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# Optimized Energy Control for Steam Generators

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**ABSTRACT**

This paper introduces an advanced model for optimizing energy management in steam generators used for steam production, focusing on controlling the air to fuel ratio across the entire firing curve and during transient operations. In today's world, environmental issues such as pollution and global warming are increasingly prominent due to the widespread use of electrical devices, electric vehicles powered by conventional electricity sources, and rising energy consumption. Despite these challenges, steam generators offer significant advantages such as high efficiency, reliable operation, low emissions (with regular maintenance), and flexibility in fuel sources. However, traditional maintenance practices often overlook critical parameters like the air to fuel ratio, which is crucial for achieving environmental sustainability, efficiency, and minimizing fuel consumption. The steam generator system is simulated using Simulink/MATLAB to explore its operation under various load conditions and to analyze how the air to fuel ratio changes with power output. This work has been implemented in the field on various types of burners and igniters that differ in design and fuel usage. We observed a significant improvement in the air-to-fuel ratio and a noticeable increase in efficiency. Our ongoing efforts aim to further enhance these results and improve the response time in adjustments based on the oxygen and carbon monoxide levels measured from the boiler's flue.

***Keywords:***

Steam generator; energy management; steam production

## 1. Introduction

In industrial furnaces, the air-fuel ratio represents the relationship between the mass of air and the mass of fuel in the fuel-air blend. The stoichiometric air-fuel ratio denotes the precise ratio at which the fuel burns completely without excess air or fuel. For most industrial fuels, this ratio typically stands at approximately 14.7 parts of air to 1 part of fuel [1].

Imagine a critical task akin to crafting the perfect recipe, where instead of flour and sugar, your components are air and fuel. In the realm of internal combustion engines, engineers face exactly this challenge – achieving the optimal air-fuel mixture. This ratio, quantified as the mass of air to the mass of fuel, profoundly influences the efficiency and cleanliness of engine operation.

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Similar to baking, precision is paramount. Too much flour results in a dense cake; too little and it crumbles. Similarly, an engine's performance suffers with an incorrect air-fuel mix. The ideal ratio, known as the stoichiometric ratio, ensures thorough combustion of the fuel, maximizing power output while minimizing harmful emissions.

But why is this ratio so crucial? Internal combustion engines function by burning fuel to generate energy, a process requiring oxygen primarily sourced from the incoming air. Inadequate air (lean mixture) prevents complete fuel combustion, resulting in wasted fuel, reduced power output, and increased emissions. Conversely, excessive air (rich mixture) can lead to problems such as overheating and heightened hydrocarbon emissions.

Achieving the perfect equilibrium between power, efficiency, and emissions remains a constant pursuit for engine designers. Modern engines employ sophisticated management systems that continually monitor and adjust the air-fuel ratio based on variables like engine speed, load, and temperature.

Understanding the air-fuel ratio extends beyond engineering circles; it is fundamental for anyone curious about internal combustion engines. A deeper exploration of this concept illuminates the intricate interplay between air and fuel that drives our cars, trucks, and machinery forward.

In the upcoming sections, we will delve into the science underpinning the air-fuel ratio, explore lean and rich mixtures, and uncover how engine management systems uphold the optimal balance for peak performance and reduced environmental impact.

## 2. Different Furnaces Fuels

Furnaces are used to heat materials to high temperatures for a variety of purposes, including melting, annealing, and brazing. The type of fuel used in a furnace depends on the temperature required, the desired atmosphere, and the cost of the fuel.

