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Cofiring of Oil and Gaseous Fuels Through an Innovative Coaxial, Double Swirl Burner

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Abstract: *This paper presents a newly designed coaxial burner capable of simultaneous combustion of oil and gas fuels. The burner addresses the need for renewable energy production from syngas and biofuels derived from solid waste. The focus is on evaluating the burner's effectiveness in co-firing light diesel fuel and LPG, including flame appearance and exhaust emissions. The study establishes a reference for future comparisons when burning syngas and blended biofuels. The burner configuration allows for various influential variables, such as oil/gas ratio, and inner/outer air ratio. The evaluation concentrates on visible flame appearance, exhaust emissions, and heat transfer to the cooling water jacket. The experiments are conducted at a fixed 55 kW input load. Results indicate that different inner/outer air ratios have minimal impact on CO_2 and O_2 levels but affect CO and NO_X levels, both in single fuel burning and co-firing scenarios. Increasing inner air reduces CO levels, particularly in oil fuel burning, while decreasing inner air reduces CO levels in co-firing.*

Keywords: Co-firing, multiphase combustion

1. INTRODUCTION

The necessity of burning biofuels arises from several factors, including the depletion of fossil fuels over time due to the tremendous rise in the global energy demand without any replenishment. Second, the massive amount of solid and organic waste generated by rural and urban activities could be utilized as an alternative fuel in the energy sector. Reforming these wastes into a combustible mixture via gasification, fermentation, pyrolysis, or any other suitable technique is considered a feasible method to control wastes while generating energy. Third, in terms of environmental aspects, the net zero-carbon emission principle involves emitting the same amount of CO_2 as is removed from the atmosphere [1], implying that the CO_2 in the atmosphere is neither growing worse nor better. Combustion exhaust gases are the primary source of CO_2 in the atmosphere, therefore, burning biofuels is one application of this principle since the CO_2 is consumed during the production of biofuels, Therefore when they are burned, CO_2 is expelled back into the atmosphere.

On the other hand, burning of pure biofuels comes with several technical challenges, e.g., their heating value is much lower than that of fossil fuels which makes them poor alternatives for generating electricity in times of high demand. In addition, they contain a large number of impurities, which adversely affect the combustion stability and combustion efficiency. A good transition could be the so-called ‘Cofiring’. Cofiring of liquid and gaseous fuel simultaneously is one of the promising techniques to improve burning such fuels. The liquid fuel droplets need to absorb latent heat to first evaporate and then combust, this heat can be easily obtained from burning gaseous fuel around the liquid spray.

Cofiring of multiphase fuels is rarely discussed within the scientific community, as the control system of such burner requires precise control of two fuel streams and two air streams simultaneously. This is considered challenging when it comes to combustion stability and emission control. However, recently, with the emergence of burning biofuels (syngas and biodiesel), the need for burning these fuels together grew to increase the combustion efficiency of such low-grade fuels. Therefore, this area of research is of great interest to many researchers.

The co-firing of palm methyl esters (PME) with natural gas (NG) is studied [2], and a coaxial burner with an air-assisted atomizer is utilized. Key findings include: (i) The PME flame structure was observed in both PME and PME/NG co-firing flames, with the diesel flame changing at higher swirl angles due to rapid oxidation of soot. (ii) PME and PME/NG flames exhibited higher levels of CH* and OH* radicals compared to diesel fuel, attributed to ethane in NG. (iii) Increasing the NG percentage reduced NO but increased CO emissions in PME/NG co-firing while raising the swirl angle decreased NO emissions. (iv) Inadequate fuel-air mixing at a high equivalence ratio resulted in significant CO levels, which were improved by increasing air input and lowering the equivalence ratio.

