# Steam Reformers Optimization through Modification of Fuel Gas System Using Oxy Fuel Combustion Mixture

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## Abstract

Reduced energy consumption is a major goal in the petroleum refining sector, and this is achievable through improving the fuel gas system.

Any gas, refinery, or petrochemical industry's fuel consumption is the key factor determining its operational costs. Consequently, if the fuel gas system is optimized, significant energy savings can be achieved without sacrificing the steam reformer's lifespan, and operational expenses can be reduced.

The aim of the present study is to investigate the effects of changing (air, fuel) composition and find the effect on the combustion efficiency using ASPEN HYSYS® simulation.

It has been determined that by adjusting the parameters of the fuel gas system, the fuel optimization goal of this study has been met.

By using excess oxygen resulted from air separation unit in addition to combustion air, the reaction section efficiency improved by 5%. The use of wasted oxygen to increase heating value of fuel gas system and decreased the air consumption thus economical saving.

The modifications have been demonstrated to reduce energy consumption by as much as 30 %, reduce equipment size by 10 %, and cut emissions by 10 %, all while keeping the system's thermal performance at a high level. When we save energy, we release less carbon dioxide and other greenhouse gases into the atmosphere.

The flames with mixed oxygen and combustion air were much more stable and homogeneous (both temporally and spatially) as compared to the room-temperature combustion air.

To ensure accuracy, a simulation was run in ASPEN HYSYS®; this confirmed the findings and revealed a decrease in fuel requirement of 4.92 %, making the process more cost-effective.

modification saved amounts of fuel gas per year would be (1401600*0.035315 = 49497.504 MMBTU/year). money saved per year would be (49497.504*5.75 = **284610.648 USD/year**) per only 1 fired heater.
***Keywords:*** Optimization; reformer Efficiency; combustion air; fired heater; Air to Fuel Ratio; Flue Gases.

## 1. Introduction

For chemical plants designed to commercially produce high-quality hydrogen, the efficiency of the plant is closely connected to the thermal efficiency of the steam reformers, the most energy-intensive component.

Furthermore, the flue gases that result from burning fuel are the primary source of greenhouse gases. Reaction section fuel optimization is essential for environmental preservation and reduced energy use [1].

Moreover, the efficiency of the reformer's thermal system is managed by the way in which heat is distributed throughout the combustion chamber.

It takes a lot of energy to run a reformer because they only consume around 75%-80% of the fuel sent to the furnace. The rest is wasted as unburned fuel in the flue gases. Flue gases with high quantities of nitrogen oxides (NOx) and carbon are also created because of this. Since the fuel and flue gases are both gaseous, it is not possible to separate them and reuse the fuel.

Therefore, one method to guarantee fuel optimization is to increase the efficiency of the fuel gas system to ensure maximum fuel combustion.

Studies have been done to improve the efficiency of industrial reformers, which will lead to lower fuel consumption and improved economics and environmental sustainability [2].

Adding too much air to a reformer can increase wasteful flue gas output and dampen the flame, both of which waste energy [3]. As a result, maximizing the surplus air can drastically improve fired heaters and steam reformers performance also will cut down on flue gas emissions.

Pretreatment, process adjustments, combustion modifications, and post treatment are only some of the well-established strategies for managing and decreasing NOx. Partially or totally premixed flames have been cited in several recent studies as a promising method that has the potential to drastically cut NOx emissions [4-5].

Considering a variety of partial premixing, Seiser et al. [6] investigated the extinction and flammability limitations of laminar partially premixed flames in a counter flow arrangement. They found that as premixing was increased, the flame temperature dropped.

Partial premixing was described by Sayangdev and Aggarwal [7] as a primary method for lowering NOx and soot emissions from fires.

The use of oxy-combustion technology is another method for decreasing NOx emissions [8,9].

Oxygen is the oxidizer in oxy combustion technology. Most combustion by-products include carbon dioxide and water vapor. However, when fuel is burned with only oxygen, the resulting flame temperature is very high [10].

Flue gas volume and mass are decreased by this method. significant, with concomitant benefits including decreased heat losses and a smaller flue gas treatment system [11].

To achieve the same level of stability as air-fuel combustion, Ditaranto and Hals [12] observed that oxy-fuel combustion needs at least 30% oxygen.

The properties of oxy methane were investigated quantitatively by Liu et al. [13]. a simulated combustion in a gas turbine combustor. The result was that Increasing the amount of oxygen in the oxidizer mixture raises the tolerable temperatures.

Laminar methane-oxygen and methane-air diffusion fires were studied by Joo et al. [14] and their structures and soot concentrations were examined across an operating pressure range of up to 60 bar. Overall, the soot concentrations in air-methane flames were found to be greater than those in oxygen-methane flames across the whole pressure range tested.

