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Research Article

Experimental study on the combustion of gaseous based fuel (LPG) in a tangential swirl burner of a steam boiler

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ABSTRACT

In this study, pollutant gas emissions and combustion efficiency of LPG fuel burning in a steam boiler were investigated experimentally and compared with the diesel fuel-based results. Designed and manufactured of a new tangential swirl burner, and used for gaseous fuel combustion (LPG) in the boiler that was already designed to be operated with liquid fuel (diesel). The study involves conducting experiments using a broad range of equivalence ratios (Φ) and with three different diameter ratios (dr = 1/10, 1/15, and 1/20) (diameter ratios = The variable diameter of the burner is compared against the fixed diameter of the boiler). The volumetric ratios of CO_2, CO as well as the HC content in the exhausted gases are measured and the boiler efficiency is predicted. The obtained results revealed that the replacement of the liquid fuel burner with the tangential swirl gas (LPG) burner is simple, inexpensive, and had no negative effect on the other parts of the boiler. In addition, the lowest pollutant gas concentrations detected in the exhausted gases and the highest boiler efficiency are obtained with a diameter ratio of 1/10. In comparison with diesel fuel combustion, the LPG fuel offered the cleanest combustion at Φ approaching 1 and above, required less O_2 for complete combustion, and had the least HC content in the exhaust gases at the lean mixing area. Finally, the boiler efficiency operating with LPG fuel was higher than that obtained with diesel fuel for all equivalence ratios.

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INTRODUCTION

Energy is essential for the development and prosperity of the worldwide economy and it is ultimately crucial for entire industrial activities, which account for approximately 35% of the gross energy consumption in the world [1]. Meanwhile, energy demand is growing because of population growth and the continuing development of technologies around the world. Recent studies disclosed that the annual energy required could be increased by 1.7% until 2030. Fossil fuels like oil, coal, and gas are still the main sources of energy, making up about 80%

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of all energy needs, while 11% of energy needs come from renewable sources [2–4]. Fossil fuels, such as oil, coal and gas continue the main source of energy where it contributes about 80% of the total energy needed, whilst the contribution of renewable energy with only 11% [2, 5, 6]. As a result, various environmental challenges that must be addressed, such as global warming, air pollution, and ozone depletion, may accelerate dramatically. Consequently, the greatest challenge presently facing the world is how to mitigate demand for burning fossil fuels to generate power. For this reason, emphasis has been directed on considering alternative energy sources or enhancing the energy utilization of equipment [7]. Boilers are pressure vessels that are used to heat water or generate steam for use in a variety of industrial purposes, including space heating and power generation. Boilers are becoming the greatest alternative for converting various fossil fuels, such as oil, gas, and coal, which are utilized to generate a major amount of the world's power, in this context. Consequently, even a slight improvement in boiler efficiency will lead to a substantial decrease in energy use in power generation or for heating purposes [8, 9].

Boiler efficiency is the proportion of the total thermal energy provided to the boiler that is effectively absorbed by the steam or hot water produced. Thus, to enhance the efficiency of the boiler, the quantity of heat being absorbed by the fluid (water) in the boiler has to be maximized. This can be accomplished by optimizing several effective parameters, such as excess air, fuel type, and flow rate, amount of steam required or load, and so on [10, 11]. For example, a boiler must be supplied with more surplus air than theoretically required to ensure that the combustion is complete; otherwise, carbon monoxide (CO) may quickly accumulate or, in the worst-case scenario, produce smoke in the flue gas. Differently, redundant excess air is a large amount of air that is not needed that is heated in the burning chamber and then mixed with the flue gases at the temperature of the stack [9, 12].

The performance of fuel combustion and efficiency of boilers and furnaces are the targets of various experimental studies because of the ultimate importance as stated above.

However, Tanetsakunvatana and Kuprianov [13] studied experimentally the impact of different operational parameters, such as the ratio of excess air and load, as well as fuel quality, on the thermal performance, flue gas emission, and heat losses of a 300 MW boiler. The findings revealed that the excess air ratio, load, and fuel quality only slightly affected the thermal efficiency of the boiler. The emissions in all examined scenarios were below the threshold of the national norm. Al-Omari [14] performed an empirical investigation on the combustion of a mixture of co-firing used engine lubricating oil (UELBO) and LPG in a small furnace, covering a broad spectrum of fuel/air ratios. The results showed that even when a small amount of UELBO was cofired with LPG, the thermal radiation of the flam gases improved significantly. Later, Al-Omari et al. [15] assessed experimentally the characteristics of combustion and heat transfer of a mixture of LPG and used engine oil in a furnace. To do so, the data obtained from the new fuel was compared with the results of diesel and used cooking oil. Depending on their results, they concluded that the ratio of the liquid fuel to LPG was about 0.2, which led to improved heat transfer to the walls of the furnace. In their study, Ghorbani et al. [16] conducted a comparison of the combustion efficiency and the emissions of CO, CO_2, NOx, and SO_2 flue gases between several biodiesel blends (B5, B10, B20, B50, B80, and B100) and conventional petroleum diesel fuel. The experiments were carried out in a boiler, considering different input air flow rates and two energy levels, especially 219 kJ/h and 249 kJ/h. The results suggested that the combustion efficiency of biodiesel was somewhat lower than that of diesel fuel at higher energy levels. On the other hand, at a low energy level, diesel was deficient compared to biodiesel fuel. Furthermore, all tested biodiesel fuels except B10 emitted fewer pollutant flue gases than diesel. Osvaldo et al. [17] investigated experimentally the flashback in different geometrical configurations of a tangential swirl burner in a 100 kW boiler. A central fuel injector was implemented, and the process, however, was visualized via a high-speed camera. They observed that for a given range of swirl numbers, the resistance to flashback was significantly improved by using a central fuel injector. Hasan et al. [18] conducted experimental investigations on flashback and blowoff in various geometrical configurations of a tangential swirl burner that was tested in the boiler. The key finding of this paper is that flashbacks tend to happen more rapidly in confined spaces compared to open areas due to the negative pressure created in the confined space. This negative pressure serves as a warning sign for the occurrence of flashbacks, flame instability, and increased energy release. The operational window is significantly restricted in comparison to the non-confined region. Although many new LPG burners with different efficiencies have been put on the market. Jangala et al .[19] developed an updated version of the design, in which the only holes that are nearby are the ones that provide fuel at the identical flow rate and volume. Through a series of simulations, it was determined that various angles yield a wide range of results. Furthermore, a guiding vane is employed to potentially enhance combustion by exerting a circular influence on the burner. A copper metal prototype can undergo a boiling water test to ascertain its optimal efficiency for a certain purpose.