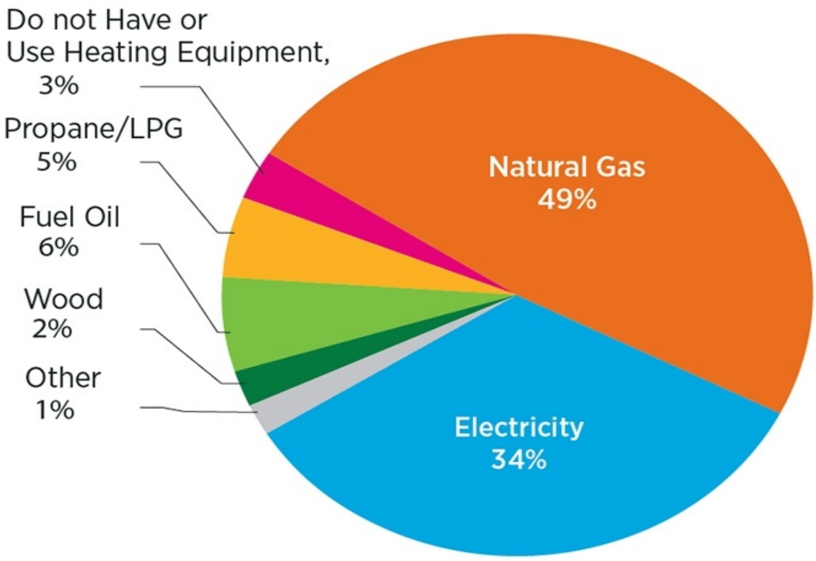


**Fig.1.** Different Furnaces Fuels [2]

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- **Natural gas**: Natural gas is a clean-burning fuel that is relatively inexpensive. It is often used in residential and commercia furnaces [3].


**Fig. 2.** Natural gas burner

- **Propane**: Propane is a gas that is similar to natural gas. It is also a clean-burning fuel, but it is more expensive than natural gas. Propane is often used in industrial furnaces [4].

- Oil: Oil is a fossil fuel that is burned to produce heat. It is less efficient than natural gas or propane, but it is still a popular choice for industrial furnaces.

- **Electricity**: Electric furnaces use electricity to heat elements that then heat the air or other material in the furnace. They are very efficient, but they can be expensive to operate [5].

- **Wood**: Wood is a renewable fuel that can be burned to produce heat. It is often used in small furnaces.

- **Natural gas and light Oil furnace:** This type of furnace uses a combination of natural gas and oil to heat the air or other material in the furnace. It is a good choice for areas with variable fuel prices, as it can switch to the more economical fuel source.
- **Heavy Oil and LPG gas furnace:** This type of furnace uses a combination of oil and gas to heat the air or other material in the furnace. It is a good choice for areas where natural gas is not available, or where the cost of oil is lower than the cost of natural gas.

The choice of the best dual fuel furnace for an industrial application will depend on a number of factors, including the climate, the cost of fuels, and the environmental regulations in the area.

**Here are some of the benefits of using dual fuel furnaces in industrial applications [6]:**

- They can save money on fuel costs, especially if the prices of the two fuels fluctuate.
- They can provide backup heat in case one fuel source is unavailable.
- They can reduce emissions, as they can use the cleaner-burning fuel when available.

However, dual fuel furnaces can also be more expensive to purchase and install than single fuel furnaces. They also require more maintenance and can be more complex to operate.

If you are considering using a dual fuel furnace in your industrial application, it is important to weigh the pros and cons carefully to decide if it is the right choice for you.

The choice of fuel for a furnace also depends on the environmental regulations in the area where the furnace is located. Some fuels, such as wood, Coal may produce more pollutants than others.

## 3. How to adjust the air to fuel ratio?

Fine-tuning the air-fuel mixture in industrial furnaces is crucial for enhancing combustion efficiency, reducing emissions, and maintaining optimal performance. The approach for adjusting this ratio varies depending on the furnace type, fuel type, and the specific combustion control system employed. Below are general procedures to facilitate this adjustment process [7]

### *3.1 Use Combustion Control Systems*

Many industrial furnaces are equipped with combustion control systems that automatically adjust the air-to-fuel ratio based on real-time measurements. These systems often utilize sensors to monitor parameters like oxygen concentration in the flue gas. Adjustments are then made to maintain the desired ratio.

### *3.2 Analyze Flue Gas Composition:*

Regularly analyze the composition of the flue gas to understand the combustion process. The presence of certain gases, such as oxygen, carbon dioxide, and carbon monoxide, can provide insights into the combustion efficiency and guide adjustments to the air-to-fuel ratio.

### *3.3 Refer to Combustion Charts and Curves:*

Combustion charts and curves specific to the type of fuel being used can provide guidance. These charts typically illustrate the relationship between the air-to-fuel ratio and parameters such as combustion efficiency and emissions. Operators can refer to these charts to identify the optimal ratio.

### *3.4 Adjust Dampers and Air Inlets:*

In some cases, manual adjustment of dampers or air inlets may be necessary. This involves regulating the flow of air into the combustion chamber. Care should be taken not to introduce excessive air, which can lead to energy loss and increased emissions [8].

