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REVIEW ARTICLE

A review on comparative analysis of different types of burners for oxy-fuel SCO_2 recirculation and air-fuel combustion systems

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ABSTRACT

Due to the global warming and strict environmental regulations encourages researchers to develop efficient combustion system that produce low level of harmful gases. This article focuses on review of different studies and experiment carried out in the sphere of oxy-fuel and air fuel combustion. In order to compare the results of oxy-fuel and air fuel combustion and find a suitable and efficient combustion system.

Keywords: combustion system; burners; SCO_2; flue gas recirculation; comparative analysis of burners

1. Introduction

The increasingly stricter environmental regulations encouraged researchers to develop combustion systems that can meet such restrictions. Older gas turbine engines for power generation used non-premixed flame combustors thanks to their superior stability characteristics[1]. In any case, these combustors are not utilized since they create unsatisfactorily high concentrations of NO_x toxin emissions. There are numerous distinctive sorts of cutting-edge combustion system currently in utilize completely different mechanical, aviation and power generation sector. Fundamental objectives of these modern combustion system are to decrease particular GHG.

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Most of the researchers are currently considering around Supercritical carbon dioxide (SCO_2) control cycle may be a promising innovation to solve global energy production and environmental issues like other renewable energies. This innovation can capture carbon dioxide when burned directly with natural gas and produces small or no emissions when combined by implication with renewable energy. In addition, the SCO_2 cycle has higher effectiveness compared to the conventional Brayton and Rankine cycle. Other than that, it works with high pressure SCO_2 working fluid with more compact component compared to conventional power cycles.

Approximately twenty years later, Angelino[2] and Feher[3] displayed the basics of the SCO_2 power cycle. Angelino[2] proposed different layouts of basic CO_2 cycles, whereas proposed purely SCO_2 cycles. In any case, this innovation was nearly deserted until 2004 when Dostal et al.[4], proposed it for new generation of nuclear reactors. Several studies have examined hybrid SCO_2 power systems with different renewable energies such as solar, and nuclear. It can also be utilizing waste heat through integrated cycle with different industrial waste heat. Fossil fuels are the major resource of worldwide energy[5] and their combustion products result in environmental pollution and greenhouse effects. So, modernization of SCO_2 technology proposes a solution by introducing direct semi-closed oxy-combustion cycles such as Allam cycle[6]. The cycle is developed by 8 Streams Capital and combines oxy-combustion with SCO_2 cycle. Its important point is the capacity to capture the produced CO_2 from the oxy-fuel combustion process and its high-power cycle effectiveness. To explore its feasibility and to demonstrate the plan and operation of the whole cycle, a 50 MWth natural gas demonstration plant is built in LaPort. Heatric company developed the heat exchangers for this cycle while Toshiba provides its turbine and combustor.

Among oxy-fuel cycles, the SCOC-CC cycle has the simplest configuration. It is a semi-closed oxy-fuel gas turbine cycle that involves the recovery of heat from the CO_2 turbine exhaust gases in a waste heat boiler that generates steam for a steam turbine plant[7].

The Brayton cycle with supercritical CO_2 was mentioned for the first time in 1948. Sulzer Bros patented the Brayton cycle with partial condensation of carbon dioxide. After that, CO_2 power cycles aroused the interest of power plant researchers and developers. Research in this area has been conducted in many countries. In the Soviet Union, D. Gokhshtein and G. Verkhivker[8] were engaged in the development of CO_2 power cycles in 1969; in one of their works, they presented a thermal scheme of a nuclear power plant with carbon dioxide as a coolant and working fluid (**Figure 1**).

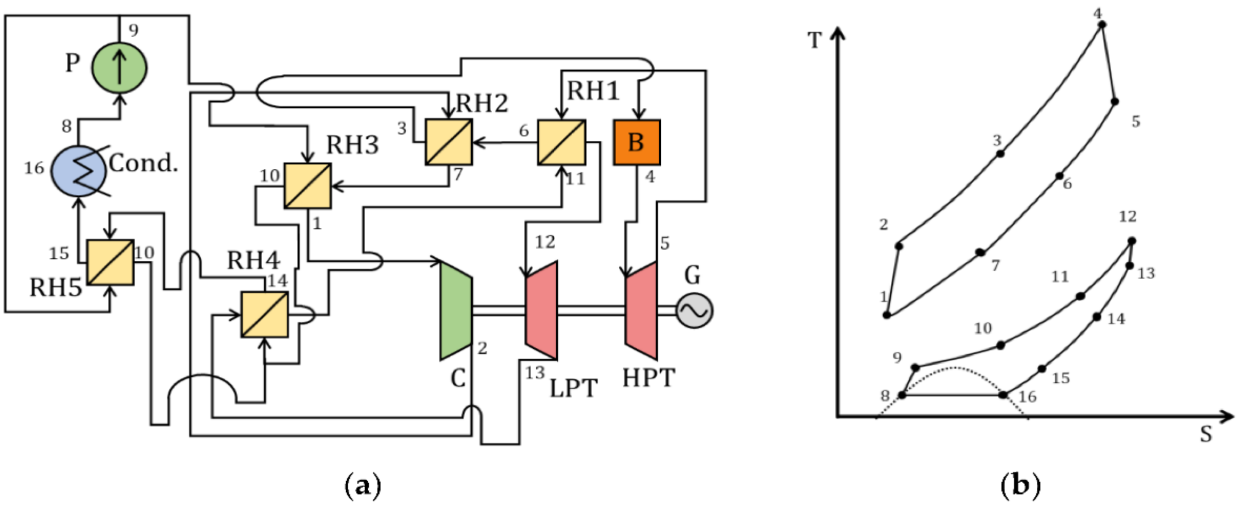


Figure 1. Cycle proposed by Gokhshtein and Verkhivker: **(a)** schematic diagram; **(b)** T–S diagram [11]. B—boiler; LPT—low-pressure turbine; HPT—high-pressure turbine; G—generator; Cond.—condenser; P—pump; RH1, RH2, RH3, RH4, RH5—regenerative heat exchangers[8].

