and tube heat exchanger. The novelty of the current study lies in the adavanced analysis focusing on determining the scopes of improvement and calculating the amount of avoidable exergy destruction. Advanced exergy analysis plays a crucial role in identifying the area/focus of improvement in a particular component from the whole system, but little work has been done up to now on a shell and tube heat exchanger. Most of the research has been carried out to calculate the exergy destruction of the system however, the advanced analysis representing the avoidable and unavoidable component of exergy destruction is very limited. Thus, this paper focuses on a shell and tube heat exchanger, work which has been lacking to date.

The objectives of this study are: (i) Regenerating the results of the test case by using the Kern method, (ii) Conducting advanced exergy analysis on the system designed, (iii) Analysing the results of the advanced exergy analysis and finding the scope for improvement in the system. Section 3 describes the methodology of the investigation along with a flow chart. It presents thermodynamic modelling of the system for exergy analysis and advanced exergy analysis, further presenting the correlations for dividing exergy destruction. Section 4 includes the results and discussions of the advanced exergy analysis. Lastly, section 5 offers the conclusions from the results obtained where the improvement potential of the system is considered.

2. Methodology

A shell and tube heat exchanger was designed with the help of the Kern method [22] using MATLAB software, considering various data from Ref. [18]; all the data considered are given in Table 1. Thermal and hydraulic parameters were calculated from the data. Then the exergy calculations were made to find the stream exergies and exergy destruction. Using those calculated data, advanced exergy analysis was carried out by dividing the exergy destruction into an avoidable

Table 1
Configuration of STHE [18].

Sr.	Parameters	Value
1	Mass flow rate shell, kg/s	27.80
2	Mass flow rate tube, kg/s	68.90
3	Shell side temperature outlet, ∘C	40
4	Shell side temperature inlet, ∘C	95
5	Tube side temperature inlet, ∘C	25
6	Tube side temperature outlet, ∘C	40
7	Fouling resistance, R_f shell, m^2.K/W	0.00034
8	Fouling resistance, R_f/tube, m^2.K/W	0.00020
9	Length of the tube (L_t), m	4.83
10	Number of pair of sealing strip, N_{ss}	2
11	Diametral shell-to-baffle clearance, L_{sb}, m	0.0051
12	Diametral tube-to-baffle clearance, L_{tb}, m	0.0008
13	Baffle thickness, t_b, m	0.005
14	Bypass channel diametral gap, L_{bb}, m	0.019
15	Allowable operating pressure of tube side, P_t, kPa	100
16	Heat Duty, MW	4.34
17	Pressure Drop, kPa	≤100

component, an unavoidable component, an endogenous component, an exogenous component, etc. The results were then analyzed, and the potential for improvement is discussed at the end. The detailed flow-chart of the methodology adopted for the current investigation is presented in Fig. 1.

3. System description and thermodynamic model

In the current section, the shell and tube heat exchanger system under consideration is explained in detail. The initial conditions of the water at the inlet and outlet of the shell and tube side are mentioned. Further, the thermodynamic equations used to calculate the exergy destruction is presented.

3.1. System description

In order to conduct the exergy and advanced exergy analyses of a shell and tube heat exchanger, the design parameters were considered with reference to the work of Jamil et al. [18], as shown in Table 1. The system consisted of two centrifugal pumps (at each inlet, shell side and tube side) and one segmental baffled shell and tube heat exchanger with water flowing in both shell and tube sides (hot water was flowing through the shell side, while colder water was flowing through the tubes). The schematic representation of the system is shown in Fig. 2. The change in the density of the water with respect to temperature helps fluid flow inside the tubes, thus requiring less pumping power. The pressure at the inlet of the shell side was 1.54 bar, and at the outlet it was 1.5 bar, while for the tube side inlet and outlet the pressures were 1.072 bar and 1 bar, respectively. More details about the configuration of the shell and tube heat exchanger are given in Table 2.