The flame of a model gas turbine combustor, which was the subject of experimental and numerical research by Nemitallah and Habib [15], was subjected to a diffusion oxy-fuel combustion experiment. When the oxygen fraction in the air dropped below 25%, the stability of the oxy-fuel combustion was observed to be compromised.

Rashwan et al. [16,17] investigated the influence of partial premixing on oxygen-fuel combustion. They reported that the oxygen fraction range for a steady flame is between 29% and 40%. In addition, they reported that the stability range of air–fuel combustion is greater than that of oxy–fuel combustion due to the detrimental influence of $CO_2$ on the combustion process.

Kutne et al. [18] investigated the influence of oxygen fraction on the parameters of oxy-fuel combustion. Even under stoichiometric conditions, operation with oxygen fractions lower than 22% was deemed impossible.

Laminar flame speed of $CH_4$ under atmospheric conditions was investigated by Hu et al. [19], who looked at the impact of varying the equivalency ratio (from 0.8 to 1.2), oxygen concentration (from 25% to 35%), and dilutions ($N_2$ and $CO_2$). They discovered that the premixed oxy-methane mixture's laminar flame speed is highest under stoichiometric circumstances.

Cryogenic engineering is the study and application of methods, processes, and tools designed for use at extremely low temperatures. Utilization of Low Temperature Phenomena is the focus here. A cryogenic system is any interdependent set of components that operates at extremely low temperatures.[20]

All the energy for refrigeration comes from the compression of air at the inlet of the unit, making it essential for the cryogenic separation process to have a very tight integration of heat exchangers and separation columns to achieve a decent efficiency.[21]

An air separation unit's refrigeration cycle, which uses the Joule-Thomson effect to maintain low distillation temperatures, and an insulated space for the cold equipment are both necessary for the process (commonly called a "cold box"). This refrigeration cycle relies on a powerful quantity of energy produced by an air compressor to chill the gases. Expander turbines are used in modern air conditioning and refrigeration units to provide efficient cooling, with the output also driving the air compressor.[22]

The primary cryogenic processes are the elementary LINDE-HAMPSON cycle, the CLAUDE cycle, etc. The LINDE cycle is easy to understand and has low running costs. The CLAUDE cycle is employed primarily to create a very pure end-result.[23]

The use of computer-based simulation for a variety of chemical engineering applications is increasingly commonplace. Our goal is to model $O_2$ production using the widely used aspen HYSYS software. We simulated $O_2$ production by making various assumptions and utilizing synthetic units.

The literature rarely explored the combined effect of partial premixing and oxygen combustion on flame stability and exhaust emissions, as evidenced by the preceding discussions. The purpose of this experiment is to examine the combined effects of oxy-combustion and partial premixing of the oxidizer with the fuel on flame stability and emission reduction.

To achieve such objective, simulation of areal petrochemical plant was run in ASPEN HYSYS®; using excess oxygen from air separation unit mixed with combustion air thus combustion heating value increased, and energy saving achieved as a result of lower combustion air flow. The limitations of combustibility and the emissions of CO and NOx are studied in relation to the premixing ratio and the equivalence ratio.

## 2. Case study

The fuel gas system is the heart of any refinery plant since it is used to heat and reform steam in the fired heaters and provide the desired reaction conditions in the steam reformers.

The data we're using is representative of a real-world refinery facility; our case study will focus on the steam reforming segment to cut down on fuel gas used in the reactions.

the characteristics of partially premixed flames with varying premixing ratios under the burning of methane in various oxidizer conditions, including air and oxygen, were explored.

To determine the efficiency of the proposed adjustment, we will apply it to one of the consumers (a fired heater) in the reaction section (there are three trains total, each consisting of three fired heaters and three steam reformers).

Fired heater contains 6000 $Nm^3/h$ of fuel gas and 42500 $Nm^3/h$ of dry air, and the fuel gas system comprises of a fuel gas drum to condense any heavies or water associated with fuel gas.

To increase the temperature of the process stream from $130^0C$ to $500^0C$, a cylindrical fired heater with 4 burners and 2 convection sections beside 1 radiation section is employed.

The composition of the fuel gas used in a real-world scenario, at temperatures of $30^0$ C and pressures of 4 $kg/Cm^2$, is depicted in Table.2; the composition of the combustion air, at temperatures of $27^0$ C and pressures of 1 $kg/cm^2$ raised by a forced fan, is depicted in Table.1.

