A Review on the Combustion Characteristics of an Asymmetric Swirling Combustor in Flameless Mode

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A Review on the Combustion Characteristics of an Asymmetric Swirling Combustor in Flameless Mode

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Abstract: As the population of the world is growing rapidly, the demand for energy that is clean and efficient is increasing. Combustion is one of the major ways of energy conversion that produces very high amount of pollutant emission, as such the research arena has been taken over by coming up with combustion processes that are cleaner and efficient by the combustion engineers. Flameless combustion is one of the new techniques discovered by researchers to suppress NOx emission due to the low temperature inside the combustion zone that is well below the dissociation temperature of Nitrogen. Homogenous or proper mixing is another major factor that enhances combustion efficiency. An asymmetric swirling combustor is a unique shaped combustor that was developed by researchers in order to enhance better mixing inside the combustion zone without the need for an external swirler. The review investigated several parameters such as temperature uniformity, fuel flexibility and level of pollutant emission as discussed by researchers and it was found that the asymmetric swirling combustor is very efficient with temperature uniformity of about 0.9, thermal efficiency of 53% and very low NOx and CO of about 2ppm and 24ppm according to researchers. It was recommended that the combustor should be investigated under different flow configurations i.e. forward and reverse flow in order to know the optimum direction of flow for the asymmetric swirling combustor.

Keywords: flameless, combustion, emission, swirler, asymmetric, pollution

1. Introduction

Combustion process is one of the oldest human civilization used by man for several purposes such as heating, cooking etc. Presently, most of the modern technological developments we have in world such as electricity, automobiles and industrial processes are products of combustion processes[1]. The level of development or otherwise of countries nowadays is defined by the level of energy a country has and the ability of the country to utilize or convert the energy usually through combustion processes[1]. High amount of energy demand are achieved through combustion processes in one way or the other[2],[3]. The global need for energy is increasing every day as a result of many factors such as increase in population, technical and societal developments[4],[5]. A consequence of the combustion process is the production of high level of pollutant emission arisen from the combustion of fossil fuel[6]. This pollutants produced, have serious negative impact on the populace and the earth itself as the heat produced in the combustion process leads to environmental issues such as global warming and climate change[7],[8]. Figure 1 below the global CO_2 emission produced from 1900 to data, the chart shows how emission is growing over the years. Flameless combustion is one of the strategies researchers have developed to improve combustion effectiveness and lower pollutant emission[9]. The most interesting thing about this form of combustion is the moderate level of temperature produced at the flame that is not too high. Low levels of NO_X are produced as a result of the reaction, which has uniform temperature inside the combustion zone that is well below NOx formation. There is less oxygen present in this form of combustion than there is in the environment. The combustion process is associated with larger reaction zone, unvarying temperature inside the combustion zone and a totally invisible flame[10].

Flameless combustion operates on the basic principle of exhaust gas and heat recirculation. The oxidant stream is heated by the exhaust gases, which also serves as a diluent and lowers the oxygen content in the oxidant stream, keeping the combustion zone at a low temperature and reducing NO production[11]. When something is described as flameless, it means that it has much less visible flames than a typical, conventional flame would. Flameless combustion is a prospective combustion method that can combine extremely low emissions with great efficiency with the aid of a high flue gas recirculation rate[12].

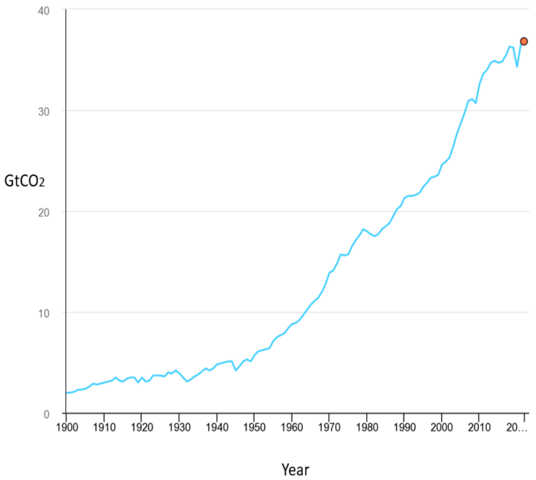

Fig. 1: Global CO2 emission from combustion[13]