García-Contreras [20] experimentally assessed the possibility of using a 50/50 volume percent of tire pyrolysis liquid (TOL)/ diesel fuel blend as the alternative fuel of a residential boiler of 29.1 kWth by comparing its potential with conventional diesel fuel. The experiments were carried out during the start-up period of the machine and under different fuel-air mixing ratios and operational conditions. The results demonstrated that the 50/50 blend resulted in a slightly higher thermal efficiency than diesel fuel. In their study, Sungur et al. [21] conducted an experimental assessment to determine the effects of introducing nanoparticles of aluminium oxide (Al_2O_3) and titanium oxide (TiO_2) at concentrations of 100, 200, and 300 parts per million (ppm) to diesel fuel. The main objective was to assess the impact of these nanoparticles on the efficiency of combustion and the emission of a flame tube boiler. The findings demonstrated that the use of nanoparticles decreased the temperature range associated with peak size, while simultaneously enhancing thermal efficiency from around 90.4% to 90.9%. Huang et al. [22] investigated experimentally the feasibility of using castor oil and diesel blend fuel with different mixing ratios in a 300 kW oil-fired furnace instead of pure diesel fuel. The tests were carried out under a minimum excess CO_2 concentration in the exhausted gases. The results showed that combustion with oil/diesel blend fuel was extremely stable, and NO and CO emissions were only slightly affected as the castor oil content in the blends increased. Kotb and Saad [23] compared the thermal efficiency and CO emissions of LPG fuel burned in a counter and concurrent swirl burner with that of a non-swirl burner. The stability of flame and height of port of the concurrent and counter-current swirl burners were compared as well. Their results revealed that under all operational conditions, the thermal efficiency of both swirl burners was higher than that of non-swirl and the swirl burners emitted less CO than the non-swirl burner. Mahfouz et al. [24] tested the waste cooking oil (WCO) blended with light diesel and mixed with 20% by mass of heavy diesel. Fuel combustion was achieved by using a swirled vane burner mounted inside and outside the boiler at various loads. The results disclosed that a sufficient amount of heat was produced from blending waste cooking oil and the heavy diesel oil at all loads; the best thermal energy peak was obtained by the heavy diesel oil. Park et al. [25] recently assessed the properties of bioliquid fuel and heavy oil fuel combustion in a 0.7 MWth furnace and a 75 MWe boiler. Upon comparing the flames of the two fuel types, it was seen that the bioliquid fuel exhibited a cleaner flame in comparison to the heavy oil fuel. The gas temperature in the burner zone of the bioliquid fuel, on the other hand, was higher than that of the heavy oil fuel. NOx and SOx gas emissions were also significantly reduced when bioliquid fuel was used.

Previous research has shown that numerical simulation (CFD) is a significant tool for investigating many processes found in laboratories and occurring in real-world boilers and furnaces [26–32].

An extensive review of the relevant literature demonstrates that the CFD successfully simulated pollutant gas emissions [33–41] heat transfer by radiation [26, 27, 42–46] and finally turbulent combustion in laboratory and large-scale boilers and furnaces is discussed. The most recently indicative study was carried out by Darbandi et al. [47] where they simulated numerically and measured experimentally the combustion of heavy oil fuel in a large boiler testing 24 burners. The sensitivity analysis was performed in order to reduce NO emissions from the fuel without any negative impact on the combustion efficiency. The results showed that the emission of boiler NO and the combustion efficiency can be controlled by a suitable alignment of air distribution, which decreased emissions of NO by about 30% and swirled intensity in the three stage burner.

On the one hand, there are obvious efforts everywhere to improve combustion efficiency and thus reduce flue gas emissions, which cause many environmental issues such as global warming, and on the other hand, to reduce oil demand, which normally depletes from day to day. From this point of view, the present study aims to investigate the feasibility of using LPG, which is widely available in Iraq, as an alternative fuel in a steam boiler that is already designed to operate with diesel fuel. To do so, the boiler combustion chamber was first replaced by a newly designed and manufactured tangential swirl burner to be consistent with LPG fuel. Then, the efficiency and flue gas emissions (CO and CO_2 as well as HC content), which indicate how much the combustion process is efficient, were investigated under different equivalence ratios and diameter ratios.

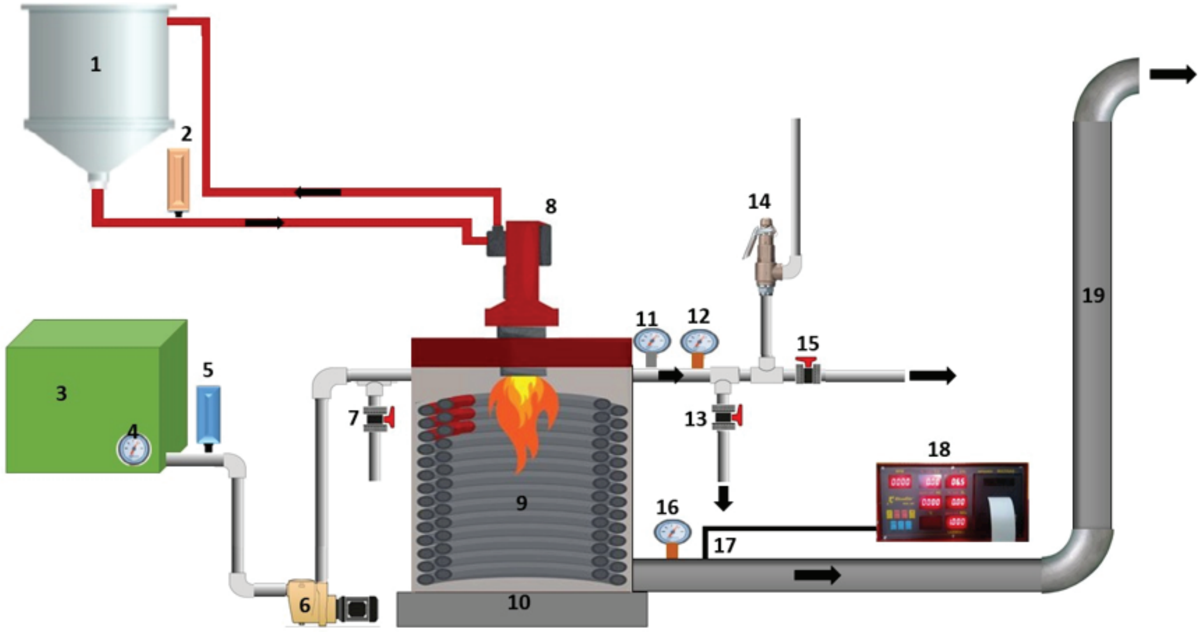
MATERIALS AND METHODS

Diesel Fuel Test

Figure 1 presents the diagram of the experimental setting employing diesel fuel. A steam boiler type GMT/20–V, made in Italy with a capacity of up to 140 kW, was used in this study. The boiler was a water tube type where water flows through the coil while heat is conducted indirectly from the fuel flame through the coil wall. Figure 2 and Table 1 illustrate the schematic of the boiler and the boiler's operational characteristics. The boiler was supplied with a vane swirl guide (model: JGN 80/1) diesel burner equipped with a swirl atomizer. The diesel fuel injector (single back type 1.5GAL 60S LE) with a capacity of 5.84 kg/h is composed of a 60^{o} solid cone angle of droplets that evaporate and burn simultaneously. An electrical electrode with an electric arc was used to start the ignition and switch off once the flame began self-sustaining.

Table 1. Boiler's operating characteristics

Property	Quantity
Steam production, (kg/h)	200
Capacity, (kW)	140
Pressure, (bar)	11.76
Empty weight, (kg)	750
Minimum length burner head, (mm)	220



1- Diesel tank, 2- Water tank, 3- Thermometer, 4- Water thermometer, 5- Water flow meter 6- Feed water pump, 7-Draining valve, 8-Diesel burner, 9- Helically coiled tube, 10-Boiler, 11-Pressure gauge, 12- Thermometer, 13- Steam vent valve, 14- Safety valve, 15- Steam supply valve, 16- Exhaust gas thermometer, 17- Exhaust gas analyzer prop, 18- Exhaust gas analyzer, 19- Chimney.

Figure 1. Schematic illustrating the configuration of the experimental apparatus employing diesel fuel.