3.2. Exergy modelling

Kern's approach is one of the oldest methods of designing a shell and tube heat exchanger and it was used in the current investigation [23]. Thermodynamic calculations were made to find values of the Reynolds number (*Re*), Nusselt number (*Nu*), heat transfer coefficient (*h*), pressure drop (*ΔP*), overall heat transfer coefficient (*U*), shell side heat transfer coefficient (h_s) and tube side heat transfer coefficient (h_t). All the calculations for the design and analysis were carried out using MATLAB software. The equations used for calculations with the Kern method [24] are shown below:

$$Re_t = \frac{\rho_t\ \vartheta_t\ D_t}{\mu_t} \tag{1}$$

$$t = \frac{(t_{in} + t_{out})}{2} \tag{2}$$

$$h_t = \frac{\rho_t\ (1.35 + 0.02t)\ \vartheta_t}{(1000\ D_t)^2} \tag{3}$$

$$\Delta P_t = \frac{\rho_t\ \vartheta_t^{\ 2}\left[\left(\frac{L_t f_t}{D_t}\right) + P_c\right] N_p}{2} \tag{4}$$

$$\mathrm{P_c} = 2.5$$

$$Re_s = \frac{G_s D_{eq}}{\mu_s} \tag{5}$$

$$h_s = j_h k_s Re_s \left(\frac{Pr_s^{0.33}}{D_{eq}}\right) \tag{6}$$

$$f_s = 2\ b_o\ Re_s^{-0.15} \tag{7}$$

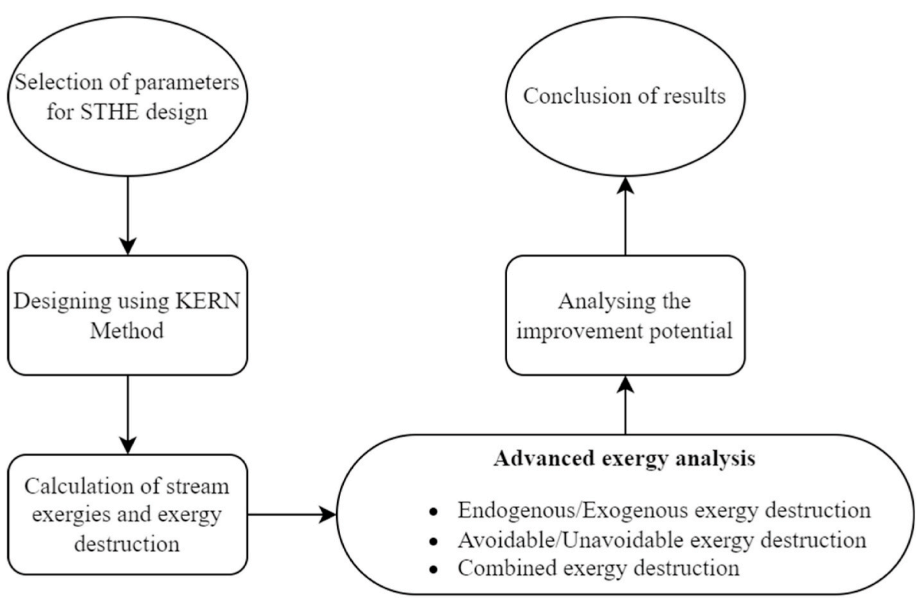

Fig. 1. Flow chart of the methodology.