In the first loop, the reactor is cooled by carbon dioxide (3–4), which then expands from 3 MPa (675 °C) to 1 MPa (539 °C) in a turbine to generate electric power (4–5). Then, the hot gases pass sequentially through the first regenerative heater (5–6), in which they give off heat to the second cycle, thereby ensuring its initial temperature of 509 °C. Then, exhaust CO_2 gases enter the second regenerative heater (6–7), where the working fluid of the first loop compressed in the compressor is heated from 173 to 320 °C. In the third regenerative heater (7–1), carbon dioxide also gives heat to the second loop, after which, it is compressed in the compressor and passes sequentially through the second regenerative heater and the reactor back into the turbine.

In the second loop, CO_2 is also used as a working fluid. In a gas turbine, carbon dioxide expands from 23.5 (509 °C) to 6 MPa (355 °C) (12–13) and then it passes sequentially through two regenerative heaters (13–15), the cold source (15–8), pump (8–9) and the regenerator system (9–12), in which the coolant temperature rises to the initial value[8].

The most critical part of this cycle along with its turbine is the combustion system. There are several studies carried out about combustion of oxy-fuel in the environment of SCO_2. For this there is such a requirement to develop suitable boilers and burner for oxy-fuel combustion with SCO_2 flue gas recirculation.

2. Burners and boilers development for oxy-fuel combustion with SCO_2

The key point in improvement of the oxy-fuel combustion process is the improvement of burner and boiler designs. The design of the boiler is directly dependent on the operation of the plant. **Table 1** summarized desirable features required within the operation of the burners[9].

Table 1. Different features adapted for oxy-fuel combustion.

Burner characteristics	Requirements
Quick start with ignition and flame stability	Can be ignited within 5 seconds • Hot, warm and cold start feature • Ability to easily switch between air-fuel and oxy-fuel combustion mode (and vice versa)
High combustion efficiency: • Low excess O_2 • Emissions • Less UBC in ash	• Excess O_2 in the flue gas (downstream of the boiler) must be less than 4% • It must be able to meet emission limits such as CO and NO_x. • Unburnt combustible materials in the ash should be less than 2%
Transport gas and comburent (oxidant/combustion gas)	•Expected to handle comburent using air or O_2-mixed with flue gas (21%–39%) • Expected to handle fuel transport gas using air or O_2 depleted CO_2-rich flue gas • Should be able to operate smoothly with fuel loading of up to 5 kg/kg transport gas
Possibility to swirl the secondary air/RFG (recirculation flue gases)	• Should have optimal intermixing of coal stream by swirling the secondary air/RFG • Should be able to manage the flame characteristics, shape and length with regard to the heat transfer behavior
Operation flexibility • with variable fuel quality • with variable load demand	Capable of handling wide range of particle size distribution • Should respond well with variation to LHV • Capable of operating the burners between 40%–100% of the load with stable flame and good ramp rate.

Several different large-scale burners (i.e., > 15 MWth)—as summarized in **Table 2**—have been evaluated to date by various original equipment manufacturers (OEM) in several pilot scale test campaigns. The references listed in **Table 2** should provide a wealth of information about the different burner characteristics—such as flame shape, length, luminosity and others. The information about the flames including the flame pictures taken from these tests should be useful in specifying the inputs to the different furnace or combustion models. The development of oxy-fuel burner and boiler designs includes the following main areas:

• Fundamentals of devolatilization and char burnout;

• Flame stability and burner aerodynamics;

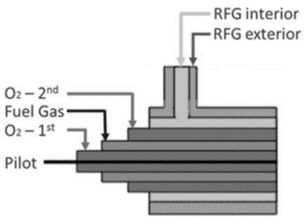
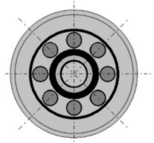
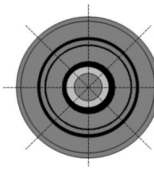
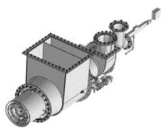
• Heat transfer – Radiation and Convection;

• Corrosion.

2.1. Devolatilization and char burnout

There is interest in understanding the effects of carbon dioxide-rich conditions (e.g., oxygen-rich fuel conditions) on coal volatilization and coke depletion. This information is important for testing and monitoring the progress of such cases. For a long time, domestic factories used different grades of coal to test one and the other weather. The main results of different studies on coal pyrolysis and coke combustion in gas-rich conditions are shown below.

Table 2. Large scale burners tested for oxy-fuel combustion.