Internal recirculation captures the high velocity exhaust gas from the separated fuel. High peak temperatures are avoided and pollutant emissions are reduced due to less oxygen in the combustion zone and more balanced chemical energy release. When swirling flameless combustion is employed in direct injection of both fuel and air, a flame stabilizer is not required. Instead of using a swirler, which is generally used in most standard combustors to establish an auto swirling process, air will be pumped tangentially and axially to impart whirling[2]. Some few advantages of combustion in flameless mode are extremely minimal pollutant output, uniform temperature distribution inside the combustion chamber, and a stable and clean combustion[14,15]. The innovative combustion method was created, to help increase combustion efficiency while reducing pollution emissions[16]. During combustion tests with a self-recovering burner in 1989, an unexpected outcome was discovered that when the inside temperature of the combustor was around 1,000°C and the temperature of air was preheated to 650°C, there was no visible flame or ultra-violent signal observed. The exhaust gases had less than 1 ppm of CO, indicating that the fuel had been completely burned, and nearly no NO_X emissions due to stable and smooth combustion. For this phenomena, was called "Flameless Oxidation" (FLOX)[16]. The term "moderate combustion" or "intense low oxygen dilution" (MILD) combustion is another term for this novel combustion technology[17]. While operating at higher temperatures, High-Temperature Air Combustion (HiTAC) was demonstrated by Japanese researchers to be virtually identical to MILD combustion[18], whereas CDC is based on HiTAC with the exception that the combustion intensity is higher with shorter residence times[19]. Swirling is a very significant parameter in flameless combustion, it promotes excellent mixing between fuel and oxidizer, thereby enhancing combustion efficiency with lower level of pollutant emission. Previous research has shown that flameless combustion was achieved with an asymmetric swirling combustor operating in forward flow configuration. Reverse flow configuration is a situation whereby the exhaust hole of the combustor is on the side of the fuel and oxidizer inlet, it gives favorable residence time, increase the rate of internal recirculation of exhaust gases while simultaneously diluting the oxidizer so as to lower the oxygen concentration. Hence, there is need for further investigation of the performance of the asymmetric swirling combustor under reverse flow condition to check if we can have better performance of the combustor.

2. Fundamentals of Swirling

The One of the challenges faced during combustion is proper mixing between the constituents of combustion i.e. oxidizer and fuel which lead to combustion instability. Swirling, which is an organized set of flow pattern of the mixture of air and fuel rotating inside the combustion chamber of a combustor[20]. It is required in order to enhance the combustion process by forming a secondary recirculation zone[21]. The flames produced in this type of combustion are referred to as swirling flames, and they have a very wide variety of practice like gas turbines, utility boilers, industrial furnaces, internal combustion engines, as well as a variety of other useful heating devices are just a few examples of applications[22]. Typically, swirling combustion involves running the mixture through a swirler or group of swirlers to add an azimuthal component to the flow, which fixes the flame or mixture[23]. Swirling flows can be found in a plethora of applications in both reactive and non-reactive systems. Applications for non-reacting situations include: jet pumps, spraying systems, cyclone separators, and many more[24]. It is used in a variety of combustion systems, including internal combustion engines, utility boilers, industrial furnaces, gas turbines, and numerous other useful heating appliances. Swirling jets are employed to control flames, and the advantages of incorporating swirl into the design of flame stabilizers for industrial burners have been established[25]. Combustion intensity is increased in swirling flows due to improved mixing and longer residence time due to creating additional recirculating flows which also aids in flame stabilization as well[26),27),28].

Moreover, turbulent swirl is a common occurrence in real-world combustion systems[20]. Complex flame-flow interactions are present during the propagation of flames in turbulent flow fields. A fundamental interaction of this type is the rotating gas as it flow pass the flame as shown in Fig 2 below[29–31]. Given the relevance of rotating flame as one of the key ideas for comprehending the complex process of flame-flow interactions, numerous studies on rotating Bunsen burners have been undertaken[25]. Investigations were conducted to determine how the premixed flames' morphology, stability, and extinction limits were impacted by centrifugal and Coriolis accelerations[25]. The ability of the burner rim to stabilize the flame was discovered to be achievable only at sufficiently low angular velocities, among other findings. The flame flashes back inside the burner tube when rotated quickly. Basic characteristics for stable flame configurations have been identified, and a mathematical model that defined the primary characteristics of spinning flames has been developed.