The burner characteristics of technical and design aspects are shown in Table 2. The heating energy generated from the combustion of diesel fuel was transferred to the water in the boiler, subsequently being emitted as steam through the surface of the coiled tube. The exhaust gases exited the boiler pipe and traveled to the chimney via a 12 cm diameter inner exhaust pipe. The temperature of inlet water, outlet water/steam, and exhausted gas were measured via K-type thermocouples with about 0.5 °C accuracy. As shown in Figure 1, all the thermocouples were tidally fixed in their locations, and the temperature readings were locally taken. An exhaust gas analyzer with a prop (type T156/D3) was used to analyze the exhausted flue gases. However, the concentration of CO, CO_2, HC, and O_2 was measured, and the results can be directly read on the analyzer or printed out via a technical option on the device.

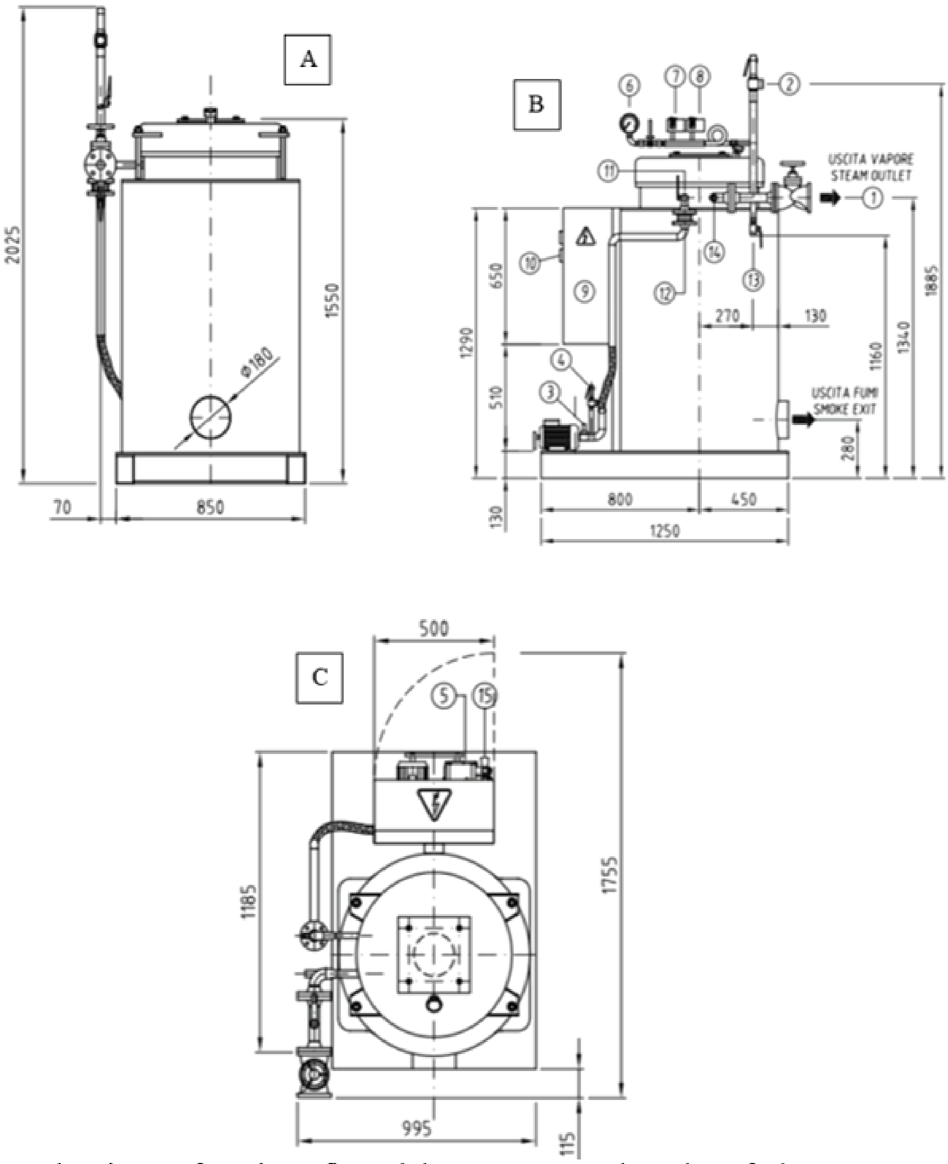
In the first set of experiments, diesel (produced by Aldoura Refinery Plant-Iraq) was used as a fuel. The general specifications of the diesel fuel are given in Table 3. The diesel fuel system comprises a main fuel storage tank of 20 L volume, a diesel level indicator, which is a scaled plastic small-diameter tube, a valve for controlling the fuel flow rate from the storage tank to the boiler, and connection pipes. The diesel fuel flow rate was measured using a 500 mL capacity transference plastic tube with 0.5 mL sections, together with a digital timer that had an accuracy of around 0.01 s. The stopwatch was employed to quantify the overall duration needed to burn a precise quantity of fuel (400 mL) within the boiler. The water system consists of a water storage tank with dimensions of 81x81x50 cm, a low-pressure water pump, a valve, and a rotameter to measure the inlet water flow rate.

Table 2. Technical characteristics of the diesel fuel burner

Property		Quantity
Thermal capacity, (kcal/h)	Minimum	42000
	Maximum	155000
Combustion process		One-stage
Minimum gas pressure, (mbar)		17.5
	Burner length	55.2
Dimensions, (cm)	Flame cover length	14
	Burner width	46
	Flame cover width	11
Specifications for the fan motor		$1\phi \sim 240\ W$
Control unit		G 790

LPG Fuel Test

A similar unit (a boiler) was used to experiment with the thermal efficiency of LPG combustion in a vertical



1- steam outlet valve, 2- safety valve, 3- flow switch, 4- overpressure valve outlet, 5- feed water pump, 6- pressure gauge, 7- high to the low pressure switch, 8- safety pressure switch, 9- electric panel, 10- steam thermostat, 11- back washing blow-down, 12- check valve, 13- start-up blowdown, 14- thermostat prop, 15- water inlet.coiled tube, 10- Boiler, 11-Pressure gauge, 12- Thermometer, 13- Steam vent valve, 14- Safety valve, 15- Steam supply valve, 16- Exhaust gas thermometer, 17- Exhaust gas analyzer prop, 18- Exhaust gas analyzer, 19- Chimney.

Figure 2. Schematic describing the configuration of the GMT/20-V Boiler: A- Front perspective B- Side perspective C- Top perspective

steam boiler. However, Figure 3 illustrates the schematic of the experimental setup (with the new changes) that was used. The LPG fuel specification is presented in Table 4. The burner used with diesel fuel was replaced with a newly conceived and manufactured tangential swirl burner, as seen in Figure 4. The current burner is equipped with two side air intakes, each with a diameter of 1.4 cm, which promote the formation of vortices within the combustion chamber. Figure 3 depicts the presence of liquefied petroleum gas (LPG) in the air. The LPG is introduced into the swirl chamber through a 0.6 cm diameter intake tube located at the bottom. Consequently, a uniform blend of fuel and air was formed, prepared for combustion at the outlet of the burner. The air supply for the burner was provided by a Banzai CT-375 QC air compressor, manufactured in Japan. The compressor has an operating pressure range of 11.5 to 14 bar and a maximum flow rate of 755 L/min. The LPG fuel was supplied to the boiler from a pressurized cylinder

