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INCINERATOR EFFICIENCY IMPROVEMENT IN SULFUR RECOVERY UNIT USING OXYGEN ENRICHMENT TECHNIQUES

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Abstract

Incineration process is used in almost sulfur recovery units in order to make the process effluents releasable into the atmosphere. The hazardous and pollutant sulfur containing compounds are converted to sulfur dioxide using thermal incineration. Because of high temperature of this process, the released heat is recovered as preheating streams or steam generation purposes. Improving the incineration process and reducing the thermodynamic irreversibilities not only results a more sustainable and environmentally-harmless operation, also reduces the energy consumption and costs. Oxygen enrichment of combustion air is one the improvement technique in incinerators and combustion systems. In this paper, the effects of oxygen enrichment on the incineration efficiency are studied using exergy analysis methodology. The results show that oxygen enrichment could be a helpful and simple way to improve the efficiency of incineration 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.

Keywords: Exergy Analysis; Irreversibility; Oxygen Enrichment; Incineration; Sulfur Recovery Unit.

1. Introduction

Oil and gas processing is inevitable of combustion, which usually is considered as the major potential source of thermodynamic losses and irreversibility in the plant. Combustion processes are 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 [1].

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. To reduce this inherent irreversibility requires a reduction in the rate of increase in entropy, 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. Oxygen enrichment of the combustion air reduces nitrogen dilution and thus 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. 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 [1-2]. In this paper, a typical incinerator in a sulfur recovery unit 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.

Sulfur recovery unit in crude and natural gas refineries recovers elemental sulfur from acid gas streams. Most of sulfur recovery units whole the world, are working based on Claus process. The acid gas stream after enrichment, routed to Claus reaction furnace in which thermal conversion takes place. Then the catalytic reactions are followed in two or three Claus catalytic reactors. The tail gas stream from Claus section contains toxic and hazardous compounds (mainly hydrogen sulfide, carbon disulfide, carbonyl sulfide, and sulfur dioxide) which cannot be released to atmosphere. In many sulfur recovery units, there is a tail gas treatment section for further sulfur recovery and absorption of remained acid gas via alkanoamine-based absorption operations. In order to meet the environmental regulations, the off gases should be treated in an incinerator to minimize the concentration of the restricted components in effluents. The hot flue gas is utilized for energy recovery and high pressure steam generation, and then the cooled effluent stream (containing sulfur dioxide, carbon dioxide and water) is released to atmosphere through a proper stack.

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 [2, 12].

Many combustion-based 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. Since the incineration process is a side-treatment in sulfur recovery units which only converts the effluents to a chemically harmless and releasable stream to the atmosphere, it is associated with high amounts of thermodynamic losses. Several works were focused on the energy recovery of flue gas stream. Nasato *et al.* [10] developed a model from reaction quench times in waste heat boilers in sulfur recovery units. In a similar work, Boroujerdi *et al.* [11] studied energy recovery techniques from sulfur recovery unit incinerators. Their technical evaluations show that flue gas energy could be utilized in preheating air and acid gas streams as well as high pressure steam generation.

2. Methodology

2.1 Assumptions

A typical incineration system including a methane burner is considered as a case study. Exergy analysis in normal operating conditions and different oxygen enrichment levels is performed and the effects of oxygen enrichment on the waste heat boiler exergetic efficiency and irreversibilities are 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. The burner fuel gas is considered as pure methane, and the tail gas stream contains 37.81% (molar) carbon dioxide, 48.5% nitrogen, 0.28% methane, 0.04% hydrogen sulfide, 0.11% carbon monoxide, 2.5% hydrogen, 10.16% water and 0.6% oxygen. Steam is generated at the constant pressure of 4.4 MPa in waste heat boiler. It is assumed that all the inlet streams 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 tail gas.