If the air-to-fuel ratio is not within the desired range, it may be necessary to adjust the fuel system or the combustion air system. The specific adjustments that are needed will depend on the specific problem that is being encountered.

It is important to note that adjusting the air-to-fuel ratio can be dangerous if done incorrectly. It is best to leave this task to a qualified technician.

Here's a brief overview of how exhaust gas analysis is conducted and what the measurements indicate:

- **Oxygen ($O_2$) Measurement:**

  Oxygen levels in the flue gas provide insights into the completeness of combustion. Too much oxygen can indicate excess air, while too little oxygen may suggest incomplete combustion. The optimal oxygen level depends on the type of fuel and combustion conditions.

- **Carbon Dioxide ($CO_2$) Measurement:**

  $CO_2$ levels are directly related to the efficiency of combustion. High $CO_2$ levels generally indicate efficient combustion, while low levels can suggest incomplete combustion. Monitoring $CO_2$ is essential for assessing the air-to-fuel ratio.

- **Carbon Monoxide (CO) Measurement:**

  Elevated levels of CO in the flue gas can be an indicator of incomplete combustion. Efficient combustion processes aim to minimize CO emissions, as high levels pose health and environmental risks.

- **Nitrogen Oxides ($NO_x$) Measurement:**

  $NO_x$ compounds, including nitric oxide (NO) and nitrogen dioxide ($NO_2$), are pollutants associated with combustion. Monitoring and controlling $NO_x$ emissions are critical for meeting environmental regulations. High combustion temperatures and excess air can contribute to $NO_x$ formation.

- **Sulfur Dioxide ($SO_2$) Measurement:**

  If the fuel being burned contains sulfur, the combustion process can produce sulfur dioxide. Monitoring $SO_2$ emissions is crucial to comply with environmental standards, as sulfur dioxide contributes to air pollution and acid rain.

There are a few ways to check the air-to-fuel ratio in industrial furnaces. One way is to use a flue gas analyzer. A flue gas analyzer is a device that measures the concentration of various gases in the flue gas, including oxygen, carbon monoxide, and carbon dioxide. The air-to-fuel ratio can then be calculated from these measurements [9].

Another way to check the air-to-fuel ratio is to use a $CO_2$ probe. A $CO_2$ probe is a sensor that measures the concentration of carbon dioxide in the flue gas. The air-to-fuel ratio can then be calculated from this measurement.

Finally, the air-to-fuel ratio can also be checked by comparing the temperature of the flue gas to the temperature of the furnace. The flue gas will be cooler if there is more air in the mixture, and it will be hotter if there is more fuel in the mixture.

The specific method that is used to check the air-to-fuel ratio will depend on the type of furnace and the availability of equipment.

Here are some additional things to keep in mind when checking the air-to-fuel ratio in an industrial furnace:

- The furnace should be operating at its normal operating conditions.
- The flue gas should be sampled from a representative location in the furnace.
- The flue gas analyzer or $CO_2$ probe should be properly calibrated.
- The results of the air-to-fuel ratio measurement should be interpreted in accordance with the furnace manufacturer's recommendations.

## 4. Why Is the Air To Fuel Ratio Important

In combustion processes, the relationship between the mass of air and fuel is usually quantified by their ratio. The highest achievable heat energy output occurs when the mass flow rate of air entering the combustion area aligns correctly with the mass flow rate of fuel entering the burner [9].

The following generic equation can be used to describe the combustion of fuel:

Fuel + Air → CO2 + H2O + Heat [10]

where:
CO2 = carbon dioxide
H2O = water
Air = 21% oxygen (O2) and 79% nitrogen (N2)
Fuel = hydrocarbon such as natural gas or liquid fuel oil

Air is mostly made up of oxygen and nitrogen. It is the oxygen in the air that reacts with the carbon in the fuel to produce carbon dioxide and water vapor. This reaction is highly exothermic, meaning that it releases a large amount of heat energy.

Carbon dioxide is a greenhouse gas, so it is important to ensure that the combustion process is as efficient as possible in order to minimize emissions. Water vapor is also produced during combustion, but it is not a greenhouse gas [11].

