

Optimization of steam reformers through fuel gas system modification

Mohamed ahmed gabr ^{1*}, Fatma Khalifa Gad ²

¹ Egyptian propylene and polypropylene company, propylene production department, production department, Egypt

² Suez University, Faculty of Petroleum and Mining Engineering, Department of Petroleum Refining and Petrochemical Engineering, Egypt

*Corresponding author**

Mohamed ahmed elsayed gabr

Email: mohamed.elga@pme.suezuni.edu.eg

Tel: +2 01099908346

Abstract

Energy saving considered very important concern in every Process of refinery industry and could be accomplished through fuel gas system optimization.

Fuel consumption is the main core that control the operating cost of any gas, refinery, or petrochemical industry. Therefore, any optimization applied to fuel gas system will lead to lower operational costs and thus significant energy saving, also will allow the steam reformer's thermal efficiency to be increased without shortening the unit's service life.

The aim of the present study is to investigate the effects of changing [(air, fuel) characteristics (pressure, temperature, flow rates, composition)] on the combustion efficiency using ASPEN HYSYS® simulation.

In this study the goal of fuel optimization has been achieved by improving the efficiency of the fuel gas system parameters.

The use of preheated air-fuel mixture at this temperature the reaction section efficiency improved by 5%. The use of waste steam to preheat air or fuel reduce the wasted steam and thus economical saving.

The modifications have been shown to provide significant reduction in energy consumption (up to 30%), downsizing of the equipment (about 10%) and lower emissions (about 10%) while maintaining high thermal performance of the system. Energy savings converted to reduction of CO₂ and other greenhouse gases to the environment.

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

Simulation on ASPEN HYSYS® was performed to validate all the results and it also showed 4.92% reduction in fuel demand, thus making the process more economical.

Keywords: Optimization; reformer Efficiency; Air-Fuel Mixture; Air Preheater; Air to Fuel Ratio; Flue Gases.

1. Introduction:

The thermal efficiency of the steam reformers, which is the most energy-intensive component, is directly related to the plant's efficiency in chemical manufacturing facilities built to commercially manufacture high quality hydrogen. Furthermore, the main source of greenhouse gases is the flue gases

that arise from burning fuel. To preserve the environment and cut down on energy use, reaction section fuel optimization is crucial [1]. Additionally, the reformer thermal efficiency is controlled by the temperature distribution inside the combustion chamber.

Most of reformers only use 75–80% of the fuel delivered to the furnace, while the remaining fuel being lost as unburned fuel in flue gases, which results in a highly energy-intensive operation. Additionally, because of this, flue gases with high levels of NO_x and carbon are produced. It is not possible to fully recover the fuel from the stack flue gases since both the fuel and flue gases are in the same phase. Therefore, increasing the fuel gas system efficiency to achieve maximum fuel combustion is one technique to assure fuel optimization. Multiple studies have been conducted to increase industrial reformers efficiency, which will also decrease fuel consumption, making the operation more cost-effective and environmentally beneficial [2].

One of the causes of energy losses in reformers is excess air, which raises the production of flue gases and lowers flame temperature [3]. Therefore, optimizing the extra air can greatly increase boiler efficiency and decrease flue gas production. The temperature of the air-fuel mixture, or excess air, also affects the steam reformers efficiency in addition to the amount. The combustion chamber emits more carbon monoxide (CO) because of the combustion and its products being quenched by too much cold air, which is a sign of inefficient combustion [4]. The input of hot combustion air to the furnace was found to boost both its efficiency and temperature [5], [6]. In actuality, the steam reformer's efficiency rises by 1% for every 20°C increase in combustion air temperature [7]. To obtain high combustion efficiency and lower CO emissions, preheating of the air-fuel combination might be used. the steam methane reforming process' endothermic properties propose maintaining a high temperature within the reformer because a greater conversion of hydrogen can proceed by an increased outer reforming tube wall temperature.[8]