Another investigation to examine the properties and stability of co-firing syngas and diesel fuels by [3]. The study employed a mechanical jet atomizer for diesel fuel injection at the center of the burner and an axial swirler at the burner rim to feed premixed syngas with air into the combustor. The study concluded that: (i) Increasing syngas content led to a decrease in NOx percentage and an increase in CO percentage in the flue gases. (ii) The increase in syngas percentage negatively affected the lean flammability limit, as it increased at the expense of liquid ratio and lowered atomization pressure. The study suggests utilizing an air-assisted atomizer to separate atomization quality from the thermal load. (iii) The presence of syngas in the mixture improved flame

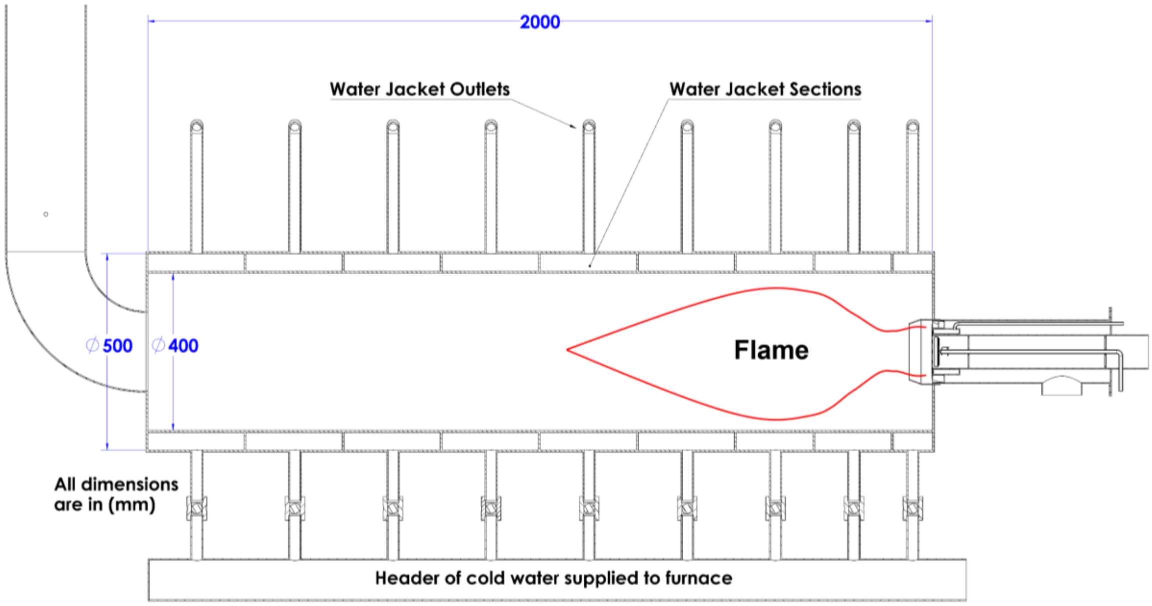

Figure 1 Schematic diagram for the combustor

stability, as evidenced by lower fluctuation coefficients of C* and CH* radicals over time, indicating stronger stability.

The co-firing diesel or biodiesel with a CO_2/CH_4 mixture as a diluent is investigated [4]. They observed decreased CO and NOx emissions when biodiesel was co-fired with the CO_2/CH_4 mixture. Additionally, diesel fuel exhibited a higher tendency for soot formation compared to biodiesel when using CO_2/CH_4 blends.

The flame structure and local extinction properties of ethanol/methane co-combustion are studied by [5], The study included ethanol-only, co-firing, and methane-only test cases. Under lean conditions, it was found that increasing the gaseous fuel reduced the stable flame's air/fuel range and increased the likelihood of flame lift-off.

The cofiring of CH_4 (methane) with C_7H_{16} (methanol) is investigated by [6]. The results showed that adding CH_4 could lead to instability in the attachment point of the liquid fuel near the bluff-body edge, resulting in local extinction or an overly rich region unsuitable for flame propagation. This study highlighted how multiphase combustion influences spray flame behavior and stabilization characteristics. However, despite these changes, the global extinction characteristics indicated that dual-fuel spray flames were more resistant to blow-off compared to single-fuel spray flames at the same equivalence ratio.

