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IRREVERSIBILITY REDUCTION IN COMBUSTION PROCESSES USING OXYGEN ENRICHMENT TECHNIQUE: AN EXERGY ANALYSIS APPROACH

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Abstract

Combustion is an inevitable part of most oil and gas treatment plants. Because of high temperature of the combustion process, the released heat is often recovered as pre-heating streams or steam generation purposes. Improving the combustion process and reducing the thermodynamic irreversibilities not only results a more sustainable and environmentally-harmless operation, also reduces the energy consumption and operational costs. Oxygen enrichment of combustion air is one of the improvement techniques in combustion systems. In this paper, the effects of oxygen enrichment on the efficiency of a typical coal-based steam generator are studied using exergy analysis methodology. The results show that oxygen enrichment could be a helpful and simple way to improve the efficiency of combustion processes. Also, the trend of changes in operational parameters shows that the oxygen enrichment level of 35% vol. could be considered as an optimum enrichment level. Using this enrichment level, the rational and conventional efficiencies of the boiler will increase to 44.9 % and 93.3% correspondingly.

Keywords: Exergy Analysis; Irreversibility; Oxygen Enrichment; Combustion.

1. Introduction

Combustion is an inseparable part of the most processes in oil, gas and petrochemical industries, which usually is considered as a major source of thermodynamic losses and irreversibilities in the plants. Combustion process is often accompanied by heat transfer as well as fluid friction and mixing so there is usually more than one form of irreversibility present. In principle it is impossible to evaluate in this case what part of the total irreversibility is due to any particular cause. The process of combustion can be examined, however, by assuming that it takes place under adiabatic conditions and that irreversibilities due to friction and mixing are negligible.

Because of the exothermic nature of the combustion reactions and also high chemical exergy of the hydrocarbon fuels, the change in entropy, is much larger than the entropy difference between products and reactants at the reference environment temperature [1]. To reduce this inherent irreversibility, a reduction in the rate of increase in entropy is required, which is always associated with an increase in the maximum temperature of the products. Thus, three ways could be considered for this purpose including isochoric combustion, preheating the reactants, and oxygen enrichment of the combustion air.

Isochoric combustion involved changing the character of the process. Isochoric curves in a temperature-entropy (T-S) diagram are steeper than isobaric curves which for a given fuel (given calorific value) the entropy increase will be less and also the temperature of final products will be higher than in an isobaric process.

Pre-heating the reactants is the most common way of reducing irreversibilities of a combustion process. Pre-heating is usually carried out using combustion products (flue gas) after they have performed their main heating duty and before they are released into the atmosphere. Pre-heating the reactants causes lower entropy production rate and higher product temperature.

Oxygen enrichment of the reactants reduces nitrogen dilution and thus also decreases the heat capacity of the reactants and products. This leads to a reduction in entropy production rate and an increase in the temperature of final products. The reduction in irreversibility rate produced by oxygen enrichment is often greater than the exergy of the oxygen used, and the effect of this method could be enhanced by combining with other techniques [1]. Also, some other results such as higher flame temperature, destruction of undesirable compounds in the fuel and reduction in the size of equipments or increase in capability of the process will be achieved by this method. In this paper, a typical combustion process is studied from exergy and thermodynamic irreversibility point of view, and also the effects of oxygen enrichment on the exergy efficiency and irreversibility are compared with the normal operating conditions [2].

The exergy analysis method is an alternative based on the concept on exergy, loosely defined as a universal measure of the work potential or quality of different forms of energy in relation to a given environment (reference environment). The loss of exergy, or irreversibility, provides a generally applicable quantitative measure of process inefficiency. Unlike the traditional criteria of performance, the concept of irreversibility is firmly based on the two main laws of thermodynamics. The exergy balance for a control region, from which the irreversibility rate of a steady flow process can be calculated, can be derived by combining the steady flow energy equation (first law) with the expression for the entropy production rate (second law). Although the second law is not used explicitly in the exergy analysis method, its application to process analysis demonstrates the practical implications of the second law [1-2].