However, a 20 K increase in the temperature of the outer reforming tube wall over the design temperature can cut the 100,000-hour projected service life in half. Additionally, the reforming tube wall may rupture when the outer wall temperature of the tubes significantly exceeds the intended value, leading to production and financial losses. Therefore, the reformer must be operated at suboptimal conditions when the temperature nonuniformity inside the combustion chamber is severe, where the overall average operating temperature of the reforming tubes is sufficiently lower than the design value to account for the wide range of the outer reforming tube wall temperatures. Additionally, it is believed that compared to a balanced reformer, an imbalanced one has a considerably reduced radiative heat transmission efficiency.[9] The maximum variation in the radially averaged outer reforming tube wall temperature between reforming tubes at a specific axial location is referred to as the degree of nonuniformity in the temperature distribution. A set of infrareds (IR) camera sensors placed around an online reformer may measure the degree of temperature distribution nonuniformity, which can be as high as 110 K. An unbalanced reformer is one that has a significantly nonuniform temperature distribution. [9]

Due to the significant degree of temperature distribution nonuniformity, the reformer must be run in less-than-ideal conditions where its potential to produce hydrogen is greatly diminished.[9] By raising the temperature of the inflow air with preheating processes, fuel consumption is decreased. To reduce overall energy consumption, modern furnaces use the stack's heat recovery and the air preheating of the burner [10]. Such heat exchangers prevent major energy waste in the environment while also preheating the incoming air and consuming less fuel. Fuel characteristics, preheat temperature, and air oxygen concentration all affect the thermal and chemical behavior of high-temperature air combustion flames.

Higher heat fluxes than regular air is produced by flames with heated air. The efficiency of the thermal cycle may be increased by preheating the oxidant (rather than the fuel due to potential fuel decomposition and safety concerns) to very high temperatures [11].

The heat exchanger extracts the sensible heat from the exhaust gases in either scenario. This thermal energy is removed and incorporated into the furnace's heat input, serving as a direct indicator of how much energy may be conserved while maintaining other conditions. The preheating of the air or fuel, water heating, and steam generation are just a few uses for the extracted energy. If the total energy recovered is the same in each situation, the effect is the same from the perspective of energy recovery. However, in the case of air preheats, the temperature of the adiabatic flame will rise, leading to a subsequent rise in the cycle's thermal efficiency [12].

2. Case study:

At any refinery plant fuel gas system considered the main core to reach the desired reaction conditions at both fired heaters and steam reformers. In our case study, data represents actual refinery plant that uses propane as its feed stock with 99.5 % to reach 30% of conversion of propylene, and we will focus on steam reforming section to reduce fuel gas consumption at reaction section.

Reaction section consists of 3 parallel trains (3 fired heaters followed by 3 steam reformers), we will apply the proposed modifications to one of consumers (Fired heater) and considering the results also applying energy and exergy calculations to one of the fired heaters to find the effectiveness of proposed modifications. Fuel gas system consists of fuel gas drum to condense any heavies or water associated with fuel gas, fired heater has 6000 Nm³/h of fuel gas and 42500 Nm³/h of dry air.

Cylindrical Fired heater used with 4 burners and 2 convection sections beside 1 radiation section to raise process stream temperature from 130⁰C to 500⁰C. Table.1 represents fuel gas composition used at real case with temperature 30⁰ C and pressure = 4 kg/cm². combustion air composition presented at Table.2 which used at ambient temperature of 27⁰C and pressure = 1 kg/cm² raised by forced fan.

Table 1. Fuel Gas Composition

No.	component	formula	Mole fraction %
1	methane	CH ₄	44
2	Ethane	C ₂ H ₆	1.74
3	Propane	C ₃ H ₈	0
4	ethylene	C ₂ H 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 ₂ O	0

Table 2. Combustion Air Composition

No.	component	formula	Mole fraction %
1	Oxygen	O ₂	21
2	Nitrogen	N ₂	79
3	water	H ₂ O	0

The real case was simulated using the ASPEN HYSYS® software, a simulation program that mathematically models the chemical processes. It is used to solve problems in chemical engineering, complicated process challenges involving mass and heat transfer and energy balances, vapor-liquid equilibrium, kinematics, equipment designing and chemical reactions.