In a study by [7], hydrogen (H_2) and methane (CH_4) were investigated along with n-heptane using the same burner in previous studies [5,6].

The primary objective of this study is to establish a comprehensive performance database for the newly developed burner using conventional fuels like LPG and light diesel. This database will serve as a valuable reference for future investigations involving the combustion of biofuels such as syngas and biodiesel. The experimental program is designed to examine emissions of LPG, light diesel, and their co-combustion for different operating conditions of liquid-to-gas fuels ratios and excess air percentages. By analyzing these parameters, a better understanding of the burner's performance can be obtained, facilitating future research on alternative and sustainable fuel sources.

2. TEST RIG

2.1. Combustor

The combustor shown in Fig. (1) is the same as in [9] and is made of a thick metal sheet with a 0.7 cm thickness and has a horizontal, cylindrical, water-cooled flame tube with an internal diameter of 40 cm and a length of 2 m. The 500 mm outside diameter water jacket that is split into 9 contiguous segments with increasingly longer lengths along the flame tube cools the flame tube. Each segment receives cooling water from the main cooling water header at the bottom of the combustor through a pipe. Each cooling segment's entry tube has a ball valve on it, which controls the flow rates of cooling water to each segment separately. The hot water leaves the cooling segments from the top through tubes that are positioned in the center of each one. A standard type K thermocouple detects water temperatures before and after entering the cooling segments, while a turbine flow meter measures water flow rates.

2.2. Burner

The primary and secondary combustion air approach the burner by two concentric pipes, the outer and inner air pipes have a 45° swirler and a stabilizer disc at their end sections, respectively. The burner has two fuel lines: one for liquid fuel and the other for gaseous fuels. The liquid fuel line has a nozzle at the burner rim with a capacity of 1.5 G/hr. The gaseous fuel line ends with a gas hub fixed at the burner rim. The Hub is equipped with 12 screwed outlets to allow for the installation and removal of nozzles of various sizes up to 3 mm and the ability to select the number of nozzles used. In this study, the Hub is equipped with twelve 2.5 mm nozzles, As shown in Fig. (2).

A blocking ring is installed on the outer swirler to reduce the air outlet area which increases the momentum of the air through it, by blocking half of the outer swirler diameter (the inner portion), As for the initial design, the air momentum through the outer swirler was not high

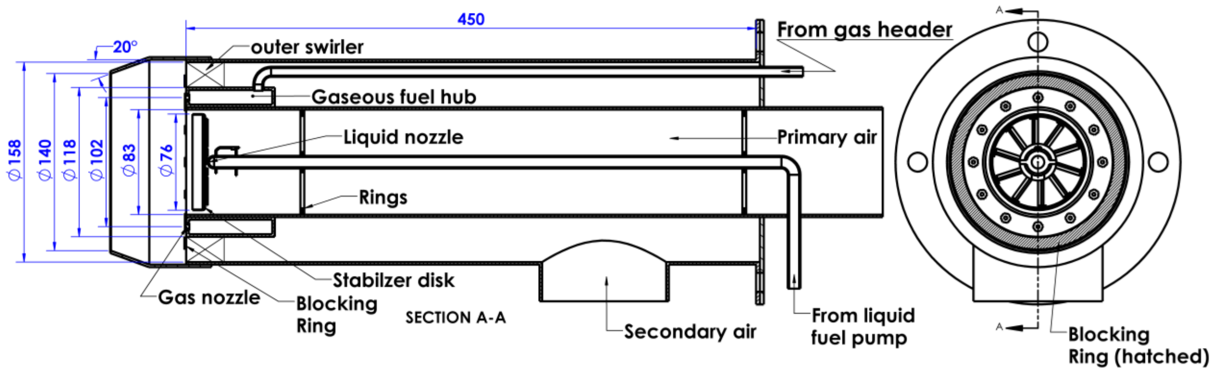

Figure 2 Burner design, with blocking ring installed on half of the outer swirl (hatched area)
All dimensions are in (mm)

enough to match with other air and fuels streams. As shown in the hatched area in Fig. (2).

