Conventional and Advanced Exergetic and Exergoeconomic Analysis Applied to an Air Preheater System for Fired Heater (Case Study: Tehran Oil Refinery Company)

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ABSTRACT: *The present paper evaluates the plan of combustion air pre-heater installation on the fired heater from thermodynamics and thermos-economics point of view. As a real case study, one of the fired heaters (H_101) of Distillation unit in Tehran Oil Refinery, Iran, is intended. With applying an air pre-heater in this study, flue gases temperature falls down from 430 ºC to 200 ºC and combustion air temperature grows up from 25ºC to 350 ºC. By examining the energy and exergy analyses before and after the installation of air pre-heater, the increase in thermal efficiency by 20% and exergy efficiency by 37% and accordingly decreasing fuel consumption by 20% is observed. It is also indicated that the most exergy destruction is accrued in the fired heater (57.24%). In this study for the first time, based on advanced exergy analyses and concepts of endogenous/exogenous and avoidable/unavoidable parts, exergy destruction, exergy destruction cost rates and capital investment of combustion air preheater system are found which results show the endogenous and unavoidable parts in overall system are dominant. Also, the effect of flue gases temperature (T_5) on the system performance is investigated through sensitivity analyses. It is seen that with rising T_5, thermal efficiency and exergy efficiency in real, theory and unavoidable conditions decrease. The results demonstrate the majority parts of exergy destruction in fired heater and air preheater is endogenous, unavoidable and unavoidable endogenous. Considering the cost of air preheater and related equipment and operating and maintenance costs annually, the payback period is estimated to be less than 2 years. In this research, the EES and Excel were applied to calculate the amount.*

KEYWORDS: *Air pre-heater; Thermal efficiency; Exergy efficiency; Exergy analyses; Advanced exergy analyses.*

INTRODUCTION

In the oil refining industry, fired heaters are the largest consumer of fossil fuels, however, due to environmental and economic issues, serious researches and investments in energy saving and recovery are needed. For raising the efficiency of industrial fired heaters, heat recovery from high temperature exhaust gases to the fresh combustion

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air has been an effective way which is not new as a technology. It is so- called heat recirculating combustion, which has been realized with a heat exchanger or a recuperator to improve the thermal efficiency of the system [1-3].

Katsuki and *Hasegawa* [4] reviewed various aspects of combustion heat recovery technology with high frequency alternating current And showed that using the heat to preheat combustion air has advantages such as saving fuel, reducing emissions of NOx and increasing the heat transfer efficiency. *Weber, Orsino, et al.* [5] simulated Natural gas combustion using air at high temperature (1300 °C) through a mathematical model in semi-industrial scale based on fluid dynamics, he believes that this method is widely used for the design of industrial fired heaters Because, in addition to saving fuel consumption and reduce carbon dioxide emissions, this technology provides Uniform and high heat transfer rates for many processes. *Choi* and *Katsuki* [6] showed that combustion in ultra-low concentrations of oxygen in the fired heater is possible through combustion air preheating by heat recovery from flue gases in fired heaters. *Kawai, Yoshikawa et al.* [7] provided a boiler which in it fuel effectively burns by high temperature preheated air, This type of boiler for flue gases from coal gasification and wastes without dioxins emissions that have low Btu is appropriate. *Ghodsipour* and *Sadrameli* [1, 8, 9] carried out experimental and sensitivity analyses of a rotary air preheater for the flue gas heat recovery. *Wang, Zhao et al.* [8, 10, 11] Applied exergy analyses to measure the Irreversibility effect of air preheating on thermal power plant efficiency. *Wu, Chen et al.* [12] showd combustion with highly preheated air is an effective way to ignite and burn the low-calorific value liquids. *Hasanuzzaman, Saidur et al.* [13] Examined utilization energy of fired heater and found that most exergy lost (57%) happens in the fired heater so to improve the overall efficiency of the fired heater heat recovery used to preheat the combustion air which in addition to increasing efficiency, the fuel consumption 8.1% was saved. *Hasanuzzaman, Rahim et al.* [2] reviewed energy efficiency and savings strategies in the combustion based industrial process and showed in the fired heater up to 25% energy can be saved by using recuperator also indicated through economic analyses that the payback period of applying recuperator is less than 2 years and It can be lesser if the operating hour would be comparatively high. *Varghese* and *Bandyopadhyay* [14] examined Issues related to energy targeting in fired heaters and heat exchangers and showed that variables such as the type of fuel and preheated air temperature affect the performance of the fired heater.

Shekarchian, Zarifi et al. [3] reviewed Preheating processes that can improve thermal and exergy efficiency of the fired heater and The heat recovery and air preheating methods which reduce fuel consumption by about 7.4 percent and reduce heat losses of fired heaters. *Aisyah, Rulianto et al.* [15] analyzed the effect of pre-heating system on improving the efficiency of the small fired heaters with LPG fuel and showed using pre-heating system increases combustion efficiency up to 6.75% and decreases CO emissions up to 49.06%. *Huang, Zhang et al.* [16] examined the effect of pre-heated air temperature on moderate and severe combustion of synthesis gas derived from coal combustion with a low concentration of oxygen and showed that this type of combustion only happens if pre-heated air is used.

Exergy analyses is a powerful tool that identifies the sources of thermodynamic inefficiencies by means of identifying and quantifying the useful part of energy (exergy), irreversibilies (exergy destruction) and exergy losses, so applying exergy analyses will identify areas of improvement of systems. Exergy measures the real potential for enhancing the system components to create a fundamental change. This type of analyses is widely used in recent years for a wide range of energy conversion systems [17-19] however conventional exergy analyses only investigates the performances of components individually and ignores the interactions between the system components also it does not evaluate the potential for improving a component. These issues are considered in the advanced exergy analyses by splitting the exergy destruction into Endogenous/exogenous and Unavoidable/avoidable parts [20-23] and the resulting combined parts. In recent years, advanced exergy analyses have been successfully applied for many simple and complex energy conversion systems [21, 24-27]

In this paper the air pre-heater installation plan for the fired heater of Tehran oil refinery distillation unit has been evaluated through conventional and advanced exergy analyses, in order to calculate the flow of exergy, identify the most effective component and source of exergy destruction, as well as deciding about changes