Figure.1 represents the based or the main simulation of the process representing the feed preheater and its firing system, all modifications would be applied to the feed preheater firing system to reach the optimum conditions required for achieving energy saving purpose.

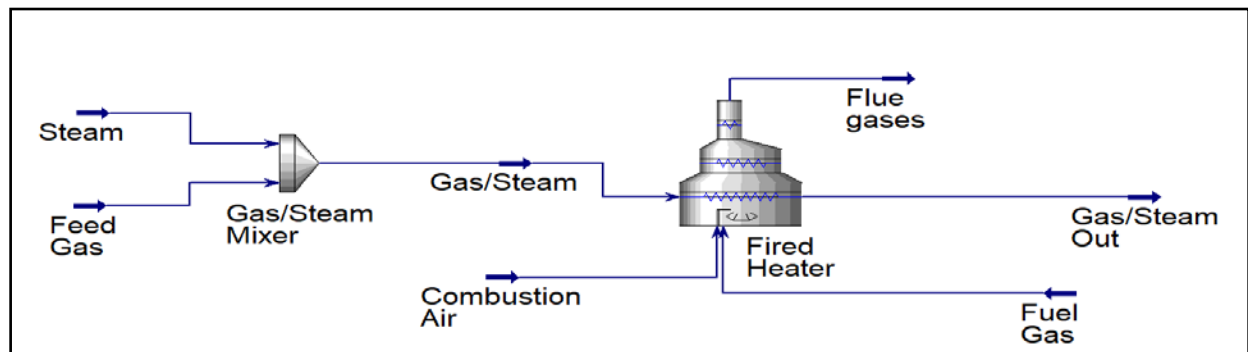


Figure 1. ASPEN HYSYS Based Simulation Of Process

3. Results and discussion:

As illustrated in Fig. 1, the fired heater considered in the present study consists of three sections, and the process gas/steam fluid enters the furnace through mainstream and passes through vertical coils till passing out with higher temperature. four burners used at firing system and fuel gas/air flows through the convective, and then radiative sections, while exposed to combustion gases or flue gases. 4 proposals tested through our case study trying to achieve the optimum operating parameters (Lower fuel gas consumption with higher heating value or higher calorific value) taking into consideration energy saving purpose.

3.1 increasing fuel gas temperature using heat exchanger.

the main idea was to increase the fuel gas inlet temperature using a new heat exchanger that uses wasted or excess MP steam with an amount of 30000 kg/h and $T=255^{\circ}\text{C}$ and $P=12\text{ kg/cm}^2$. (Using hysys simulation as shown in figure (2)):

Table 3. Case 1 Original Air, Fuel Parameters

parameters	feed gas	steam	fuel	air
Pressure kg/cm^2	14.5	12	4	1
Temperature $^{\circ}\text{C}$	120	255	30	27
Flow rate Nm^3/h	35000	105 Ton/h	7200	42500
Adiabatic flame temperature $^{\circ}\text{C}$			505.6	

Case 1: as illustrated in table.3 our instant situation with normal conditions as the fuel gas temperature is 30°C and the fuel gas consumption during normal operation is $7200\text{ Nm}^3/\text{h}$.