Burners	Information	Reference
	Manufacturer: Air Liquide Power Rating: 8 MWth (per burner) x4 Type of burner: low NO_x swirl burners Fuel: NG Project Tested: 2009–2013 Project: Total Lacq	[10]
	Manufacturer: Alstom Power Power Rating: 30 MWth Type of burner: Low NOx jet/swirl burner (Type A) Fuel: Lignite Project Tested: 2008–2009 Project: Vattenfall Schwarze Pumpe	[9,11,12]
	Manufacturer: Alstom Power Rating: 30 MWth Type: Low NO_x pure swirl burner (Type B) Fuel: Lignite Projected Tested: 2008–2009 Project: Vattenfall Schwarze Pumpe	[9,11,12]
	Manufacturer: Doosan Babcock Energy Ltd. Power Rating: 30 MWth Type: Low NO_x pure swirl pre-mixed burner Fuel: Lignite Project Tested: 2001–2012 Project: Vattenfall Schwarze Pumpe	[9,13,14]

Regarding devolatilization, it is said that the release of volatile substances is higher in a CO_2-rich environment compared to an N_2-rich environment. Al-Makhadmeh et al.[15] carried out pyrolysis in a drip furnace using slightly volatile bituminous and lignite coals at temperatures between 700 and 1100 °C in the environment of CO_2 and N_2. The results showed that in a CO_2-rich environment above 850 °C, the release of large amounts of heat and lignite increased by 10% and 11–14%, respectively. The results can be explained by the Boudouard response. Rathnam et al.[16] measured the volatility of four Australian pulverized coals in a heating tube at 1400 °C under simulated air (O_2/N_2) and oxygen-enriched fuel (O_2/CO_2) combustion conditions. Higher volatile yields were observed for all coals tested in the oxy-fuel combustion environment. In addition, the volatile compound yields of all coals at high temperatures are higher than the volatile compound yields obtained from industrial analyses. Zeng et al.[17] used a bed reactor to study the evaporation behavior of different coal types (lignite, sub-bituminous coal and eastern high-volatile bituminous coal) at different temperatures under N_2 and CO_2 entrained beds. The thing is that at temperatures above 1400 °C the next air emission is greater in the CO_2 environment than in the N_2 environment.

Another finding related to change is the change in the morphology of the pyrolysis product in a gas-rich environment. The gas concentrations of H_2, CO and CH_4 as a function of temperature in experiments conducted by Al-Makhadmeh et al.[15]. According to it, H_2 is the least gas during pyrolysis in N_2-rich conditions, while CO with more than 100% N_2 is clearly volatile oils during pyrolysis in CO_2 environment. The effect of such gases can be further explained by the Boudouard reaction and the water-gas exchange reaction above 850 °C.

There is interest in understanding the effects of carbon dioxide-rich conditions (e.g., oxygen-rich fuel conditions) on coal volatilization and coke depletion. This information is important for testing and monitoring the progress of such cases. For a long time, domestic factories used different grades of coal to test one and the other weather. The main results of different studies on the pyrolysis of coal and the combustion of coke in oxygen-rich gas are presented below.

Rathnam et al.[16] compared the carbonization of three Australian coals in a drop tube furnace at 1400 °C in O_2/N_2 (Combustion) and O_2/CO_2 (oxygen-rich combustion) environments. Additionally, the oxygen concentration varies between 3% and 21% by volume in O_2/N_2 and 5% to 30% by volume in O_2/CO_2. In this study, the unstable yield obtained in O_2/N_2 at 1400 °C was subtracted from the measured add up to coal burnout to calculate char burnout. Rathnam et al.[16] studied the phenomenon of coal depletion by increasing the oxygen concentration in the air and oxygen-rich fuel environment. Increased coal depletion in the O_2/CO_2 environment was observed in almost all oxygen concentration ranges examined. This development is attributed to the coke gasification reaction in the presence of carbon dioxide. However, Al-Makhadmeh et al.[15] found that under O_2/CO_2 conditions, O_2 emission is lower, reducing the reaction and delaying the effect of coal combustion, but after a sufficiently long residence time, the maximum combustion is under O_2/N_2 conditions.

In summary, the oxygen-rich combustion environment affects both coal pyrolysis and coke combustion, but some effects still need to be clarified. Boudouard and homogeneous water-gas exchange reactions have significant effects on coal pyrolysis and coke combustion.

2.2. Flame stability and burner aerodynamics

To date, most studies have found that coal ignition is hindered in CO_2-rich environments, indeed at comparable gas temperature profiles. Liu et al.[18] explained that increased coal ignition delay in 20 kW scale tests on O_2/CO_2 coal combustion. Kiga et al.[19] performed microgravity measurements of the combustion of coal clouds in 40 vol% O_2 with N_2, CO_2 and Ar as a balance gas and found that the flame speed decreased in the order: Ar, N_2 and CO_2. Molina and Shaddix[20] showed through single particle experiments that the presence of CO_2 and a lower O_2 concentration increment the start delay time but have no measurable effect on the time required to total volatile combustion, once it is started.

Pilot-scale tests appeared that the start and flame stability is on the one hand dependent on the oxygen concentration in the oxidant and on the other hand sensitive to the changed volume flow in oxy-fuel operation. This is clearly demonstrated from the results displayed by Zhang et al.[21,22]—where the relationship between flame shapes and to the probability density functions (PDFs) utilized to measure the fluctuating flame standoff distance in a 40-kW test rig assessing a well-established turbulent co-axial jet flame were displayed.