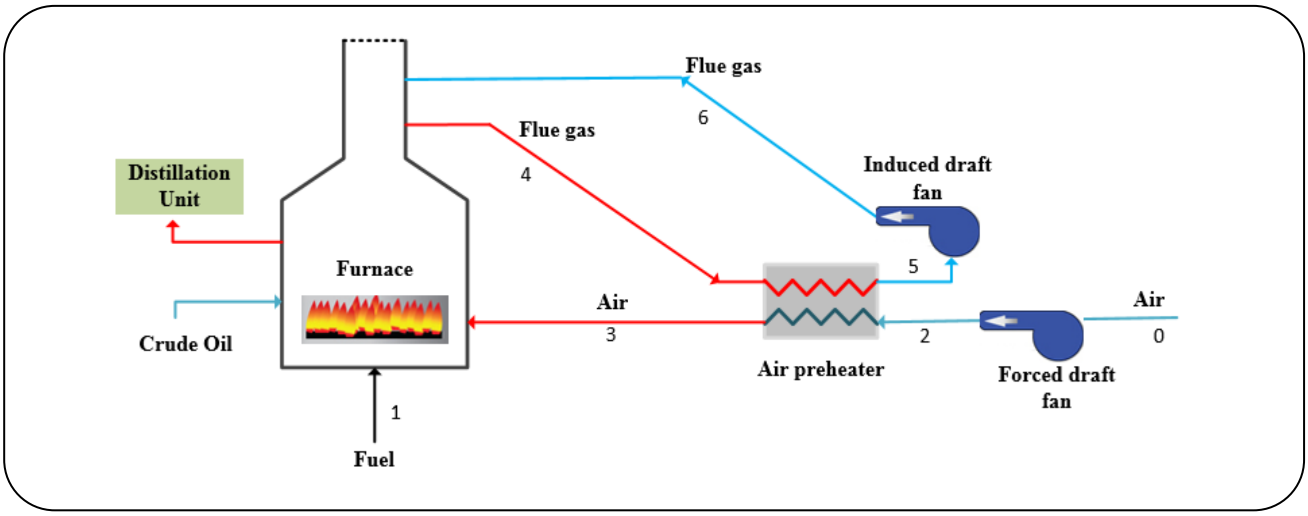

Fig. 1: Combustion air preheating system.

in operation conditions or structure of a system that will lead to a system with more efficiency and saving energy.

SYSTEM DESCRIPTION AND ASSUMPTION

The system of Heat recovery from flue gases to pre-heat combustion air is shown in Fig. 1. The system includes a fired heater, Air Pre-heater (AP), Forced Draft (F.D) fan and Induced Draft (I.D) fan. The environment air at 20 °C enters F.D fan which supplies the required air flow for combustion in the fired heater, after passing the AP, its temperature rises to 350 °C then goes to the fired heater and mixes with fuel at 35 °C and combustion happens. Crude oil enters the fired heater at 240 °C and exits at 361 °C .leaving flue gases with a temperature of 430 °C flow into the air preheater in order to heat the combustion air, so low temperature flue gases (minimum 393K because of the dew point restrictions) through I.D fan which creates the appropriate suction, transfer to stack and finally released to the atmosphere. In this study flue gases from one of the fired heaters (H_101) of Distillation unit in Tehran Oil Refinery, Iran, is considered, Necessary data for the analyses of the fired heater (H_101) and some inputs which have been assumed for thermodynamic modeling are shown in Table 1. Natural gas is used as fuel in the fired heater.

METHODOLOGY

Energy analyses

In this study, for simplicity of calculation complete combustion has been considered.

the overall complete combustion of hydrocarbons equation is written as [28]:

$$C_aH_b + \left(a+\frac{b}{4}\right)(O_2+3.77N_2) \rightarrow \quad (1)$$

$$CO_2 + \frac{b}{2}H_2O + 3.77\left(a+\frac{b}{4}\right)N_2$$

In this Study, according to the above equation, with considering that natural gas is used as fuel in the fired heater and combustion reaction is assumed to be complete, can be written as follow:

$$CH_4 + 2(O_2+3.77N_2) \rightarrow CO_2 + 2H_2O + 7.54N_2 \quad (2)$$

In order to determine the performance of fired heater operation from the perspective of energy, based on flue gases analyses, excess air percentage is calculated as follows [29]:

$$\%Ex.Air = \frac{O_2 - 0.5CO}{0.2682N_2 - (O_2 - 0.5CO_2)} \times 100 \quad (3)$$

The combustion efficiency is calculated based on the proposed method in standard (ASME PTC 4-1), in the following equations EA is the ratio of the theoretical to actual air percent, T_g is the temperature of the flue gases before damper, T_0 is the ambient air temperature, Body.loss is the heat loss from fired heater body which is considered 3 %, η_1 is fired heater efficiency before preheater installation and η_2 is fired heater efficiency after preheater installation [29].

Table 1: Input data for the system.

Parameters	
Dead state temperature, (K)	298.15
Dead state pressure, (bar)	1.013
Input air temperature, T_0 (K)	298.15
Input air pressure, P_0 (bar)	1.013
Fuel temperature, T_1 (K)	308.15
Fuel pressure, P_1 (bar)	1.013
Fuel flow rate, $\dot{m}_1$ (kg/s)	1.48
Fuel-air ratio, λ	1 / 12.38
Crude oil input temperature (K)	513.35
Crude oil output temperature (K)	16
Crude oil input pressure (bar)	634.55
Crude oil output pressure (bar)	2.62
Crude oil flow rate (kg/s)	135.27
Flue gas temperature, T_4 (K)	703
Isentropic efficiency of fans	0.8
AP effectiveness factor, E	0.8

$$EA = 1 + \frac{EX.Air}{100} \quad (4)$$

$$\eta_{comb} = 99 - (0.001244 + 0.0216 \times EA)(T_g - T_0) \times 1.8 \quad (5)$$

$$\eta_{fur} = \eta_{comb} - body.loss \quad (6)$$

$$stack.loss(\%) = 100 - \eta_{comb} \quad (7)$$

$$Saving\ Fuel(\%) = \frac{\eta_2 - \eta_1}{\eta_1} \quad (8)$$

The result of these analyses is shown in Table 3.

Conventional Exergy analyses

Despite mass and energy, exergy is not conserved in thermodynamic processes, in other words, is destroyed by irreversibility with in a system consequently an exergy balance must include an exergy destruction term, so for the kth component, it is expressed as following [17]:

$$\dot{E}x_{D,K} = \dot{E}x_{F,K} - \dot{E}x_{P,K} \quad (9)$$

Where $\dot{E}x_{D,K}$, $\dot{E}x_{F,K}$ and $\dot{E}x_{P,K}$ represent exergy destruction rate, fuel exergy rate and product exergy rate for kth component respectively.