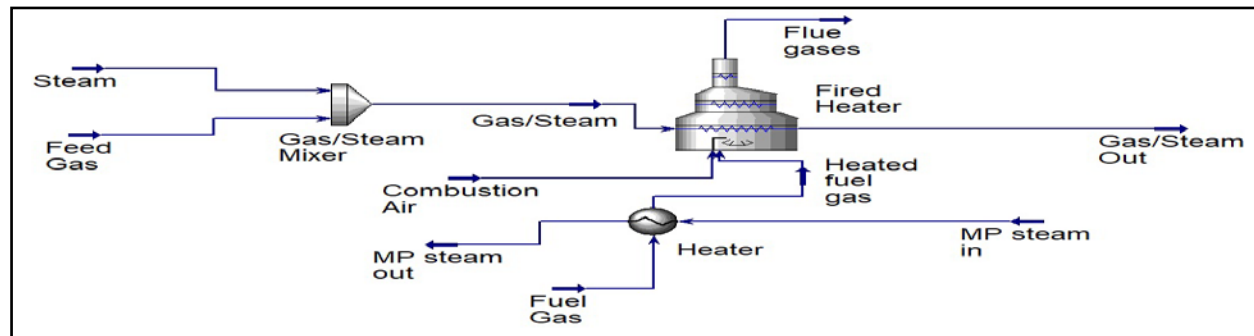


Figure 2. Heating Fuel Gas Using Heat Exchanger with MP Steam

Case 2: increasing fuel gas temperature from 30°C to 100°C using heat exchanger, results as illustrated in table.4 showed slight increase in the adiabatic flame temperature about 216 °C only without any change in the LHV (lower heating value=net calorific value) 5.088*105 kJ/Kgmole. also, it was noticed that fuel gas consumption increased by 950 Nm³/h to reach the same outlet temperature for the fired heater as the heat capacity increased thus combustion air increased by 6000 Nm³/h which will load the combustion air fan.

Table 4. Case 2 Fuel Gas T=100°C

parameters	fuel	air
Pressure kg/cm ²	4	1
Temperature °C	100	27
Flow rate Nm ³ /h	8150	<u>48500</u>
Adiabatic flame temperature °C	722.4	

Case3: increasing fuel gas temperature from 30°C to 150°C using heat exchanger, results as illustrated in table.5 showed slight increase in the adiabatic flame temperature about 30 °C only without any change in the LHV (lower heating value=net calorific value) 5.088*105 kJ/Kgmole.

Table 5. Case 3 Fuel Gas T=150°C

parameters	fuel	air
Pressure kg/cm ²	4	1
Temperature °C	150	27
Flow rate Nm ³ /h	8340	<u>48900</u>
Adiabatic flame temperature °C	755.9	

also, it was noticed that fuel gas consumption increased by 1140 Nm³/h to reach the same outlet temperature for the fired heater.

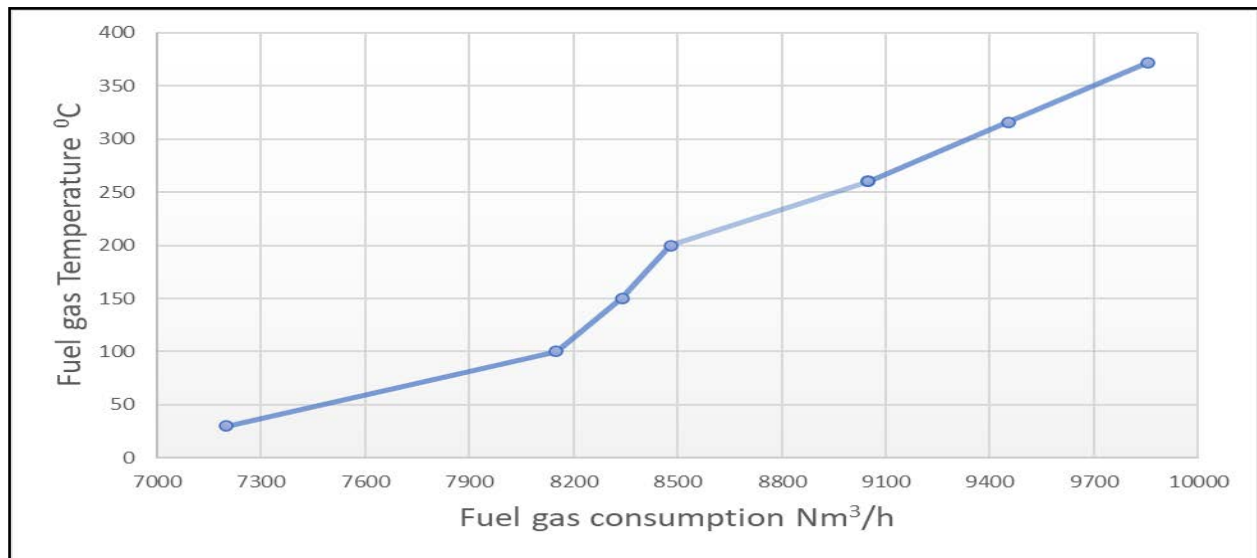


Figure 3. Fuel Gas Temperature Vs Fuel Gas Consumption

As shown in figure.3 when we increased fuel gas temperature using heat exchange with MP steam, fuel gas consumption increased, and heating value didn't have any observable increase at the same conditions of achieving fired heater outlet temperature.