A research conducted focused on how to stabilize a flame in a laboratory combustor using the combustors rim hydrodynamics. In a different theoretical investigation on the subject, the shape of the flame produced in the combustor was analyzed using rotating tubes so as to study the stabilization of the flame. According to the study, flame stabilization tends to be lessened at very high flow rate due to flashback from the flame.

3. Effect of Swirling

Swirl has a considerable effect on both reactive flows and inert jet. The size, stability, and level of combustion intensity of the flame are affected by the swirl in the reacting flow while for non- reactive flow, the swirl affects jet development, entrainment and decay. These effects are greatly influenced by how much swirl is added to the flow[32,33]. Swirl is commonly expressed as the ratio of axial flux of tangential momentum to the product of the nozzle radius and axial flux of axial momentum. The higher the swirl number, the more intense the effect it has on the combustion.

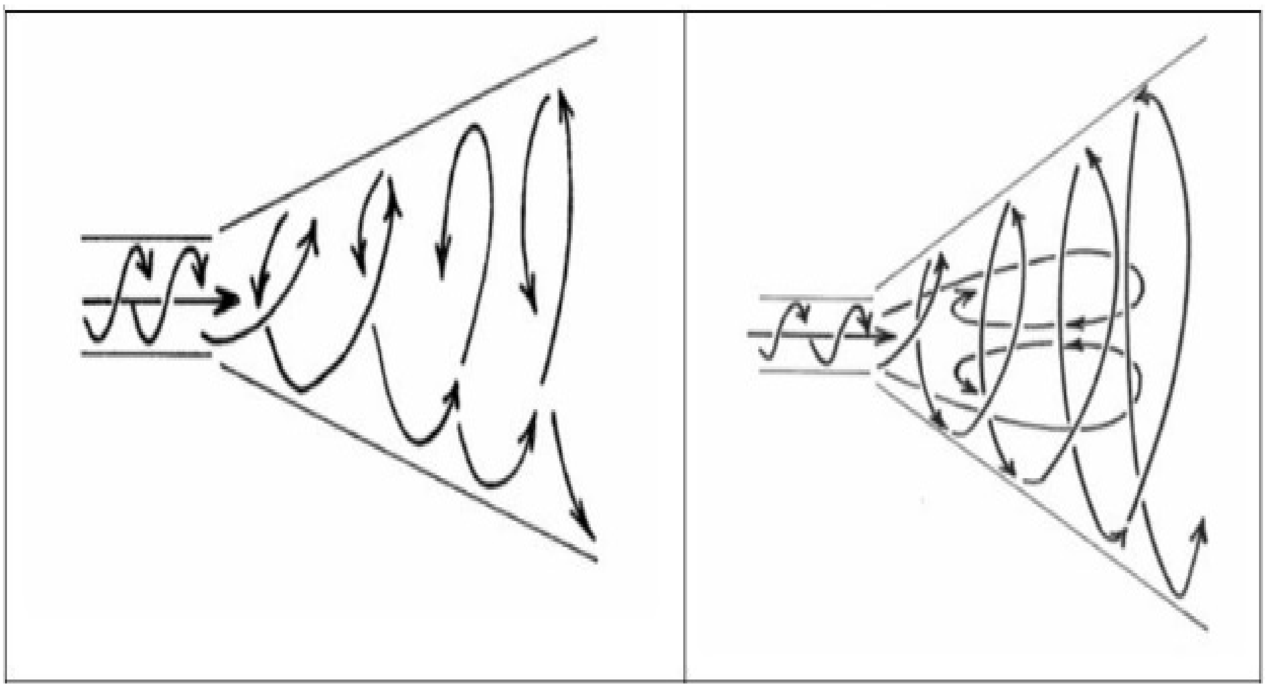

Fig. 2: Low swirl observed to be wide and slow in the jet (left) High swirl observed to be wider, slow with center toroidal recirculation zone (right) [25])

