Non-Premixed Cofiring of Two Fuel phases: Performance and Emissions Study for a New Air Staged Burner

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Non-Premixed Cofiring of Two Fuel phases: Performance and Emissions Study for a New Air Staged Burner

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Abstract: *This work focuses on the cofiring of liquid and gaseous fuels through a new burner design, as a technique to enhance combustion efficiency, particularly with biofuels, which can significantly reduce emissions and improve combustion stability. This study is an extension to a previous one [1], by investigating the performance of a staged combustion through a double-swirl burner. One case is diesel fuel firing and two cases of cofiring diesel with LPG at different heat share ratios (LGR 80/20 and 70/30), by comparing their thermal and chemical structures and the heat transfer by convection and radiation. The findings reveal that the visual appearance of the flames is strongly affected by the heat share ratios, including the flame lengths and luminosities. In addition, incorporating LPG enhances preheating, vaporization, and oxidation, resulting in higher total heat transfer while lower radiation due to lower flame luminosity.*
Keywords: Cofiring, multi-phase fuels, LPG, Air staged combustion

1 INTRODUCTION

Industrial burners play a critical role in high-temperature processes across various sectors, from automotive and petrochemicals to power generation. However, conventional single-fuel systems raise concerns regarding environmental impact and fluctuating fuel prices. Dual-fuel/cofiring technology presents a compelling solution to enhance both efficiency and sustainability in industrial burner operations [1,2].

Dual-fuel technology empowers burners to operate on two distinct fuel sources, offering the flexibility to switch based on factors like cost or availability [3]. Cofiring, a more advanced approach, involves the simultaneous combustion of multiple fuels, leading to optimized combustion processes and reduced emissions [4].

Integrating dual-fuel/cofiring systems into industrial settings holds significant promise. This technology allows for the utilization of cleaner fuel alternatives, such as biofuels, either in conjunction with or as a substitute for conventional fossil fuels, thereby mitigating greenhouse gas emissions, reducing operational costs, and strengthening energy resilience [5].

Despite these advantages, adopting this technology requires overcoming challenges. Burner design adaptations and strict adherence to environmental regulations are crucial considerations [6].

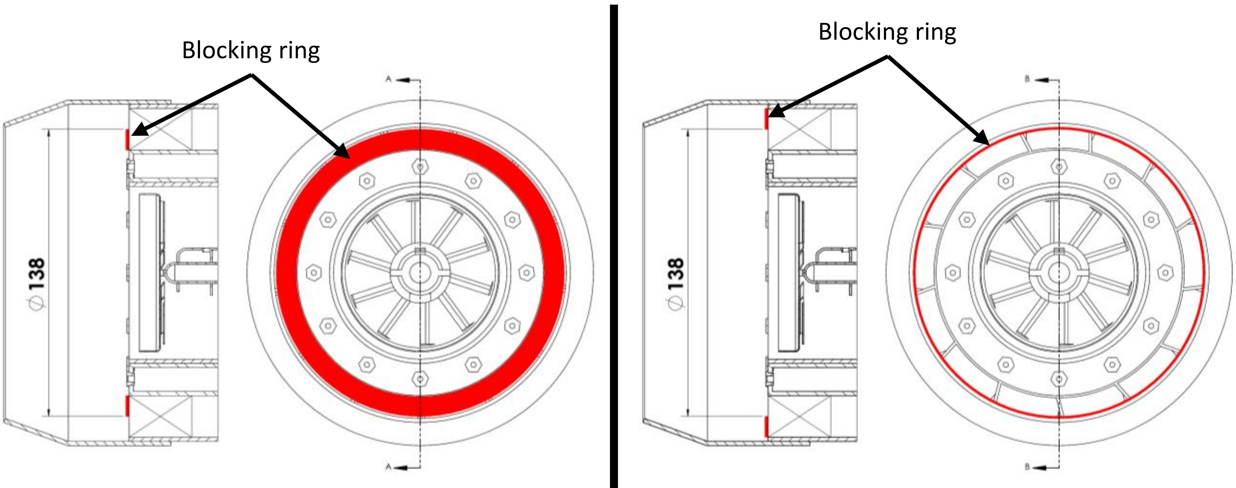
This growing interest in dual-fuel/cofiring technology coincides with the escalating demand for alternative energy sources driven by dwindling fossil fuel reserves [7]. Biofuels, derived from abundant organic waste generated in rural and urban environments, offer a promising solution [8]. Processes like gasification, fermentation, and pyrolysis can transform these wastes into biofuels that adhere to the concept of net zero-carbon emissions, as the CO_2 released during combustion is theoretically recaptured by the plants used for biofuel production [9]. However, challenges persist due to the lower heating value and presence of impurities in biofuels, which can negatively affect combustion stability and efficiency [10].