3.2 increasing fuel gas temperature by mixing wasted LP steam with fuel gas.

Regarding to the proposal of adding (LP steam) stream directly to be mixed with fuel gas header. as seen in (figure 4) (HYSYS simulation) showed that if we used about 10000 kg/hr of wasted LP steam (166 °C) mixed with fuel gas of fired heater, the mixture heat will increase to about (114.4°C) without any condensation of steam at these conditions after mixing and after entering the burners.

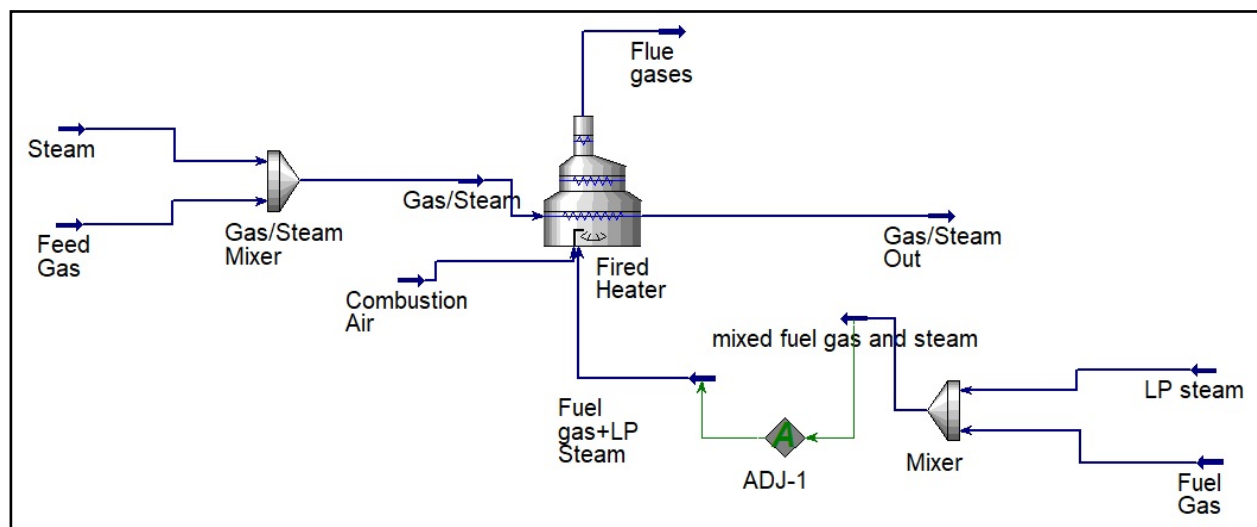


Figure 4. Mixing Fuel Gas with LP Steam

The heat capacity of the mixture changed after adding steam with that high temperature (32.87kJ/Kgmole-c) increased to (34.35 kJ/Kgmole-c).

The LHV (lower heating value=net calorific value) of fuel gas used about 5.088×10^5 kJ/Kgmole, but after adding steam it was found that the LHV decreased to about 1.961×10^5 kJ/Kgmole. that indicates to keep the outlet temperature constant we will need to consume more fuel gas reached $9000 \text{ Nm}^3/\text{h}$ even we have mixture with higher temperature.

Table 6. increasing fuel gas temperature by mixing wasted LP steam with fuel gas

parameters	fuel	air
Pressure kg/cm^2	4	1
Temperature $^{\circ}\text{C}$	114.4	27
Flow rate Nm^3/h	9000	51000
Adiabatic flame temperature $^{\circ}\text{C}$	500	

the outlet temperature after mixing with small amounts of steam about 5% should be the same without any increasing but the peak temperature which represents in the study the adiabatic flame temperature decreased with about 6°C .