The exergetic efficiency is written as [17]:

$$\varepsilon_k = \frac{\dot{E}x_{P,k}}{\dot{E}x_{f,k}} \quad (10)$$

The exergy destruction ratio is defined as [17]:

$$y_{D,k} = \frac{\dot{E}x_{D,k}}{\dot{E}x_{f,tot}} \quad (11)$$

Exergy balance for the overall system becomes [17]:

$$\dot{E}x_{F,tot} = \dot{E}x_{P,tot} + \sum_k \dot{E}x_{D,K} + \dot{E}x_{L,tot} \quad (12)$$

Where $\dot{E}x_{L,tot}$ is the rate of exergy. The conventional exergoeconomic relations can be expressed in a similar way.

Cost balance equations applied to the kth component of the system can be written as follows [30]:

$$c_{P,k}\dot{E}x_{P,k} = c_{F,k}\dot{E}x_{F,k} + \dot{Z}_k \quad (13)$$

Where $c_{F,k}$ and $c_{P,k}$ are the average cost per unit exergy of fuel and product respectively which are defined as follows [31]:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}x_{F,k}} \quad (14)$$

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}x_{P,k}} \quad (15)$$

$\dot{Z}_k$ is the investment cost rate which is calculated as follow [32]:

$$\dot{Z}_k = Z_k^{CI} \times CRF \times \frac{\phi}{t} \quad (16)$$

Where Z_k^{CI} is the capital investment cost, the maintenance factor (ϕ) and number of hours per year that the unit operates (t) Are considered to be 1.06 and 7446h in order. CRF is the Capital Recovery Factor that it is determined by using the following equation [33]:

$$\mathrm{CRF}=\frac{i(1+i)^N}{(1+i)^N-1} \quad (17)$$

Where i is the interest rate and N is estimated component lifetime which are assumed to be 10% and 20 year respectively [31].

The cost rate associated with fuel (methane gas) introduced into the fired heater is obtained as following [34]:

$$\dot{C}_f=c_f\times\dot{m}_f\times \mathrm{LHV} \quad (18)$$

Where the unit cost of fuel, c_f, is considered 0.004 $/MJ based on [35], $\dot{m}_f$ is the fuel mass flow rate and LHV is the fuel lower heating value.

Unit cost of ambient air which enters to F.D fan (c_0) is assumed to be zero.

Cost of exergy destruction ($\dot{C}_{D,k}$), relative cost difference (r_k) and the exergoeconomic factor (f_k) are key parameters for exergoeconomic analysis of thermal systems which are estimated as Eqs. (19)_(21) [17]:

$$\dot{C}_{D,k}=c_{F,k}\dot{E}x_{D,k} \quad (19)$$

$$r_k=\frac{c_{P,k}-c_{F,k}}{c_{F,k}} \quad (20)$$

$$f_k=\frac{\dot{Z}_k}{\dot{Z}_k+c_{F,k}(\dot{E}x_{D,k}+\dot{E}x_{L,k})} \quad (21)$$

Advance Exergy analyses

The endogenous ($\dot{E}x_{D,K}^{EN}$) exergy destruction in a component is due only to the irreversibility within a component when all other components operate ideally and the component being considered operates with its real efficiency. The exogenous exergy destruction ($\dot{E}x_{D,K}^{EX}$) is caused in the kth component by the irreversibility that occur in the rest of the components [36]

$$\dot{E}x_{D,K}^{EX}=\dot{E}x_{D,K}-\dot{E}x_{D,K}^{EN} \quad (22)$$

The unavoidable exergy destruction ($\dot{E}x_{D,K}^{UN}$) part of the component cannot be eliminated due to physical and economic constraints, even if the best available technologies would be used. The avoidable exergy destruction ($\dot{E}x_{D,K}^{AV}$) can be reduced and indicates potential for improvement of the components [37].

$$\dot{E}x_{D,K}^{UN}=\dot{E}x_{P,K}\times\left(\frac{\dot{E}x_D}{\dot{E}x_P}\right)_K^{UN} \quad (23)$$

$$\dot{E}x_{D,K}^{AV}=\dot{E}x_{D,K}-\dot{E}x_{D,K}^{UN} \quad (24)$$

Assumptions of theoretical and unavoidable conditions in suggested system are summarized in Table 2 [9, 11, 38].

In a detailed advanced exergy analysis, by combining the two splitting concepts unavoidable/avoidable and endogenous/exogenous parts, the important variables for the evaluation of a system can be estimated as follows [39].

$$\dot{E}x_{D,K}^{EN,UN}=\dot{E}x_{P,K}^{EN}\times\left(\frac{\dot{E}x_D}{\dot{E}x_P}\right)_K^{UN} \quad (25)$$

$$\dot{E}x_{D,K}^{EX,UN}=\dot{E}x_{D,K}^{UN}-\dot{E}x_{D,K}^{EN,UN} \quad (26)$$

$$\dot{E}x_{D,K}^{EN,AV}=\dot{E}x_{D,K}^{EN}-\dot{E}x_{D,K}^{EN,UN} \quad (27)$$

$$\dot{E}x_{D,k}^{EX,AV}=\dot{E}x_{D,k}^{EX}-\dot{E}x_{D,k}^{EX,UN} \quad (28)$$

It is obvious that for reducing the exergy destruction, the designer must focus on the endogenous avoidable ($\dot{E}x_{D,K}^{EN,AV}$) and exogenous avoidable ($\dot{E}x_{D,K}^{EX,AV}$) exergy destructions. Table 4 presents the results obtained from advanced exergy analyses for each component.

The same as exergy destruction rate division, the endogenous and exogenous parts of the investment cost and the cost of the exergy destruction determine the economic interactions between components as define in Eqs.(29)_(30) [40, 41].

$$\dot{C}_{D,k}=\dot{C}_{D,k}^{EN}+\dot{C}_{D,k}^{EX} \quad (29)$$

$$\dot{Z}_k=\dot{Z}_k^{EN}+\dot{Z}_k^{EX} \quad (30)$$

The endogenous Costs rate ($\dot{C}_{D,k}^{EN}$ and $\dot{Z}_k^{EN}$) is calculated as follows [41]:

$$\dot{C}_{D,k}^{EN}=c_{F,k}^{real}\dot{E}x_{D,k}^{EN} \quad (31)$$

$$\dot{Z}_k^{EN}=\dot{E}x_{P,k}^{EN}\left(\frac{\dot{Z}}{\dot{E}x}\right)_k^{real} \quad (32)$$

Table 2: Assumptions for the real, theoretical and the unavoidable processes conditions.