A key perspective in the design of oxy-fuel systems, therefore, is to introduce sufficient oxygen into the pulverized coal flame for satisfactory ignition, and to guarantee stabilization. After all, it is additionally important that flue gas recycling is in a range to allow a satisfactory balance of the heat transfer in radiative and convective sections. Grathwohl et al.[23] have developed, built and tested a highly variable burner that permits a partial or indeed a complete coordinate infusion of the oxygen in the burner into the combustion zone. the measured temperature profiles of one discuss and three diverse oxy-fuel flames that were obtained with this burner.

Grathwohl et al.[23] also reported that CO_2 can influence coal ignition when the aerodynamics of the burner and the proportion of CO_2 within the oxidant are not optimized. The streamlined stabilization by the burner and its geometry/swirl is at least as much critical than the accessibility of oxygen.

2.3. Heat transfer—radiation and convection

In combustion applications, convective heat transfer depends on the convective heat transfer coefficient h and the driving temperature difference ΔT between the flue gas and the surface. The convective heat transfer coefficient can be a function of thermal conductivity, characteristic length and Nusselt number depending on the Prandtl number and Reynolds number.

The second is the viscosity calculated from the total length properties and corresponding kinematics. The kinematic viscosity ratio of CO_2 and N_2 is about 0.64, and the thermal conductivity is about 1.11, so convective heat transfer increases while the density and bulk gas temperature remain constant during the transition from air to oxygenated combustion. Both the velocity and temperature of the volumetric gas depend on the ratio. In real oxy-fuel applications, the speed decreases because the low flow rate negatively affects the heat transfer.

Flue gas will be used to control the temperature, thereby decreasing its temperature while increasing the gas speed. Interactions between fuel composition, fuel velocity, and temperature affect the heat transfer rate studied by Woycenko et al.[24]. He showed that the ratio of hoxy to hair increases with increasing recycle ratio indicating that the increase in velocity over-compensates the decrease in the driving temperature difference. However, this ratio is close to one in realistic recycle ratio ranges of between 0.55 and 0.70. In general, the recycle ratio is an appropriate tuning parameter to achieve similar boiler performance for air and oxy-fuel combustion as shown by Payne et al.[25] and Andersson et al.[26]. This will be the aim, especially if the existing boiler needs to be converted from air work to oxygen-rich gas work.

In coal-fired boilers, heat transfer to the furnace is determined by Radiant heat transfer to other buildings actually involves combustion products CO_2, H_2O, and other issues (e.g., carbon, soot, and fly ash). Due to the high concentration of triatomic gases CO_2 and H_2O during the combustion of oxygen, the emission will vary greatly as the gases are opaque to electricity such as N_2[27]. Various studies (Andersson et al.[26]; Viskanta[28]) have also shown that small particles, and thus similar properties and concentrations as oxygen are expected for the transfer of energy in the field.

Andersson et al.[26] compared the energy conversion of air combustion of lignite and oxy-fuel combustion in a 100-kW combustion test rig. They found that the fuel consumption of oxy-fuel combustion increased compared to air combustion, due to more carbon dioxide in the oxy-fuel combustion Andersson et al.[29] in another study found that the power output from a propane flame with 21% oxygen by volume in the gas was close to that of a flame containing air, despite the temperature and less cooling of the flames. That is, the high concentration of CO_2 in the OF21 (21% O_2 and 79% CO_2) flame restores the level of to some extent. Therefore, carbon dioxide changes temperature and emissions in the presence of oxygen.

A study conducted by Johansson et al.[30,31] mentioned the importance of particle explosion in the same Chalmers reactor and identified temperature, soot formation, particle loading and diffusion as the main effects on furnace power.

2.4. Corrosion

Many scientists think that oxy-fuel combustion will pose more danger. The reason is that the concentration of corrosive gases such as SO_2/SO_3, HCl, H_2O increases and the CO_2 fraction is high. In addition, increased sulfate deposit formation during the combustion of oxy-fuel is associated with corrosion in the furnace head.

Results of Kull et al.[32] and Kranzmann et al.[33] concluded that high CO_2 partial pressure causes alloy carbon enrichment (i.e., carburization) and causes local incomplete oxide layer. Abellán et al.[34] studied the oxidation behavior of various martensitic 9%–12% chromium steels in sample gas mixtures containing CO_2 and H_2O. They analyzed carburization a lot and concluded that the layer of steel without chromium content or chromium-based steel is permeable for carbon dioxide molecules. Therefore, product deterioration over time can be a problem, especially for rare metals. Similar observations were reported by Otsuka[35], who stated that carburization increased with increasing temperature. In an early corrosion study by Kull et al.[36] reported that carburization of austenitic steels was associated with an increase in microhardness, while many other oxy-combustion studies failed to show similar results. The presence of water vapor is believed to inhibit carburization because water vapor adsorbs on the metal to a greater extent than carbon dioxide. There is a lot of water vapor in the wet, oxygen-rich fuel combustion air loop, so carburization can be effectively prevented. However, under reduced conditions such as high temperatures, carburization can be a problem. Water wall in some processes (e.g., progressive oxygen combustion). According to the results of Gosia Stein-Brzozowska et al.[37], it was observed that sulfur-induced corrosion increased in samples exposed to oxygen combustion air. The higher corrosion rate observed for the oxy-fuel sample may be due to the higher SO_2 fraction of the oxy-fuel. Additionally, under certain conditions, the release of SO_2 from sediments to the material surface will cause corrosive behavior. The oxy-fuel model is exposed to a greater fraction of carbon dioxide at higher altitude compared to the airbox, which apparently causes a rapid and effective reaction of carbon monoxide in the device, resulting in increased microhardness. Experimental results show that the growth of the oxide layer in samples exposed to CO_2-rich air is affected by the increase in the CO_2 partial pressure. In addition, dependence on the chromium content and oxidation potential of the austenitic surface under oxygen-enriched combustion conditions was noted.