3.3 increasing combustion air temperature using heat exchanger.

regarding to the proposal of combustion air temperature using heat exchanger, the main idea was to increase combustion air temperature using a new heat exchanger that use wasted MP steam with an amount of $30000 \text{ kg}/\text{h}$ and $T=255^{\circ}\text{C}$ and $P=12 \text{ kg}/\text{cm}^2$. (Using hysys simulation as shown in figure (5)):

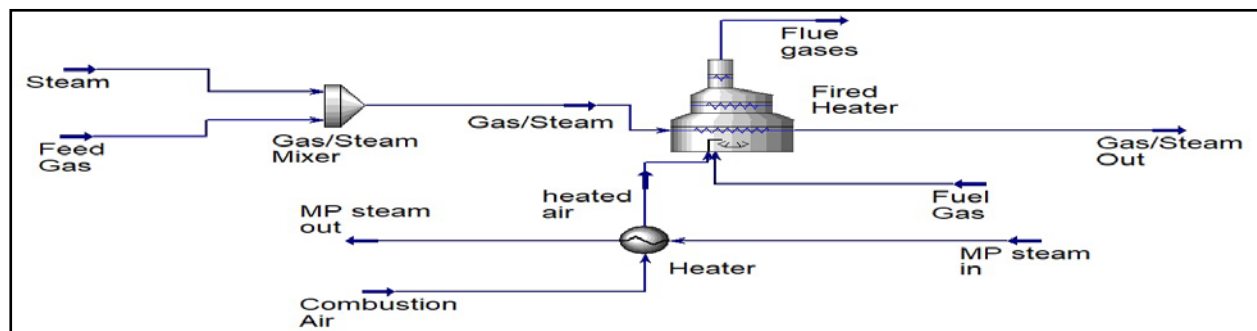


Figure 5. heating of combustion air using heat exchanger

Case 1: as illustrated in table.6 our instant situation with normal conditions as the combustion air temperature is 27°C and the fuel gas consumption during normal operation is $7200 \text{ Nm}^3/\text{h}$.

Table 7. case 1 original air, fuel parameters

parameters	fuel	air
Pressure kg/cm^2	4	1
Temperature $^{\circ}\text{C}$	30	27
Flow rate Nm^3/h	7200	42500
Adiabatic flame temperature $^{\circ}\text{C}$	505.6	

Case 2: as illustrated in table.7, increasing combustion air temperature using new heat exchanger from 27°C to 100 °C, results showed increase in the adiabatic flame temperature with about 48°C.

Table 8. Case 2 combustion air T=100°C

parameters	fuel	air
Pressure kg/cm ²	4	1
Temperature °C	30	100
Flow rate Nm ³ /h	7180	42500
Adiabatic flame temperature °C	553.6	

Even the fuel gas consumption decreased by 20Nm³/h but the LHV (lower heating value=net calorific value) 5.088*105 kJ/Kgmole still constant achieving the same outlet temperature.

Case3: as illustrated in table.8, increasing combustion air temperature using new heat exchanger from 27°C to 200 °C, results showed increase in the adiabatic flame temperature with about 68°C., fuel gas consumption will decrease with 230 Nm³/h without any change in furnace box temperature or fired heater outlet temperature. Also, the LHV (lower heating value=net calorific value) 5.088*105 kJ/Kgmole still constant achieving the same outlet temperature.

Table 9. Case 3 combustion air T=200°C

parameters	fuel	air
Pressure kg/cm ²	4	1
Temperature °C	30	200
Flow rate Nm ³ /h	6970	41000
Adiabatic flame temperature °C	574.2	

