

Effect of Some Parameters on Exergetic Efficiency of a Combustion System in a Petrochemical Plant

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ABSTRACT: In this study, second law (exergy) analysis of a combustion system, located in İzmir Aliğa, was carried out to reveal the true magnitude of thermodynamic inefficiencies within the system and to evaluate the potential causes of the process irreversibilities. For this purpose, available combustion system that consists a combustion chamber (burner), a furnace (fired heater) and an air preheater was investigated by considering the effects of two parameters such as type of fuel and combustion air temperature. By applying exergy analysis to the system with available conditions, it was seen that burner operates with 76.8% exergy efficiency while furnace and air preheater units have 43.5% and 33.2% of exergetic efficiencies, respectively. Additionally, results of exergy analysis showed that changing temperature of combustion air and fuel type have significant impacts on exergy efficiencies of the units, especially on air preheater.

KEYWORDS: exergy, combustion, burner, furnace, air preheater.

I. INTRODUCTION

In various industries including petrochemical plants and petroleum refineries, furnaces has a widespread usage area to supply high temperature heating to the process fluids. They are one the major energy consuming units. Hence, thermal efficiency of the combustion system has a significant impact on the plant's energy saving. The highest thermal efficiency is increased when the amount of heat delivered to process units is maximized and stack gas emissions (waste heat, CO₂, NO_x, etc.) and fuel used is minimized. It's well known that significant amount of energy is lost via stack gas [8,9] and placing a heat recovery device like air preheater, can substantially reduce these losses.

The first law thermodynamics deals conventionally with the utilization of energy. It gives us basic informations about thermal losses and the effectiveness of the resources. Nevertheless, it is inadequate when the quality aspect of energy use is taken into account. Second law analysis, however, can reveal whether or not and by how much it is possible to design more efficient energy systems by reducing the thermodynamic inefficiencies caused by entropy generation in existing systems. It provides more meaningful information for efficient improvement of process units [2].

Bejan et.al [1] developed 'fuel-product' concept which became very crucial in recent studies in defining exergetic efficiency which is one of the most significant value for evaluating thermal performance of a component in a system.

In the former studies, Shekarchian et al. [10] has analyzed economic benefits of incorporating both heat recovery and air preheating techniques into the existing different fired heater units in a petroleum refinery. In addition to energy analysis, second law efficiency and the rate of irreversibilities in the system were also analyzed via an exergy analysis. It was seen from the study that both analyses were satisfying that heat recovery enhanced both first law and second law efficiency from 63.4% to 71.7% and from 49.4% to 54.8%, respectively. Regulagadda et.al [7] carried out a study about second law analysis of a thermal power plant along with a parametric study that investigates the effects of different parameters like temperature and pressure on the system performance. They concluded that the maximum exergy destruction occurred in boiler unit and efforts at improving plant's performance should be directed to improving boiler efficiency.

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In this study, a combustion system which is used for heating aromatic hydrocarbons in a petrochemical plant was analyzed via exergy analysis. The effect of two system parameters such as fuel type and combustion air temperature on exergy efficiency were investigated .

II. RELATED WORK

The combustion system in the plant consists of three different units. In the burner, 4000 kg/h natural gas is burned with 20% of excess air and hot combustion gases supplied from the burner is used to vaporize an aromatic hydrocarbon feed flowing through the tubes in the furnace with the capacity of 38.7 Gcal/h. However, flue gas leaving the furnace is at 400°C and still contains considerable amount of thermal energy. To recover this waste energy, an air preheater with the capacity of 3.3 Gcal/h is used. With the aid of this unit, combustion air entering the burners is preheated from 15°C to 191°C. Flow chart of the system with actual operating conditions is shown in Figure 1.