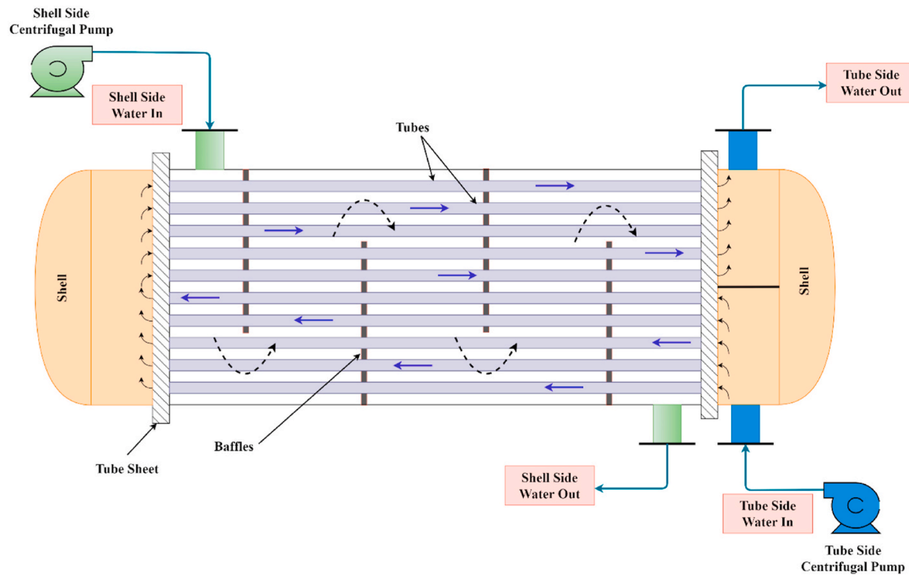

Fig. 2. Schematic diagram of the system.

Table 2
Design variables considered [18].

Sr.	Parameters	Lower bound
1	Layout, degrees	45°
2	Shell diameter, m	1
3	Tube outside diameter, m	0.015
4	Baffle cut, %	20
5	Baffle spacing, m	0.427
6	Number of tube passes	2
8	Number of tubes	1752

$$\Delta P_s = \rho_s\, \vartheta_s^2\, f_s\, \frac{L_t\, D_s}{2\, B_s\, D_{eq}} \tag{8}$$

The value b_o is considered 0.72 according to the study of Peters and Timmerhaus [25].

The inlet and outlet streams of the shell and tube sides were analyzed once the design of the STHE was complete. Exergy represents the maximum amount of reversible work that can be obtained. The stream exergies for the exergy analysis of the system were calculated using the following formulae [26,27]:

$$Ex = [(h_1 - h_0) - T_0(s_1 - s_0)] \tag{9}$$

where h and represent the enthalpy and entropy of the streams, h_1 and s_1 are the specific enthalpy and the specific entropy at the initial temperature, respectively. T_0 is the dead state temperature, usually referred to as the ambient temperature of the surroundings with which the system tries to attain equilibrium. h_0 and s_0 are the enthalpy and entropy of the system at the dead state [28,29]. The dead state is the condition at which the system is considered in thermal and chemical equilibrium with its surroundings. The ambient pressure and temperature are 1 bar and 25 °C, respectively. Apart from this, the energy provided to the streams by the pumps and the power required by the pump to work is also considered for exergy calculations. The exergy for these can be calculated as [30].

$$Ex_{hot} = [(h_1 - h_0) - T_0(s_1 - s_0)]\, \dot{m}_s \tag{10}$$

$$Ex_{cold} = [(h_2 - h_0) - T_0(s_2 - s_0)]\, \dot{m}_t \tag{11}$$

The power required by the pumps is [31],

$$PP_t = \frac{\dot{m}_t \Delta P_t}{\eta_P} \tag{12}$$

$$PP_s = \frac{\dot{m}_s \Delta P_s}{\eta_P} \tag{13}$$

$$PP = PP_t + PP_s \tag{14}$$

where η_P shows pump efficiency, which is 70 %.

Exergy destruction refers to the irreversibilities associated with the system, such as surface friction, fouling resistance, pressure drop, etc. The difference of exergies at the entry and exit of the HE gives the exergy that has been destroyed [29,32].

$$X_{D,STHE} = Ex_{c,i} + Ex_{H,i} - Ex_{C,O} - Ex_{H,O} \tag{15}$$

$$X_{D,P} = Ex_{P,i} + W - Ex_{P,O} \tag{16}$$

$$XD = X_{D,STHE} + X_{D,P} \tag{17}$$

Here $X_{D,STHE}$ is the total exergy destruction by STHE, and $X_{D,P}$ is the total exergy destruction by both pumps. Combining these will result in total exergy destruction (XD). Another term, exergy efficiency, is one of the three objective functions that indicates how well the exergy is being utilized and it is calculated as,