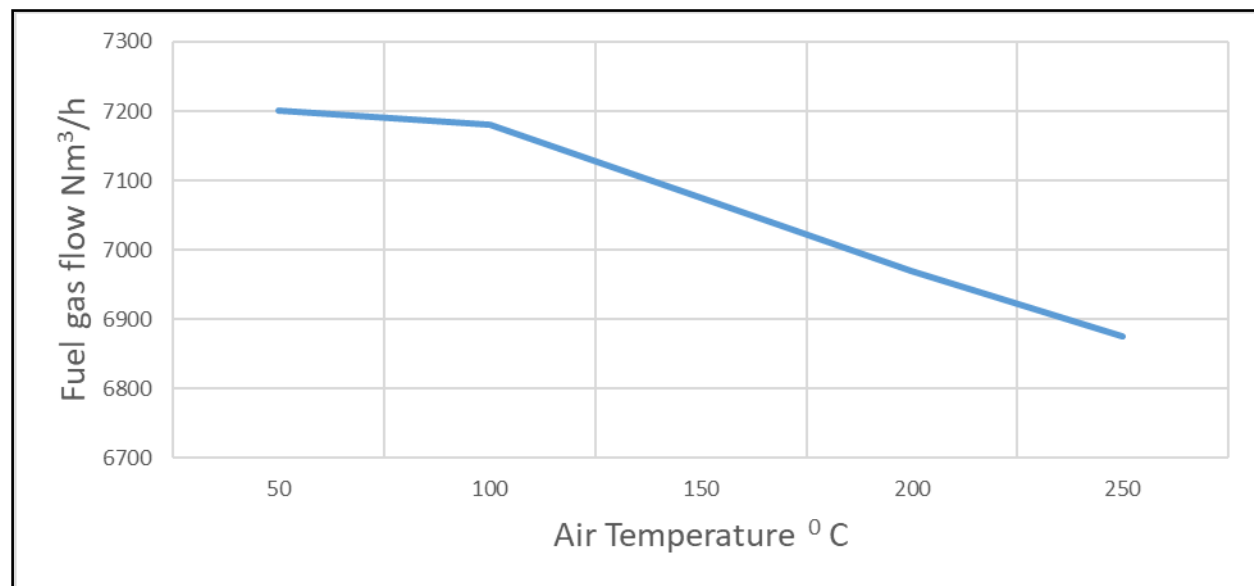


Figure 6. Air Temperature vs Fuel gas consumption

As shown in figure .6 when we increased air temperature using heat exchange with MP steam, fuel gas consumption decreased, and heating value didn't have any observable increase at the same conditions of achieving fired heater outlet temperature.

3.4 increasing combustion air temperature by mixing wasted LP steam with combustion air.

Regarding to the proposal of adding (LP steam) stream directly to be mixed with combustion air of fired heater, as shown in figure.7 (HYSYS simulation) showed that if we used about 10000 kg/hr of LP steam (166 °C) mixed with about 46000 Nm³/hr (30 °C) of combustion air (fired heater conditions) the mixture total temperature will increase to about (61°C).