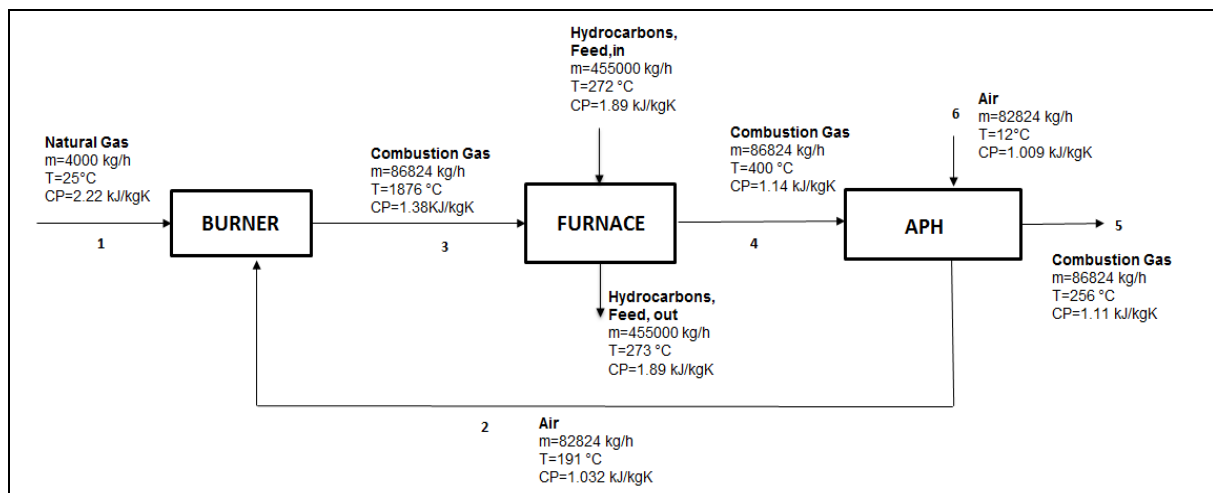


Fig. 1. Flow diagram of the system with operating data

III. EXERGY ANALYSIS

In a control volume, the following equation shows the exergy balance for the k -th component of an energy system at steady state:

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} + \dot{E}_{L,k} \quad (1)$$

where $\dot{E}_{F,k}$, $\dot{E}_{P,k}$ are the fuel and product exergy rates, $\dot{E}_{D,k}$ is the rate of exergy destructed in the component due to irreversibilities and it provides a thermodynamic measurement of the system inefficiencies [4,3]. $\dot{E}_{L,k}$ is the loss of exergy caused by heat loss only [1,6]. If all the boundaries of a system is set to reference conditions as in this study, then the term $\dot{E}_{L,k}$ is eliminated.

The exergetic efficiency is a common measure for assessing the thermodynamic performance of a system component in an industrial plant and it is traditionally defined as:

$$\eta = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} = \frac{1}{1 + \left(\frac{\dot{E}_{D,k}}{\dot{E}_{F,k}}\right)} \quad (2)$$

To calculate the product and fuel exergy rates of each unit, the exergy flow rates of the process streams should be calculated first. The exergy rate of a stream can be expressed as the sum of parts; physical, potential kinetic, and chemical exergy rates relative to the dead state (T_o, P_o) [5]:

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$$\dot{E}_x = \dot{E}_x^{FH} + \dot{E}_x^{FT} + \dot{E}_x^{KN} + \dot{E}_x^{CH} \quad (3)$$

If the system is at rest with the environment as in this study, then \dot{E}_x^{FT} and \dot{E}_x^{KN} exergy changes becomes negligible and the total exergy rate of each stream can be represented as the sum of the \dot{E}_x^{FH} and \dot{E}_x^{CH} where;

$$\dot{E}_x^{FH} = (h - h_0) - T_0 (s - s_0) \quad (4)$$

$$\dot{E}_x^{CH} = \sum x_k \dot{e}^{CH} + RT_0 \sum x_k \ln(x_k) \quad (5)$$

To determine the exergy flow rates of the streams, firstly, classical energy and material balances were applied to the system to find the all flow rates, stream compositions and heat duties of system components by using actual operating data of the main streams obtained from the plant. These values are shown in Table 1 and accepted as “reference case” in this study.