Low swirl is used to categorize the type of swirl that is relatively low, i.e. the swirling number is usually less than 0.4. In this type of swirl, the flow is usually not altered by the velocity of the swirl[25]. Figure 2 (left) below shows a low swirl in a jet flow, producing only large lateral pressure gradient frequently. The jet produced with low swirl are relatively slower and wider than non- swirling jet. Flames produced with low swirl have serious issues with instability and as such are not commonly used practically but there is no doubt that it gives good foundation for simulation purposes similar to other basic research[34]. In some instances, low swirl may result in changing the structure of a flow, which suggest that may have a recirculation zone[21]. Some few examples of geometrical constraints that cause recirculation regions in low swirl applications include: quarl or diverging nozzle, rapid increase in flow area, flame stabilizer in v shape and bluff body flame holder. According to Gupta[35], swirl causes flame to prolong in applications that require low swirl. High swirl flow is the type of swirl flow whereby there is high recirculation zone caused by large axial and radial pressure difference. The swirl number is usually greater than 0.6and a center toroidal recirculation zone (CTRZ) is created and seen unlike in low swirl[36]. As shown in the Figure 2 (right) above, high swirl jet flow frequently produces considerable pressure difference between the lateral and longitudinal. The flow is substantially slower, wider and accompanied with a center toroidal recirculation zone[37]. The presence of the recirculation zone helps to stabilize the flame in combustion by mixing the hot products of combustion in a region of lower velocity in order to match the flame speed with the flow velocity[26].

4. Asymmetric Swirling Combustor

The stability of a combustion process is a key factor in pollutant emission reduction by enhancing rigorous mixing between the fuel and oxidizer in order to produce vortex flame inside the combustion chamber[38]. The term vortex flame was first discussed by Gabler[39]. He investigated the level of pollutant emission reduction achieved using a vortex flame. It was discovered during the experiment that stability has enhanced in the combustion process, such that even at the lean flammability limit of the fuel he used in the experiment, the combustion was still sustained. The vortex combustor developed by Gabler[39] was cylindrical in shape with tangential and axial ports of air, beside the axial port for the fuel. The vortex was formed as a result of the impact of the tangential air on the axial air and fuel, there by inducing a rotary form of motion for the mixture and the flame at large[40].

Several of the fundamental characteristics of vortex flames were documented along with a succinct description of the flame anatomy. These characteristics include improved stability close to the fuel's lean flammability limit and some basic temperature profiling. By injecting air through a tangential port in a cylindrical combustion chamber, a swirling vortex flame was produced. When the asymmetric fuel input was applied in the studies by Gabler[39], they discovered that the flame showed similarity with that of a swirl flame. Yet, when the asymmetric fuel inlet was applied, the resulting flame completely differed from swirl-stabilized flames in terms of its features. One of the major differences observed is that the length of the flame is shorter in asymmetric combustor. The flame's characteristic blue hue, which effectively defines premixed flames, is the second distinction while the third is the stability of the flame. According to Gabler[39], this type of asymmetrically fueled flame offers a wider range of stability than a swirl stabilized flames.

Gabler's vortex combustor concept was enhanced by Saqr[41] who changed the combustor shape to be asymmetric with two inlets for both air and fuel coupled with coaxial recess points as shown in the Figure 3. The asymmetry of the fuel input port is described by Gabler as "asymmetric." However, Saqr[41] uses the word to describe the asymmetry of the combustor shape that has been proposed to increase the vortex flames' and aerodynamic properties (a shorter flame and improved stability across a wider range of equivalency ratios). According to Muhsin[42], under extremely lean conditions, an asymmetric vortex combustor has demonstrated good combustion stability with wider flame stability envelope when using biogas as compared to pure methane[43–45]. The two effects that cause a flame to be stable are the trapped vortex effect of the backward-facing step and the powerful tangential vortex contained in the flame zone. As shown in Figure 3 below, the asymmetric vortex combustor is schematically represented with an asymmetric distance of "a," a fuel shift distance of "b," and an inner diameter of "d." The vortex flame concept creates flame stability by quickly combining air and fuel upstream of the reaction zone and stabilizing the reaction zone at the margin of a driven vortex field[41].