$$\eta_{ex} = \frac{1 - XD}{PP + Ex_{Hot,inlet} + Ex_{Cold,inlet}} \tag{18}$$

3.3. *Advanced exergy analysis*

Exergy destruction of the system is calculated through the exergy of the inlet and outlet streams. However, this exergy destruction does not determine the scope for improvement in the system. The quality of irreversibility present in individual components in the system can be known with the help of advanced exergy analyses [33]. The division of the exergy destruction into unavoidable, avoidable, exogenous, and endogenous components is known as advanced exergy analyses [34], as shown in Fig. 3. The endogenous part of exergy destruction is independent of the exergy destruction of the other components in the system. It is presumed that the other system components work on ideal efficiency and have zero exergy destruction, but the component itself runs on current efficiency. Whereas the exogenous part of the exergy

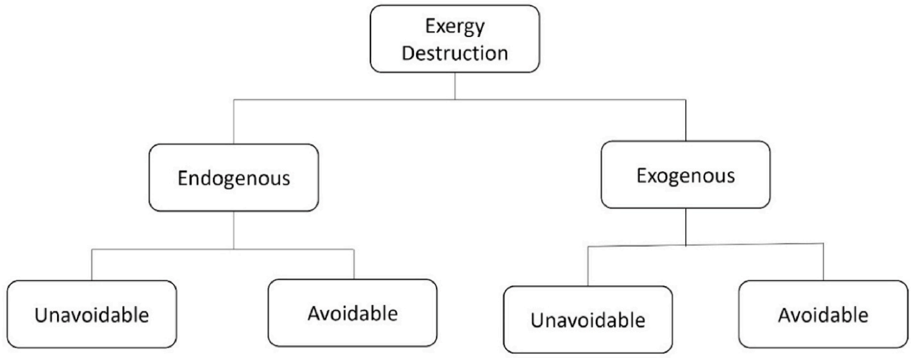

Fig. 3. Division of exergy destruction.

destruction accounts for the irreversibilities of the other system components. Since the endogenous exergy destruction is a function of the component's exergetic efficiency, the exergetic efficiency must be kept constant while the exergy destruction in the other components is varied. The division of exergy into endogenous and exogenous components of exergy helps in determining the reasons for the irreversibilities and further the avoidable component of exergy can be reduced by incorporating necessary changes in the shell and tube heat exchanger.

3.3.1. avoidable and unavoidable exergy destruction

The avoidable part of exergy destruction of a component is the amount of exergy destruction, which can be avoided by overcoming the technical limitations present in the component such as design, fabrication, materials, etc. The Avoidable part of exergy destruction can be calculated by subtracting the unavoidable part of exergy destruction from the total exergy destruction. It can be given as,

$$E_{D,k}^{AV} = E_{D,k} - E_{D,k}^{UN} \tag{19}$$

An unavoidable part of the exergy destruction of a component is the amount of exergy destruction that is bound to occur, no matter what technology is used and how much system design optimization one can do [35]. So, while focusing on optimizing any component, this part of exergy destruction is usually neglected as it cannot be improved. According to the second law of thermodynamics, a system cannot be 100 % efficient; the system is bound to pass through a phase of irreversibility. Due to the presence of irreversibilities, the component cannot behave as ideal. The unavoidable part of exergy of any kth component can be given as,

$$E_{D,total}^{UN} = E_{D,A}^{UN} + E_{D,B}^{UN} + E_{D,C}^{UN} \tag{20}$$

$$E_{D,A}^{UN} = \frac{E_{P,total}}{\varepsilon_B^{UN}\varepsilon_C^{UN}}\left(\frac{1}{\varepsilon_A^{UN}} - 1\right) \tag{21}$$

$$E_{D,B}^{UN} = \frac{E_{P,total}}{\varepsilon_A^{UN}\varepsilon_C^{UN}}\left(\frac{1}{\varepsilon_B^{UN}} - 1\right) \tag{22}$$

$$E_{D,C}^{UN} = \frac{E_{P,total}}{\varepsilon_B^{UN}\varepsilon_A^{UN}}\left(\frac{1}{\varepsilon_C^{UN}} - 1\right) \tag{23}$$

where A, B, and C represent three components of the system.