By using stream’s conditions given in Table 1, the enthalpy and entropy values of each streams were calculated and exergy flow rates of the streams were shown in Table 2.

As stated before, the exergetic efficiency of a unit can be defined as the ratio of the product exergy rate over fuel exergy rate. Therefore, it is of great importance to specify the fuel and the product streams properly within a unit. For the burner, exergetic efficiency can be defined as:

$$\epsilon_{Burner} (\%) = \frac{E_{x3}}{E_{x1} + E_{x2}} \times 100 \quad (6)$$

Exergetic efficiency of the furnace is found as follows:

$$\epsilon_{Furnace} (\%) = \frac{\Delta E_{x,feed}}{E_{x3} - E_{x4}} \times 100 \quad (7)$$

In this equation exergy change of aromatic feed stream (benzene), $\Delta E_{x,feed}$, was calculated as 16.11 MW by the following equation:

$$\Delta E_x = (h_{vapor} - h_{liquid}) - T_0 (S_{vapor} - S_{liquid}) \quad (8)$$

The exergetic efficiency of air preheater unit can be expressed as follows:

$$\epsilon_{APH} (\%) = \frac{E_{x2} - E_{x4}}{E_{x1} - E_{x3}} \times 100 \quad (9)$$

The calculated unit exergy efficiencies with operating conditions are given in Table 3.

In Table 3, it can be clearly seen that high exergy destruction results in low efficiency within a thermal system. These destructions are caused from process irreversibilities. In the reference case, although the lowest exergetic efficiency was seen in air preheater unit, almost 60% of total exergy destruction occurred in the furnace unit where the aromatics are vaporized. In this unit, thermodynamic irreversibilities are arised from high temperature difference between the process fluids. 36% of total destruction was in the burners (combustion chamber). It is mainly caused by chemical exergy change. In the air preheater unit, 4% of total exergy was destroyed as a result of finite temperature difference between the streams.

In this study, two parameters were investigated. Effect of combustion air temperature and fuel type on exergetic efficiency of combustion system were studied.

Table 1. Operating conditions of the system (reference state)

Stream No	Fluid Type	Flow Rate (kg/h)	Composition(%)					T (K)
			CH ₄	N ₂	O ₂	CO ₂	H ₂ O	
1	NG	4,000	100	-	-	-	-	298
2	Air	82,824	-	79	21	-	-	464
3	CG	86,824	-	73	3	8	16	2,149
4	CG	86,824	-	73	3	8	16	673
5	CG	86,824	-	73	3	8	16	529
6	Air	82,824	-	79	21	-	-	285

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Table 2. Rates of physical, chemical and total exergies of the streams

Stream No	Fluid Type	\dot{E}_{x}^{PH} (MW)	\dot{E}_{x}^{CH} (MW)	\dot{E}_{x}^{total} (MW)
1	NG	0.00	54.17	54.17
2	Air	0.75	0.04	0.79
3	CG	40.7	1.52	42.26
4	CG	3.70	1.52	5.23
5	CG	1.68	1.52	3.20
6	Air	0.07	0.04	0.11

Table 3. Exergetic efficiencies of the units

Unit Name	$\dot{E}_{x_{Fk}}$ (MW)	$\dot{E}_{x_{Pk}}$ (MW)	$\dot{E}_{x_{Dk}}$ (MW)	η (%)
Burner	54.96	42.26	12.70	76.89
Furnace	37.04	16.11	20.92	43.51
Air Preheater	2.02	0.67	1.35	33.24

IV. RESULTS AND DISCUSSION

Changing air preheating temperature has affected all the system units differently (Figure 2). Increasing the air temperature can only be achieved by increasing the heat load of the air preheater unit by adding extra heat transfer surface area in it. However, the increase in the combustion air temperature is limited due to the differences between the air and combustion gas flow rates.