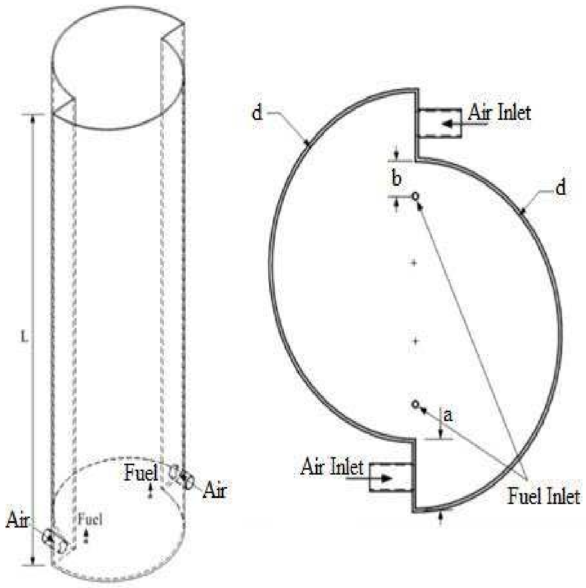

Fig. 3: Front view of the A.S. Combustor (left)top view (right) [41]

As a result, the vortex flame produces a bluish tint despite not being a pre-mixed flame which result in greatly improving the stability and shortcomings of the premixed flames[46]. Usually, mixing inside combustion zone and stabilization of flame are done differently when using a regular combustor unlike the asymmetric combustor because it does not presence of axial air. In asymmetric vortex combustion, fuel is fed asymmetrically into a driven, controlled vortex field, where it is swiftly combined with fresh air before combustion[47]. The edges of the vortex start to burn. To optimize the upstream mixing of fuel and fresh air, a recirculation zone is made in the center to circulate exhaust gases. The reaction zone encircles the recirculation zone circumferentially, while the heat transfer from such mixing occurs in the flow's core area. Both large-scale and meso-scale AVC have recorded this scale-independent phenomenon[46,48,49]. A recirculation zone forms downstream of the vortex with center recirculation zone (CRZ) in a swirl stabilized non premixed combustion is known to play a significant impact in flame stability as shown below in Figure 4. The incoming fresh reactant stream is mixed with the heated product gases. As a result, a well-stirred reactor with high and consistent temperature is created in the combustion zone[41)].

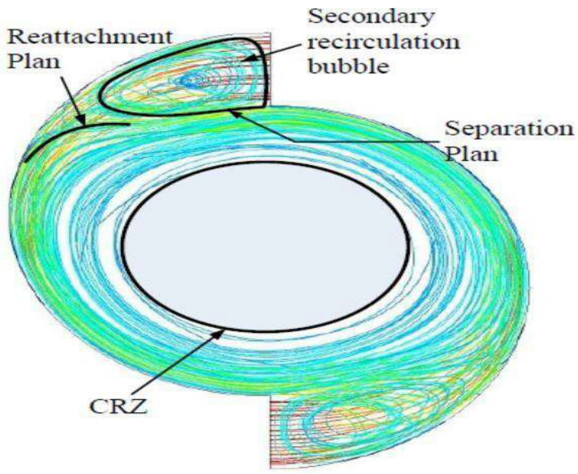

Fig. 4: Secondary recirculation zone[41)]

5. Flameless Combustion

A combustion process whereby there is absence of flame signature in the process, thereby reducing the combustion temperature and provide a uniform temperature inside the combustion zone is referred to as flameless combustion. This goes a long way in suppressing the level of pollutant emission been produced in industrial processes which is the global trend now in order to achieve a sustainable environment. The novel combustion process has different names such as Colorless Distribution Combustion in the United State of America, Moderate and Intensive Low Oxygen Dilution (MILD) combustion in Italy[50)], High Temperature Air Combustion (HiTAC) in Japan[18)], Flameless Oxidation (FLOX) in Germany[16)], Low NOx Emission Injection in the United State of America etc. Flameless combustion is a promising technology as different forms of liquid and gaseous fuels, such as methane, ethanol or ethane[51),5)] as well as biogas have been used to test the flameless approach[52),53)].

Flameless combustion is suitable for industrial applications requiring uniform temperature distribution throughout the combustion furnace[54)]. Flameless combustion have great potentials in glass factories and cement plants[55)], gas turbines[56),19),57),58)] and industrial boilers[59)]. Figure 5 shows the effect of temperature on oxygen concentration and recirculation ration. It can be observed that flameless combustion is achieved in the region of lower oxygen concentration and higher recirculation ratio. This explains why the flame temperature is high in conventional combustion up to the dissociation temperature of Nitrogen while in flameless the peak temperature is relatively low, hence low NOx emission[60)].