**Table 1. Fuel Gas Composition**

| No. | component | formula | Mole fraction % |
|---|---|---|---|
| 1 | methane | $CH_4$ | 44 |
| 2 | Ethane | $C_2H_6$ | 1.74 |
| 3 | Propane | $C_3H_8$ | 0 |
| 4 | ethylene | $C_2H_4$ | 0 |
| 5 | Nitrogen | $N_2$ | 0.006 |
| 6 | Hydrogen | $H_2$ | 54 |
| 7 | Carbon dioxide | $CO_2$ | 0.214 |
| 8 | Carbon monoxide | CO | 0.037 |
| 9 | water | $H_2O$ | 0 |

**Table 2. Combustion Air Composition**

| No. | component | formula | Mole fraction % |
|---|---|---|---|
| 1 | Oxygen | $O_2$ | 21 |
| 2 | Nitrogen | $N_2$ | 79 |
| 3 | water | $H_2O$ | 0 |

The ASPEN HYSYS® software was used to model the real-world scenario. computing software that mathematically models chemical processes for simulation purposes. In the field of chemical engineering, it is employed to address issues that arise. kinematics, equipment design, and chemical reactions all contribute to the complexity of the process difficulties.

The feed preheater and its firing system are depicted in Figure.1; all changes would be made to the feed preheater firing system to achieve the optimal conditions necessary for energy savings.

At standard atmospheric pressure, the boiling points of nitrogen (78.08%), oxygen (20.95%), and argon (0.93%) are -195.79 $^0$C, -183$^0$ C, and -185.84$^0$ C, respectively. to segregate them based on the temperatures at which they boil. Separation of a gas mixture is most efficient when the boiling temperatures of the components are very different from one another.

Comparatively, the boiling points of oxygen and argon are lower. Moreover, argon's lower percentage in the air makes it less efficient.

Rectification columns use counter-flowing evaporation and condensation cycles to separate air. In this way, the lighter component (the vapor) rises in the column through the heavier liquid, and the heavier component (the liquid) descends across the vapor stream.

A small amount of the higher boiling point component condenses in the vapor as it passes through the liquid zone, while a small amount of the lower boiling point component evaporates from the liquid.

To put it another way, when the vapor rises through the liquid, it becomes more concentrated in the low-boiling component, while the liquid sinks, it becomes more concentrated in the high-boiling component. This means that the heavy component is at the base of the column and the light component is at the top.

How can atmospheric gases, which have a very low boiling point, be condensed in a distillation column, given that all other chemical distillation columns use cooling towers or water?

The Linde double column system, so named because its rectification columns are joined one on top of the other, was developed to address this issue.

The lower column is run at a pressure of 5 atm to 6 atm (500 kPa to 600 kPa), while the higher column runs at a pressure of only 100 kPa (1 atm). Nitrogen has a higher boiling point at 5 atmospheres (94.2 K) than oxygen has at 1 atmosphere (90.2 K).

That's why oxygen condenses at the bottom of the first column and causes boiling at the top of the second column (nitrogen).

So, the top column's boiler is associated with the lower column's condenser via a heat exchanger. A portion of the liquid nitrogen is created by the lower column and fed to the upper column for reflux.

To model the steps involved in extracting nitrogen from ambient air, HYSYS is used as simulation software. This simulator is effective because it produces results that are comparable to those produced by actual industrial plants. It provides a solid thermodynamic foundation for elucidating the relevant physical properties, transport parameters, and phase behavior.

## 3. Results and discussion

Considering the three-part fired heater shown in Fig. 1, we find that the process gas/steam fluid enters the furnace by the mainline, passes through the vertical coils, and exits the furnace at a higher temperature. Fuel gas/air travels through the convective and subsequently the radiative sections while being subjected