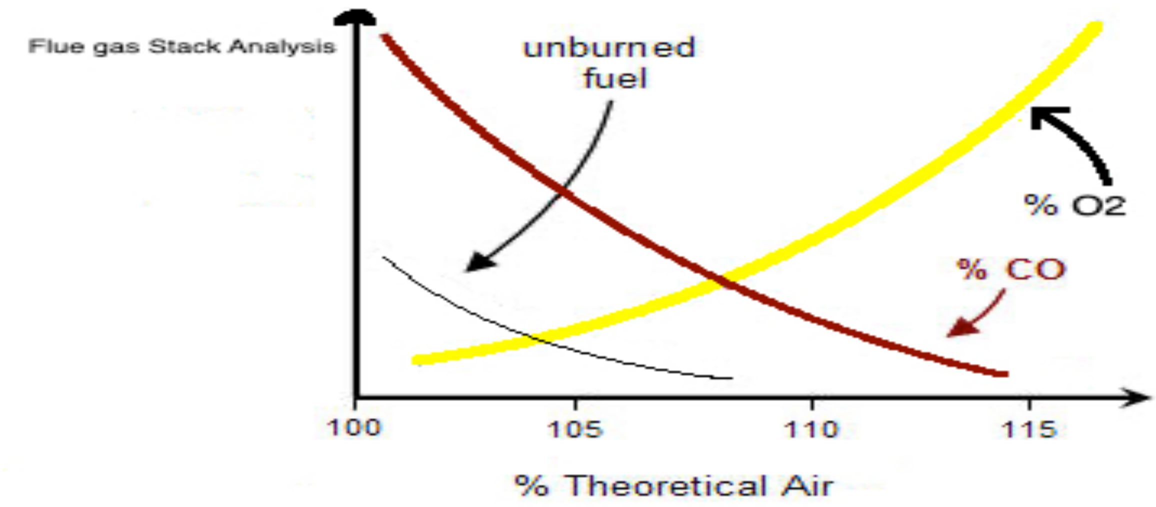


**Fig. 3.** Ratio control and metered aircmbustion processes [12]

The interplay among air-to-fuel ratio, pollution generation, and heat energy wastage serves as a basis for designing control systems. In laboratory conditions featuring perfect mixing and unlimited time, the minimum air quantity needed to completely convert hydrocarbon fuel into carbon dioxide and water—termed "stoichiometric" air—can be determined through experiments.

However, real-world combustion processes lack perfect mixing and unlimited time. Therefore, even if air is supplied in exact stoichiometric proportions to fuel, incomplete combustion and energy wastage still occur. Practical burners typically exhibit performance resembling the graph below. Operating with higher air-to-fuel ratios incurs costs due to wasted energy used to heat excess oxygen and nitrogen. Conversely, reducing the air-to-fuel ratio accelerates losses from incomplete combustion and pollution formation [13].

For each specific burner design, an optimal air-to-fuel ratio exists that balances these competing factors to minimize overall losses. As indicated in the graph, gas or liquid fuel burners commonly operate with 5% to 20% excess air, representing 105% to 120% of theoretical air, to strike this balance.

The air-to-fuel ratio is the ratio of the mass of air to the mass of fuel in a fuel-air mixture. The stoichiometric air-fuel ratio is the ratio at which the fuel is completely burned with no excess air or fuel. For gasoline, the stoichiometric air-fuel ratio is approximately 14.7:1, which means that for every gram of fuel, 14.7 grams of air are required [14].

*4.1 Advantages of achieving a stoichiometric air-fuel ratio:*

• Optimal combustion: Ensures complete combustion of fuel, maximizing power output and efficiency.
• Reduced emissions: Minimizes emissions by precisely balancing fuel and air without excess released into the environment [15].
• Smooth engine operation: Maintains smooth engine operation by preventing knocking or pinging.

*4.2 Disadvantages of maintaining a stoichiometric air-fuel ratio:*

• Not universally ideal: May not suit all operating conditions; richer mixtures could be necessary for cold starts or high-performance demands [16]
• Requires precise management: Demands meticulous control of the fuel injection system to ensure accurate fuel delivery.
• Potential for reduced fuel efficiency: Could be less fuel-efficient compared to leaner mixtures, especially at low engine loads.