5.1 The Concept of Flameless Combustion

During the previous century's oil crisis, researchers in combustion science andtechnology focused on increasing combustion performance by conserving energy and reducing pollutant emissions. They observed that heating combustion air saves energywhile providing maximum combustion performance[61)]. Excess Enthalpy Combustion is a flameless combustion method that uses preheated air at temperatures ranging from 600 to 700 degrees Celsius. As previously stated, two types of flameless combustion burners are available, one from Germany and the other from Japan. In the German design, the fuel jet is placed in the center. The flameless oxidation burner developed by WS Wärmeprozesstechnic GmbH in Germany is the most well-known example ofthis type. Energy conservation is the purpose of flameless combustion, which is accomplished by preheating air combustion with around 80% of exhaust gases[62)]. On this type of burner, the REGEMAT or REKUMAT regenerator is mounted[63)]. The FLOX burner is based on the concept of high-velocity jets that produce internal flue gas recirculation, resulting in intense internal mixing and oxygen dilution. The FLOX burner uses air as an oxidizer. The REBOX W burner, designed by Linde AG[64)], is a newly designed FLOX burner that utilizes pure oxygen as its oxidizer.

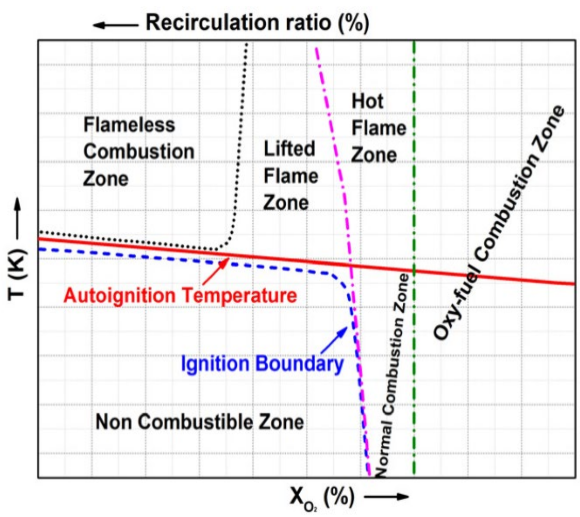

Fig. 5: Schematic of different combustion stages[65)]

A burner with a central air jet and several fuel jets was created by the Japanese.In the early 1990s, Tokyo Gas Company introduced and refined the direct fuel injection (DFI) concept. The idea was to dilute the gasoline and/or the air. In line with this concept, they developed the NFK-HRS burner series (HRS high cycle regenerative combustion system) after investigating the ideal separation distance between fuel and air for reducing NO emissions[67)]. The International Flame Research Foundation (IFRF) of Holland built a number of natural-gas burners during their SCALING 400 experiments following a fruitful examination in the early 1990s[68)]. The highlighted burner had individual fuel injectors surrounding the central air injectors, similar to an FDI system of burners. Using thermal power ranging from 30 kW to 12 MW, NO_X emissions were decreased by about 80%[69)]. A multiple jet burner with independent fuel and air injections, as well as a gas-fired burner with seven fuel ports and seven air ports alternately positioned inside a ring organized around a core premixed pilot flame were both developed by the Canadian Gas Research Institute (CGRI). Through the Centre for Advanced Gas Combustion Technology, the project's purpose is to reduce NOX and CO emissions (CAGCT)[10]. Fuel/Oxidant Direct Injection (FODI) was designed into the CGRI burner as a separate injection into the furnace.

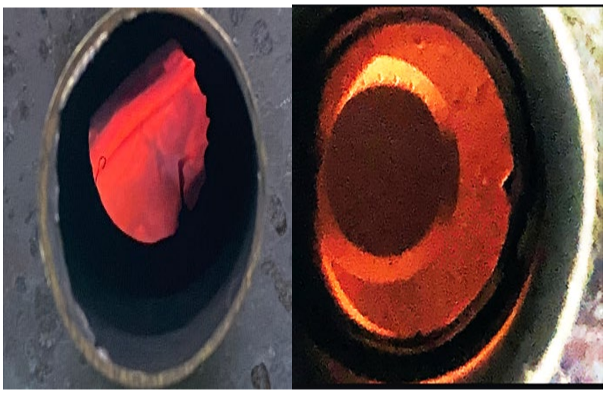

Fig. 6: Images of flame mode combustion (Left) and flameless combustion in HiREF lab