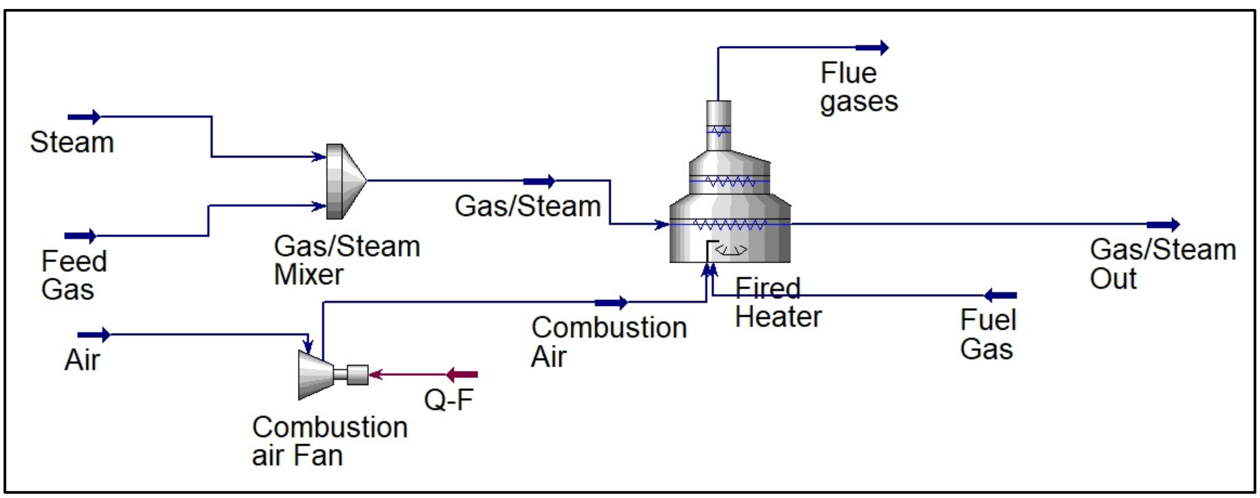


**Figure 1. ASPEN HYSYS based Simulation of Process**

to the combustion gases or flue gases from the four burners utilized in the firing system.

Our case study tried to find the most cost-effective combination of features (lower fuel gas usage with higher heating value or higher calorific value and lower electrical consumption). As we have air separation unit that produces about 10000 $Nm^3/h$ of pure oxygen that have concentration of 99.24% and argon with 0.76%.

Our petrochemical plant designed to convert propane to propylene through steam reformer as primary reactor and ten conversions also increased through secondary reactor that increases propane conversion by 5%.

Sometimes due to lack or shortage of propane we forced to cut oxygen flow to secondary reactor and thus all 10000 $Nm^3/h$ of pure oxygen wasted to atmosphere as air separation unit can't be stopped due to needs of pure $N_2$. table.1 represents compositions and specifications of each material stream for inlet and outlet of air separation unit.

**Table 3. specifications of material streams**

| parameters | AIR | GOX | LOX | GAN |
|---|---|---|---|---|
| Temperature $^0C$ | 28.79 | 16.04 | -183.3 | 13.19 |
| Pressure KPa | 101.3 | 101.3 | 101.3 | 101.3 |
| Molar flow Kgmole/h | 4521 | 943.1 | 0.04461 | 3553 |
| Nitrogen mole fraction | 0.7812 | 0.000011 | 0 | 0.9915 |
| oxygen mole fraction | 0.2095 | 0.9924 | 0.98889 | 0.0044 |
| Argon mole fraction | 0.0093 | 0.0076 | 0.0076 | 0.0041 |