Many processes and systems have been improved and optimized using exergy analysis. Bassily [3-4] showed that the efficiency and power of the double and triple-pressure reheat combined cycles could be enhanced using irreversibility reduction in the heat recovery steam generators. His work emphasized on the effect of feed preheating on the reduction of irreversibility in thermal units. Som and Datta [5] investigated exergy aspects and thermodynamic irreversibilities in combustion processes. Different affecting parameters such as combustion chamber geometry, temperature gradients, fuel economy, mixing, etc. and their effects on the exergy efficiency of the process studied thoroughly. In a similar work Wang *et al.* [6] performed an exergy analysis on the air pre-heaters in thermal power plants and determined amounts and sources of exergy destruction. Also, there are numerous attempts for thermodynamic irreversibility minimizing via exergy analysis. Sarkar *et al.* [7] minimized exergy losses in heat exchangers for trans-critical carbon dioxide systems. Their work caused improvements in heat exchanger mechanical design and operating condition. In a similar work the thermodynamic losses within a sulfur recovery unit was studied using exergy analysis by Samimi *et al.* [8]. The minor process modifications in arrangements and operating conditions which improve the plant's exergy efficiency were reviewed in their work. Ensinas *et al.* [9] also showed the application of exergy analysis in reduction of irreversibility generation in sugar and ethanol production plants.

2. Methodology

2.1. Assumptions

A typical combustion system including a coal fired steam boiler is considered as a case study. Exergy analysis in normal operating conditions and different oxygen enrichment levels is performed and the effect of oxygen enrichment on the steam boiler exergy efficiency and irreversibility is studied. As is shown in figure 1, the studied system is composed from three sub-regions including (I) adiabatic combustion, (II) heat transfer (steam generation) and (III) mixing effluents with ambient air.

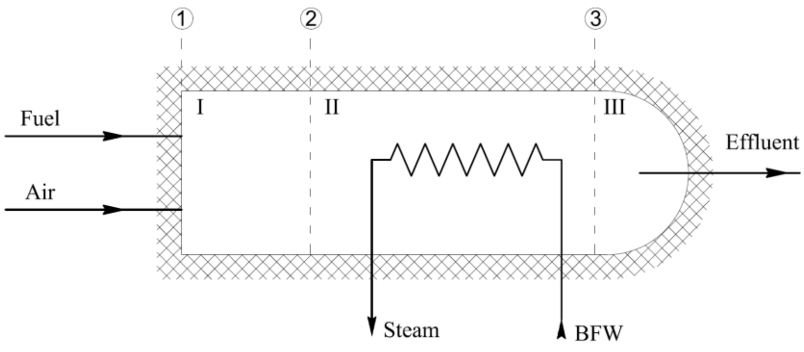

Fig.1 Scheme of a coal fired steam boiler

The coal fuel is anthracite (comprising 78.2%wt. carbon, 2.4% hydrogen, 0.9% nitrogen, 1% sulfur, 1.5% oxygen, 8% water and 8% ash) and steam is generated at the constant pressure of 20 MPa. Both the fuel and the air are delivered at standard temperature and pressure. At normal condition, a 30% excess air over the stoichiometric requirement is provided. Any heat loss and pressure drop is neglected in the system. All the calculations are carried out based on 100 kg fuel.

2.2. Calculations

For each sub-region and for each case of oxygen enrichment, energy and exergy analysis as well as thermodynamic irreversibility calculations are performed and at the end, rational efficiency of the boiler is compared with the conventional combustion efficiency.

2.2.1. Sub-region (I)

By performing a material balance on the system and assuming the combustion reactions carried out completely, the chemical composition of the product could be calculated as 12.34 %(wt) CO_2, 3.10 % H_2O, 66.79 % N_2, 17.68 % O_2, and 0.09 % SO_2. For the sub-region (I), energy balance could be considered as equation 1.

$$m_F(\Gamma)^0 = \sum_k n_k\, h_{ph,k} = (\theta_2 - \theta^0)\sum_k n_k\, c_{p,k}^h \qquad (1)$$

The c_p^h values for each component at a trial combustion temperature could be extracted or calculated using standard references. The combustion product temperature (θ_2) obtained from equation 1 should be corrected by trial and error approach.