Component	Real Condition	Theoretical Condition	Unavoidable Condition
I.D Fan	η_{is} = 80%	η_{is} = 100%	η_{is} = 95%
F.D Fan	η_{is} = 80%	η_{is} = 100%	η_{is} = 95%
Fired heater	$\dot{Q}_L \neq 0$	$\dot{Q}_L \neq 0$	$\dot{Q}_L \neq 0$
	λ = 1/12.38	λ = 1/12	λ = 1/12
	ΔP = 0.09 bar	ΔP = 0.04	ΔP = 0.04
AP	E = 80%	E = 100%	E = 85%
	ΔP = 0 bar	ΔP = 0 bar	ΔP = 0 bar

After calculating the rate of the endogenous cost, exogenous costs rate is estimated using the Eqs. (33)-(34) [41].

$$\dot{C}_{D,k}^{EX} = \dot{C}_{D,k} - \dot{C}_{D,k}^{EN} \tag{33}$$

$$\dot{Z}_{k}^{EX} = \dot{Z}_{k} - \dot{Z}_{k}^{EN} \tag{34}$$

Also, The real potential to improve the costs economically, by dividing investment cost and the cost of the exergy destruction into avoidable and unavoidable parts can be assessed which for costs associated with exergy destruction are calculated as shown in Eqs. (35)_(37) [41]:

$$\dot{C}_{D,k} = \dot{C}_{D,k}^{UN} + \dot{C}_{D,k}^{AV} \tag{35}$$

$$\dot{C}_{D,k}^{UN} = c_{F,k}^{real}\dot{E}x_{D,k}^{UN} \tag{36}$$

$$\dot{C}_{D,k}^{AV} = c_{F,k}^{real}\dot{E}x_{D,k}^{AV} \tag{37}$$

As well the unavoidable and avoidable cost rates related to investment costs within each component of the system are obtained by Eqs. (38)-(40) [41]:

$$\dot{Z}_{k} = \dot{Z}_{k}^{UN} + \dot{Z}_{k}^{AV} \tag{38}$$

$$\dot{Z}_{k}^{UN} = \dot{E}x_{P,k}^{real}\left(\frac{\dot{Z}}{\dot{E}x_{P}}\right)_{k}^{UN} \tag{39}$$

$$\dot{Z}_{k}^{AV} = \dot{Z}_{k} - \dot{Z}_{k}^{UN} \tag{40}$$

As well as for the better understanding of the costs associated with internal operating conditions and interactions between components, investment cost and the cost of the exergy destruction for each component can be divided into unavoidable endogenous, unavoidable exogenous, avoidable endogenous and avoidable exogenous as shown in Eqs. (41)-(48) [41].

$$\dot{C}_{D,k}^{UN,EN} = c_{F,k}^{real}\dot{E}x_{D,k}^{UN,EN} \tag{41}$$

$$\dot{Z}_{k}^{UN,EN} = \dot{E}x_{P,k}^{EN}\left(\frac{\dot{Z}}{\dot{E}x_{P}}\right)_{k}^{UN} \tag{42}$$

Where Due to technical limitations, there is no possibility of a reduction in $\dot{C}_{D,k}^{UN,EN}$ and $\dot{Z}_{k}^{UN,EN}$ [41].

$$\dot{C}_{D,k}^{UN,EX} = \dot{C}_{D,k}^{UN} - \dot{C}_{D,k}^{UN,EN} \tag{43}$$

$$\dot{Z}_{k}^{UN,EX} = \dot{Z}_{k}^{UN} - \dot{Z}_{k}^{UN,EN}$$

Where Due to the technical limitations of other components, there is no possibility of a reduction in $\dot{C}_{D,k}^{UN,EX}$ and $\dot{Z}_{k}^{UN,EX}$ [36].

$$\dot{C}_{D,k}^{AV,EN} = \dot{C}_{D,k}^{EN} - \dot{C}_{D,k}^{UN,EN} \tag{45}$$

$$\dot{Z}_{k}^{AV,EN} = \dot{Z}_{k}^{EN} - \dot{Z}_{k}^{UN,EN} \tag{46}$$

Which the reduction in $\dot{C}_{D,k}^{AV,EN}$ and $\dot{Z}_{k}^{AV,EN}$ by increasing the component's efficiency is possible [41].

$$\dot{C}_{D,k}^{AV,EX} = \dot{C}_{D,k}^{EX} - \dot{C}_{D,k}^{UN,EX} \tag{47}$$

$$\dot{Z}_{k}^{AV,EX} = \dot{Z}_{k}^{EX} - \dot{Z}_{k}^{UN,EX} \tag{48}$$

Which the reduction in $\dot{C}_{D,k}^{AV,EX}$ and $\dot{Z}_{k}^{AV,EX}$ by increasing the efficiency of other components is possible [41].

RESULTS AND DESCUTION

Energy, Conventional and advanced exergy analysis results of fired heater combustion air preheating system

The results of the fired heater performance in both current and optimized conditions (using combustion air preheater) based on energy and exergy analyses,

Table 3: Results of the system performance current and optimized situations.

	η_{fur} (%)	η_{comb} (%)	Stack loss (%)	ε_k (%)	$y_{D,k}$ (%)
Current condition	74.93	77.93	22.07	28.91	64.72
Optimized condition	91.07	94.07	7.52	39.99	55.18

Table 4: Detail results of the conventional and advanced exergetic results for all the components.

Components	$\dot{E}x_D$ (kW)	y_D (%)	ε (%)	$\dot{E}x_D^{AV}$ (kW)	$\dot{E}x_D^{UN}$ (kW)	$\dot{E}x_D^{EN}$ (kW)	$\dot{E}x_D^{EX}$ (kW)	$\dot{E}x_D^{EN,UN}$ (kW)	$\dot{E}x_D^{EN,AV}$ (kW)	$\dot{E}x_D^{EX,UN}$ (kW)	$\dot{E}x_D^{EX,AV}$ (kW)
I.D fan	42.61	0.06	80	33.75	8.85	1.87	40.74	0.39	1.48	8.46	32.27
F.D fan	15.08	0.02	80	11.90	3.17	14.62	0.46	3.07	11.54	0.09	0.36
Fired heater	40,455	57.24	37.95	2954.22	37500.77	40,566	-111	38523.78	2042.21	-1023	912
AP	708	1	73.75	245.62	461.87	694	13.8	447.23	246.46	14.63	-0.83
Overall	41,220	58.31	38.9	3245.51	37974.68	41,276	-56	38974.48	2301.70	-999.81	943.81

are shown in Table 3. Results demonstrate that in optimized condition combustion efficiency (20%), fired heater efficiency (16.4%) and exergy efficiency (11.08%) increase and stack loss (14.55%) and exergy destruction (9.54%) decrease, also about 20% saving in fuel consumption is observed.