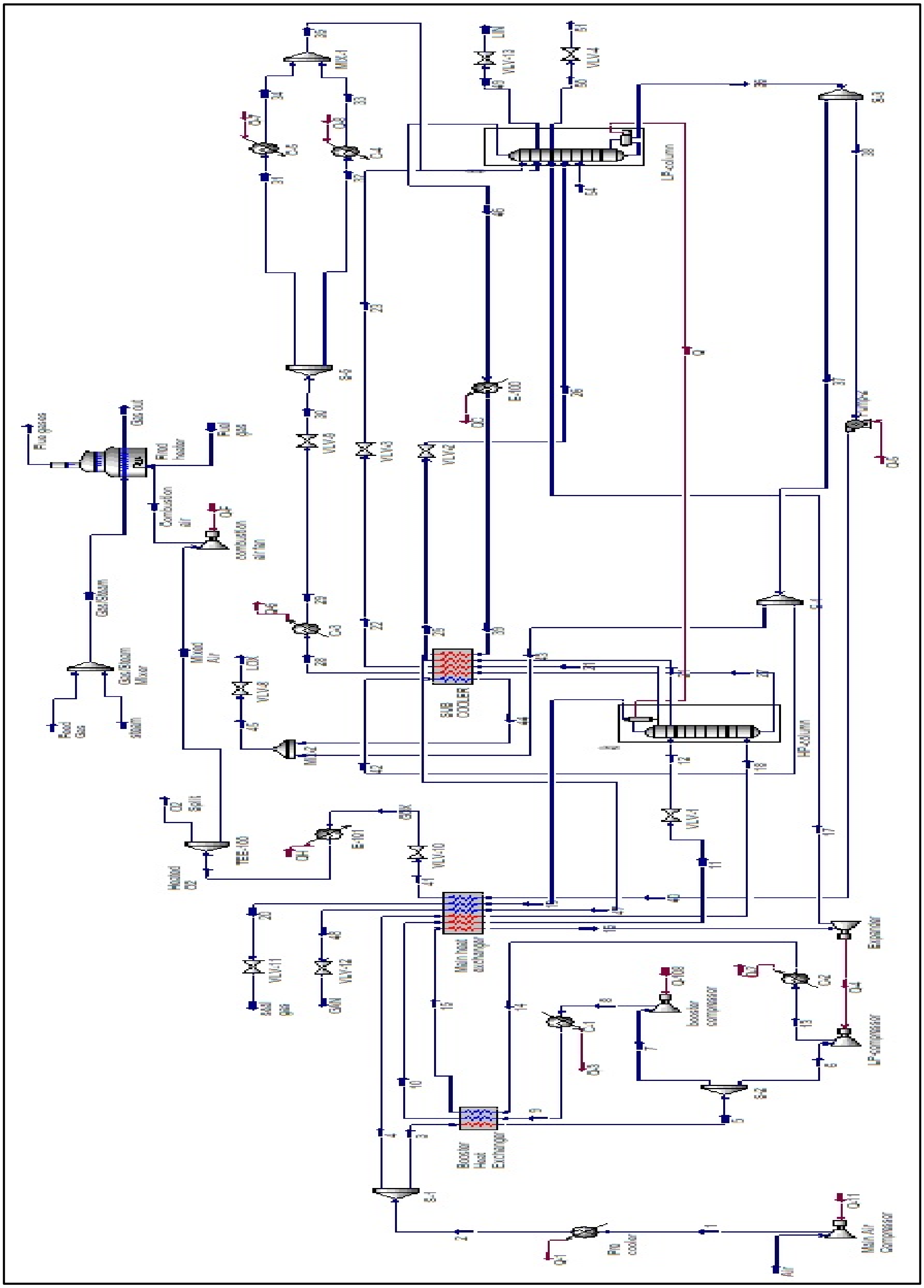

**Figure 2. steady state process flow diagram of air separation unit in aspen HYSYS**

### 3.1 increasing Oxygen concentration at combustion air

the main idea was to increase the oxygen concentration at combustion air, combined with the air separation unit oxygen production which represents about 10000 $Nm^3/h$, as shown in figure.2 air separation unit simulated using ASPEN HYSYS and mixed with the fired heater combustion system.

Table.4 represents the original case for combustion system parameters and specifications and results shown that consumed power for combustion air fan was about 49.6741 KW for air flow of 46000 $Nm^3/h$. and fuel gas consumption reached about 7790 $Nm^3/h$.

**Table 4. original air, fuel parameters**

| parameters | Fuel gas | Air | Flue gases | Combustion air fan |
|---|---|---|---|---|
| **Pressure kg/cm$^2$** | 4 | 1 | | |
| **Temperature $^0$C** | 30 | 30 | 505.3 | |
| **Flow rate Nm$^3$/h** | **7790** | 46000 | | |
| **Duty KW** | | | | 49.6741 |

As shown in figure.2 produced oxygen from air separation unit used as combustion air with oxygen concentration of 99.24% and thus fuel gas consumption decreased with 160 $Nm^3/h$ at the same heating value while the power consumption for the combustion air fan decreased to 10.2885 KW/h due to decreased flow of combustion air to 9500 $Nm^3/h$.

Table.5 represents results from the proposal of relacing combustion air with gaseous oxygen (GOX) resulted from air separation unit.

**Table 5. air with 99.24% of oxygen, fuel parameters**

| parameters | Fuel gas | Air | Flue gases | Combustion air fan |
|---|---|---|---|---|
| **Pressure kg/cm$^2$** | 4 | 1 | | |
| **Temperature $^0$C** | 30 | 30 | 1191 | |
| **Flow rate Nm$^3$/h** | **7630** | 9500 | | |
| **Duty KW** | | | | 10.2885 |

Also results showed that flue gases temperature increased greatly reached about 1191$^0$C and thus fuel gas consumption decreased as a result.

Table 6, Table7 and Table.8 show the effect of increasing oxygen concentration at all operational parameters such as:

- Combustion air fan power consumption (duty KW).

- fuel gas consumption $Nm^3/h$.

- combustion air flow $Nm^3/h$.

- flue gases temperature $^0C$.

**Table 6. Effect of $O_2$ concentrations at operational parameters (1)**

| | Air concentration | | Air concentration | | Air concentration | |
|---|---|---|---|---|---|---|
| **Air content** | **$O_2$** | **$N_2$** | **$O_2$** | **$N_2$** | **$O_2$** | **$N_2$** |
| **Mole fraction** | 0.21 | 0.79 | 0.3 | 0.7 | 0.4 | 0.6 |
| **Fuel flow ($Nm^3/h$)** | 7790 | | 7720 | | 7700 | |
| **Air flow ($Nm^3/h$)** | 46000 | | 32000 | | 24000 | |
| **Flue gases Temperature ($^0C$)** | 505.3 | | 637.9 | | 760.4 | |
| **Fan duty (KW)** | 49.6741 | | 34.5451 | | 25.8 | |