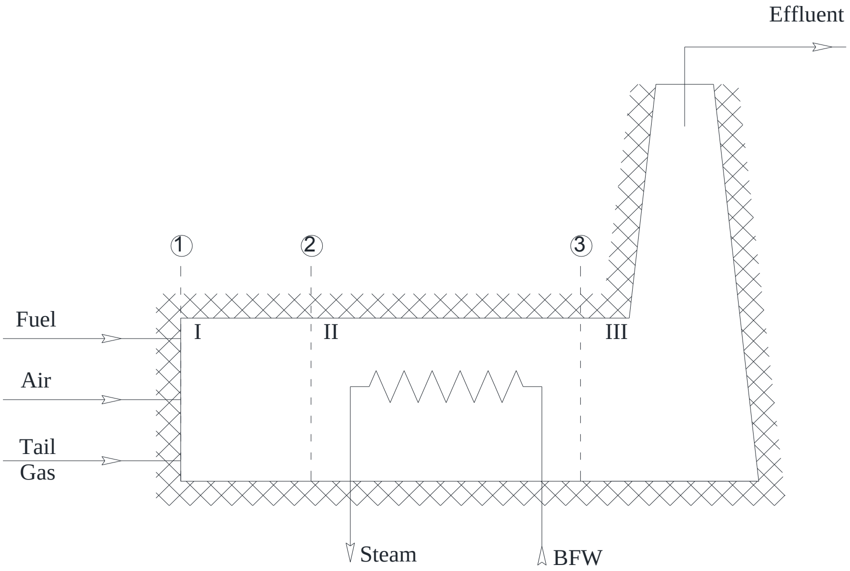

Fig 1 Scheme of an incinerator

2.2 Calculations

For each sub-region and 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 waste heat 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.

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

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 through a 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.

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

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

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

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 boiler feed water. Enthalpy and entropy values of the saturated steam and water at the pressure 4.4 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:

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

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

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

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

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 waste heat boiler is calculated in each case and compared with the corresponding 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.

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

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

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. Seven enrichment levels were studied and irreversibilities and efficiencies in each case were compared. Figures 2 to 5 as well as tables 1 and 2 represent the obtained results for different conditions. It should be noted that all calculations were carried out based on 100 kg tail gas.