In summary, most comparative studies show that corrosion is also a significant problem under oxy-fuel combustion conditions. According to Anheden et al.[38] this may require special requirements. In oxy-fuel boiler design, design research should be taken into account to select suitable heat exchangers for different alloys.

3. Different types of air-fuel burners

3.1. Stagnation Point Reverse Flow (SPRF) burners

As mentioned earlier, non-premixed flames can cause excessive NO_x emissions due to the high temperature of the stoichiometric zone in the flame. However, non-premixed fuels can also be used to reduce NO_x emissions if the mixture is optimized to reduce the stoichiometric zone in the combustion chamber. This can be achieved by carefully designing the generator to control the mixing process and reduce the time the fuel remains on the flame. This method is best in the case of jet flame with high coaxial air velocity. Acceleration increases slip, which improves the mixing of air and fuel before combustion occurs, thus reducing the tendency for the stoichiometric region to form. Rapid injection also reduces the time the fuel remains on the flame, thus reducing nitrogen oxide emissions. Another way to control NO_x emissions is flue gas recirculation (FGR), where reactants are diluted with inert (cold) exhaust gases to reduce the gas concentration before the combustion process, thus delaying the ignition lag time. The ignition delay allows air and fuel to mix in the burner before combustion begins, even in non-premixed flame mode. Additionally, a reasonable rate of recirculation of exhaust gas can spread the combustion zone over the entire combustion area instead of a single point. Therefore, a temperature difference is achieved in the combustion zone and accordingly, NO_x emissions are reduced to a lower level. However, mixing the reactants with inert gas causes the flame to burn faster, thus mixing efficiency decreases and the flame disappears easily.

Recently, a proposal for a new gas turbine combustion chamber design called stagnation point reverse flow (SPRF) combustor has been presented to meet the steady, frozen and low flame conflict. The small size of the SPRF combustion chamber supports gas circulation because the outlet port is in the same geometric plane as the inlet port, while the other end is closed. This design creates a low-pressure area near the closed end, as shown in **Figure 2**, which helps maintain a stable combustion process. When hot products come out of the oven, they interact with the reactants to form a more complex mixture. The reagents are diluted with many free radical-laden combustion gases, which lowers the temperature, thus reducing nitrogen oxide and carbon dioxide emissions and establishing the explosion limit.

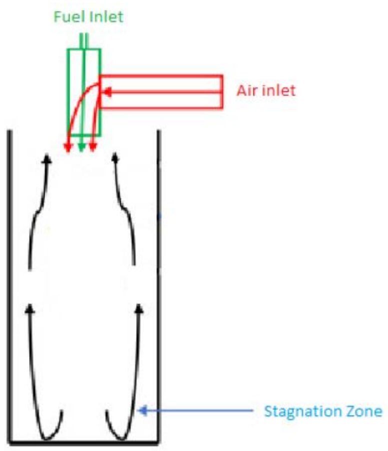


Figure 2. SPRF gas turbine combustor.

Many studies have recently been conducted to evaluate the performance of SPRF burners considering various operating conditions. Gopalakrishnan et al.[39] attempted to study the process of reducing NO_x emissions in a non-rotating SPRF combustor in non-premixed mode. The burning flame exits the injector, effectively mixing air and fuel before combustion begins, resulting in low NO_x emissions. Bobba et al.[40] tried to study the stability mechanism and flame structure of methane-air flame in non-rotating SPRF combustion chamber. The results show that there are two stable regions in the combustion chamber and a significant region with strong turbulence and low velocity in the lower part of the inlet section. Increasing the density of the shear layer gives access to more gas recirculation, thus increasing the reaction and improving the flame. The second stabilization zone is close to the stagnation zone of the wall. Analysis of the combustion flame shows that the flame throughout the combustion chamber is generally in a thin layer. Castela et al.[41] conducted an experiment to understand the events occurring in the SPRF combustor. The data recorded for a given air preheat inlet temperature shows that increasing the air inlet speed has a significant effect on reducing NO_x emissions. Additionally, increasing the air entry rate allows the flame to operate more stably in weaker conditions. Undapalli et al.[42] performed a large eddy simulation (LES) of a SPRF combustor, considering non-premixed and premixed combustion modes. The non-premixed flame is removed while the premixed flame is connected to the injector. Lifting the flame in the non-premixed mode allows for a longer ignition delay, resulting in better mixing of the reactants. This could justify the similar NO_x emissions achieved in non-premixed and premixed combustion modes.

Moderate or intense low oxygen dilution (MILD), also known as flameless combustion, is a combustion engine that also uses a combustion engine and can widely achieve very low NO_x emissions and wide limits. Flameless combustion in the burner can be achieved by increasing the inlet temperature of the reactants above the auto-ignition temperature of the mixture and at the same time adding enough inert gas to increase the ignition delay. These conditions make flames invisible while keeping emissions very low. Although used in many industrial applications, the use of MILD combustion in gas turbines is still in the research and development stage. Many studies have been done on MILD combustion for gas turbine applications. Luckerath et al.[43] studied flameless combustion for gas turbine applications at 20 bar operating pressure. Levy et al.[44] proposed a new gas turbine combustion chamber design that can utilize MILD combustion by creating a large area in the combustion chamber. In another study, Lammel et al.[45] were able to use a high-speed generator to achieve low CO_2 and NO_x emissions. Additionally, Arghode et al.[46] discussed the concept of flameless combustion for gas turbine applications and the possibility of achieving ultra-low NO_x emissions.