The method of delaying the mixing of fuel and oxidant streams until both have been sufficiently diluted by the entrainment of cooled furnace gases is known as Fuel/Oxidant Direct Injection (FODI). Work on a flameless pulverized coal burner is now undertaken in the EU. Based on WS's FLOX gas burners, this technology was developed by WS Wärmeprozesstechnik GmbH (Gesellschaft mit beschränkter Haftung). The IVD (Institute of Process Engineering and Power Plant Technology, Universität Stuttgart) studied the Pressurized Pulverized Coal Combustor (PPCC). The concept of a flameless pulverized coal burner is similar to the "German" design for a flameless gas combustion burner previously discussed. To reduce NOX emissions, Zhang[70] used both flameless oxidation (FLOX) and continuous staged air combustion (COSTAIR). According to their findings, FLOX technology reduced NOX emissionsby 90%, while COSTAIR technology reduced NOX emissions by 80 to 85%, indicating that FLOX technology was more successful. The Royal Institute of Technology in Sweden performed multiple tests with liquefied propane gas (LPG) using an industrial combustor that has a regenerative heat exchanger. A single jet flame combustor was used in these test under steady state condition. They investigated size, color, visibility, lift off distance and flow structure of the flame[71]. Cavigiolo[72] described a moderate combustion laboratory-scale burner. This machine had a high internal recycled ratio, a high back mixing ratio, andthe capacity to replicate burned gas recycling from the outside[72]. The recently discovered phenomenon of flameless combustion has substantially reduced emissionsand improved combustion performance. In an experiment conducted in 1989, the flame was invisible and self-recuperative burning was utilized. The combustor temperature was 1000°C and the fuel was totally burned in this circumstance although there was no visible flame. Under these conditions, the fuel was completely consumed with no apparent flame[63]. The combustion was stable, NO_X emissions were minimal, and the exhaust produced little noise and has a low carbon monoxide concentration (1ppm). Figure 6 shows the image of combustion in asymmetric swirling combustor, the left image shows the combustion in flame mode while the right image shows the combustion in flameless mode. It can be clearly seen that there is no visible flame appearing in the right image while Figure 7 shows flameless formation with time, it combustion started in flame mode and transit to flameless mode over time.

During flameless combustion, the fuel together with the oxidizer are fed into the combustion chamber at a very high speed. This leads to the combustion of the mixture in the combustion zone even at points close to the injection point. The combustion process is associated with several features such as very low temperature gradient, recirculation of exhaust gases[73]. As a result, there is essentially little thermal NOx formation in the reaction zone due to the extremely low flame temperature and oxygen partial pressures. Recirculating flue gas supplies the energy needed for ignition. As a result, the furnace temperature for flameless oxidation must be at least 800-900 °C. It is still difficult to achieve an even temperature field inside a combustion chamberwith extremely low NOx emissions and improved combustion stability[2]. Flamme's flameless oxidation burner invented the first flameless combustion furnace and found flameless combustion (FLOX). To generate a flameless combustion process, two requirements must be accomplished.

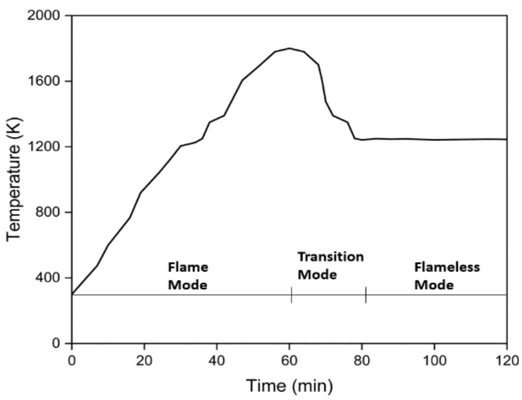

Fig. 7: Flameless formation over time

Flameless combustion has been confirmed to be achieved using different forms of fuel, ranging from gaseous to liquid.[74]. Abdulrahman[5] operated a combustor with ethanol, flameless combustion was achieved at lean equivalence ratio with very minimal emission.