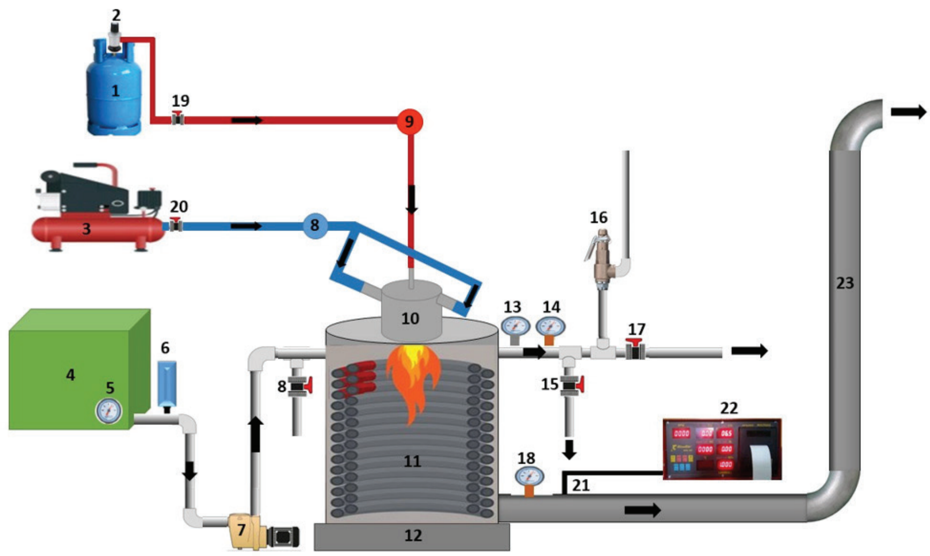
Table 3. Specification of diesel fuel used in the experiments

Parameters	Value
Density (g/cm^3) at 15 °C	0.870
Flash point °C (min)	54
Viscosity (cst) at 40 °C (max)	12-18
Pour point c (max)	+9
Sulfur Content % wt (max)	2.5
Diesel Index (min)	50
Carbon Residue % wt (max)	1.5
Water % v (max)	0.5
Ash Content % wt (max)	0.1
Gross Calorific Value (kcal/kg)	10500

of about 100 L capacity. Both the air and LPG flow rates were measured by rotameters with about ± 0.25 L/min ± 0.5 L/min inaccuracy, respectively.

Experimental Procedure

The manufacturing process of the tangential swirl burner, as well as all steam generation trials, was conducted at the labs of the Technical College of Engineering/Al Furat Al Awsat Technical University-Najaf [48]. The procedure of the experiments for both fuels (diesel and LPG) is quite similar. However, the experiment begins by checking the water level and diesel fuel level in their tanks (no level for LPG). The water is conveyed to the boiler using a pumping



1- LPG gas tank, 2- Regulator, 3- Air compressor, 4- Water tank, 5- Water thermometer, 6- Water flow meter, 7- Feed water pump, 8- Drain valve, 8-Air rotameter, 9- LPG rotameter, 10- Tangential swirl burner, 11- Helically coiled tube, 12- Boiler body, 13- Steam pressure gauge, 14- Steam thermometer, 15- Steam venting valve, 16- Safety valve, 17- Steam supply Valve, 18- Exhaust gas thermometer, 19-LPG control valve, 20-Air control valve, 21-Exhaust gas analyzer prop, 22- Exhaust gas analyzer, 23- Chimney.

Figure 3. Schematic illustrating the configuration of the experimental apparatus employing LPG fuel.

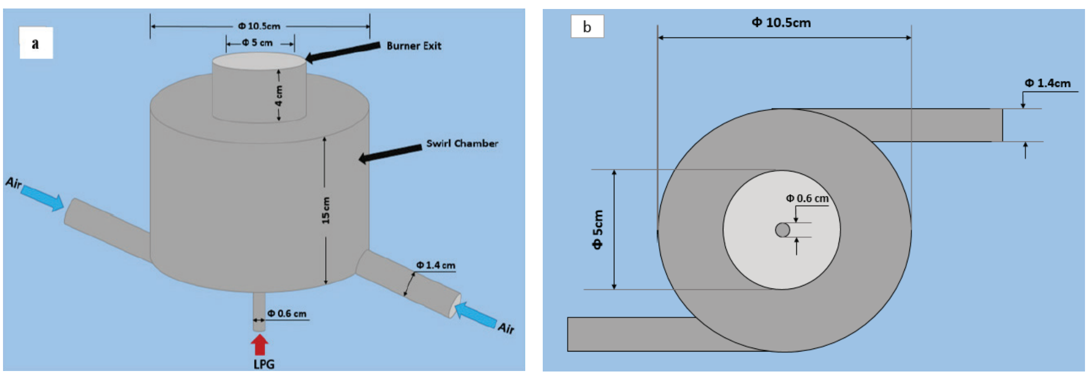


Figure 4. Geometrical parameters of the newly created Tangential Swirl Burner a) front view b) top view.

Table 4. Standard specification for LPG fuel used in the experiments

Properties	Values
Density, (kg/cm^3)	1.85
Flammability Limits	4.1-74.5
Auto Ignition Temperature for Air, (°C)	588
Low Calorific Value, (kj/kg)	42790
Gross Calorific Value, (kj/kg)	49707
Octane Number	+105
Flame Velocity, (m/s)	0.48
The Adiabatic Temperature of The Flame, (K)	2263
Quenching Distance, (mm)	-
Fuel/Air Mass Ratio	0.064
Heat of Combustion, (MJ/kg-air)	1.9-8.5
Flammability Limits	3

mechanism, with the quantity of water being regulated by the graded height of the level indicator. Thereafter, the burner is turned on and diesel fuel is supplied from its storage tank (or pressurized cylinder in the case of LPG) to the burner. Simultaneously, the air is provided via an internal fan in the case of diesel fuel, and its flow rate is controlled manually by a gate. In the case of LPG fuel, the air is supplied to the tangential swirl burner via the compressor and the LPG fuel and air mixture is entered into the burner tangentially. The burner is ignited by an external ignition.

During the burning of diesel fuel, the temperature of water increases fast, reaching roughly 100 oC in about 2 minutes. Simultaneously, the pressure escalates and reaches around 3 bar. Nevertheless, the ventilating valve is unsealed to release any trapped air until the pressure decreases to a range of 1 to 2 bar, at which point it is sealed once more. The heat transfer process continues until the water is converted into steam within the boiler, reaching a steam temperature of 160 ^{o}C and a pressure of roughly 4.5 bar. This process typically takes around 1.5 minutes. At that time, the produced steam is supplied by opening the steam outlet valve. The temperature at different locations is measured, and the exhaust gases are analyzed. Now water is pumped again to the boiler to repeat the process in less than 2 minutes. In the case of LPG fuel combustion in the tangential swirl, the temperature of water increases gradually, slower than that of the combustion of diesel, and reaches 100 ^{o}C within about 15 minutes, and the pressure increases to around 3 bar. Consequently, the venting valve is opened to expel the air from the system, decreasing the pressure to around 1 to 2 bar, after which it is closed once more. Due to the continuous LPG fuel combustion in the burner, the temperature of the water in the coil is increased above 100 ^{o}C where it evaporates. When the temperature of the steam approaches 145 ^{o}C and the pressure reaches around 2.5 bar, the steam is expelled from the boiler by opening the steam valve after approximately 3 minutes. At that time, the temperatures are measured, the exhaust gases are analyzed, and new water is pumped again to the boiler for nearly every 3 minutes.