3.2. Dry Low-NO_x/Low-Emissions (DLN/DLE) burners

Recent advances in the development of future gas turbine technology aim to increase efficiency and reduce nitrogen oxide (NO_x) emissions. Many methods have been developed to reduce nitrogen oxide emissions. The formation of nitrogen oxides during the combustion process is closely related to the flame temperature. Lowering the temperature using diluents such as water or steam is the most promising way to reduce NO_x emissions, especially in power plants. However, this is often affected by reduced overall engine efficiency, possible corrosion from water pollution, and reduced or quenched CO depletion. Solutions that do not involve steam or water injection include lean premix (LPM) burners using dry NO_x (DLN) or dry low emission (DLE) technology [47]. This type of combustion in a gas turbine reduces nitrogen oxide emissions to single digits.

The main design criteria for the performance of DLE combustors are (1) compliance with emission standards at maximum load and (2) control of emissions throughout the entire engine load range. Other important factors that ensure stable combustion and a wide operating range in all types of engines include the rapid response of the system to changes, especially in twin-engine engines, the ability to maintain very low combustion acoustics and the ability to switch smoothly from one fuel to another[48]. Different manufacturers have different designs for the DLE content of the generator to reduce NO_x emissions without using steam or water injection.

This burner concept allows three types of injection: pilot injection, channel injection and 18-arm rotary injection. Later models provide a better mixture. The design has been shown to reduce NO_x emissions to below 10 ppmv and reduce CO and unburned hydrocarbon emissions when operated on natural gas at pressures up to 11 bar[47]. The scheme shown in **Figure 3** represents the design concept of the premixed two-stage DLN-1 combustor that can use natural gas and liquid fuels[49]. This engine has four main parts: fuel injector, primer, venturi, and center stem/cover assembly. This product gives three values: primary, secondary and dilution.

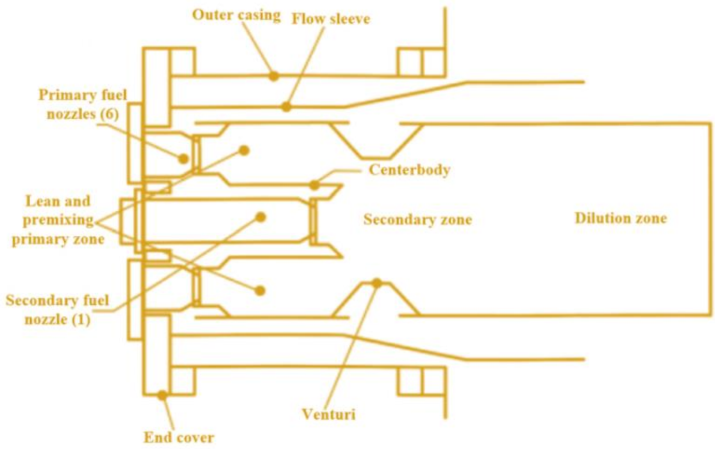


Figure 3. G.E DLN burner[49].

The burner operates in four different modes: main mode, lean mode, auxiliary mode and premix mode, as shown in **Figure 4**. In main mode fuel enters only through main nozzles and main air enters through vortices. In this mode, initial flame ignition and low loads of up to 20% occur[39]. The lean-to-lean mode is selected by supplying fuel to the first and second zones at medium engine loads. The oil mixes with air and passes through the vortex in the middle of the body outlet, creating a secondary mixture. The secondary operating mode is a transition between lean and premixed mode, with the flame only in the secondary zone. While the fuel supply to the main nozzle gradually decreases, the fuel to the auxiliary nozzle increases, extinguishing the flame. In premixed mode, some fuel still enters the primary head, but the flame is retained only in the secondary remote area. This mode minimizes gas emissions. When this generator operates with carbon monoxide at base load, CO and NO_x levels can be as low as 25 ppmv and 9.0 ppmv, respectively[49].

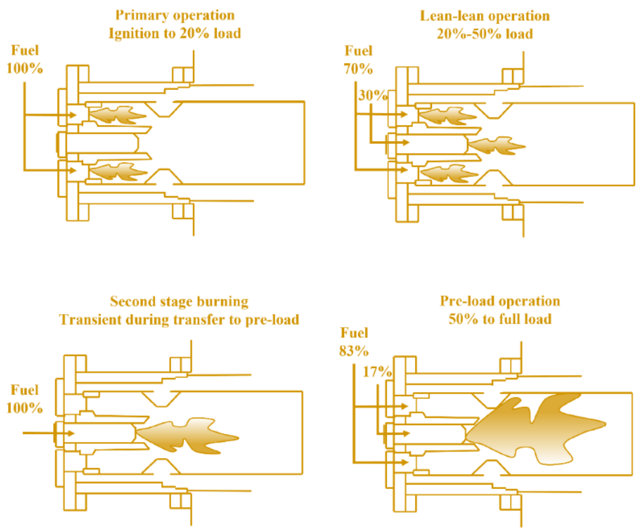


Figure 4. DLN operation on different fuel mode[47].