Cofiring, the simultaneous combustion of biofuels with traditional fuels like natural gas, liquified petroleum gas (LPG), or diesel oil, emerges as a potential solution to these limitations [4]. By blending biofuels with conventional fuels, cofiring can improve combustion characteristics and ensure stable operation [11]. While complexities in controlling dual fuel and air streams have limited widespread adoption in the past, advancements in biofuels like syngas and biodiesel have renewed interest in cofiring, making it a subject of intense research efforts [12,13].

Swirling flows are a cornerstone technique for achieving stable combustion in practical applications, such as power generation systems. However, their implementation presents challenges when utilizing low-reactivity fuels like biofuels. These fuels are susceptible to flame blowout due to their inherent combustion characteristics. Additionally, biofuels typically possess lower heating values compared to traditional hydrocarbon fuels. This necessitates higher flow rates to achieve the desired energy output. Consequently, any fluctuations in fuel composition or flow rates can significantly impact combustor efficiency and performance [14].

Pulverized coal-fired furnaces utilize swirl burners to achieve two primary goals: enhanced flame stability and the generation of compact, high-intensity flames. These objectives contribute to a reduction in furnace size and promote thorough fuel burnout [15]. The swirling motion is imparted to the secondary air stream prior to its introduction into the furnace.

For premixed combustion applications, a promising technology is the double-swirl burner. This design employs two separate swirling streams, one for fuel and another for air. The interaction creates a powerful recirculation zone within the flame core. This technique demonstrates promising results, including improved flame stabilization and the ability to control exhaust emissions from low-reactivity fuels such as biogas and ammonia [16,17].



Previous study configuration [1] This study configuration

Figure 1 Burner rim configurations used in the previous and current studies.

In a recent study, Mater et al. [18] explored the cofiring of LPG and diesel fuels utilizing an innovative double swirl burner. This study meticulously evaluated flame characteristics and exhaust emissions, comparing the performance of cofiring against standalone diesel combustion. The results revealed that incorporating LPG led to enhanced preheating of the oil spray, promoting faster vaporization and oxidation, which significantly reduced CO emissions by up to 95% at a liquid-to-gas ratio (LGR) of 70/30 compared to pure diesel. Additionally, the overall flame temperature was directly linked to the LGR operating condition.

The present study emphasizes the potential benefits of cofiring LPG with diesel in enhancing combustion efficiency and reducing harmful emissions within dual fuel/cofiring technologies. The primary objective is to establish a comprehensive performance database for a modified burner configuration, building on our previous work [1], utilizing LPG and light diesel as conventional fuels. This database serves as a valuable reference for evaluating the burner's performance in future research involving biofuels such as syngas and biodiesel. The experimental program focuses on analyzing flame structure, heat transfer, and emissions from diesel and diesel/LPG flames.

2 TEST RIG

2.1 Burner

The burner configuration is explained in detail in [1], however, only a simple modification has been made on it as shown in Figure 1, this modification is made based on the mapping results, which showed better performance for the current study configuration regarding the CO and NO emissions. In addition the Swirl Number (SN) is slightly altered due to this modification from 0.94 of previous configuration to 0.93 for the current configuration, which is calculated for the annular geometry using equation (1) [19].

$$SN = \frac{2}{3}\left(\frac{1-(R_{in}/R_{out})^3}{1-(R_{in}/R_{out})^2}\right)\tan(\theta) \qquad (1)$$

2.2 Combustor

The combustor as well is the same as in [1], however, in this study the focus is not only on the emission analysis in the chimney as in [1], therefore, some other details related to the inflame and heat transfer measuring systems are explained as shown in Figure 2. The measuring holes are used to insert the thermo-couple for inflame temperature measurement and the gas analyzer probe to measure the inflame species concentrations.