Boiler Efficiency

The efficiency of a boiler is directly correlated with the rate at which heat is transferred and the efficiency of fuel combustion. During full combustion, the combustion efficiency is high because the fuel burns and generates just water, carbon dioxide, and heat. Insufficient oxygen levels lead to incomplete combustion, resulting in reduced combustion efficiency and therefore lower boiler efficiency. To ensure safety, it is crucial to maintain the boiler functioning in a condition of complete combustion. Additionally, an excessive amount of non-combustible fuel might potentially lead to a boiler explosion. The combustion efficiency of low-pressure steam boilers typically stands at about 80% [49]. The efficiency of the system for combustion is influenced by many variables, including the parameters utilized for the boiler, fuel, and working fluid temperature. When oxygen is substituted for air in the fuel combustion process, the resultant mixture consists of water and carbon dioxide. By use of the condensation process, it is possible to separate these products, enabling the recycling of a portion of carbon dioxide back into the combustion chamber. This recycling process has an impact on the transmission of heat to the water pipes. [49, 50]. To start the combustion process, it is crucial to maintain the correct fuel/air ratio and reach the necessary ignition temperature of the fuel. The process of boiler combustion occurs inside the confines of the combustion chamber. The equation representing the combustion process [51]:

$$C_m H_n + \left(m + \frac{n}{4}\right) O_2 + \left(m + \frac{n}{4}\right)\left(\frac{79}{21}\right) N_2 \rightarrow \mathrm{m}CO_2 + \frac{n}{2} H_2O + \left(m + \frac{n}{4}\right)\left(\frac{79}{21}\right) N_2 \tag{1}$$

Stoichiometric combustion refers to the full burning of fuel in ideal conditions. The oxidation of C, S, and H atoms results in the formation of H_2O and CO_2. The F/A ratio, often known as the Fuel/Air ratio, is a crucial metric used to represent combustion. It can be expressed either in terms of size or mass. The ratio is deemed similar when the amount of air is sufficiently accurate to potentially ignite all fuel through combustion. Attaining Stoichiometric combustion is practically challenging due to insufficient time for fuel and air to mix adequately. Consequently, combustion activities take place in the presence of an excess of air [13, 51]. The equation for calculating the stoichiometric (F/A) ratio is [52]:

$$FAR_{stoicio} = \frac{Weight\ of\ the\ Fuel}{Weight\ of\ the\ Air} \tag{2}$$

The equation for calculating the equivalence ratio is [13]:

$$\Phi = \frac{FAR_{act}}{FAR_{stoic}} \quad (3)$$

The equivalence ratio pertains to the condition of combustion, specifically when:

$\Phi < 1$ (Conditions of a fuel-lean mixture)

$\Phi > 1$ (Conditions of a fuel-rich mixture)

$\Phi = 1$ (Ideal state will be satisfied)

The general equation for calculating boiler efficiency [53]:

$$\text{Boiler efficiency } (\eta) = \frac{Heat_{output}}{Heat_{input}} * 100\% \quad (4)$$

$$\text{Boiler efficiency } (\eta) = \frac{m^{\cdot}_{s}\,(h_s - h_{fw})}{m^{\cdot}_{f} * GCV} * 100\% \quad (5)$$

Where, η: Boiler efficiency, $m^{\cdot}$: mass of steam product (kg/hr), $m^{\cdot}_{f}$: mass of fuel injected into the combustion chamber (kg/hr), h_s: Enthalpy of saturated steam at operating pressure (kJ/kg), h_{fw}: Enthalpy of feed water (kJ/kg), GCV: Gross Calorific Value.

RESULTS AND DISCUSSION

The primary objective of this study is to facilitate the use of LPG as a substitute fuel in a steam boiler that was initially designed to operate with diesel fuel. Therefore, the original boiler burner was replaced by a newly designed and manufactured tangential swirl burner to fit with burring LPG. However, two sets of experiments were carried out, utilizing a wide range of equivalence ratio and diameter ratio, and a comparison between them regarding the pollutant gaseous emissions (CO and CO_2) as well as the HC content and O_2 in the exhaust gases was presented. Further, the boiler efficiency operating with diesel fuel and LPG fuel was compared.

Assessment of LPG Fuel

Figure 5 illustrates the relationship between the volumetric ratio of CO_2 emission and the equivalency ratio (Φ) during LPG burning, using three distinct diameter ratios (dr). The CO_2 emissions rise progressively until they reach a maximum value of Φ = 1, after which they decline rapidly. This behaviour is entirely in line with the observation that fuel combustion takes place in a swirl burner when Φ <1, indicating lean combustion. Nevertheless, a decrease in Φ corresponds to an improvement in the reaction. This phenomenon can be ascribed to an abundant supply of surplus air, which facilitates the occurrence of the reaction [54]. Nevertheless, the highest percentage of CO_2 volume is achieved when Φ = 1, indicating a more stratified optimum combustion condition. The emission of CO_2 is greatly diminished when the equivalency ratio (Φ > 1) grows in the rich combustion zone, suggesting a reduction in the quantity of surplus air present in the burner. This suggests that the combustion process in the burner is still effective, but with a limited quantity of surplus air. The result illustrates that the combustion of LPG in the tangential swirl burner may still take place even when there is a restricted amount of air available. Moreover, Figure 5 graphically illustrates the influence of the diameter ratio (the ratio between the variable diameter of the burner and the constant diameter of the boiler) on the CO_2 emissions. It is evident that, for the same Φ, the quantity of CO_2 emitted during burning rises as the diameter ratio increases. As the diameter ratio increases, the level of CO_2 emissions also increases. Figure 5 demonstrates that the CO_2 curve seen in the study conducted by Milcarek et al. [55] has similar characteristics to the CO_2 curves observed in the present investigation.

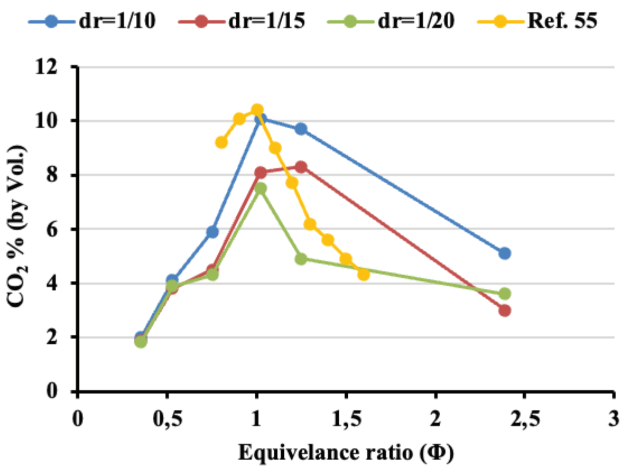


Figure 5. Variation of CO_2 released with exhaust gases at three different diameter ratios.

Figure 6 illustrates the variations in the volumetric proportion of carbon monoxide (CO) in exhaust fume for three different diameter ratios, similar to Figure 5. The graph illustrates that the emission rate of CO in the exhaust gases rises as Φ grows in the lean combustion region, and reaches its minimum concentration at Φ = 1. Nevertheless, when Φ undergoes acceleration of 1, the carbon monoxide (CO) once again builds up in the exhaust fumes. This aligns well with our comprehension of fuel combustion since a value of Φ approaching 1 indicates that the reaction is progressing towards perfection. Conversely, when the value of Φ is less than 1 and the reaction is reversed, the pace of the chemical reaction in the burner decreases or the process requires longer time to fully oxidize, resulting in a higher quantity of carbon monoxide (CO) emissions [52]. When the fuel-air combination in the burner exceeds the stoichiometric ratio (Φ > 1), it leads to a combustion area characterized by an abundance of fuel and a shortage of oxygen. As a result, there is a significant increase in the level of carbon monoxide (CO) in the exhaust emissions, suggesting an unfavourable chemical reaction. The surplus fuel in the burner also serves as a coolant.