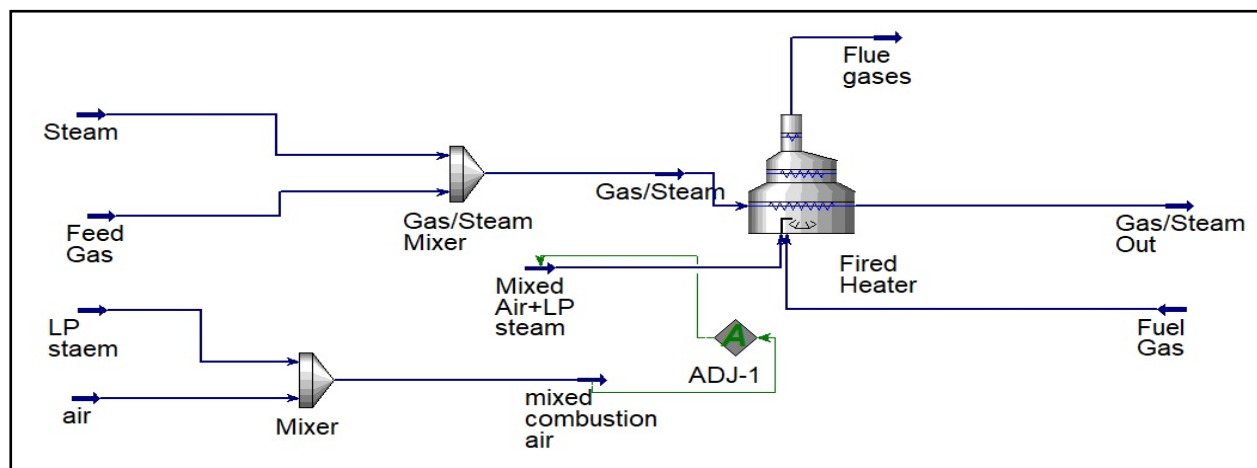


Figure 7. mixing combustion air

The adiabatic flame temperature (flue gases temperature) after combustion decreased slightly from 505° C to 503° C. about (2 °C)

Table 10. mixing wasted LP steam with combustion air

parameters	fuel	air
Pressure kg/cm ²	4	1
Temperature °C	30	61
Flow rate Nm ³ /h	7950	46000
Adiabatic flame temperature °C	503	

Even the heat capacity of mixture of air and steam increased from (29.21 kJ/Kgmole-c) to (30.43kJ/Kgmole-c) after mixing but due to the properties of steam in heat transferring and absorbing, the combustion mixture temperature decreased which will lead to more fuel consumption to keep outlet temperature constant and to keep the lower heating value still constant.

4. Economic study:

Fuel gas system optimization can help the refinery business reduce its energy consumption, which is of paramount importance. In the gas, refinery, and petrochemical industries, fuel consumption is the fundamental factor determining operating expenses. As a result, improving the fuel gas system will result

in substantial energy savings and reduced operating costs, and will also allow for an increase in the thermal efficiency of the steam reformer without reducing the unit's lifespan. According to our study the most effective modification would be increasing air temperature from 27⁰C to 200⁰C using heat exchanger that uses about 30 ton/hr of wasted MP steam.

As fuel gas consumption will decrease with 230 Nm³/h per fired heater and regarding that total amounts of saved fuel gas per year would be (230*24*365 = 2014800 Nm³/year)

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

taking into consideration that 1 Nm³ = 0.035315 MMBTU

total saved amounts of fuel gas per year would be (2014800*0.035315 = 71152.662 MMBTU/year)

money saved per year would be (71152.662*5.75 = 409127.8 USD/year) per only 1 fired heater if the proposed modification applied to all fuel gas consumers (3 fired heaters + 3 steam reformers) the total saved money would be (409127.8*6 = 2454766.839 USD/year)

5. Conclusion:

- changing fuel gas temperature to any higher value will not have any observable effect on the adiabatic flame temperature.

- adding or mixing fuel gas with steam will have reversible effect as the steam considered heat absorbent and thus adiabatic flame temperature will decrease and thus consuming more fuel gas.

- Fuel gas consumption will decrease for all consumers without affecting any operating conditions only by raising combustion air temperature to the maximum value taking into consideration design temperature of equipment.

Table 11. comparison between all proposals

parameters	Fuel gas Nm ³ /h	Air flow Nm ³ /h	Air Temperature °C	Fuel gas Temperature °C
- Original case	7200	42500	27	30
- increasing fuel gas temperature using heat exchanger	8340	48900	27	150
- increasing fuel gas temperature by mixing wasted LP steam with fuel gas	9000	51000	27	114.4
- increasing combustion air temperature using heat exchanger	6970	41000	200	30
- increasing combustion air temperature by mixing wasted LP steam with combustion air	7950	46000	61	30

- as shown in table.10 the only proposal that would have saving effect for fuel gas by increasing combustion air temperature using heat exchanger reaching 200⁰C which will save about 230 Nm³/h of fuel gas per fired heater.

The use of preheated air-fuel mixture at this temperature the reaction section efficiency improved by 4%. The use of waste steam to preheat air or fuel reduce the wasted steam and thus economical saving.

The modifications have been shown to provide significant reduction in energy consumption (up to 30%), downsizing of the equipment (about 12%) and lower emissions (about 10%) while maintaining high thermal performance of the system. Energy savings translate to reduction of CO₂ and other greenhouse gases to the environment.

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

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