*4.3 Lean air-fuel ratios:*

Lean mixtures contain more air than fuel, offering benefits such as improved fuel economy and reduced emissions. However, they can also cause engine knocking and pinging. (!7)

*4.4 Rich air-fuel ratios:*

Rich mixtures contain more fuel than air, enhancing power and performance but potentially increasing emissions and lowering fuel efficiency. (18)

Determining the optimal air-fuel ratio depends on various factors including furnece design, fuel type, and desired performance characteristics.How to Check Air to Fuel Ratio (19)

## 5. Simulink

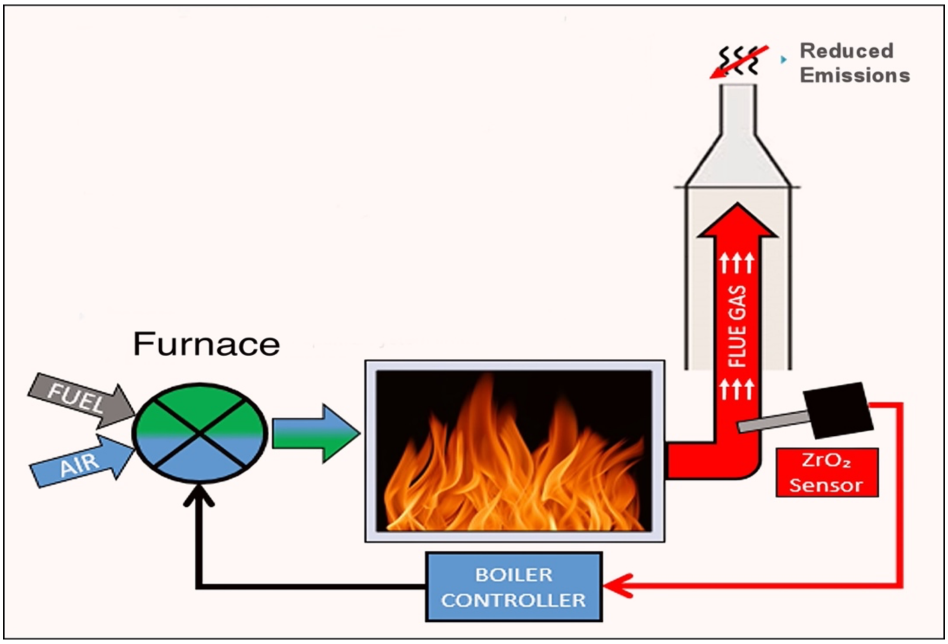


**Fig. 5.** System block diagram [20]

## 6. Simulation and Results

In these results, the results of different exhaust analysis will be reviewed under different conditions and for burners of different design and operating method adjusting the air/fuel ratio became very useful because it effects on the combustion positively, high efficiency means low fuel consumption, low money, low maintenance, And green environment:
Note: (These results take in different situation different burners fuel (oil & gas), different ambient temperature and different humidity)

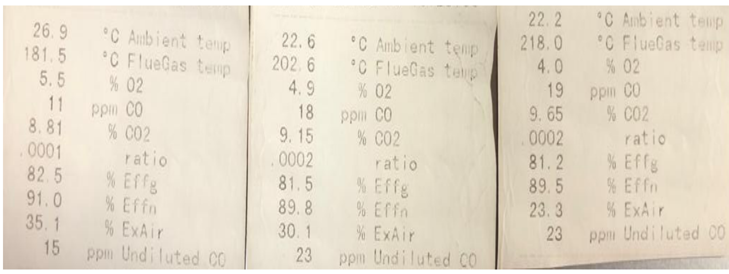


**Fig. 6.** Gas analysis after adjust air to fuel ratio

**Table 1**
Compare between gas analysis before and after adjusting air to fuel ratio

| Variables | Before adjust Air to Fuel ratio | | | After adjust Air to Fuel ratio | | |
|---|---|---|---|---|---|---|
| Ambient temp. | 26.9 | 22.6 | 22.2 | 26.9 | 22.6 | 22.2 |
| Flue Temp. | 219.5 | 232 | 237 | 181.5 | 202 | 218 |
| O2 | 3.1 | 2.9 | 2.1 | 5.5 | 4.5 | 4 |
| CO | 77 | 82 | 106 | 11 | 18 | 19 |
| CO2 | 12.9 | 13.3 | 13.8 | 8.81 | 9.15 | 9.65 |
| Efficiency | 83 | 81 | 78 | 91 | 89 | 89.5 |
| EX Air | 21 | 18.7 | 14.3 | 35 | 30 | 23.3 |

In this report the carbon in high fire rating decreased from 67 ppm to 19 ppm and the efficiency increase from 82% to 91% on low fire and 89% on high fire. (this burner is working with light oil fuel with two servo motors for air and fuel)