Figure 6 clarifies the impact of the diameter ratio on the volumetric ratio of carbon monoxide (CO) in the exhaust gases. The diameter ratio has no substantial impact on the volumetric ratio of CO emission under lean combustion circumstances (Φ <1). However, when there is a large amount of combustion, it is clear that the process produces a significant amount of CO, and this amount worsens as the diameter ratio decreases and Φ increases. This may be explained by the fact that, under these circumstances, the high-speed mixture at the burner's outlet decreases the time needed for complete combustion, so creating a favorable environment for the production of a significant quantity of CO. When operating in a lean situation (Φ <1), there is a surplus of air or O_2 in the tangential swirl burner, allowing for LPG combustion to proceed at a consistent rate throughout all diameter ratios. Figure 6 demonstrates that the CO curves of the current investigation exhibit comparable behaviour to the Milcarek et al. [55] studies in the lean area, for three different diameter ratios. The study conducted by Milcarek et al. [55] demonstrates that the concentration of CO constantly rises in the affluent area compared to the values reported in the present inquiry for three diameter ratios within the same region.

The analysis of the typical combustion process reveals a small amount of unburned hydrocarbon (HC) present in the flue gases. This can be due to either insufficient time for the reaction to complete in the burner or a deficiency of oxygen (O_2) in the burner. Figure 7 displays the relationship between hydrocarbon (HC) levels and the equivalency ratio (Φ) across three distinct diameter ratios. It is evident that when the temperature increases, there is a greater production of hydrocarbons (HC) in the exhaust fumes as the Φ value increases. Nevertheless, the hydrocarbon (HC) content was absent in the lean combustion region and for a stoichiometric ratio (Φ) of 1, without affecting the diameter ratio. This observation may be explained by the ample presence of oxygen (O_2) in the burner. On the other hand, when the air-fuel ratio (Φ) is more than 1, indicating a rich combustion zone, the concentration of hydrocarbons (HC) in the exhaust gases increases significantly. This is because there is a lack of oxygen or an excess of air in the rich zone, which negatively impacts the burning of LPG in the burner. Conversely, the HC content is considerably and inversely affected by the diameter ratio, with a decrease in HC content corresponding to a decrease in diameter ratio. The low diameter ratio refers especially to the expansive burner chamber, which leads to a significant increase in flame diameter within the boiler. As a result, this enables effective heat transfer between the flame and the surface of the coil.

As previously mentioned, the presence of excessive air in the burner has a detrimental effect on combustion efficiency. This is because some heat is lost with the exiting air, leading to a decrease in flame temperature. Figure 8 illustrates the change in the unfavourable volumetric ratio of O_2 that is emitted from the reaction in the burner at three distinct diameter ratios. When the equivalence ratio (Φ) is equal to or greater than 1 (indicating a rich combustion zone), the combustion process reaches maturity and results in the release of surplus O_2 with the exhaust gases. Conversely, in the lean combustion zone (Φ < 1), the reduction in Φ leads the combustion process to reach maturity with the release of excess O_2 with the exhaust gases. As anticipated, there is an absence of oxygen (O_2) that can be liberated alongside the exhaust gases in the combustion zone characterized by a rich fuel-to-air ratio (Φ > 1). In this zone, the reaction takes place with a deficiency of oxygen or an excess of air. However, the figure clearly illustrates the substantial influence of the diameter ratio on the amount of released O2 in this area, hence corroborating our prior

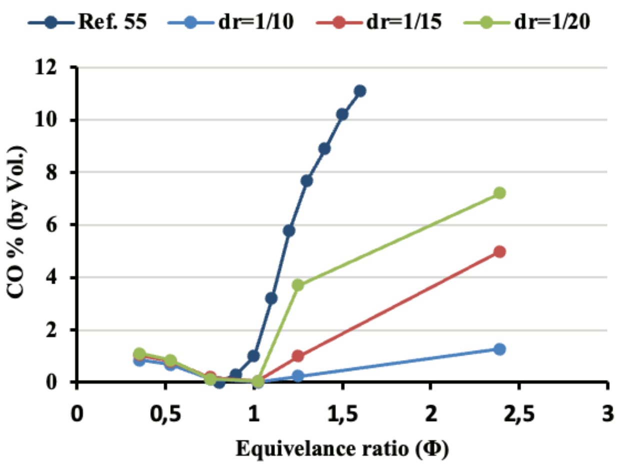


Figure 6. Variation of CO released with exhaust gases at three different diameter ratios.

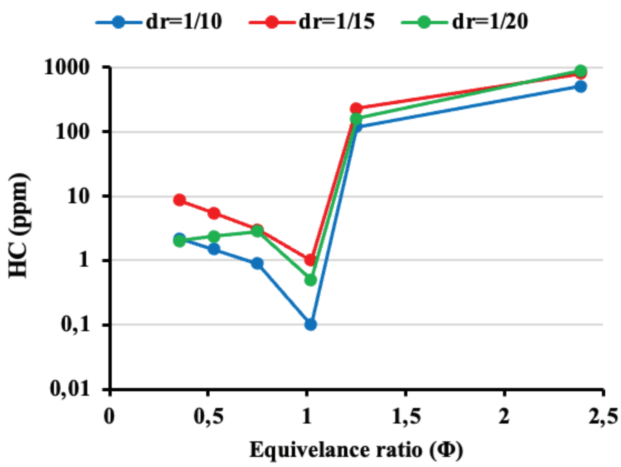


Figure 7. Variation of HC released with exhaust gases at three different diameter ratios.

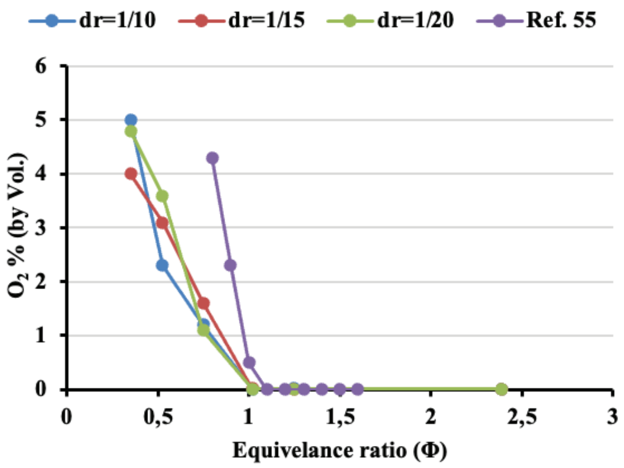


Figure 8 . Variation of O_2 released with exhaust gases at three different diameter ratios.

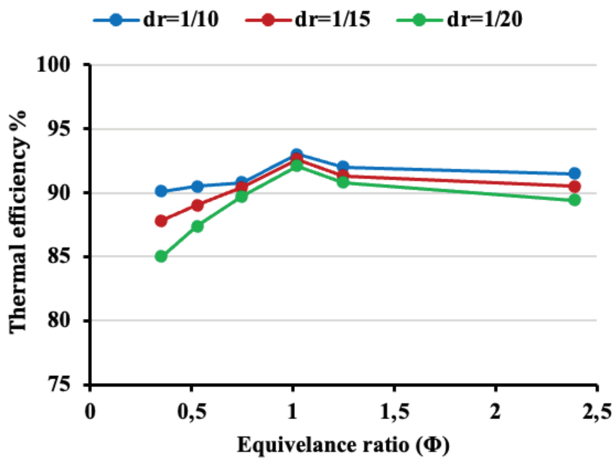


Figure 9. Variation of boiler efficiency with exhaust gases at three different diameter ratios.

discoveries. Figure 8 illustrates that the ratio of equivalence in the current study, for the three diameter ratios, is lower compared to the findings of the Milcarek et al. [55] study.