A combination of avoidable and unavoidable components of exergy destruction forms the total exergy destruction.

3.3.2. Endogenous and exogenous part of exergy destruction

The Endogenous part of the exergy destruction of a component is the amount of exergy destruction due to the inefficiency/irreversibilities present in the component itself. While calculating the endogenous part of exergy destruction, all the components except the component under consideration are considered to work at their ideal efficiency, while the component under consideration is deemed to be working at its current efficiency in the system. It can be calculated as,

$$E_{D,k}^{EN} = \frac{E_{P,total}}{\varepsilon_1\varepsilon_2\ldots.\varepsilon_n}\left(\frac{1}{\varepsilon_k} - 1\right) \tag{24}$$

The exogenous part of the exergy destruction of a component is the amount of exergy destruction due to the inefficiency or irreversibility present in the system while the component under consideration is working at its ideal efficiency. The exogenous exergy destruction can be calculated by considering the component's efficiency to be its ideal efficiency, while all the other components are performing at their current efficiency. Thus, the combination of exogenous and endogenous components of exergy destruction forms the total amount of exergy destruction present in the system or the component. It can be given as,

$$E_{D,k}^{EX} = E_{D,k} - E_{D,k}^{EN} \tag{25}$$

3.3.3. Combined exergy destruction

Up to now, the exergy destruction is split into exogenous and endogenous as well as avoidable and unavoidable components. However, combining these exergy destruction components gives us more specific details about a particular component's scope for improvement or improvement potential. So now, excessive destruction can be divided into endogenous unavoidable, endogenous avoidable, exogenous unavoidable, and exogenous avoidable.

The endogenous unavoidable part of exergy destruction gives the idea about exergy destruction, which cannot be avoided by improving the component itself. At the same time, the endogenous avoidable part of exergy destruction specifies the improvement that can be made with the component to enhance its efficiency. A similarly exogenous unavoidable part of exergy destruction refers to the exergy destruction that cannot be avoided by improving the other components of the system except the component under consideration. The Exogenous avoidable component of exergy destruction of a component refers to the exergy destruction that can be avoided by optimizing the system design or equipment optimization or by improving the technical limitations of the rest of the components other than the components under consideration. These terms can be given as,

$$E_{D,k}^{EN,UN} = E_{P,total}\left(\frac{1}{\varepsilon_K^{UN}} - 1\right) \tag{26}$$

$$E_{D,k}^{EN,AV} = E_{D,k}^{EN} - E_{D,k}^{EN,UN} \tag{27}$$

$$E_{D,k}^{EX,UN} = E_{D,k}^{UN} - E_{D,k}^{EN,UN} \tag{28}$$

$$E_{D,k}^{EX,AV} = E_{D,k}^{EX} - E_{D,k}^{EX,UN} \tag{29}$$

Fig. 2 shows the division of exergy destruction explained earlier. Considering all the data from Tables 1 and 2 and using the correlations mentioned above, advanced exergy analysis was conducted, and the results are provided in Table 3.

4. Case study and results-discussion

In this study, a shell and tube heat exchanger was designed using the Kern method by considering the reference data of various design parameters from the reference study [18]. The operating conditions are given in Tables 1 and 2. The shell and tube heat exchanger is fed with water on both the shell and tube sides. It has two centrifugal pumps at the inlet of each side to counterbalance pressure drop, pump the water, and maintain the required flow rate. MATLAB software was used to design and analyze the system. An exergy analysis of the system showed the exergy destruction occurring. However, the quality of the exergy destruction was not known. To identify the scope for improvement for both pumps and heat exchanger, an advanced exergy analysis, was carried out to observe the improvement potential available in the system. The advanced exergy analysis was performed by splitting the exergy destruction into various sub-forms, i.e., avoidable-unavoidable and endogenous-exogenous. Further, the advanced exergy analysis targets the individual component, and that gives priority to improving or optimizing the components in any system.