Assuming that there is no shaft work and heat transfer, and also that air is in the standard condition, therefore the irreversibility in the sub-region (I) could be calculated using the equation 2.

$$I_{(I)} = (E_F) - (E_2) = \ (m_F\bar{\varepsilon}_F^0) - (n_{P,2}\varepsilon_{P,2}^0 + \textstyle\sum_k n_k\, \varepsilon_{ph,k}) \qquad (2)$$

Which molar exergy of products at the end of sub-region limit ($\varepsilon_{P,2}^0$) could be calculated as equation 3.

$$\varepsilon_{P,2}^0 = \sum_k x_k\, \varepsilon_k^0 + RT^0 \sum_k x_k \ln x_k \qquad (3)$$

The standard molar exergy of each component could be extracted from standard reference tables. Substitution the calculated terms into equation 2 yields the irreversibility in the sub-region (I).

2.2.2. Sub-region (II)

In the sub-region (II) the heat released from the combustion reactions is used to generate steam from saturated water. Enthalpy and entropy values of the saturated steam and water at the pressure 20 MPa could be extracted from standard steam tables. Also heat capacity coefficients for each component could be extracted or calculated from standard reference tables at the steam saturation temperature. Therefore, applying an energy balance in the sub-region (II) yields:

$$H_2 - H_s = m_s(\bar{h}_{s,2} - \bar{h}_{w,1}) \qquad (4)$$

$$H_3 = (\theta_3 - \theta^0)\sum_k n_k\, c_{p,k}^h \qquad (5)$$

Similarly, the irreversibility in the sub-region (II) would be calculated using equation 6.

$$I_{(II)} = (E_2 - E_3) - (E_{s,2} - E_{w,1}) \qquad (6)$$

2.2.3. Sub-region (III)

In the sub-region (III) all the exergy of the effluents given by E_3 is lost through dissipation (mixing, cooling, etc); Hence, the irreversibility value in this sub-region equals to the total exergy of the final effluents.

2.2.4. Exergy Efficiencies

In order to provide a meaningful comparison between different operating cases, the rational exergy efficiency of the boiler is calculated in each case and compared with the energy-based conventional combustion efficiency. The rational exergy efficiency and conventional combustion efficiency in this system could be calculated through equations 7 and 8 respectively.

$$\psi = \frac{E_{s,2} - E_{w,1}}{E_F} \tag{7}$$

$$\eta_{comb.} = \frac{m_s(\bar{h}_{s,2} - \bar{h}_{w,1})}{m_F(\Gamma)} \tag{8}$$

3. Results and Discussion

Energy and exergy analysis as well as irreversibility calculations were carried out for normal operating condition and also in case of oxygen enrichment in different levels. Eleven enrichment levels were studied and the irreversibilities and efficiencies in each case were compared. Figures 2 to 10 represent the obtained results for different conditions. It should be noted that all calculations were carried out based on 100 kg fuel.