Conventional and advanced exergy analyses results is presented in Table 4. It can be seen from the largest source of exergy destruction is fired heater then air preheater is in second place while fans have less exergy destruction. fired heater destroys 57.24 % of incoming exergy into the system. This large amount of irreversibility in the fired heater is due to combustion reactions. So is needed to be careful in the selection and design of the components in order to have an efficient system.

Although unavoidable exergy destruction in fired heater and air pre-heater is dominant, 93% and 65% respectively, as it is seen in Table 4, fired heater and AP have the highest amount of avoidable exergy destruction for the overall system that should be noted. High temperature differences between the fluids in AP and combustion reactions in the fired heater are believed to be the main sources for irreversibility [42]. Avoidable exergy destruction portion in F.D and I.D fans (79% for both) is greater than the unavoidable part. Since the performance of components is interdependent, endogenous and exogenous exergy destruction is identified and discussed. The exergy destruction in all components except I.D fan is endogenous dominantly which its portion for the fired heater, AP and F.D fan is more than 100%, 98%, and 97% respectively. This means that most of the exergy destruction in these components are independent of their relationship with other components and mainly caused on their own. The proportion exogenous exergy destruction of the I.D fan is 95%, indicating this component is significantly affected by the rest of the components. A negative value of exogenous exergy destruction for fired heater shows that for reduction the exergy destruction of this component, exergy destruction of other components needs to be increased. The exergy destruction of the overall system is 41.209 MW and the total endogenous exergy destruction of the overall system is equal to 41.276 MW, showing that improving the performance of components has an adverse effect on the performance of other components.

Exergoeconomic and advanced exergoeconomic analyses results of Fired heater combustion air preheating system

As Table 5 demonstrates that the most summation of $\dot{Z}+\dot{C}_D+\dot{C}_L$ is belong to the fired heater and air pre-heater respectively, therefore, these components have More influence on improving the effectiveness of the overall system cost and the most significant components from the thermos-economic standpoint. The ratio of non-Exergetic costs to total costs, determined by Exergoeconomic factor (f_k). The low value of this factor for the basic units, Indicates those cost savings can be achieved by promoting the unit's efficiency even

Table 5: Exergoeconomic parameters for all the components.

Components	c_f ($/GJ)	$\dot{C}_L$ ($/h)	$\dot{C}_D$ ($/h)	$\dot{Z}$ ($/h)	$\dot{Z}+\dot{C}_D+\dot{C}_L$ ($/h)	r (%)	f (%)
I.D fan	2.72	0	0.39	0.196	0.59	29	32.07
F.D fan	2.72	0	0.15	0.123	0.27	45.86	45.48
Fired heater	3.887	67.75	559.8	44.21	671.76	168.8	7.246
AP	3.887	0	12.68	0.43	13.11	0.371	4.1
Overall	9.327	67.75	1413.36	44.91	685.7361	-	-

Table 6: The conventional and advanced exergoeconomic results for all the components.

Components	$\dot{C}_D$ ($/h)	$\dot{C}_D^{EN}$ ($/h)	$\dot{C}_D^{EX}$ ($/h)	$\dot{C}_D^{UN}$ ($/h)	$\dot{C}_D^{AV}$ ($/h)	$\dot{C}_D^{EN,UN}$ ($/h)	$\dot{C}_D^{EN,AV}$ ($/h)	$\dot{C}_D^{EX,UN}$ ($/h)	$\dot{C}_D^{EX,AV}$ ($/h)
I.D fan	0.39	0.018	0.399	0.087	0.330	0.004	0.014	0.083	0.316
F.D fan	0.15	0.143	0.0049	0.0317	0.116	0.0304	0.113	0.0009	0.003
Fired heater	559.8	567.65	-1.559	524.757	41.34	539.074	28.58	-14.31	12.76
AP	12.68	9.71	0.199	6.467	3.44	6.26	3.45	0.205	-0.012
Overall	1413.36	577.52	-0.957	531.34	45.22	545.36	32.15	-14.03	13.07

in case of increase in investment costs, On the other hand, high values of this factor imply that it is necessary to reduce investment costs despite the decrease in efficiency of the unit. the low value of f_k for fired heater indicates that the costs of the fired heater are mainly due to its high exergy destruction which can be increased by reducing exergy destruction costs through fuel pre-heating, reducing heat dissipation and excess air and raising the investment cost. The second important component from the thermos-economic point of view is AP which 4% of the total cost is associated with capital investment, operating and maintenance costs. The low value of f_k in this component can be increased by raising the capital cost up to a reasonable level. In F.D and I.D fans 45.48% and 32.07% of total costs are related to capital investment, operating and maintenance costs respectively which are reasonable amounts for fans. Product cost rate that is equal to the heating load of the system, is calculated as 1033.92 $/h.

The results for advanced exergoeconomic analyses in Table 6 show that apart from I.D fan, for the rest of the components exogenous exergy destruction cost rates are higher than the endogenous exergy destruction cost rates, which indicates that these components are less affected by the performance of other system components. The negative values of the exogenous exergy destruction cost rates show that by increasing the exergy destruction of the other components Exergy destruction cost rates of these components decreases.

Table 7 shows the endogenous investment cost rates in the fired heater, AP and F.D fan are more than exogenous investment cost rates, so investment cost rates of these components are independent of the other components. Due to the higher amounts of the unavoidable investment costs than the avoidable parts, the potential to improve the investment cost is low. The negative value of investment cost rate in fired heater indicates that the investment cost of the fired heater is reduced by increasing the investment costs of the rest of the components. The negative values of avoidable investment cost rates for I.D fan, F.D fan and AP mean that unavoidable investment costs for these components are larger than real values, which demonstrates when unavoidable conditions are applied in the system, by increasing the required area in the AP and volumetric capacity in fans, investment costs in these components rise.

As can be seen, the results of advanced exergy analyses of a system are more precise and reliable than other thermodynamic analyses methods so, besides conventional Exergy analyses, advanced exergy analyses should be used by engineers to find the more accurate results in the investigation of energy conversion systems.