In the present work, the Kern method was used for the development of thermal model of STHE. The second law efficiency of the proposed system obtained using the developed thermal model was validated with the results presented by Jamil et al. [18] for the same system. The total exergy destruction obtained for the current study is 684.6 kW as compared to the exergy destruction of 685 kW in the reported work. The advanced exergy analysis of the system was carried out, and the results obtained are given in Table 3. The total amount of exergy destruction obtained was 684.6 kW, of which 686 kW arose from the heat exchanger and a negative 1.5 kW by pumps. The results show that the maximum exergy destruction in the system is due to the heat exchanger, and 97 % of the total exergy destruction is avoidable, which shows that much improvement is needed in the system to lower the power consumption and increase the yield. The exogenous exergy destruction of the last component of any system is considered to be zero. Thus, the exogenous part of exergy destruction for the heat exchanger is zero, showing that improving the pumps will not affect the overall system performance, which holds true as the contribution to the total exergy destruction by both pumps is equivalent to zero.

Further dividing the exergy destruction into endogenous avoidable and endogenous unavoidable shows the improvement potential available in the component and the amount of exergy destruction bound to occur by the component, respectively. Furthermore, exogenous avoidable exergy destruction describes the improvement potential for the whole system by improving the other components. The exogenous avoidable part of exergy destruction for the heat exchanger is negative, which shows there is no scope for improvement in other components that can improve the system's performance. In this case, the pumps are the other components, and improvement is not beneficial to the system. So, the only primary scope of improvement to reduce the exergy destruction is by improving the heat exchanger itself.

Fig. 4 shows the division of exergy destruction into avoidable-unavoidable and endogenous-exogenous. The 'H' represents the exergy destruction in the heat exchanger, 'P' represents exergy destruction due to pumps, and 'C' represents the combined exergy destruction of the pumps and heat exchanger. It is observed from the figure that most of the endogenous part of exergy destruction is due to heat exchangers. At the same time, pumps contribute significantly less to the total endogenous exergy destruction. It indicates that improving the heat exchanger is more beneficial. The exogenous exergy destruction for the heat exchanger is zero, while pumps have negative exergy destruction, showing that enhancing the other component, i.e., the heat exchanger, will not affect the performance of the pumps. The avoidable part of exergy destruction for heat exchangers has a very high value while that of the pumps is almost zero. It shows that much improvement is needed in the heat exchanger configuration to improve the overall system's efficiency. Comparatively, the values of unavoidable exergy destruction for heat exchangers and pumps are very low. The resulting exergy destruction is bound to occur and cannot be avoided.

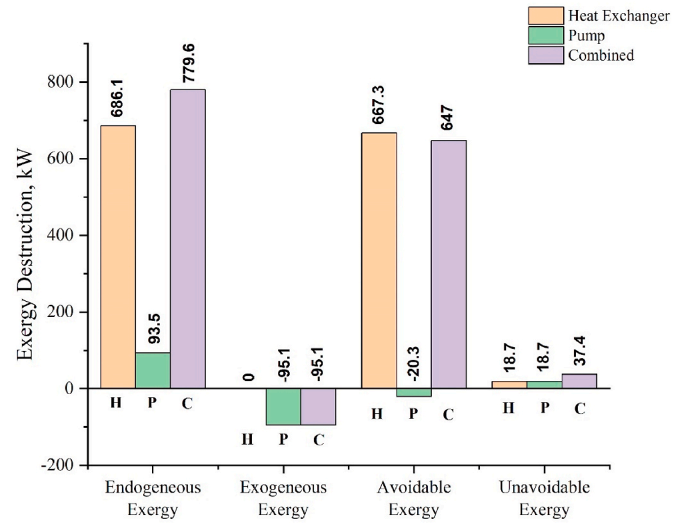

Fig. 4. Total exergy destruction for various equipment.