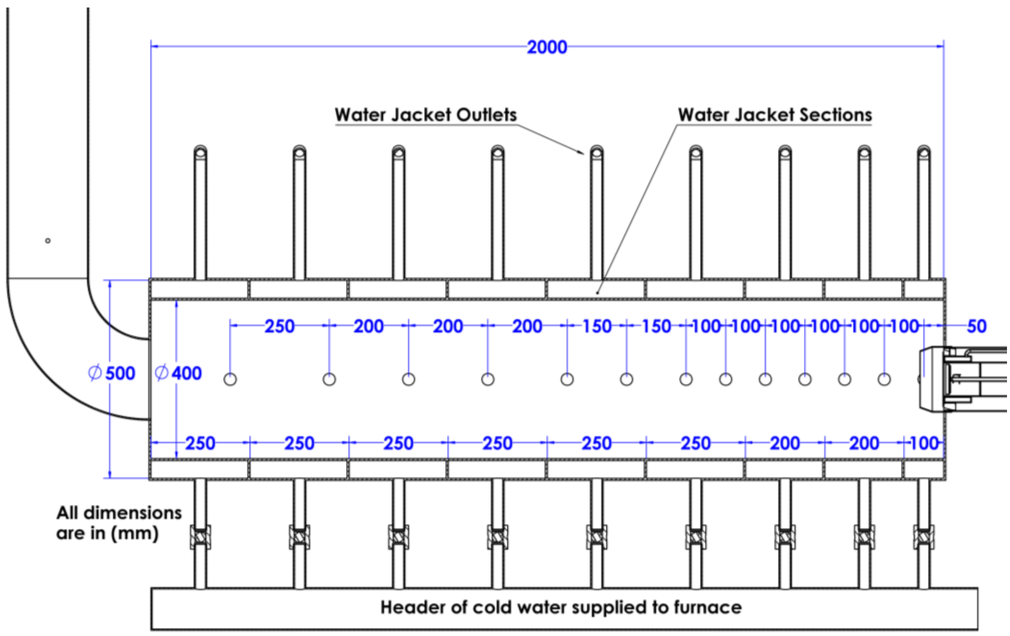


Figure 2 Combustor configuration

Table 1 Experimental program

Run No.	Fuel Type	LGR***	Fuel Flow Rate [kg/hr]		Air Flow Rate [kg/hr]	
			$\dot{m}_{oil}$	$\dot{m}_{gas}$	$\dot{m}_{inner}$ *	$\dot{m}_{outer}$ **
1	Diesel	100/0	4.5	0	39	26
2	Diesel/LPG	80/20	3.6	0.82	31	34
3	Diesel/LPG	70/30	3.15	1.26	27	38

* These amounts of air mass flow rate represent 0.6 stoichiometric air of diesel fuel only

** These amounts of air mass flow rate represent stoichiometric air of LPG + 0.4 stoichiometric air of diesel fuel

*** Liquid to Gas Ratio, which represents the heat share of each fuel in the flame from the total heat (55kW)

In addition to the water jackets are used to measure the amount heat transferred from the flame.

2.3 Measure devices

A standard S-type thermocouple (OMEGA) is used for measuring the temperature inside the flame, and a gas analyzer (LAND) is used to measure the inflame concentrations and the emissions of exhaust gases. A standard K-type thermocouple and an in-lab calibrated turbine flowmeter are used to measure the cooling water's temperature and flow rate. An in-lab calibrated radiation pyrometer is used to measure the radiative heat flux qualitatively.

Standard orifice plates are used to monitor the flow rates of air and gaseous fuels, and the gauge pressure of the liquid fuel supply line is calibrated against its flow rate to monitor it.

3 Experimental program

This study is an extension of the previous one [1], in which the focus is given to three selected cases from the mapped cases in the previous study. These three cases are pure liquid fuel firing and two cofiring cases of liquid and gaseous fuels with different liquid to gas ratios. As summarized in Table 1.

The measured quantities for the three cases are in-flame temperatures and main species concentrations as well as the amount of heat transferred to the combustor's walls through convection and radiation. In addition to visual inspection of the flames

4 RESULTS AND DISCUTION

The in-flame temperature measurements for diesel fuel firing (Run1) revealed that there are two temperature peaks, the first peak temperature is at x/D = 0.38, and the second peak is at x/D = 1.3 as shown in Figure 3 (right). These peaks are due to staged combustion, where the secondary air stream mixes with unburnt fuel and intermediate species to complete combustion at the second peak. The thermal length of the flame extends to the second peak, indicating an elongated combustion zone. This staged combustion results in lower temperatures by distributing heat release across multiple zones instead of concentrating it in one. In addition, the temperature peaks are shifted from the combustor center due to the swirling effect and the atomizer cone angle which is 45°.