Table 7: Advanced investment costs for all the components.

Components	$\dot{Z}$ (\$/h)	$\dot{Z}^{AV}$ (\$/h)	$\dot{Z}^{UN}$ (\$/h)	$\dot{Z}^{EN}$ (\$/h)	$\dot{Z}^{EX}$ (\$/h)	$\dot{Z}^{EN,UN}$ (\$/h)	$\dot{Z}^{EN,AV}$ (\$/h)	$\dot{Z}^{EX,UN}$ (\$/h)	$\dot{Z}^{EX,AV}$ (\$/h)
I.D fan	0.196	-3.99	4.19	0.009	0.188	0.184	-0.176	4.007	-3.82
F.D fan	0.123	-0.001	0.124	0.119	0.004	0.120	-0.001	0.004	-0.00003
Fired heater	44.21	43.97	0.234	45.41	-1.206	0.241	45.17	-0.0064	-1.199
AP	0.43	-42.60	43.04	0.422	0.0138	41.68	-41.26	1.36	-1.350
Overall	44.91	-1.113	46.02	45.99	-1.080	42.186	3.806	3.839	-4.919

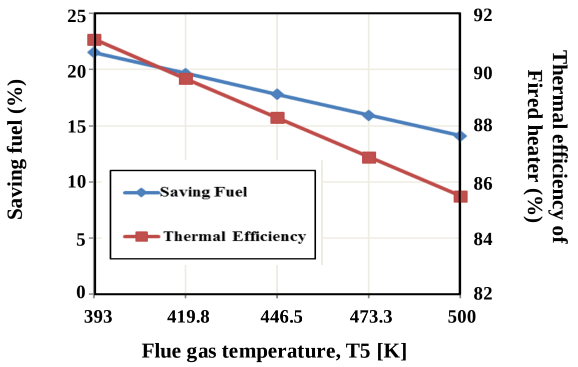

Fig. 2: Saving fuel and thermal efficiency of fired heater variation with the T_5.

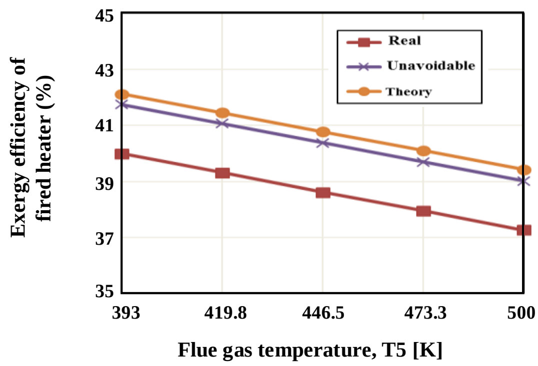

Fig. 3: Exergy efficiency of fired heater variation with the T_5.

Sensitivity study

In this section, the influence of the most effective variable, flue gas temperature (T_5) on the fired heater performance has been investigated. The flue gases temperature (T_5) is changed from 393K up to 500K in Fig. 2 and Fig. 3 as it is expected With increasing flue gases temperature, because of growth in energy waste, saving in fuel consumption (7%), thermal efficiency (5%) and exergy efficiency of fired heater in the real, theoretical and unavoidable conditions (3%) decrease, consequently exergy destruction of fired heater increases. total exergy destruction of the system in all conditions goes up to about (3%) (Fig.4).

The effect of changes in T_5 on F.D fan exergy destruction is presented in Fig. 5, it obvious that in this component the exergy destruction is independent of T_5. As it is seen the most part of its exergy destruction is endogenous (97%) and avoidable (78%) so F.D fan has the potential for improvement and almost all its exergy destruction is due to irreversibility that occurs within itself.

Fig. 6 presents the variation of exergy destruction rate of the fired heater versus T_5. It is seen that the endogenous exergy destruction is dominant in fired heater and a bit more than the total exergy destruction rate because in the theoretical operating condition, the amount of fuel exergy of fired heater increases and its exergy loss becomes zero so the difference between fuel and product exergy (destruction exergy) rises so the exogenous exergy destruction part becomes negative. Due to the high irreversibility of chemical reactions in the fired heater, the majority part of its endogenous exergy is composed of the unavoidable part compared with the avoidable part. So with increasing T_5 total, endogenous, unavoidable and endogenous unavoidable exergy destruction parts diminish while other parts of exergy destruction nearly remain constant.

It is observed in Fig. 7 as T_5 rises, total exergy destruction of AP reduces, because the fuel exergy decreases while the exergy of the product remains constant so based on equation (9) amount of exergy destruction decrements. The endogenous and unavoidable parts

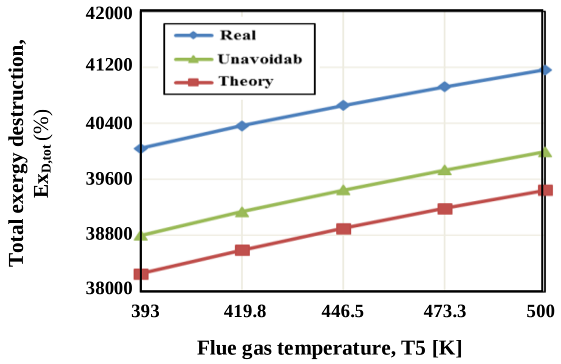

Fig. 4: Total exergy destruction variation with T.

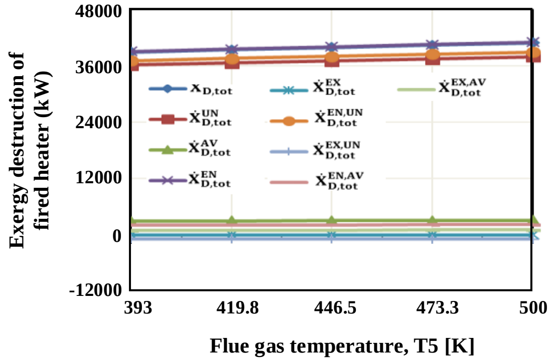

Fig. 6: Fired heater exergy destruction variation with the T_5.