**Table 7. Effect of $O_2$ concentrations at operational parameters (2)**

| | Air concentration | | Air concentration | | Air concentration | |
|---|---|---|---|---|---|---|
| **Air content** | **$O_2$** | **$N_2$** | **$O_2$** | **$N_2$** | **$O_2$** | **$N_2$** |
| **Mole fraction** | 0.5 | 0.5 | 0.6 | 0.4 | 0.7 | 0.3 |
| **Fuel flow ($Nm^3/h$)** | 7680 | | 7670 | | 7660 | |
| **Air flow ($Nm^3/h$)** | 19000 | | 15800 | | 13500 | |
| **Flue gases Temperature ($^0C$)** | 862.6 | | 957.5 | | 1023 | |
| **Fan duty (KW)** | 20.588 | | 17.12 | | 14.66 | |

**Table 8. Effect of $O_2$ concentrations at operational parameters (3)**

| | Air concentration | | Air concentration | | Air concentration | |
|---|---|---|---|---|---|---|
| **Air content** | **$O_2$** | **$N_2$** | **$O_2$** | **$N_2$** | **$O_2$** | **$N_2$** |
| **Mole fraction** | 0.8 | 0.2 | 0.9 | 0.1 | 0.99 | 0.001 |
| **Fuel flow ($Nm^3/h$)** | 7650 | | 7650 | | 7630 | |
| **Air flow ($Nm^3/h$)** | 11800 | | 10500 | | 9500 | |
| **Flue gases Temperature ($^0C$)** | 1087 | | 1144 | | 1191 | |
| **Fan duty (KW)** | 12.81 | | 11.37 | | 10.28 | |

Comparing and using different concentrations for oxygen used as combustion air and find the effect at Combustion air fan duty or power consumption as shown in figure.3

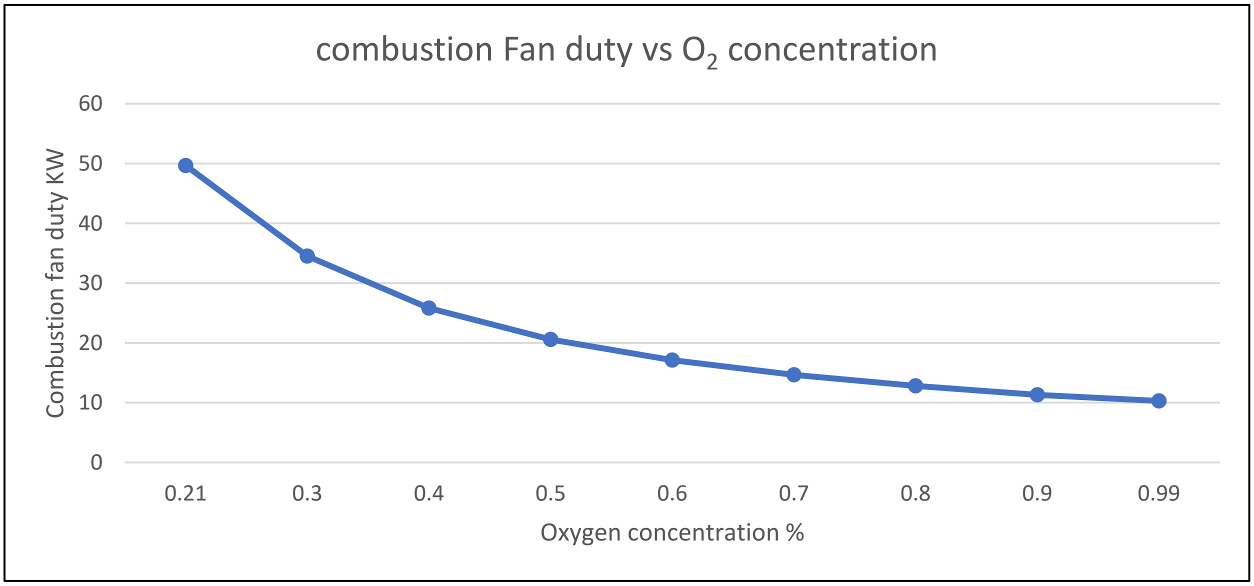


**Figure 3. relation between oxygen concentration and duty of combustion air fan**

by increasing oxygen concentration, power consumption for combustion air fan decreased and thus energy saving, or power saving could be achieved at different high values of oxygen concentration.