2.3 Measuring devices

The in-flame concentrations and exhaust gas emissions are measured by a gas analyzer (LAND). The flow rates of air and gaseous fuels are measured by standard orifice plates. The differential pressures across them are measured by a digital manometer model Dwyer 477A-3. While the liquid fuel flow rate is calibrated against the gauge pressure of the supply line. The images reported in this paper are taken by a NIKON D5100 DSLR Camera with an exposure time of 1/30 second and located 2 meters from the flame.

2.4 Fuel Properties

Liquid fuel is light diesel with a heating value of 44 MJ/kg and gaseous fuel is LPG with a heating value of 48.5 MJ/kg [10]

air flow rate, and inner/outer air ratios, as shown in Table 2

3.1 Limitations of operation

First, it is important to identify the limitations of a stable burner operation. As shown in Table 1, the burner operating regime is highly dependent on the liquid-to-gas ratio. As shown, there are two limits for each ratio, lower limit and upper limit. For cofiring, the lower load limit tends to increase from 30 kW to 70 kW by changing the LGR from 100/0 up to 50/50. The reason for that is the poor atomization at low oil pressures. Below this limit, the oil spray converts into a spray with a low surface-to-volume ratio, resulting in low efficiency of combustion, extinction, or even inability for ignition. The upper limit increases from 70kW to 100kW by changing the LGR from 100/0 up to 50/50. This limit is mainly driven by the maximum capacity of the oil pump. For the pure gas case, the lower limit is mainly controlled by the lower flammability limit of the mixture. The maximum limit is

Table 1 Different firing cases, at different loads and LGR

Load (kW)

Liquid/Gas ratios	10	20	30	40	50	60	70	80	90	100
LGR100/0 (Pure oil)							**High atomization pressure exceeding the maximum limit**			
LGR80/20										
LGR70/30										
LGR60/40	**Poor atomization for liquid fuel**									
LGR50/50										
LGR0/100 (Pure Gas)							**Maximum limit of gaseous fuel flow rate**			

3. EXPERIMENTAL PROGRAM, RESULTS, AND DISCUSSION

The experimental program is divided into two sections: First, visual mapping for different single-fuel/cofiring flames at different loads and liquid-to-gas ratios (LGRs), as shown in Table 1. Second, exhaust emission mapping at a fixed thermal power of 55 kW and varying the total

driven by the maximum flow for the pressure regulator. In other words, these limitations only apply to this specific work. By modifying the pumping, measuring devices, and fuel nozzles, the operating limitations can be altered accordingly.
Furthermore, as shown in Table 1, when the oil-fuel ratio decreases the available loads increase, this is because of the reduction in the atomization quality of liquid fuel

when the pressure decreases, which forces to increase in the loads as a solution to maintain the oil flow rate at a certain minimum value that keeps the atomization pressure at its lowest applicable value. This suggests using another atomization technique instead of the pressure jet atomizer to unlink between the required oil flow rate and quality of atomization such as using an air-assisted atomizer in future research.

3.2 Flame appearance

The visual mapping reports the changes in the flame shape and brightness at different thermal power and LGRs. Natural chemiluminescence images are utilized to distinguish between the different flame zones along the flame height.

As the load increases the flame length and diameter increase as expected, however as the LGR increases and flame length decreases while the diameter increases. As shown in Fig. (3) and Fig (4). This is attributed to the easiness of burning gaseous fuel which doesn't require atomization or evaporation before starting to combust, unlike liquid fuel.

Different distinct zones appear in the flame photos, These zones are, a very bright zone in the middle of the flame which represents a soot oxidation region, a low bright zone at the edges of the flame represents a saturated region of exhaust gases, finally, a moderate bright region above the very high bright region which represents a region where most of the soot is oxidized while exhaust gases still forming through the chemical reaction between air and fuel.