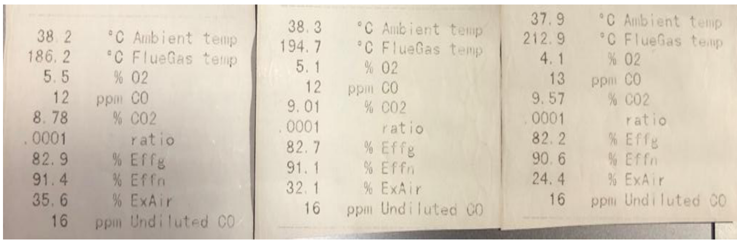


**Fig. 7.** Gas analysis after adjust air to fuel ratio

**Table 2**
Compare between gas analysis before and after adjusting air to fuel ratio

| Variables | Before adjust Air to Fuel ratio | | | After adjust Air to Fuel ratio | | |
|---|---|---|---|---|---|---|
| Ambient temp. | 38 | 38 | 37.9 | 38 | 38 | 37.9 |
| Flue Temp. | 206 | 232 | 251 | 186 | 194 | 212 |
| O2 | 4.2 | 3.9 | 3.2 | 5.5 | 5.1 | 4.1 |
| CO | 46 | 57 | 78 | 12 | 12 | 13 |
| CO2 | 10.78 | 11.01 | 11.57 | 8.78 | 9.01 | 9.57 |
| Efficiency | 86.4 | 83.1 | 80.6 | 91.4 | 91.1 | 90.6 |
| EX Air | 24.6 | 22 | 19 | 35.6 | 32 | 24.4 |

In this report the carbon in high fire rating decreased from 54 ppm 13 ppm and the efficiency increase from 84.2 % to 91.4% on low fire and 90.6% on high fire. (this burner is working with natural gas fuel with three servo motors for air, fuel and AUX).

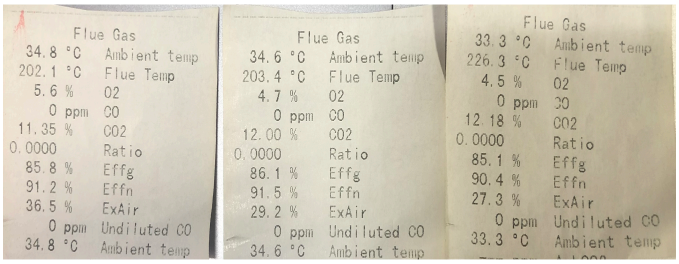


**Fig. 8.** Gas analysis after adjust air to fuel ratio

**Table 3**
Compare between gas analysis before and after adjusting air to fuel ratio

| Variables | Before adjust Air to Fuel ratio | | | After adjust Air to Fuel ratio | | |
|---|---|---|---|---|---|---|
| Ambient temp. | 26.9 | 22.6 | 22.2 | 34 | 34 | 33 |
| Flue Temp. | 219.5 | 232 | 237 | 202 | 203 | 226 |
| O2 | 3.1 | 2.9 | 2.1 | 5.6 | 4.7 | 4.5 |
| CO | 77 | 82 | 106 | 0 | 0 | 0 |
| CO2 | 12.9 | 13.3 | 13.8 | 8.81 | 9.15 | 9.65 |
| Efficiency | 83 | 81 | 78 | 91 | 89 | 89.5 |
| EX Air | 21 | 18.7 | 14.3 | 35 | 30 | 23.3 |

In this case the CO always zero (this is special case) this burner is low NOx Burner and the efficiency between 91.2% on low fire and 90.4% on high fire. (this burner is low NOx Burner natural gas fuel and this burner with AUX control and with VSD for air control)