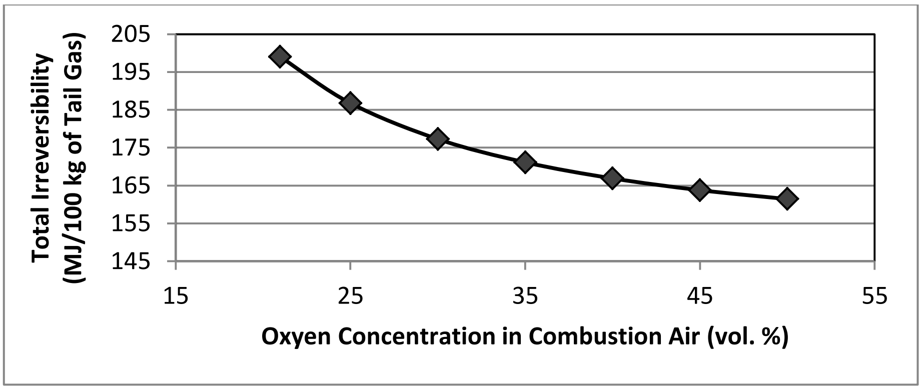

Fig 2 Total irreversibility in incinerator at different oxygen enrichment levels

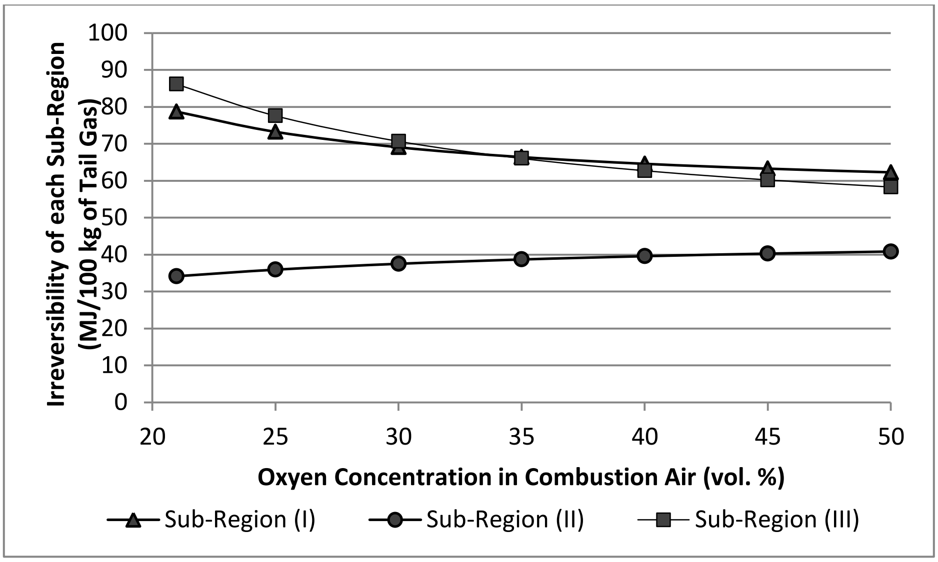

Fig 3 Irreversibility in each sub-region of incinerator at different oxygen enrichment levels

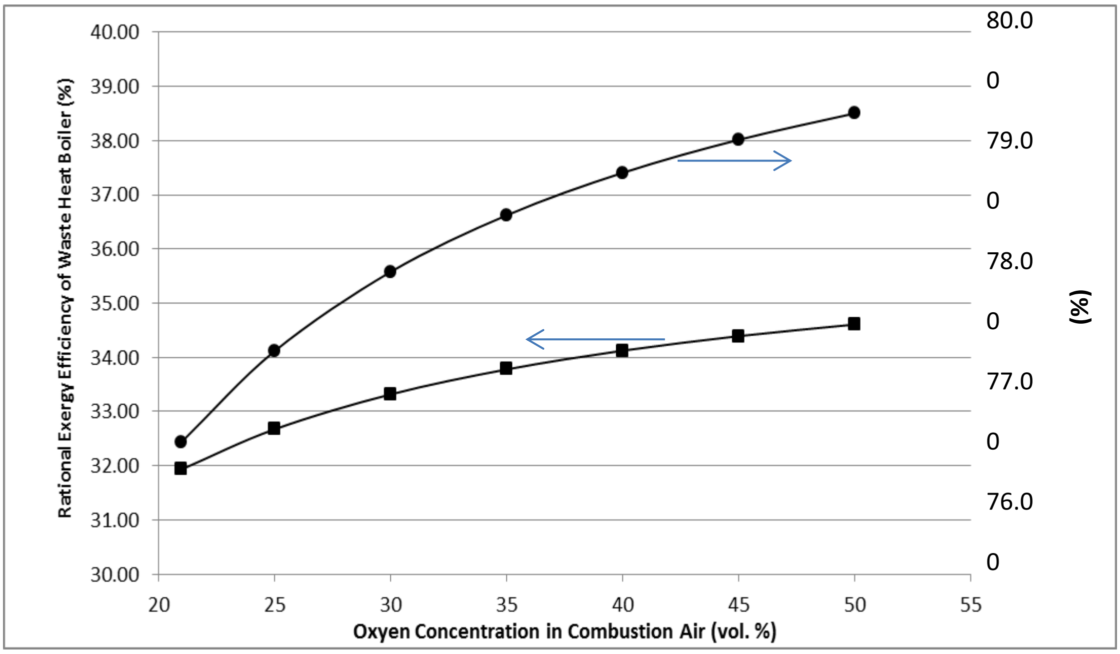

Fig 4 Exergy and energy efficiencies of waste heat boiler at different oxygen enrichment levels