In cofiring scenarios, the two distinct temperature peaks vanish, as shown in Figure 4 (rights). This is due to two factors: the burning of gaseous fuel with secondary air creates a hot shield around the liquid fuel flame, and the reduced atomization quality of the liquid fuel, caused by lower fuel line pressure, slows its evaporation. However, this reduction in atomization is mitigated by the hot

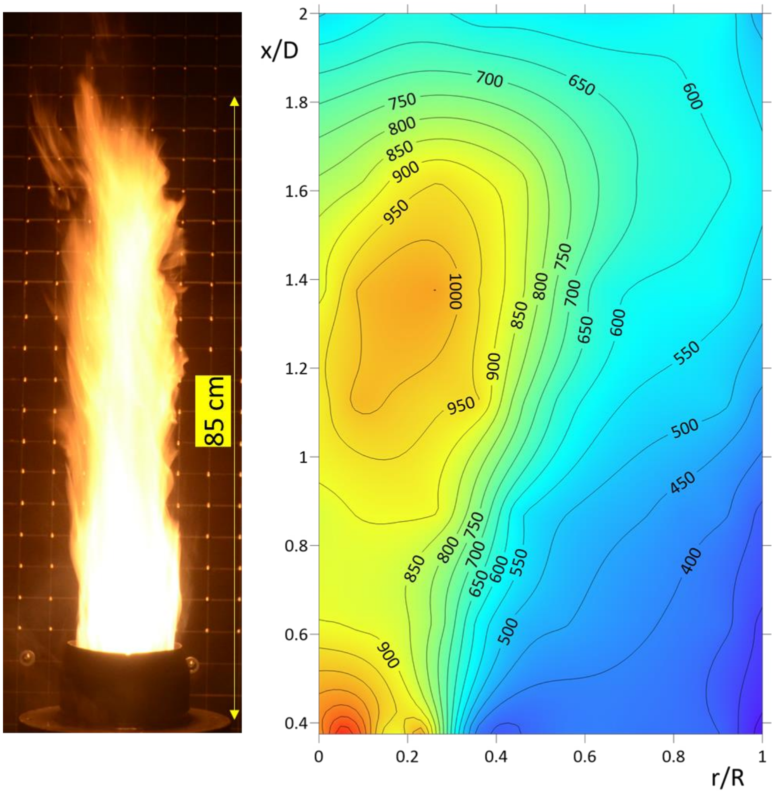


Figure 3 Run 1(Diesel Fuel only), Temperature (°C) contours from combustor measurements (right), flame appearance outside of combustor (left)