The boiler functions as a heat exchanger, facilitating the indirect passage of heat from the combustion side to the waterside. Therefore, the efficiency of the boiler may be measured as a quantification of how well the heat transfer mechanism is functioning. Nevertheless, the efficiency of the boiler may be influenced by other factors, including the boiler's physical state and the combustion process's integrity. Figure 9 illustrates the relationship between boiler efficiency and three distinct diameter ratios. As expected, the efficiency value increases from its minimum point in the lean combustion zone (Φ <1) to its maximum point Φ =1, then decreases slightly and remains constant in the Φ >1 region. This phenomenon may be explained by the reduction in the amount of excess air or oxygen (O_2) when the stoichiometric ratio (Φ) approaches 1. As a result, the detrimental impact of the excess air is mitigated due to the decrease in heat loss caused by the excess air exiting the burner. Insufficient air in the combustion zone with extra fuel (Φ >1) of the burner has a negative impact on the reaction, resulting in reduced combustion efficiency or boiler efficiency.

Figure 9 illustrates the impact of the diameter ratio on the efficiency of the boiler. The superior performance of the larger diameter ratio is seen over the whole range of equivalence ratios, surpassing both of the smaller diameter ratios. Compared to the small diameter ratio, the big diameter ratio results in a significantly larger flame diameter that extends across practically the whole internal diameter of the boiler and approaches the boiler wallAs a result, there will be a very effective exchange of heat between the flame and the water, especially near the boiler wall. Nevertheless, the dimensions of the burner have a lesser impact on the efficiency of the boiler in the area of abundant combustion as compared to the area of lean combustion. This phenomenon may arise as a result of the elevated flame temperature neutralizing the impact of the flame size on the rate of heat transmission.

According to the data analysis provided earlier, the most favourable diameter ratio to be used and compared to the original design of the boiler system is 1/10.

Comparison Between Diesel and LPG Fuel

Aiming to assess LPG fuel combustion in a steam boiler, a comparison of its thermal performance with diesel fuel is carried out in this section. However, Figure 10 illustrates the volumetric proportion of CO_2 generated from the combustion of LPG and diesel fuel. The proportion is measured as a function of the equivalency ratio, with a diameter ratio of 1/10. For both types of fuel, CO_2 increases with any increment in equivalence ratio, especially with the LPG type, which seems to produce CO_2 slightly higher than that of diesel until the equivalence ratio becomes 1. At this point, the CO_2 increment of diesel fuel becomes higher than that of LPG fuel by about 11.4%. Thereafter, (Φ >1) the volumetric ratio of CO_2 reduces sharply and gradually for diesel fuel and LPG fuel, respectively.

Figure 11 provides more insight into the comparison of LPG and diesel fuels by illustrating the change in the volumetric ratio of CO generated by burning both fuels at a diameter ratio of 1/10, as a function of the equivalency ratio (Φ). It is evident that the concentration of CO gas reduces substantially as Φ increases for both types of fuel. The minimal value of CO gas is observed at Φ = 1, when the net CO gas becomes zero. Subsequently, the concentration of CO gas steadily increases for LPG fuel, but abruptly increases for diesel fuel. This suggests that the burning of LPG fuel may be more environmentally friendly compared to diesel fuel.

Figure 12 illustrates the relationship between the concentration of O_2 and the equivalency ratio (Φ) for three

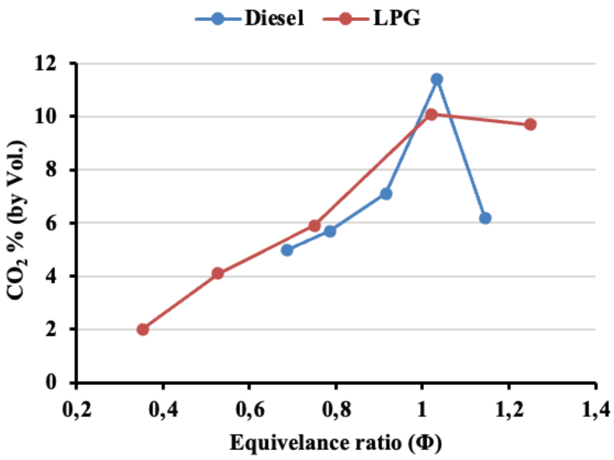


Figure 10. A comparison of CO_2 produced and released by diesel fuel and LPG fuel for dr=1/10.

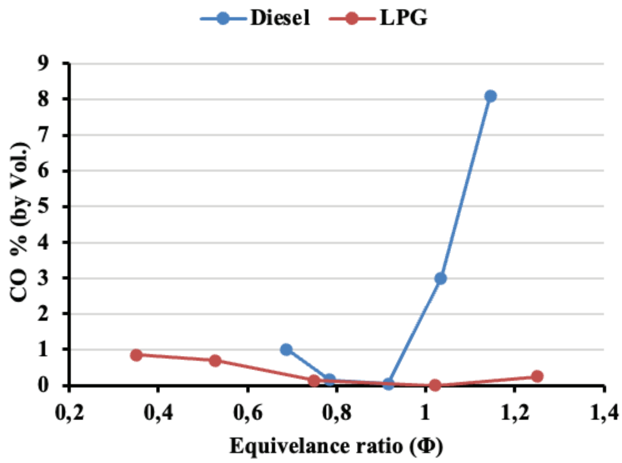


Figure 11. A comparison of CO produced and released by diesel fuel and LPG fuel for dr=1/10.

distinct diameter ratios for both fuels. As seen in the diagram, the amount of oxygen (O_2) decreases rapidly in the region of weak combustion (Φ<1), becomes zero at Φ=1, and remains constant for all values of Φ>1. Nevertheless, the disparity in the oxygen level of the fuel was only evident inside the lean combustion region. Within this particular setting and for the purpose of comparing the two fuels, at a specific value of (Φ≈0.17), the volumetric ratio of O_2 in LPG fuel surpasses that of diesel fuel by nearly 78%. This implies the potential for achieving complete combustion with little O_2 when using LPG fuel.

Figure 13 shows the variation of HC concentration (in ppm volume) of both types of fuels in the exhaust gases with an equivalence ratio at a diameter ratio of 1/10. As seen in the diagram, the hydrocarbon (HC) concentration in the flue gases for both fuel types is negligible until Φ = 1. This is anticipated because of the surplus amount of air present in the burners. When the value of Φ is greater than 1, the HC of diesel fuel grows at a steeper rate compared to that of LPG fuel. However, for an accurate comparison between the two fuel types, at a constant Φ (Φ ≈1.145) the figure obviously reveals that the diesel fuel produces much more HC than LPG fuel by about 63%. This gives an indication that the combustion of LPG fuel is cleaner or more mature than that of diesel fuel.