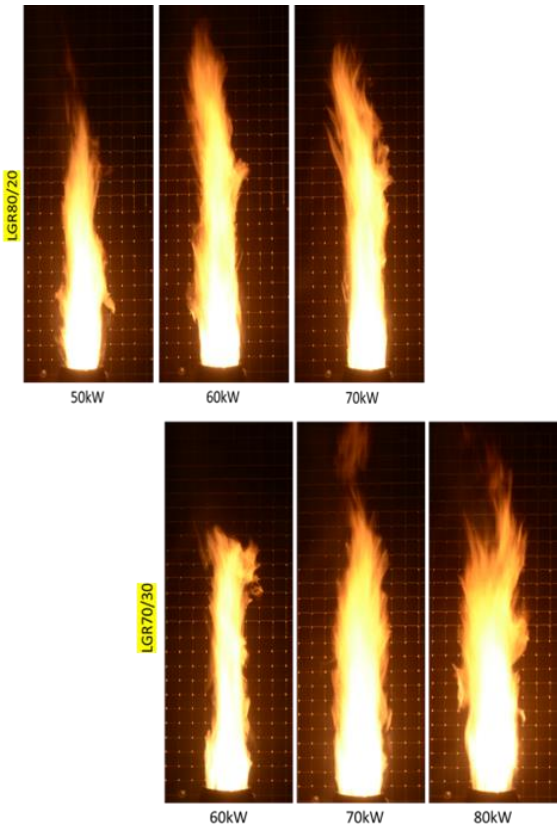

Figure 3 Flame photos for LGRs 80/20 and 70/30

3.3 Exhaust gases mapping results

The experimental program consisted of three firing cases: liquid fuel firing, gaseous fuel firing, and the co-firing of liquid and gaseous fuels simultaneously. For each firing case, three different amounts of air were utilized through the inner air passage. Additionally, multiple outer air amounts were studied for each inner air amount. As shown in Table (2).

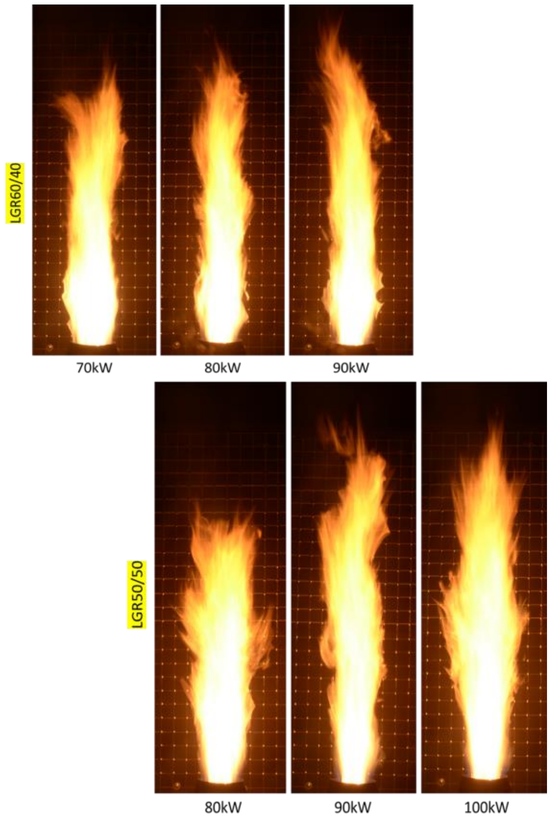

Figure 4 Flame photos for LGRs 60/40 and 50/50

Furthermore, all the species mapping results are normalized at 15% O_2 (base) for all measured species.

$$Normalized = measured * \frac{20.9 - O_2\,(base)}{20.9 - O_2\,(measured)} \quad (1)$$

The trend of O_2 for all tested conditions is the same, as shown in Fig. (5), Fig. (6), and Fig. (7), the O_2 levels continue to increase while the excess air factor increases. However, in the cases of firing gaseous fuel only and co-firing it with liquid fuel, the levels of O_2 and CO_2 show perfect matching for almost all measured points, which indicates that adding gaseous fuel enhances the combustion of liquid fuel. Moreover, the CO_2 is produced through the chemical reaction unlike the O_2 which is related to the amount of air entering the combustor, therefore, the CO_2 amount is limited to the amount of fuel which logically reduces its percentage while increasing the amount of excess air. However, due to the normalization of CO_2 @15% O_2, the percentage of CO_2 doesn't have a negative slope as expected, instead, the CO_2 trends are horizontal. Which validates the normalization at 15% O_2.