By applying different concentrations for oxygen at HYSYS simulation used as combustion air and find the effect at fuel gas consumption as shown in figure.4

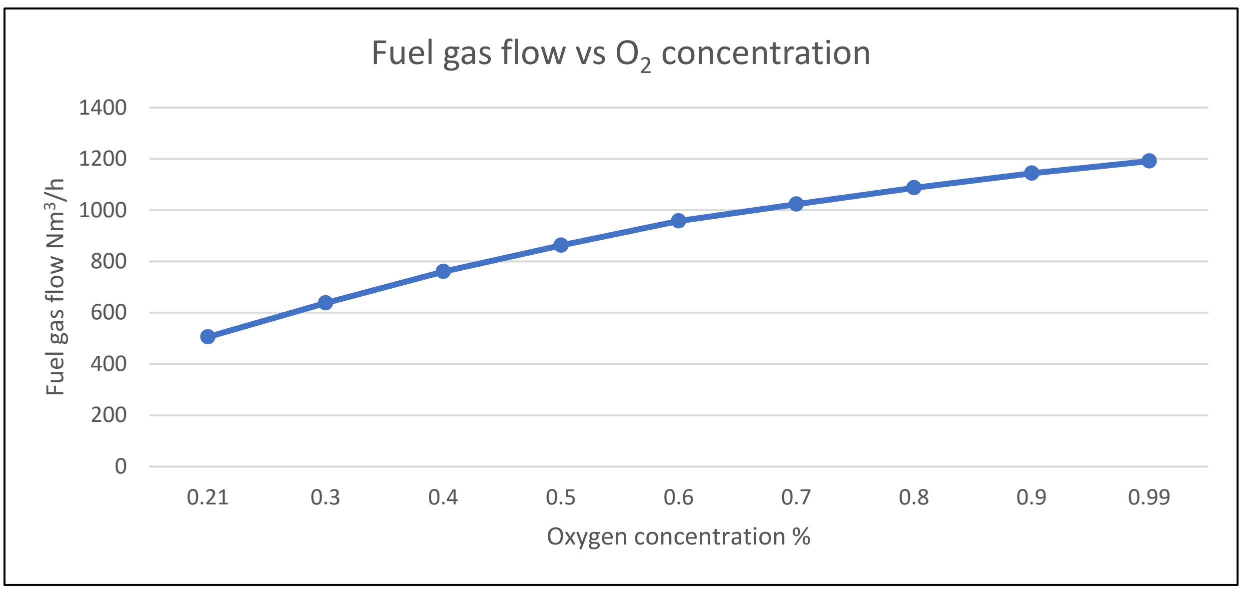


**Figure 4. relation between oxygen concentration and fuel gas flow**

increasing oxygen concentration, Fuel gas flow or fuel gas consumption decreased and thus fuel gas saving, or power saving could be achieved at different high values of oxygen concentration.

By changing concentrations for oxygen at HYSYS simulation used as combustion air and find the effect at combustion air flow as shown in figure.5

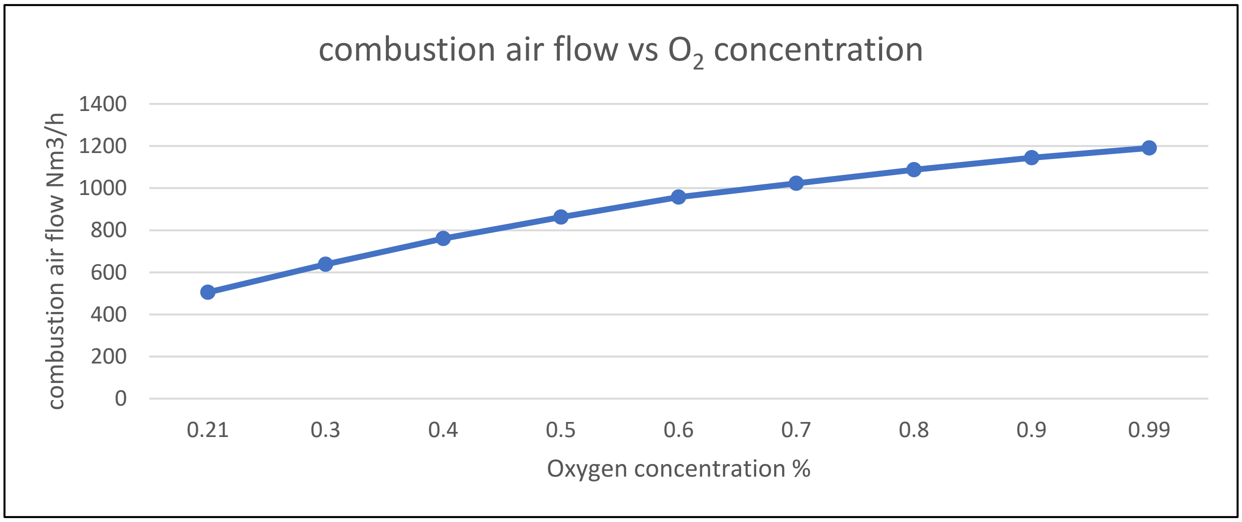


**Figure 5. relation between oxygen concentration and combustion air flow**

by increasing oxygen concentration, combustion air flow decreased and thus energy saving, or power saving as the load of combustion air fan will decrease and that could be achieved at different high values of oxygen concentration.