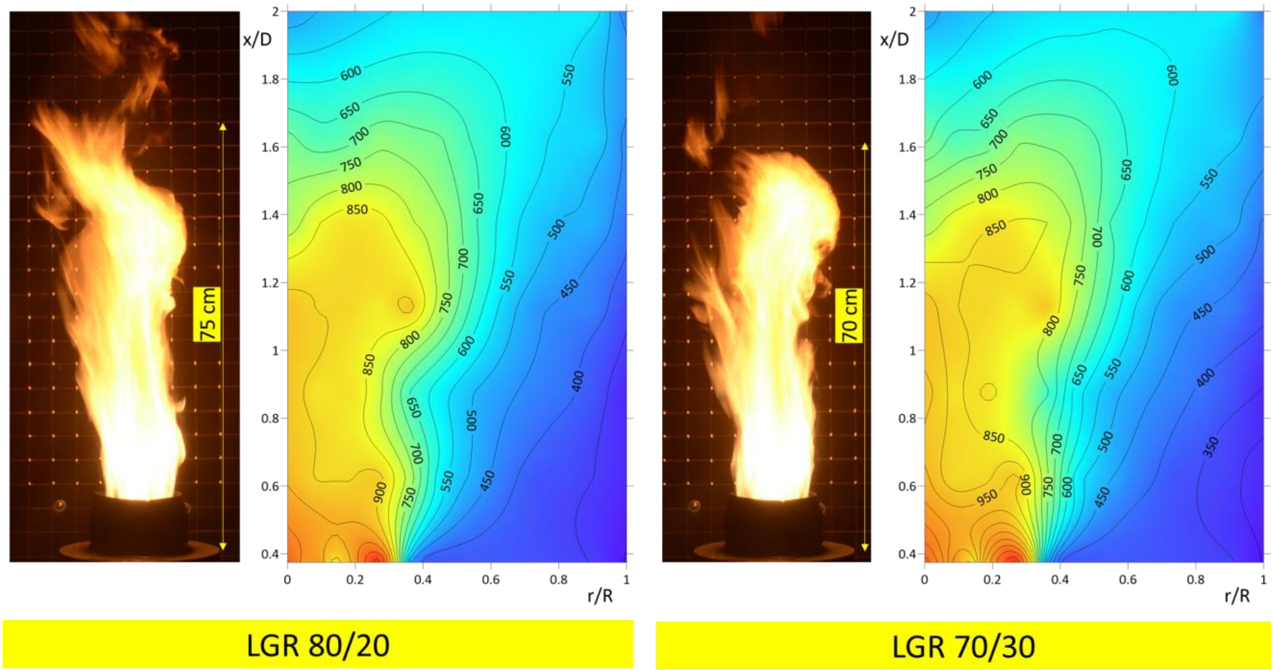


Figure 4 Cofiring cases, run 2 and 3 on the left and right respectively. For each case, Temperature (°C) contours from combustor measurements (right), flame appearance outside of combustor (left)

gaseous fuel flame enhancing the vaporization of the liquid fuel. The heat from the gaseous fuel flame aids in the evaporation of the larger liquid fuel droplets, distributing combustion more evenly throughout the reaction zone. As a result, the heat release is better distributed, reducing maximum temperatures and NOx emissions, as indicated by the temperature distribution in Figure 4.

Thermal efficiency is evaluated by measuring the heat transferred to the cooling water surrounding the combustor, as shown in **Error! Reference source not found.**. Generally, gaseous fuel flames transfer heat more effectively than liquid fuel flames, as observed in [2]. This improved heat transfer enhances the vaporization of liquid fuel droplets, ultimately improving the combustion of the liquid fuel, which gives an advantage to cofiring to burn low grade liquid fuels.

Furthermore, radiation heat transfer, measured qualitatively by a radiation pyrometer, is nearly the same for all flames, with run 1 having the highest level. Radiation depends on the luminous areas in the flame, which are the soot oxidation zones. Soot formation is higher in pure liquid fuel due to its lengthy combustion process involving vaporization and diffusion, unlike gaseous fuel which only requires diffusion to burn, which explains the reason for different flame lengths shown in Figure 4 (left) and Figure 5 (lefts). As a result, radiation heat transfer decreases when the LGR decreases, potentially limiting the use of cofiring in furnaces where radiation is crucial for heat transfer.