Regarding the CO emission, in the cases of firing liquid fuel (A, B, and C) the CO trends go up with the increase of excess air, however, the levels of CO in these three cases are the highest among all the others as the maximum value is around 1400 ppm (D to K), which is attributed to the long process of firing liquid droplets starting from vaporization then mixing and ignition. The mixing of air and fuel is the dominant factor affecting the

Table 2 Mapping program for exhaust emissions of (NOX, CO2, CO, and O2) at fixed input power (55kW).

Fuel Type	Run Code	Fuel flow rate [kg/hr]		Air flow rate [kg/hr]		Excess air factor λ	
		$\dot{m}_{oil}$	$\dot{m}_{gas}$	$\dot{m}_{inner}$	$\dot{m}_{outer}$	λ_{inner}	$\lambda_{overall}$
Oil only	A	4.5	0	78	[27, 41, 53, 85, 118, 183]	1.2	[1.6, 1.8, 2, 2.5, 3, 4]
	B	4.5	0	64	[27, 41, 53, 67, 99, 132, 197]	1.0	[1.4, 1.6, 1.8, 2, 2.5, 3, 4]
	C	4.5	0	51	[27, 41, 53, 66, 80, 111, 145, 210]	0.8	[1.2, 1.4, 1.6, 1.8, 2, 2.5, 3, 4]
Gas only	D	0	4.1	94	[31, 51 69, 95, 158]	1.5	[2, 2.3, 2.6, 3, 4]
	E	0	4.1	63	[31, 46, 57, 63, 95, 126]	1.0	[1.5, 1.7, 1.9, 2, 2.5, 3, 4]
	F	0	4.1	31	[51, 63, 94, 125, 157, 219]	0.5	[1.3, 1.5, 2, 2.5, 3, 4]
Cofiring Oil and Gas	G	3.2	1.2	64	[27, 41, 53, 66, 99, 132, 197]	1.0*	[1.4, 1.6, 1.8, 2, 2.5, 3, 4]
	H	3.2	1.2	51	[27, 41, 53, 67, 79, 112, 145, 210]	0.8*	[1.2, 1.4, 1.6, 1.8, 2, 2.5, 3, 4]
	K	3.2	1.2	39	[27, 39, 53, 66, 78, 91, 124, 157, 222]	0.6*	[1, 1.2, 1.4, 1.6, 1.8, 2, 2.5, 3, 4]

*Excess air factor for inner path is calculated depending on the liquid fuel only in the cases of cofiring

diffusion flames, therefore, firing liquid droplets in a non-premixed mood produces high levels of carbon monoxide CO due to the long timescale of vaporization and mixing processes before ignition. This explains why the CO levels go from low to high in the A, B, and C cases respectively, in case A, the highest amount of air is introduced through the inner path surrounding the liquid fuel spray, then case B is lower than A, then case C lower than B.