Table 1 Irreversibilities for different oxygen enrichment levels

Oxygen Concentration (%)	Irreversibility of sub-region (I) (kJ/100 kg of tail gas)	Irreversibility of sub-region (I) (kJ/100 kg of tail gas)	Irreversibility of sub-region (I) (kJ/100 kg of tail gas)	Total Irreversibility (kJ/100 kg of tail gas)
20.98	78720.82	34146.45	86137.73	199005
25	73252.08	35931.6	77582.38	186766.1
30	69074.63	37526.57	70677.94	177279.1
35	66413.48	38691.44	66043.34	171148.3
40	64591.67	39580.47	62726.06	166898.2
45	63275.83	40280.7	60238.31	163794.8
50	62285.87	40846.2	58305.51	161437.6

Table 2. Exergy analysis results for different oxygen enrichment levels

Oxygen Concentration (%)	Steam generated in waste heat boiler (kg/100 kg of fuel)	Calculated incineration temperature (°C)	Rational efficiency of waste heat boiler (%)	Conventional efficiency of waste heat boiler (%)
20.98	76.55	802.0	31.94	72.44
25	78.32	846.6	32.68	74.12
30	79.87	889.8	33.32	75.58
35	80.97	923.5	33.78	76.63
40	81.80	950.6	34.13	77.41
45	82.44	972.8	34.39	78.02
50	82.96	991.3	34.61	78.50

According to the obtained results, higher concentration of oxygen in incineration air causes higher efficiencies and more steam generation. However, it must be noted that higher incineration 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 achieved improvements are not significant. In order to determine a feasible and meaningfully optimized enrichment level, the rate of changes in total irreversibilities and rational efficiency of waste heat boiler are chosen to be traded-off. As is shown in figures 2 to 4, the slope of trends is changed at enrichment level of 35% vol. so that the improvement through higher levels of oxygen enrichment may not be technically and economically feasible.

4. Conclusions

Incineration of tail gas streams in sulfur recovery unit is a mandatory treatment in order to meet the environmental requirements and regulations. Since in most of refineries, incineration process is performed using thermal conversion, it would be one the significant potential sources of irreversibility and thermodynamic losses. In this work, the effects of oxygen enrichment in incinerators and the associated waste heat boiler using exergy analysis were studied. The results show that oxygen enrichment by increasing incineration temperature and lowering nitrogen flow rate, could improve the combustion process thermodynamically and facilitate reaching to higher exergy and energy efficiencies. Also, trend of changes in the calculated parameters shows that a 35 vol.% oxygen enrichment in the incineration air could be used as an optimum enrichment level. Obviously, the other parameters like mechanical design and refractory considerations, economic aspects, operation policy, etc may affect the optimum enrichment range.

Nomenclature

m	*mass flow (kg)*	*I*	*Irreversibility (kJ)*
h	*Specific enthalpy (kJ/kmol)*	*R*	*Universal gas constant (8.314 kJ/mol/K)*
s	*Specific entropy (kJ/kg/K)*	*T*	*Temperature (K)*
c_p	*Specific heat capacity (kJ/kmol/K)*	*x*	*mole fraction*
E	*Exergy (kJ)*	*H*	*Enthalpy (kJ)*

Greek

θ	*Temperature (°C)*	*η*	*Conventional energy efficiency of boiler*
Γ	*Net calorific value (kJ/kg)*	$\bar{\varepsilon}$	*Specific mass exergy (kJ/kg)*
Ψ	*Rational exergy efficiency of boiler*	*ε*	*Specific exergy (kJ/kmol)*

Superscripts

h	*enthalpic*	*P*	*Product*
e	*exergetic*	*S*	*Steam*
0	*Reference environment*	*W*	*Water*

Subscripts

F	*Feed*
ph	*Physical*
k	*component k*

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