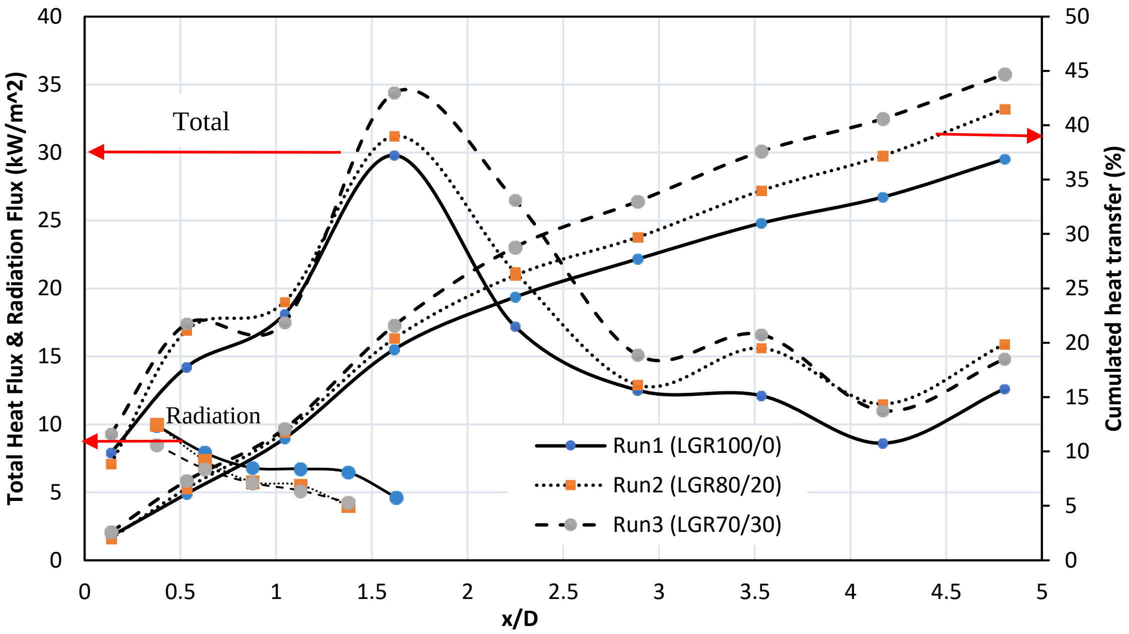


Figure 5 Total heat fluxes to the cooling water, radiation flux measured by the pyrometer, and the cumulated heat transferred at each cooling section as a percent of input heat (55kW)

The in-flame measurements for species concentrations are normalized at 15% O_2, meaning that all species concentrations are mapped so that the oxygen concentration is always 15%, this is a good way to eliminate the oxygen percentage effect on the rest of the species.
The staged combustion resulted in high CO levels inside the flame, especially in cofiring cases, however, once the secondary air starts to mix with the fuel and intermediate species the CO levels drop down to low levels, as shown in Figure 6 (above). The high CO levels in cofiring cases are attributed to the existence of the gaseous fuel which prevents the secondary air from approaching the liquid fuel until its combustion finishes, then the rest of the air can approach the liquid fuel. This is consistent with the observation of the flame shape, as in Figure 4, where the gaseous fuel flame is shorter than the liquid fuel flame.
Meanwhile, the NOx concentration is kept at low levels as the flame temperatures are not high enough to accelerate the NOx formation reactions and the amount of air inside the combustor is not high enough to provide a high probability for NOx formation.

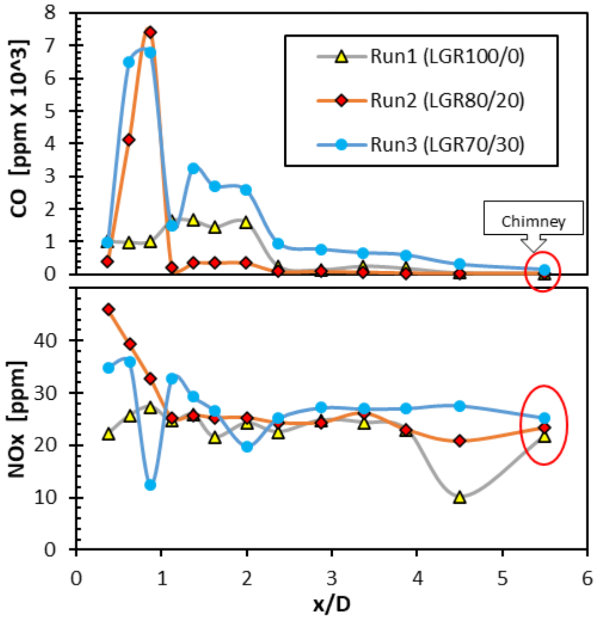


Figure 6 normalized species concentrations measurements @ 15% O_2 of CO (above) and NOx (below) at the center of the combustor.

5 CONCLUSION

This study aims to investigate a new burner design, which is intended to burn two types of fuels simultaneously, one is liquid fuel and the other is gaseous one. This work is motivated by the need for burning low grade fuels such as biodiesel and syngas. However, to form a clear understanding for the burner design, well established fuels are used in this study, Diesel and LPG. The main findings are as follow:

- Cofiring enhances the combustion of liquid fuel by providing the heat for vaporization process.
- Cofiring reduces the radiation from the flame while increasing the convective heat transferred.
- As the liquid/Gas Ratio LGR decreases the atomization quality decreases as well, but the vaporization process is enhanced.
- The staged air combustion results in low NOx concentrations in the combustion zone and in the chimney as well.
- The staged air diesel fuel cofiring with LPG results in high CO concentration inside the flame until the secondary air approaches the CO and the rest of the liquid fuel.

Those results showed that cofiring is a good technique to enhance the combustion of low-grade fuels, despite that the radiative heat flux is adversely affected. In addition, the staged air cofiring results are promising regarding the NOx and CO emissions.

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