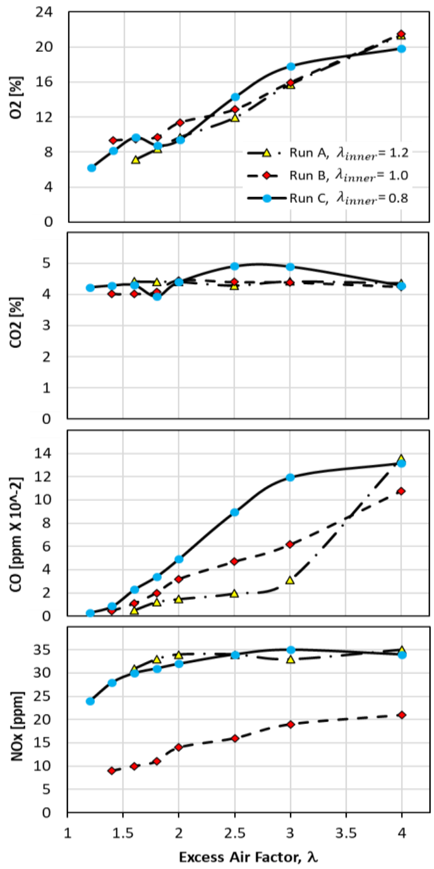

Figure 5 Emission mapping for liquid fuel firing

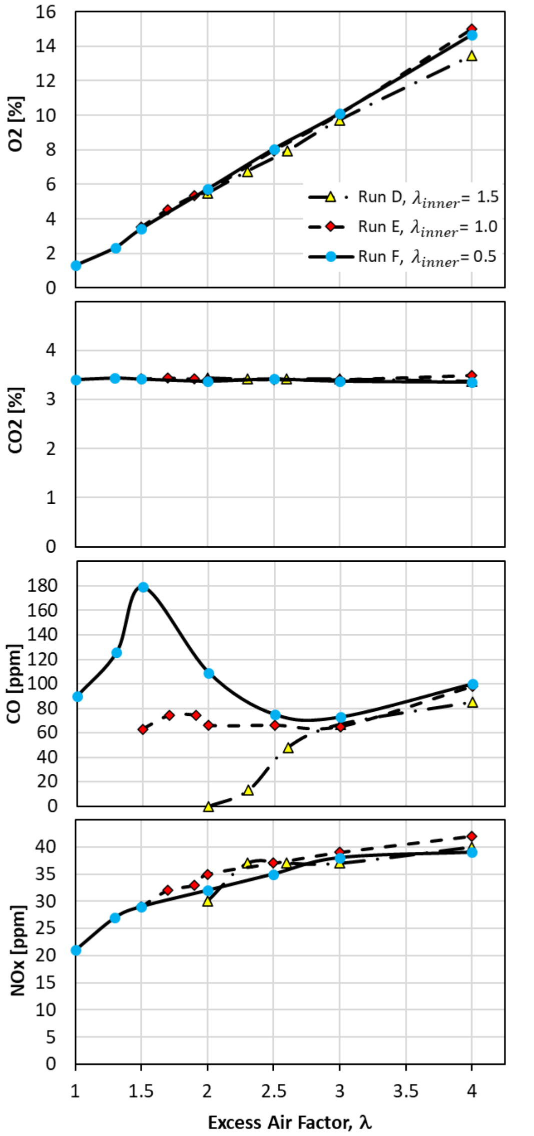

Figure 6 Emission mapping for gaseous fuel firing

In the cases of firing gaseous fuel (D, E, and F), the trends of CO curves match at high excess air factors which indicates good mixing quality of air and fuel. However, the CO curves show that increasing the air amount through the inner path dramatically reduces the CO levels, this is attributed to the inner air penetration to the central zone of the annular flame. Nevertheless, the maximum value of CO levels is much lower than the other cases of firing diesel fuel only (A, B, and C) and cofiring oil with gaseous fuel (G, H, and K).

In the cases of cofiring liquid and gaseous fuel (G, H, and K), the CO emission trends become different from firing a single type of fuel (Oil or Gas), as decreasing the amount of excess air through the inner air reduces the CO emission unlike the case (A to F) which is attributed to two factors, first, the rich combustion of liquid fuel increases its temperature and let the fuel droplets to have more time to evaporate and mix with air before reaching the annular zone where the gaseous flames exist, second, as the percent of inner air decreases and outer air percent increases which means increasing the amount of hot swirling air due to the gaseous flames, leading to faster evaporation of liquid fuel droplets.