Table 4 shows that by increasing the temperature of the air in the combustion chamber, the adiabatic flame temperature also increased (Stream 3). Hence, both fuel and product exergy rates in combustion chamber increased (Table 5) and it led to a slight increase in the combustion chamber exergetic efficiency.

In Table 4 it is seen that increasing heat duty in the air preheater also resulted in a decrease in the outlet temperatures of the combustion gases exhausted to the atmosphere (Stream 5).

Table 4. Temperatures of the streams according to combustion air temperatures

Combustion Air Temperature (°C)	Temperature (K)					
	1	2	3	4	5	6
191	298	464	2149	673	529	285
201	298	474	2156	673	522	285
211	298	484	2163	673	514	285
221	298	494	2170	673	506	285
231	298	504	2178	673	498	285

For furnace unit, although the product exergy (exergy change of aromatic feed stream) remained the same, the exergy rate of the fuel increased as a result of increasing adiabatic flame temperature. Also, it should be noted that the temperature of the combustion gases leaving the furnace was assumed to be constant. Therefore, a slight decrease in the furnace exergetic efficiency was observed under these circumstances.

In the air preheater, due to the constant temperature of the inlet combustion gases and decreasing temperature of the outlet combustion gases, fuel exergetic efficiency of this unit increased. Similarly, since the temperature of the inlet air did not change, and outlet temperature of the air increased; product exergy rate of the unit increased. (Table 5). These conditions resulted in a dramatic increase in the exergetic efficiency of the unit.

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Table 5. Exergy rates of the system units with different inlet air temperatures

Combustion Air Temperature (°C)	Burner			Furnace			Air Preheater		
	$\dot{E}_{x_{F,k}}$ (MW)	$\dot{E}_{x_{P,k}}$ (MW)	$\dot{E}_{x_{D,k}}$ (MW)	$\dot{E}_{x_{F,k}}$ (MW)	$\dot{E}_{x_{P,k}}$ (MW)	$\dot{E}_{x_{D,k}}$ (MW)	$\dot{E}_{x_{F,k}}$ (MW)	$\dot{E}_{x_{P,k}}$ (MW)	$\dot{E}_{x_{D,k}}$ (MW)
191	54.96	42.26	12.70	37.04	16.11	20.92	2.02	0.67	1.35
201	55.20	42.50	12.70	37.27	16.11	21.16	2.22	0.91	1.31
211	55.44	42.74	12.71	37.51	16.11	21.40	2.45	1.15	1.30
221	55.69	42.98	12.71	37.75	16.11	21.64	2.68	1.40	1.28
231	55.93	43.25	12.68	38.02	16.11	21.91	2.91	1.64	1.27

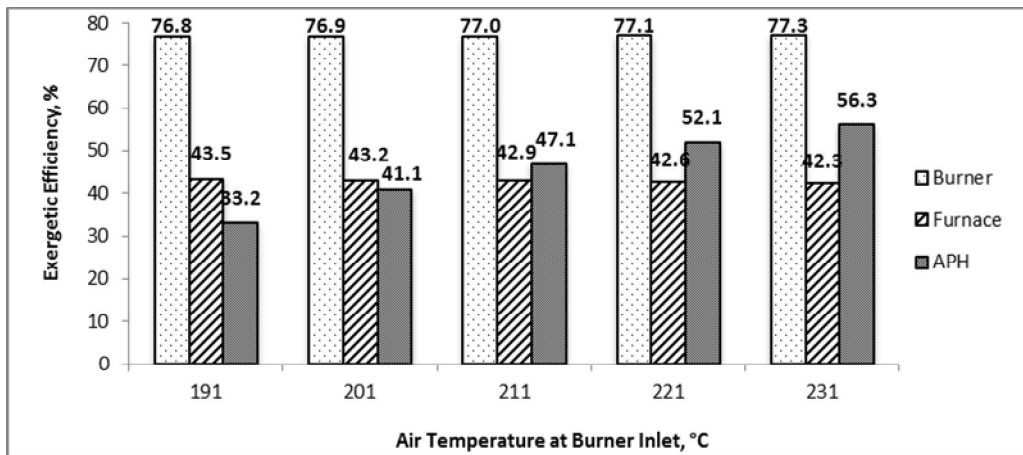


Fig. 2. Effect of preheating air temperature on exergetic efficiencies

Effect of Fuel Type:

Instead of natural gas, when a different fuel (fuel oil) is used for combustion in the system, the operating data of the units were changed and the new flow diagram obtained from the company is shown in the Figure 3. In this diagram, it is seen that almost all temperature values in the streams were higher comparing with the natural gas operating data. As seen in Table 6, the amount of fuel used increased from 4000 kg/h to 6905 while the combustion air flow rate and produced combustion gas flow rate were decreasing.

Table 6. Operating conditions of the system

Stream No	Fluid Type	Flow Rate (kg/h)	T (K)
1	Fuel Oil	6905	298
2	Air	74254	483
3	CG	81159	2266
4	CG	81159	745
5	CG	81159	575
6	Air	74254	288

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Table 7. Rates of physical, chemical and total exergies of the streams

Stream No	Fluid Type	\dot{E}_x^{PH} (MW)	\dot{E}_x^{CH} (MW)	\dot{E}_x^{total} (MW)
1	Fuel Oil	0.00	51.41	51.41
2	Air	1.08	0.04	1.12
3	CG	40.27	1.50	41.77
4	CG	5.25	1.50	6.75
5	CG	2.71	1.499	4.21
6	Air	0.06	0.04	0.10

Table 8. Exergetic efficiencies of the units when the working fuel is fuel oil

Unit Name	$\dot{E}_x_{F,k}$ (MW)	$\dot{E}_x_{P,k}$ (MW)	$\dot{E}_x_{D,k}$ (MW)	ϵ (%)
Burner	52.53	41.77	10.76	79.51
Furnace	35.02	16.11	18.90	46.02
Air Preheater	2.54	1.01	1.53	39.87

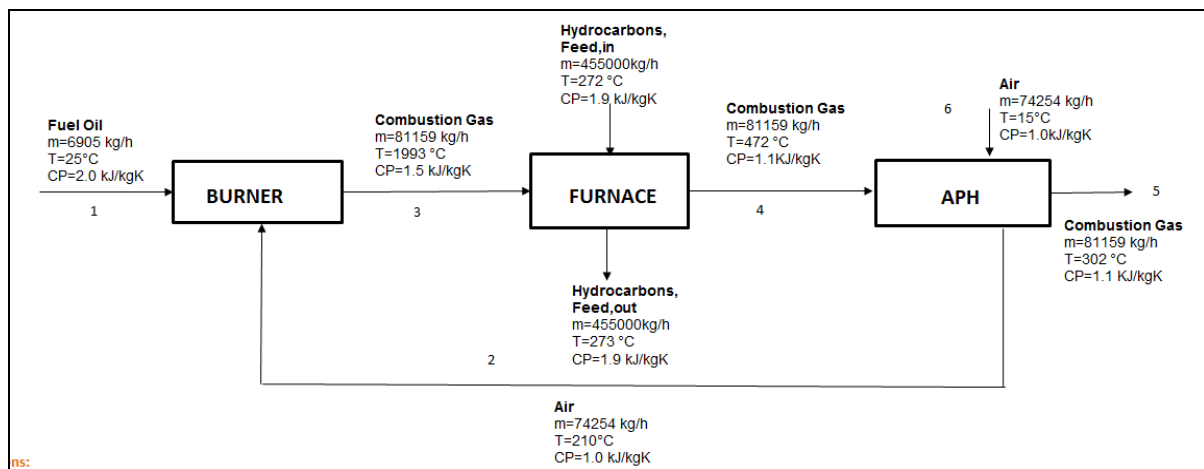


Fig. 3. Flow diagram with fuel oil combustion

Table 8 shows that both fuel and product exergy flow rates in the burner decreased due to the lower flow rate of air and lower heating values of the fuel oil, despite of the higher adiabatic flame temperature. As the amount of produced combustion gases decreased, product exergy rate of burner unit also decreased. In the furnace, fuel exergy flow rate decreased due to lower combustion gas flowrate, while the product exergy rate remained the same. This yielded a slight increase in the exergetic efficiency of the furnace. In the APH, because of the higher temperatures of the streams, both fuel and product exergy flow rates of the unit increased although the flow rates of the fluids decreased.