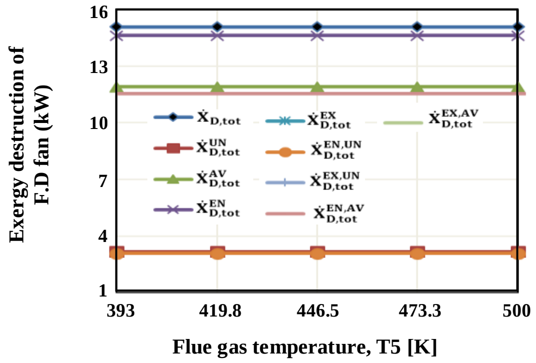

Fig. 5: F.D fan exergy destruction variation with the T_5.

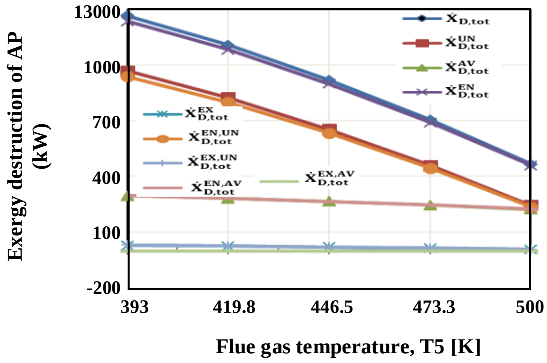

Fig. 7: AP exergy destruction variation with the T_5.

constitute 76 % and 97% of total exergy destruction respectively, with increasing T_5 these two parts and the combination of them (endogenous unavoidable part) decrease with the same slope and have a sharp decline in comparison with other parts that reduce with low slope and their quantities are negligible, So reducing of T_5 has no positive effect on this component, hence the optimum temperature should be selected.

Fig. 8 illustrates rising exergy destruction with increasing T_5 for all elements of exergy destruction of I.D fan. The slop of the exogenous part of exergy destruction is steeper than the endogenous part which implies that variation in T_5 increase effect of other components and the relationship between I.D fan and other components is strong. Furthermore, this figure shows that the avoidable portion of exergy destruction is higher than the unavoidable one which shows this component has the potential for reducing its exergy destruction and improving its exergy efficiency. The endogenous unavoidable and unavoidable parts of exergy destruction have the lowest values in comparison with other parts and increase with very small slop.

Figs. 9 and 10 show the effect of an increase in T_5 on exergy destruction, exergy lost, product and investment costs rates of the overall system. By increasing T_5 from 393Kup to 500K, exergy destruction costs 3% and exergy lost costs 61% rises while product costs 1% and investment costs 5% decrease.

The effect of T_5 variation on the F.D fan exergy destruction cost is presented in Fig. 11, as it is shown the Exergy destruction costs of this component is independent of T_5, also it is seen that the major part of exergy destruction costs of F.D fan is endogenous avoidable (76%) that indicates that the process is improved by enhancing this component.

as it is observed in Fig. 12 by changing the temperature from 393 to 500 K in the fired heater, the total costs of the Exergy destruction (5%), unavoidable (4%),

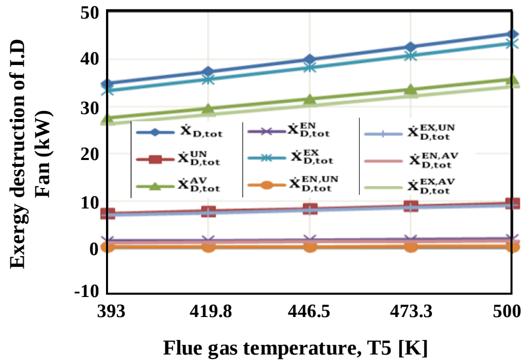

Fig. 8: I.D fan exergy destruction variation with the T_5.

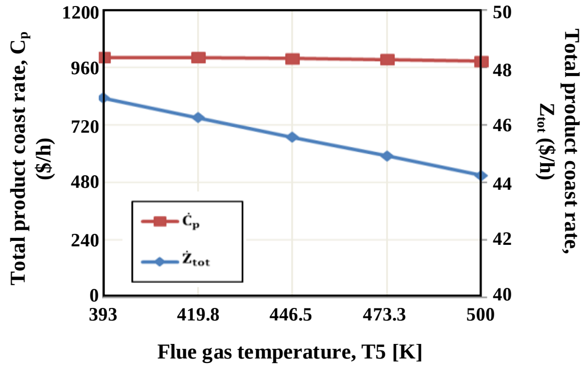

Fig. 10: Total product cost rate and total investment cost rate variation with the T_5.

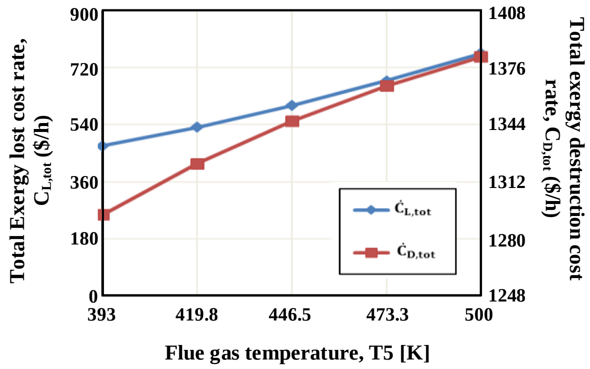

Fig. 9: Total exergy lost cost rate and total exergy destruction cost rate variation with the T_5.

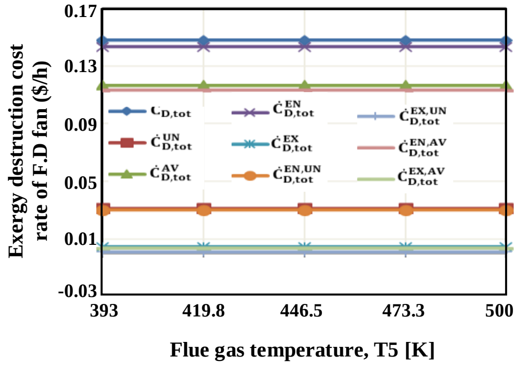

Fig. 11: F.D fan exergy destruction cost rate variation with the T_5.

avoidable (9%), endogenous (5%), endogenous unavoidable (5%) and endogenous avoidable (4%) parts of exergy destruction costs ascend while exogenous and exogenous avoidable exergy destruction costs remain relatively constant. exogenous unavoidable exergy destruction costs decline about 12% .

In Fig. 13, the effect of increasing T_5 on different parts of Exergy destruction costs of AP is shown, it can be seen that the endogenous, unavoidable and endogenous unavoidable parts constitute the most portion of its exergy destruction costs and by rising T_5 decrease about 62%, 74%, and 74% respectively. The values of other parts of the exergy destruction costs in AP are small and decline with a very slight slope.