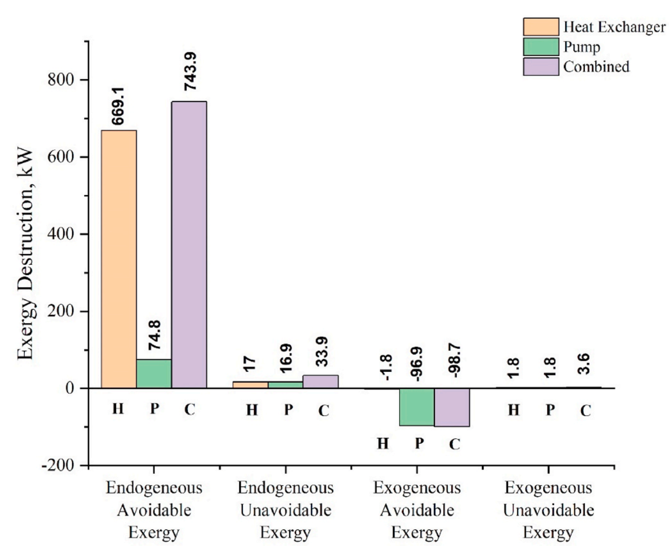

Fig. 5. Bifurcated exergy destruction of the system components.

Table 3
Results of advanced exergy analysis.

Equipment	*XD* (kW)	$E_{D,k}^{EN}$ (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)
Heat Exchanger	686.1	686.1	0	667.3	18.7	669.1	17	−1.8	1.8
Pumps	−1.5	93.5	−95.1	−20.3	18.7	74.8	16.9	−96.9	1.8
Total	684.6	779.6	−95.1	647	37.4	743.9	33.9	−98.7	3.6

Fig. 5 represents the division of exergy destruction into endogenous avoidable-unavoidable and exogenous avoidable-unavoidable. The endogenous avoidable component of exergy destruction for the heat exchangers has a very much higher value than for the pumps. It indicates that improving the heat exchanger will help significantly more than improving the pumps. While the endogenous unavoidable part of exergy destruction for both pumps has a very low value, this destruction cannot be avoided. The exogenous avoidable part of exergy destruction for the heat exchanger is zero, showing the improvement potential in the pumps. It will not affect the total system's efficiency. The pumps have a negative value, which indicates that changing the parametric values of the heat exchanger will not affect the efficiency of the pump. The exogenous unavoidable part of exergy destruction for both the pumps and heat exchangers is almost zero. Overall, it is observed that most of the exergy destruction is endogenous and avoidable for the heat exchanger, which shows the main culprit for the exergy losses in the system is the heat exchanger, and by optimizing it, much of the exergy destruction can be avoided and hence also optimizing energy and costs.

Fig. 6 depicts the results for endogenous and exogenous parts of exergy destruction in a bar chart, where the blue region is exergy destruction due to the heat exchanger, maroon is due to pumps, and yellow indicates the combined exergy destruction. For the endogenous part of exergy destruction, the heat exchanger has the highest contribution, while for exogenous, all the contribution is by the pumps and is negative as well. Fig. 7 shows the division of exergy destruction into avoidable and unavoidable parts, where the maximum amount of exergy destruction is of avoidable type for the heat exchanger. At the same time, a significantly lower contribution for pumps and heat exchangers is unavoidable.

Fig. 7 represents the avoidable and unavoidable part of exergy destruction. Majority of the exergy destruction caused by the heat exchanger is in the avoidable condition and indicates the further scope in optimization of heat exchanger design. The subsequent approach in optimization of heat exchanger design can be focused on optimizing geometric and operating parameters. Geometric parameters on shell side such as shell diameter, tube outside diameter, baffle spacing, baffle cut and tube layout and parameters on tube side such as tube inside diameter, tube material and number of tubes influence the exergy destruction. Similarly, operation parameters like fluid velocity and fluid pressure flowing through shell and tubes can be controlled and optimized to minimize the exergy destruction. For example, higher tube side flow velocity results in higher heat transfer rate along with the increased pressure drop. The change in heat transfer rate and pressure drop of STHE due to higher tube side flow velocity affect the avoidable as well as unavoidable components of the exergy. Advanced exergy analysis helps in determining the magnitude of the avoidable exergy destruction that can subsequently help in further improvising the design of the heat exchanger.