By changing concentrations for oxygen at HYSYS simulation used as combustion air and find the effect at flue gases temperature as shown in figure.6

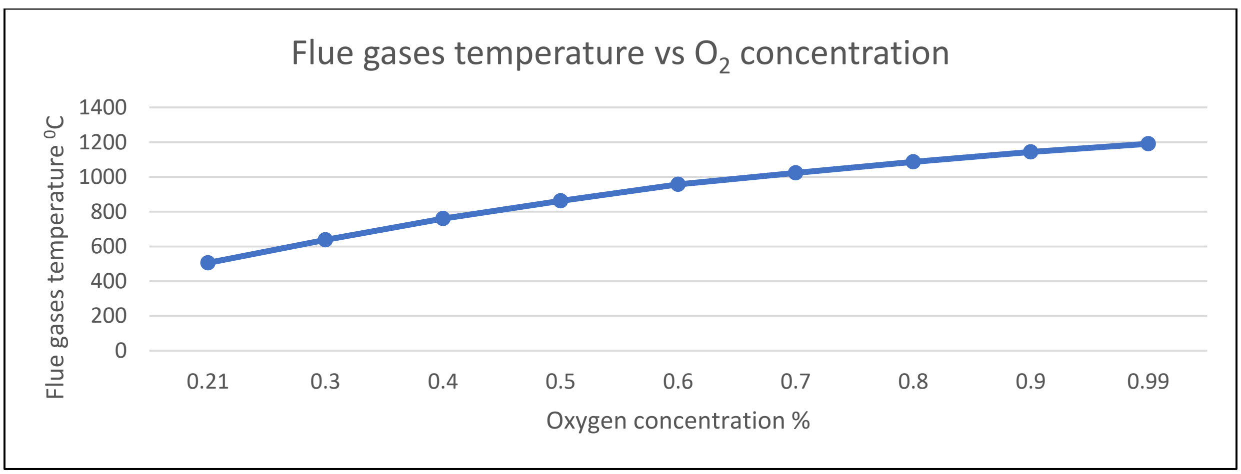


**Figure 6. relation between oxygen concentration and flue gases temperature**

by increasing oxygen concentration, flue gases temperature increased and thus getting more heat flow that could be used as source of heating over the plant and that could be achieved at different high values of oxygen concentration.

## 4. Economic study

Optimizing the refinery's fuel gas system can severely reduce the company's vital energy use. Fuel consumption is the primary component in determining operational costs in the natural gas, refining, and petrochemical industries.

By enhancing the fuel gas system, not only will significant energy savings and lower operating costs be realized, but the thermal efficiency of the steam reformer may be increased without compromising the unit's durability.

According to our study the most effective results could be obtained through using gaseous oxygen (GOX) resulting from air separation unit as combustion air for combustion system of fired heater.

- Using oxygen flow of 9500 $Nm^3/h$ and concentration of 99.24% will result in 160 $Nm^3/h$ of fuel gas to achieve the same outlet temperature. As a result, the total amounts of saved fuel gas per year would be (160*24*365 = 1401600 Nm3/year)

Prices of fuel gas: (5.75 USD per 1 MMBTU)

taking into consideration that 1 $Nm^3$= 0.035315 MMBTU

total saved amounts of fuel gas per year would be (1401600*0.035315 = 49497.504 MMBTU/year)

money saved per year would be (49497.504*5.75 = 284610.648 USD/year) per only 1 fired heater.

- using oxygen with concentration of 99.24% and flow of 9500 Nm3/h as combustion fluid beside fuel gas, would result in reduction of combustion air fan load reaching about 10.2885 KW/h thus the total saved power due to using oxygen per hour would be 49.6741-10.2885 = 39.3856 KW/h.

Prices of electrical power :( 0.08 USD per 1 KW).

Total saved amounts of electrical power per year would be (39.3856 * 24*365) = 345017.8 KW.

Total saved money of electrical power per year would be (345017.8 * 0.08 = 27601.5 USD/year).

## 5. Conclusion:

- using excess oxygen as combustion fluid instead of being wasted would increase the heating value of combustion and thus decreasing fuel gas consumption by 160 $Nm^3/h$ also this modification will cause the combustion air fan duty or load to decrease thus decreasing power consumption by 39.3856 KW/h while the flue gases temperature would increase to higher values due high combustion temperature which could have a good use with tis extra heat.

So, adding pure oxygen into combustion air thus resulting in increasing combustion temperature and decrease amount of air supplied to combustion burners which will achieve energy saving and fuel saving.

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