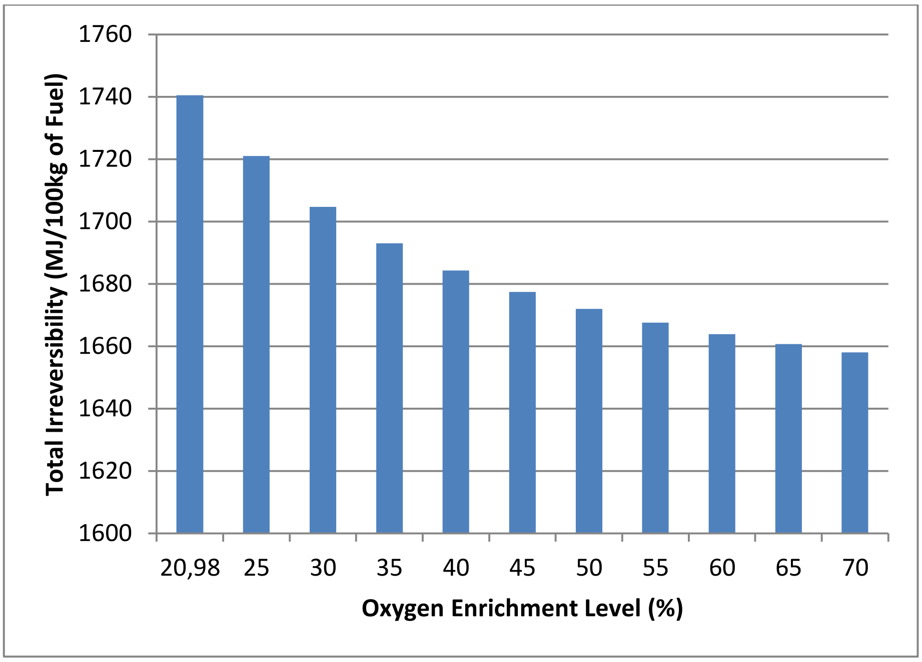

Fig. 2 Total irreversibility at different oxygen enrichment levels

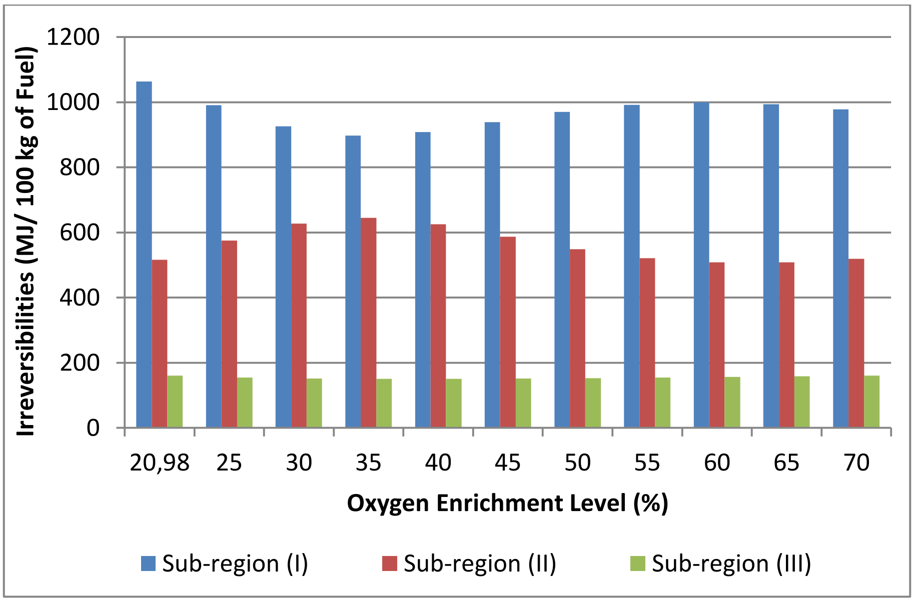

Fig. 3 Irreversibilities in sub-regions at different oxygen enrichment levels

Irreversibilities calculated in each sub-region and oxygen enrichment levels are represented in table 1. Also other parameters obtained from exergy analysis are summarized in table 2.