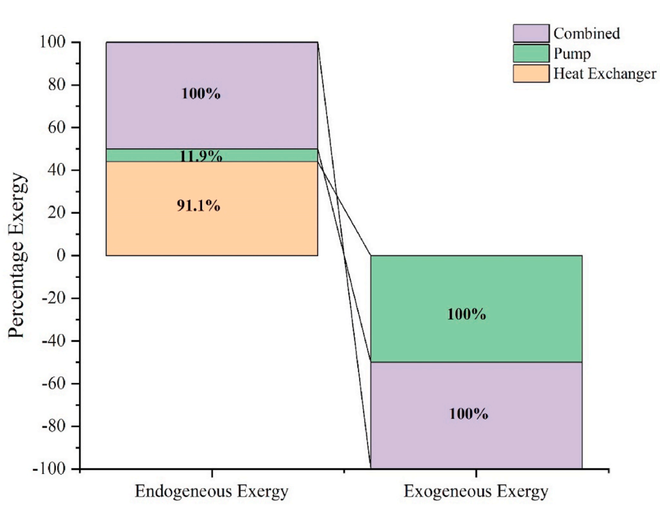

Fig. 6. Endogenous and Exogenous exergy destruction.

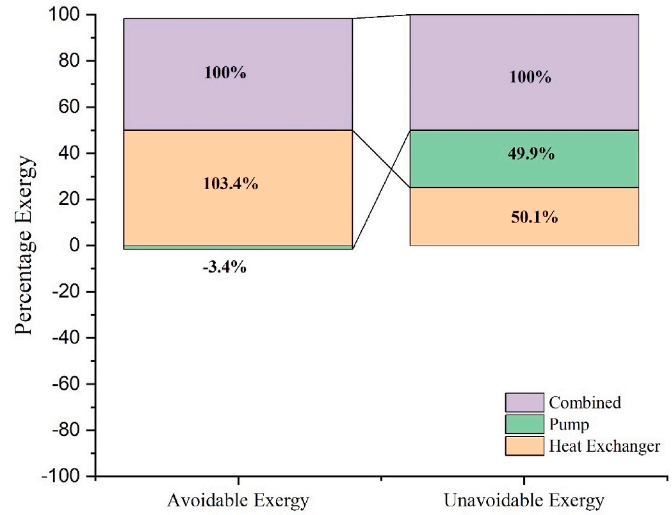

Fig. 7. Avoidable and unavoidable exergy destruction.

5. Conclusion

Exergy and advanced exergy analyses have been performed on a shell and tube heat exchanger, and the results of the advanced exergy study showed that 97.5 % of the total exergy destruction in the heat exchanger is of the avoidable type, which indicates that the system design is largely underperforming and a high degree of irreversibility is present in the system. Dividing the exergy destruction for both pumps and heat exchangers showed that most of the irreversibility is associated with the heat exchanger. The exergy destruction in the centrifugal pumps is of unavoidable type and no further design changes are required. Most of the exergy destruction of the heat exchanger, i.e., 97.5 %, is an endogenous avoidable component, which shows that 97.5 % of the total exergy destruction can be avoided by optimizing the values of the heat exchanger's design variables, configuration, materials, etc. Geometric parameters on shell side such as shell diameter, tube outside diameter, baffle spacing, baffle cut and tube layout and parameters on tube side such as tube inside diameter, tube material and number of tubes influence the exergy destruction. Similarly, operation parameters like fluid velocity and fluid pressure flowing through shell and tubes can be controlled and optimized to minimize the exergy destruction. At the same time, significantly less exergy destruction is observed for pumps. Since a considerable potential for improvement is available for the heat exchanger, improving the heat exchanger has a more significant impact on the overall performance of the system than improving the pumps.

CRediT authorship contribution statement

Parth Prajapati: Conceptualization, Data curation, Software, Writing – original draft, Formal analysis, Funding acquisition, Methodology. **Bansi D. Raja:** Conceptualization, Data curation, Formal analysis, Writing – original draft. **Hepin Savaliya:** Conceptualization, Data curation, Visualization, Writing – original draft. **Vivek Patel:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Hussam Jouhara:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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