3.3. EV/AEV/SEV burners

Although there are many competing combustion technologies in the LPM gas turbine market, some stand out for their ultra-low emissions and exceptional flexibility. For example, EV burners compete with micromixers (discussed in the next section). EV burners in particular improve engine tuning by providing a more stable flame across the operating range. Micromixers and electric burners have never been tested under oxy-fuel combustion conditions; therefore, the following brief review is specific to electric combustors and discusses their potential for use in zero-emission gas turbines. The abbreviation EV-burner stands for Enhanced Vortex Burner. This technology can achieve ultra-low NO_x emissions in LPM gas turbines and is therefore known as an environmentally friendly (EV) combustor[50], also known as an EV combustor. Its geometry consists of two semi-conical shells, one slightly offset relative to the other in the radial direction, while keeping the axes parallel. Thus, two tangential grooves of constant width are formed on the shell. Combustion air enters the burner tangentially through the slits, forming a vortex core flow with vortex breaking near the burner exit[51]. As the diameter increases, the axial vortex density increases. The departure angle is carefully designed to place the vortex break point near the burner exit.

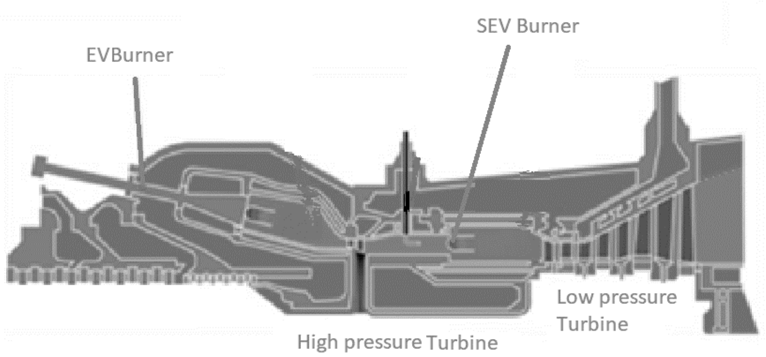


Figure 5 SEV& EV burners[52].

As shown in **Figure 5**. Premixed gaseous fuel is then injected into the combustion air through a line at the outlet of each air vent; This external injection leads to good mixing, which is a prerequisite for ultra-low NO_x emissions. EV burners have two fuel capacities: gaseous fuel (DLN technology) and liquid fuel (water injection). Vortex breakdown is one of the fundamental properties of electric currents and is also a rapid change in the pattern of strong vortices. Some studies have reported that the onset of vortex shedding is independent of the Reynolds number but mainly depends on the vortex number. Vortex bursting occurs in two different forms, axisymmetric bubble-like and spiral forms, depending on the design. The axial flow slows along the vortex axis and the velocity within the vortex weakens as the flow is recirculated and distributed over a wide area in the generator. This behavior leads to an optimal combination of reactants and a higher flame even at initial and ultra-low load. Perfect mixing prevents hot spots in the flame, keeping NO_x emissions to a minimum. The core flows quickly to prevent the flame from returning. This results in stable operation in extreme conditions, resulting in complete mixing of temperatures and reduced CO and NO_x emissions. There are several features that distinguish the EV burner design from other DLN premixed hardware:

(1) Strong vortices can only be created by tangential air entry. There is no need for storms.

(2) The air intake quickly distributes the core airflow in the axial direction, thus creating a natural barrier against flash back.

(3) There is a gap inside or in the middle of the healing area of the vortex damage that can heal the flame.

(4) The vortex break point is aerodynamically stabilized in free flow, eliminating the need for additional stabilization equipment (blind bodies, ramps, discharge extensions, etc.).

(5) No drive (non-premixed) fuel injection should help stabilize the flame at moderate to high loads. The burner can operate in 100% premixed mode, resulting in ultra-low NO_x with no combustion emissions.

At low loads, where the burner equivalence ratio is below the premix extinction limit, a separate pilot circuit injects fuel in burner centerline. The core flow becomes fuel-rich and the flame becomes more stable in the vortex break zone. Similarly, if the engine is running on liquid fuel, injection is done through the central jet nozzle in the head cover. The jet breaks up into small droplets that disperse throughout the flow field within the cone. The flame produced is stabilized by the internal recirculation zone. Due to the need to improve vaporization and mixing of liquid fuel to reduce NO_x emissions, advanced electric vehicle (AEV) combustion chambers have been developed. **Figure 6**. Instead, it uses four air intake grooves. This reduces the tangential variation in the radial velocity component, thus preventing the oil drop from hitting the cone wall. An additional mixture is fixed in the oven to facilitate the complete evaporation of the oil and the mixing of the oil phase. Axial and tangential velocity profiles in a conical section a jet-like core flow with distinct small body eddies. The highest axial velocity at the center of the vessel exit is more than twice its average value. The high axial velocity of the core flow remains throughout the mixing tube and causes the edges to rebound. Even the lowest near wall of the mixing tube can be increased by adding an air film (< 10% of total air flow). The film reduces the risk of wall rebound and locally dilutes the rich oil.