Fig. 14 illustrates by increasing T_5, avoidable and exogenous avoidable exergy destruction costs that form about 80% of the total exergy destruction costs of I.D fan, grow 30% approximately, unavoidable and exogenous unavoidable parts which constitute 20% of total exergy destruction costs, nearly increase 26%. The amount of endogenous, endogenous unavoidable and endogenous avoidable parts is insignificant and with rising T_5, does not change much.

CONCLUSIONS

In the present study, the conventional and advanced exergy and exergoeconomic analyses of combustion air preheater system According to the Tehran Oil Refinery fired heater (H_101) performance was studied. More over in this paper the advanced exergy analyses method was applied to survey the sensitivity of the different parts of exergy destruction and performance of the system. Therefore the following conclusions obtained as below:

a) The implementation of the air preheater installation, increases fired heater efficiency up to 20% and decreases fuel consumption and heat losses up to 20%.

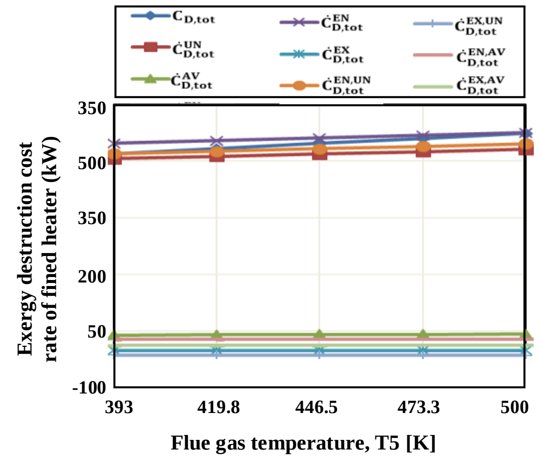

Fig. 12: Fired heater exergy destruction cost rate variation with the T_5.

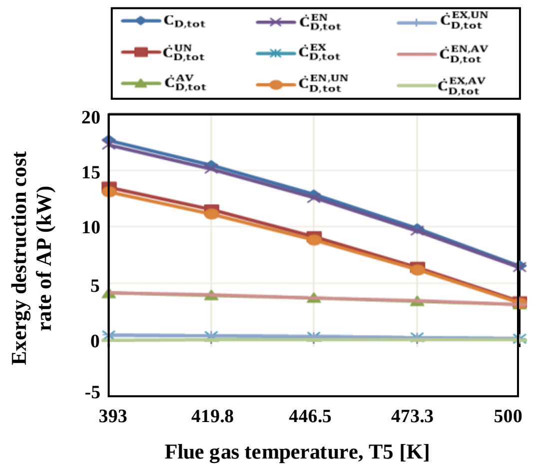

Fig. 13: AP exergy destruction cost rate variation with the T_5.

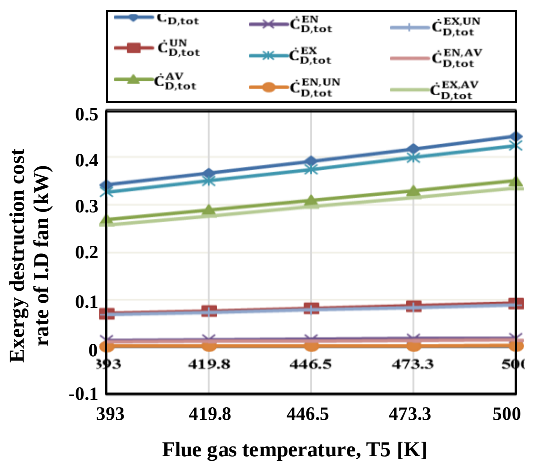

Fig. 14: I.D fan exergy destruction cost rate variation with the T_5.

b) Among all cycle components, the fired heater has the most portion of the exergy destruction rate (57%).

c) Product cost rate that is equal to the heating load ofthe system, was calculated as 1033.92 $/h.

d) With Considering the cost of AP and related equipment and operating and maintenance costs annually, the payback period is estimated to be less than 2 years, so air preheater installation plan on the fired heater (H_101) in Tehran Oil Refinery will be justified in economic terms.

Fired heater and AP have the highest avoidable exergy destruction which means these components have the most potential for enhancing the system performance.

e) Due to the ratio of endogenous exergy destruction of the system to total exergy destruction of the system it can be concluded that the relationship between the components are not very strong, which indicates that components operate independently and the irreversibilities created in them are mainly related to their performance.

f) By increasing the temperature of the flue gases (T_5), thermal efficiency and Exergy efficiency both decrease by 6% and exergy destruction of the entire system increases. Also Rising T_5, increases the total exergy destruction of the fired heater (5%) and ID fan (29%) while decreases total exergy destruction of AP (63%) and have no effect on FD fan.

Nomenclature

c	Cost Per Unit of Exergy, $/GJ
CRF	Capital Recovery Factor
CI	Capital Investment Cost, $
$\dot{C}$	Cost Rate Associated With an Exergy Stream, $/h
C_p	Specific Heat Capacity, kJ/kgK
$\dot{E}_x$	Exergy Flow Rate, kW
f	Exergoeconimc Factor
i	Interest Rate
LHV	Lower Heating Value, kJ/kg
$\dot{m}$	Mass Flow Rate, kg/s
P	Pressure, bar
PEC	Purchase Equipment Cost, $
$\dot{Q}$	Heat Rate, kW
r	Relative Cost Difference, %
t	System Operating Hours, hr
T	Temperature, °C or K
$\dot{W}$	Power, MW

y	Exergy Destruction Ratio
Z	Investment Cost, $
$\dot{Z}$	Investment Cost Rate, $/year

Greek symbols

Δ	Difference
ε	Exergetic Efficiency
η	Thermal Efficiency
Φ	Maintenance Factor
λ	Fuel to Air Ratio

Subscripts

AV	Avoidable
CI	Capital Investment Cost, $
EN	Endogenous
EN,AV	Endogenous Avoidable
EN,UN	Endogenous Unavoidable
EX	Exogenous
EX,AV	Exogenous Avoidable
N	Total Operating Period Of The System, Year
UN	Unavoidable

Subscripts

0	Ambient
comb	Combustion
D	Destruction
F	Fuel
FH	Fired Heater
k	Component
L	Loss
P	Product
tot	Total

Abbreviation

AP	Air Pre-Heater
EES	Engineering Equation Solver
F.D fan	Forced Draft Fan
I.D fan	Induced Draft Fan

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