The NO_X trends for all tested conditions go up with the increase of excess air factor, which is logical as the higher the amount of air, the higher the amount of nitrogen inside the flame, which increases the possibility of forming nitrogen oxides (NO_X).

4. CONCLUSION

To sum up, this paper introduces a newly designed burner for cofiring liquid and gaseous fuel purposes, it's ultimately designed to burn biofuels (syngas and biodiesel), however, the burner is tested using fossil fuels (Light diesel and LPG) to provide a database for future work using other types of fuel.

The visual appearance of the flames is strongly affected by the liquid-to-gas ratio (LGR) and the required thermal load. Furthermore, the mapping for available thermal loads to be achieved by the proposed burner shows that using a pressure jet atomizer links the required load with the quality of atomization of liquid fuel, which has a bad effect on the cofiring cases especially when the liquid fuel ratio decreases. Accordingly, an air-assisted atomizer is recommended to be used instead.

The exhaust gas mapping shows that the levels of CO_2 and O_2 are not affected by the burning of gaseous fuel with varying inner/outer air ratios, but the levels of CO and NO_X are. This behavior is reproduced in cofiring situations. Meanwhile, when a single fuel (oil or gas) is burned, the levels of carbon monoxide (CO) fall as the inner air flow rises, especially when burning an oil fuel. Conversely, in the case of cofiring, CO levels drop as the inner air flow rate drops.

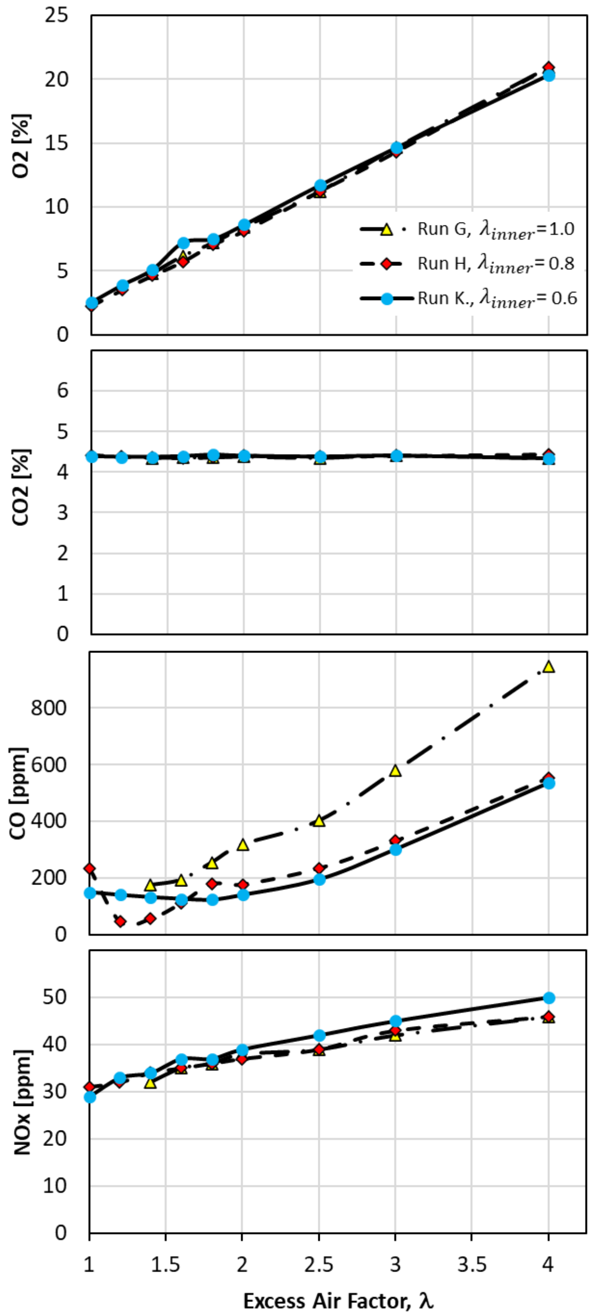

Figure 7 Emission mapping for cofiring liquid and gaseous fuel

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