EV burners were first developed and used by the former Alstom in the GT11 gas turbine, which has 36 burners with a central electric burner in a hexagonal three-ring arrangement. All burners ignite in premixed mode

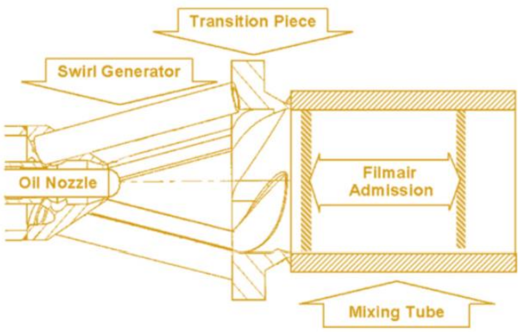


Figure 6. AEV burner design features[53].

3.4. Perforated plate burners

The PP burner has a simple orifice plate that receives a stream of pre-mixed or semi-pre-mixed fuel and oxidizer on one side and distributes this flow in the same order as it needs to be released as there is a plane on the other side. The cone-shaped flame is made of porous plates. These flames are susceptible to various complications such as flashback, extinction and explosion. Therefore, it is important to examine the safety mechanism of the flame. Kedia and Ghoniem[54] studied steady-state laminar flow, premixed methane-air flames over thermally conductive perforated plates. They investigated the steady flame that caused the explosion. From unsteady 2D simulations of the chemical kinetics of methane-air type combustion. The principle of flame explosion results from the combination of heat transfer and stretching of the flame. Jithin et al.[55] performed a study on the properties of a stable premixed propane-air flame on a porous plate using 3D simulations. They reported that increasing the speed increased the separation of the flames. For an insulated panel, this distance is zero, meaning the flame is on the panel. However, as the thermal conductivity of the panels increases, the separation distance increases. The greater the balance brings the flame closer to the plate, thus increasing the heat transfer to the plate. Similar findings were reported by Altay et al.[56] used a two-dimensional numerical model to study the stability properties of PP-stabilized methane-air flames under various operating conditions. The thermal conductivity of the thermal plate is only 10 W/m K. However, Jamal et al.[57] considered an index of up to 385 W/m·K and showed that if more heat was removed from the plate to preheat the mixture, the flame would be shorter and more stable. The authors examined the effects of plate material, thickness, and pore size and found that heat transfer through the plate is the main factor controlling all these effects. Kedia and Ghoniem[58] conducted a study on the mechanical properties and flame stability of flame retardants at different voltages. The stability of the burning flame depends on the transfer of heat from the flame to the burning plate; However, since the thermal conductivity is limited to 1.5 W/m, this change is considered as heat loss. Rashwan et al.[59] experimentally studied some of the oxy-fuel fire fixed on the PP burner. In the same balance, a stable flame is obtained with oxygen in the range of 29–42% (volume) in the O_2/CO_2 oxidant. The premix ratio of the fuel/air mixture has also been found to affect the flame. Edacheri Veetil et al.[60] numerically studied the effect of geometry on rich and lean flame in a PP burner. They reported that as the hole spacing decreases, the curvature of the flame increases and the flame decreases. Wang and Wen[61] conducted a study on laminar hydrogen flame in PP assembly channel and observed M-shaped flame. They found that the overall effect of PP was to reduce the flame underneath.

4. Conclusion

Currently world is going through a transition from direct air fuel combustion system to more environmentally friendly combustion system lot of research has been done in this regard. However, oxy-fuel combustion in environment SCO_2 flue gas recirculation shows some outstanding result. **Table 3** shows advantages and disadvantages of **SCO_2** oxy-fuel and air fuel burners.

Table 3. Comparison between oxy-fuel and air-fuel burners.

Burners	Advantages	Disadvantages
Air-fuel burners	• Excellent flame in various vortex separation-based operations • Achieve ultra-low NO_x emissions • Dual fuel capability (gas and liquid) • No additional stabilization equipment required • No need for ignition (not pre-mixed) Requires fuel injection helps stabilize pre-mixed flame • Improved engine shutdown timing	• Imperfect fuel-air mixing in fuel staging • Unsteady variation in flame surface • Variations in turbulent burning rate
Oxy-fuel burners with SCO_2 circulation	• Has a smaller size • Advances inner gas recirculation • The reactants are diluted with portion of the burnt gases • Control stochiometric ratio • Control wall temperature • Minimal GHG emission emissions as well as enhanced blowout limit • Work under high pressure • High efficiency • Low operational cost. • CO_2 capturing	• Currently undertesting phase • Flame instability • Results are preliminary based on experimental data. • high manufacturing cost.

In summary Oxy-fuel combustion could replace the air fuel combustion in some application due to its environmentally friendly characteristics. The main reason of this its compact size and minimal GHG emission. Up to 80% of the exhaust gas from the furnace is used to maintain temperature. Due to the separation of nitrogen before combustion, the net flue gas (negative) of gas oxidation is approximately 20%–25% of the air combustion system. The use of flue gas recovery will likely result in small amounts of gases such as moisture, SO_x, HCl, HF, and fly ash unless steps are taken to remove these chemicals in the reverse cycle. The same goes for NO_x, but NO_x in the stream can also be eliminated by recycling in the furnace. By treating the net flue gas after the recycling cycle, flue gas quality control costs can often be reduced.

Due to the low level of net flue gas, it is more than the flue gas in the return cycle. Designers can often accommodate more gas without removing moisture from the return loop. Fly ash is usually removed from flue gas in the recirculation loop. Oxygen-enriched combustion produces inherently low NO_x and generally does not require additional NO_x removal systems. For further purification employing CPU (CO_2 purification unit) will further minimize GHG emission.

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Conflict of interest

The authors declare that they have no conflict of interest.

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