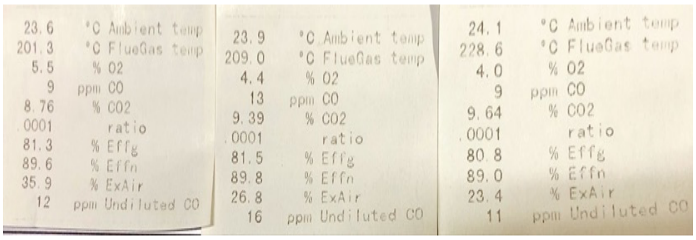


**Fig. 9.** Gas analysis after adjust air to fuel ratio

**Table 4**
Compare between gas analysis before and after adjusting air to fuel ratio

| Variables | Before adjust Air to Fuel ratio | | | After adjust Air to Fuel ratio | | |
|---|---|---|---|---|---|---|
| Ambient temp. | 23.6 | 23.9 | 24.1 | 23.6 | 23.9 | 24.1 |
| Flue Temp. | 223 | 237 | 241 | 201 | 209 | 228 |
| O2 | 4.7 | 4.1 | 3.2 | 5.5 | 4.4 | 4 |
| CO | 43 | 49 | 66 | 9 | 13 | 9 |
| CO2 | 10.1 | 10.9 | 11.9 | 8.76 | 9.39 | 9.64 |
| Efficiency | 84 | 82.8 | 81 | 89 | 89.8 | 89 |
| EX Air | 27 | 20.5 | 17.4 | 35 | 26 | 23.4 |

In this report the carbon in high fire rating decreased from 61 ppm 13 ppm and the efficiency increase from 86% to 89.6% on low fire and 89% on high fire. (this burner is working with LPG fuel with two servo motors for air and fuel).

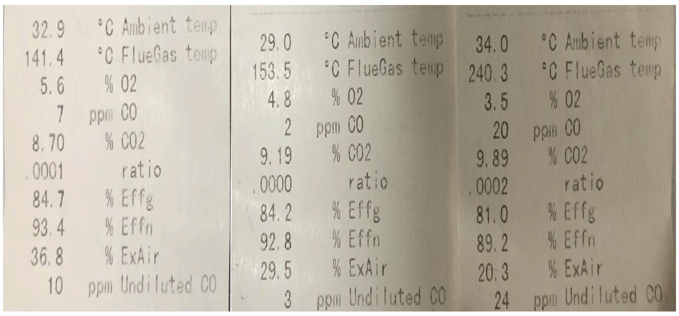


**Fig. 10.** Gas analysis after adjust air to fuel ratio

**Table 5**
Compare between gas analysis before and after adjusting air to fuel ratio

| Variables | Before adjust Air to Fuel ratio | | | After adjust Air to Fuel ratio | | |
|---|---|---|---|---|---|---|
| Ambient temp. | 32.6 | 33.7 | 34 | 32 | 29 | 34 |
| Flue Temp. | 201.5 | 206 | 230 | 141.5 | 153 | 240 |
| O2 | 7.6 | 6.9 | 5.8 | 5.6 | 4.8 | 3.5 |
| CO | 18 | 36 | 31 | 7 | 2 | 20 |
| CO2 | 7.70 | 8.16 | 9.1 | 8.70 | 9.19 | 9.89 |
| Efficiency | 82.4 | 83.1 | 80.6 | 93.4 | 92.5 | 89.2 |
| EX Air | 45 | 39 | 32 | 36 | 29.5 | 20.3 |

In this report the carbon in high fire rating decreased from 73 ppm 20 ppm and the efficiency increase from 87% to 93.4% on low fire and 89.2% on high fire. (this burner is working with dual fuel light oil fuel & LPG with three servo motors for air and fuel and VSD for rotary cup).

In these cases, we use the gas analyzer (Testo 320 LL) to make exhaust analysis based on this analysis the changes in air curve, fuel curve, Auxiliary curve, Inverter curve was applied to improve the analysis reading and it is clearly in CO, O2, Ex Air & efficiency. The results of some cases became better than other because it depends on type of fuel and control in the burner.

## 7. Conclusion

The air-to-fuel ratio plays a critical role in combustion processes. The optimal ratio for a specific burner design depends on factors such as the fuel type, desired operational performance, and environmental standards.

In theory, the stoichiometric air-to-fuel ratio represents the minimum air needed to fully convert hydrocarbon fuel into carbon dioxide and water. However, practical combustion scenarios lack perfect mixing and unlimited time, leading to incomplete combustion and energy wastage if strictly adhering to stoichiometric conditions.

Therefore, most burners operate with a slightly higher air-to-fuel ratio, typically ranging from 105% to 120% of theoretical air. This equates to operating with 5% to 20% excess air, ensuring complete combustion and minimizing pollutant emissions.

Adjusting the air-to-fuel ratio involves controlling the flow of air or fuel into the burner, either manually or automatically through a control system. This adjustment is crucial for optimizing combustion efficiency, reducing emissions, and enhancing overall performance.

By carefully managing the air-to-fuel ratio, it is possible to enhance efficiency, minimize environmental impact, and achieve optimal combustion performance in industrial processes.

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