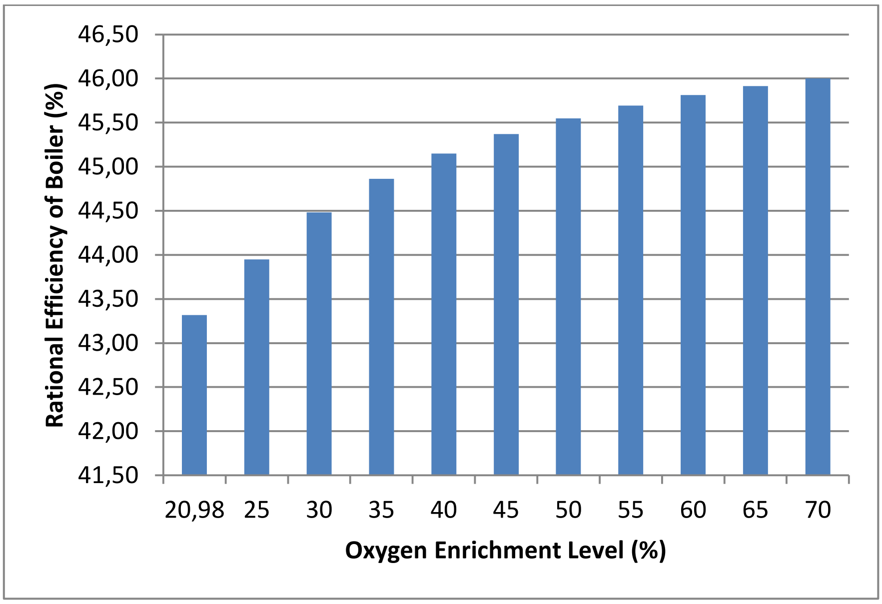

Fig. 4 Rational efficiency of the boiler at different oxygen enrichment levels

Table 1 Irreversibility for different oxygen enrichment levels

Oxygen Concentration (%)	Irreversibility of sub-region (I) (kJ/100 kg of fuel)	Irreversibility of sub-region (I) (kJ/100 kg of fuel)	Irreversibility of sub-region (I) (kJ/100 kg of fuel)	Total Irreversibility (kJ/100 kg of fuel)
20.98	1063738	516459	160253	1740449
25	990524	575612	154885	1721021
30	925858	627018	151802	1704678
35	897730	644506	150768	1693004
40	907808	625538	150903	1684249
45	938727	586964	151748	1677439
50	970455	548487	153049	1671992
55	991769	521105	154659	1667534
60	999345	507985	156490	1663820
65	993918	508268	158491	1660677
70	977686	519661	160636	1657983

Table 2 Exergy analysis results for different oxygen enrichment levels

Oxygen Concentration (%)	Steam generated in sub-region (II) (kg/100 kg of fuel)	Calculated combustion temperature (°C)	Rational efficiency of boiler (%)	Conventional efficiency of boiler (%)
20.98	948.0	1558	43.3	90.1
25	961.8	1763	43.9	91.4
30	973.5	1983	44.5	92.5
35	981.8	2168	44.9	93.3
40	988.0	2316	45.1	93.9
45	992.9	2429	45.4	94.3
50	996.8	2513	45.5	94.7
55	999.9	2578	45.7	95.0
60	1002.6	2629	45.8	95.3
65	1004.8	2669	45.9	95.5
70	1006.7	2702	46.0	95.6

According to the results higher concentration of oxygen in combustion air causes higher efficiencies and more steam generation. However, it must be noted that higher combustion chamber temperatures may be not possible due to mechanical design and refractory temperature limitations. On the other hand, despite the higher costs for oxygen enrichment in higher concentrations (>30~40%), the improvements achieved are not significant. In order to determine a feasible and meaningful enrichment level, the rates of changes in total irreversibilities as well as rational efficiency of boiler are chosen to be traded-off. The results show that oxygen enrichment of combustion air in range of 35 to 40 % could make a feasible improvement in combustion processes. Also, the trend of irreversibilities in each sub-region shows that there is a minimum in 35% enriched air for sub-regions (I) and (III), which is corresponded to a maximum for sub-region (II) due to steam generation.

4. Conclusions

The effects of oxygen enrichment of combustion air in steam generating boilers using exergy analysis were studied in this paper. The results show that oxygen enrichment by increasing combustion temperature and lowering nitrogen flow rate, could improve the combustion process thermodynamically and reach to higher exergy and energy efficiencies. Also, trend of changes in the calculated parameters shows that an oxygen enrichment of 30~40% could be used as an optimum enrichment rage. Obviously, the other parameters like mechanical design and refractory, economic considerations, operation policy, etc. may affect this range.

Symbols		***Greek:***	
M	*mass flow (kg)*	*Θ*	*Temperature (°C)*
H	*Specific enthalpy (kJ/kmol)*	*Γ*	*Net calorific value (kJ/kg)*
S	*Specific entropy (kJ/kg/K)*	*Ψ*	*Rational exergy efficiency of boiler*
c_p	*Specific heat capacity (kJ/kmol/K)*	*H*	*Conventional energy efficiency of boiler*
E	*Exergy (kJ)*	$\bar{\varepsilon}$	*Specific mass exergy (kJ/kg)*
I	*Irreversibility (kJ)*	*ε*	*Specific exergy (kJ/kmol)*
R	*Universal gas constant (8.314 kJ/mol/K)*	***Subscripts***	
T	*Temperature (K)*	*F*	*Feed*
X	*mole fraction*	*Ph*	*Physical*
H	*Enthalpy (kJ)*	*K*	*component k*

Superscripts			
H	*enthalpic*	*P*	*Product*
E	*exergetic*	*S*	*Steam*
0	*Reference environment*	*W*	*Water*

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