Finally, the efficiency of the boiler working with diesel fuel and LPG fuel is expressed in Figure 14, which illustrates the variation of the boiler efficiency of the two fuels with an equivalence ratio (Φ) at a diameter ratio of 1/10. As shown by the figure, the rise of efficiency of diesel is sharper than of LPG until Φ = 1 where at this value of equivalence ratio the efficiency of both fuels is nearly the same. Subsequently, the boiler efficiency varies depending on the kind of fuel used. Specifically, while using LPG fuel, the efficiency

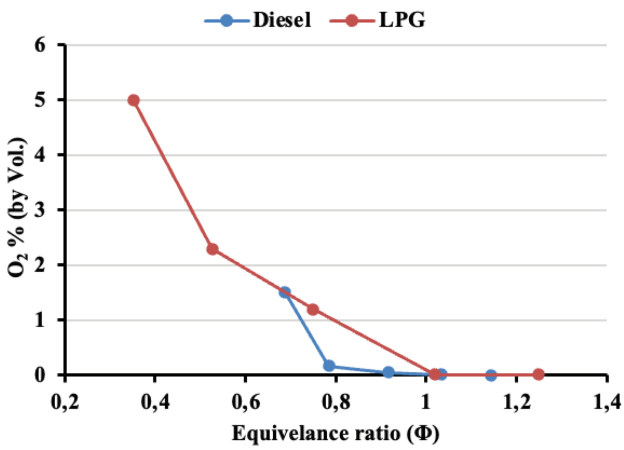


Figure 12. A comparison of O_2 released with diesel fuel and LPG fuel for dr=1/10.

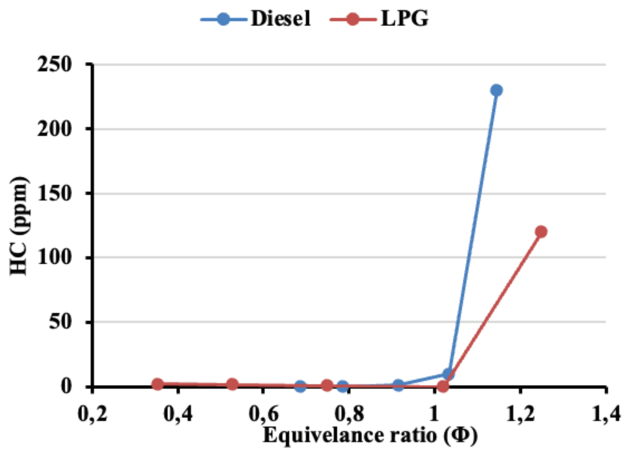


Figure 13. A comparison of HC content with diesel fuel and LPG fuel for dr= 1/10.

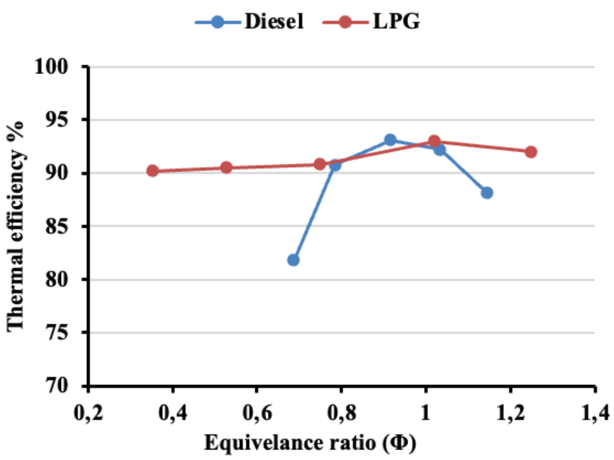


Figure 14. A comparison of boiler efficiency operating with diesel fuel and LPG fuel for dr=1/10.

remains consistently high. However, when using diesel fuel, the efficiency decreases as the equivalency ratio increases. Generally, the boiler's efficiency is greater while operating with LPG fuel compared to diesel fuel across all values of Φ, except at Φ = 1 when the efficiency of both fuels seems to be identical. This unequivocally highlights the benefits of utilizing LPG as a fuel source in the steam boiler.

CONCLUSION

This study provides empirical evidence demonstrating the viability of utilizing LPG as a substitute for diesel oil fuel in a steam boiler. In order to do this, a new tangential swirl burner was specifically developed, produced, and implemented in the boiler to ensure the most efficient operation using LPG as the fuel source. The quantities of carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbon (HC) in the exhaust emissions of LPG fuel were measured at various equivalency ratios and diameter ratios. The appropriateness of LPG fuel as a steam boiler fuel was assessed by comparing its findings with those obtained by utilizing diesel oil fuel. The experimental data allow for the following conclusions to be deduced:

1. Replacing the liquid fuel burner (diesel) in a steam boiler with a tangential swirl burner that uses gaseous fuel (LPG) is a straightforward and cost-effective technique that does not affect on the other components of the boiler.
2. During the experiments, various diameter ratios were tested, and the most efficient boiler (with an efficiency of 93%) was obtained when the diameter ratio was 1/10. This specifically pertains to the release of carbon monoxide (CO) and hydrocarbons (HC) in exhaust emissions.
3. At volumetric ratios approaching 1 and above, the amount of CO gas emitted in the exhaust gases was greater for diesel fuel (3 %Vol.) compared to LPG fuel (0 %Vol.). This suggests that the burning of LPG fuel was cleaner than that of diesel fuel.
4. The volumetric ratio of oxygen exiting with the exhaust gases in the lean combustion region was greater for the LPG fuel in comparison to the diesel. Consequently, the combustion process using LPG fuel necessitates a smaller quantity of O_2 in comparison to the amount needed when using diesel fuel.
5. No difference can be observed of HC during LPG and diesel fuel combustion at weak mixture area (Φ <1) and Φ = 1, otherwise the results revealed that at a specific Φ above 1, the HC produces with diesel fuel was much larger than of LPG which means that the combustion is better and completed with LPG fuel in comparison with diesel.
6. Finally, in spite of the equivalence ratio (Φ) was altered, the efficiency of the steam boiler in the case of LPG fuel (90.2%, 90.5%, 90.8%, 93%, 92%) (tangential swirl burner) was high and approximately constant long the entire value of Φ. On the other hand, the efficiency of the steam boiler burning diesel fuel (81.79%, 90.79%, 93.2%, 92.24%, 88.13%) was nearly the same as that of LPG fuel only at Φ = 1, otherwise, it was much less than that obtained by LPG fuel.

NOMENCLATURE

h_s	Enthalpy of Saturated Steam at Operating Pressure (kJ/kg)
h_{fw}	Enthalpy of Feed Water (kJ/kg)
$\dot{m}_s$	Mass Flow Rate of Steam (kg/hr)
$\dot{m}_f$	Mass Flow Rate of Fuel (kg/hr)
GCV	Gross Calorific Value (kcal/kg)
T	Temperature (K)
P	Pressure (bar)
$\dot{m}$	Mass Flow Rate (kg/s)
Q	Volume Flow Rate (LPM)

Subscripts

F/A	Fuel-Air Ratio
FAR_{act}	Actual Fuel Air Ratio
FAR_{stoich}	Stoichiometry Fuel Air Ratio

Greek Symbols

ρ	Fluid Density (kg/m^3)
Φ	Equivalence ratio
Ø	Diameter (m)
H	Boiler efficiency

Abbreviations

NOx	Nitrogen oxides
SOx	Sulphur oxides
CO	Carbon Monoxide
CO2	Carbon Dioxide
LPG	Liquefied Petroleum Gas

NO	Nitric oxide
C	Carbon
O_2	Oxygen
SO2	Sulfur dioxide
HC	Hydrocarbon
ppm	Parts Per Million (Volume)
WCO	Waste cooking oil
dr	Diameter Ratio
HFO	Heavy Fuel Oil
B5	Blend
UELBO	Used Engine Lubrication Oil
LHV	Lower Heating Value of Fuel

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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