Following figure shows that exergetic efficiency of the all units increased in the case of fuel oil combustion. Moreover, less amount of combustion gas with higher stack temperatures were obtained. This comparison can be supported by environmental and economical analyses to enlight designers and operators in the determination of the most convenient fuel type.

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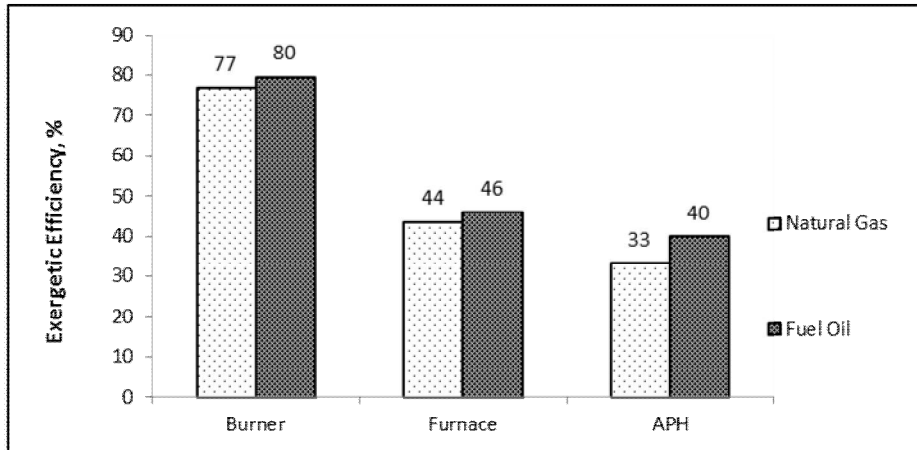


Fig.4 Comparison of the exergetic efficiencies based on fuel types

V. CONCLUSION

In this study affect of two parameters on the combustion efficiency was studied in a second law point of view. As the first parameter, effect of combustion air temperature was investigated and it was concluded that increasing the temperature of combustion directly reduces the fuel used for the combustion and increase the burner exergetic efficiency. It also had a significant effect of air preheater exergetic efficiency. If the combustion air temperature was increased from 191°C to 231 C, the efficiency of air preheater increased from 33.2% to 56.3 %.

As the second parameter, instead of natural gas, fuel oil was used as fuel for combustion and both burner and furnace exergetic efficiencies were increased by 2% and air preheater exergetic efficiency was increased by 7%. It seems that using fuel oil is more efficient than natural gas.

We have implemented an automatic text detection technique from an image for Inpainting. Our algorithm successfully detects the text region from the image which consists of mixed text-picture-graphic regions. We have applied our algorithm on many images and found that it successfully detect the text region.

VI. NOMENCLATURE

\dot{m} : mass flow rate, [kg/h]	s : specific entropy, [kJ/kgK]	Subscripts	Superscripts
T : temperature, [°C]	R : universal gas constant, [kJ/kmolK]	F : fuel	AV : avoidable
P : pressure, [bar]	x : mol fraction, [-]	P : product	UN : unavoidable
ϵ : efficiency, [-]	Q : heat flow rate, [kW]	L : loss	PH : physical
\dot{E}_x : exergy flow rate, [MW]	NG:natural gas	D : destruction	CH : chemical
h : specific enthalpy, [kJ/kg]	CG:combustion gas	o :reference state	PT : potential
			KN : kinetic

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