Table 1: Summary of works on Asymmetric combustor

S/No	Combustor Shape	Size	Combustion Mode	Fuel	Flow Configuration	Peak (ºK) Temperature	NOx Emission	Conclusion	Reference
1.	Asymmetric	Standard	Flame	Methane	Forward flow	1239	15ppm	Unusual stability was observed even at lean condition with very low emission	[39]
2.	Asymmetric	Standard	Flame	Natural gas	Forward flow	1880	92ppm	Reduced flame height was observed. There was formation of SRZ and CRZ. Swirl number dropped drastically at half of the combustion height	[41]
3.	Asymmetric	Standard	Flame	Methane	Forward flow	1150	98ppm	From the findings of the work, the combustion characteristic has no effect on changing of inlet diameter of fuel while there is great effect on air when the diameter is varied. Low NOx can be achieved by preheating inlet air.	[75]
4.	Asymmetric	Standard	Flameless	Natural gas	Forward flow	1350	24ppm	Uniform temperature distribution was observed inside the combustion chamber in the work because of the shape of the combustor without using external swirler. Also, efficiency was improved by about 10% while lowering pollutant emission.	[10]
5.	Asymmetric	Standard	Flame	Biogas	Forward flow	1800	25ppm	Result shows a very favorable combustion characteristics in both stability and emission. The swirl number ranged from 0.6 to 3, which placed it in the category of high swirl.	[42]
6.	Asymmetric	Meso scale	Flameless	Biogas	Forward flow	1705	2.2ppm	For various air configurations, low emission was observed to be produced. Additionally, it was found that the meso scale combustor's temperature and emission are both reduced when the oxygen concentration is lower.	[76]

7.	Asymmetric	Meso scale	Flame	Methane	Forward flow	_	_	From the research, it was observed that RDE has better chances of having a continuous detonation wave when using an asymmetric shaped combustor. It successfully generated a detonation wave of 6KHz at a pressure of 4.5 bar which is better than the circular RDE at the same fuel and equivalence ratio condition.	[38]
8.	Asymmetric	Standard	Flame		Forward flow	2200	15ppm	By introducing fuel and air independently, the combustor concept avoids the risks associated with improper mixing in the combustor. Extra ordinary stability was observed even at lower equivalence ratios with less emission.	[77]
9.	Asymmetric	Standard	Flameless	Propane	Forward flow	920	25ppm	The aerodynamics of the combustion in comparism to conventional combustion result in a homogeneous temperature distribution across the combustor and minimal NOx emissions at all equivalence ratios. Stoichiometry produced the most emission, which was then followed by lean and rich situations.	[78]
10.	Asymmetric	Standard	Flame	Natural gas	Forward flow	1400		The maximum tangential velocity of forced vortex flow fields is where the asymmetric vortex flames are stabilized. It was observed from the pictures taken directly of the flame that the equivalence ratio had no effect on the visual flame structure, demonstrating the flame's improved stability.	[46]

6. Asymmetric Swirling Flameless Combustion

As it has been explained earlier, combustion processes nowadays require extensive study especially on how to improve its performance[79–81]. Recently, studies have shown that using an asymmetric vortex combustor for flameless combustion is possible. The combination of the combustor shape and the mode of the combustion drastically reduced the level of emission produced and the need for a swirler in the combustor. Swirling means movement in twisting direction, in combustion there is need for both fuel and oxidizer to be properly mixed so as to enhance the combustion process[20,21]. There are several factors that influence the evolution of the swirling flameless combustion process (SFC). Matthujak[82] tested a house hold burner which operates in a swirl mode with LPG in an energy saving burner. As compared to an energy-saving burner (EB), combustion temperature and net heat flow were found to be significantly higher when heat conversion efficiency was present. The works of Alwan[78] and Asmayou[40] have clearly shown that the asymmetric swirling combustor can be operated in flameless mode. From the results obtained from their work, it is evident that an asymmetric swirling combustor has significant effect on combustion process, it accelerates homogenous mixing in the combustion zone between the fuel, oxidizer and recirculated combustion products without the need of swirler. When the combustion is operated in flameless mode, the volume of the combustion zone is increased and a well-defined temperature profile with nearly zero gradient is observed, which has significant importance especially in production industries that require uniform temperature so as to avoid defect that can lead to failure. Also, very level of pollutant emission is achieved due to the low temperature and aggressive mixing the combustor provides to the axial and tangential streams which ensures complete combustion.

6.1 Temperature Uniformity

Temperature uniformity in combustion zone is a situation whereby the temperature at all points in the combustion zone are nearly the same., It is an important phenomena in combustion studies that is dependent on the type of combustor, mode of combustion, fuel, insulation thickness and mixing. In conventional high temperature combustion processes, excessive high temperature inside the combustion zone fluctuates and lead to the formation of NOx as a result of thermal dissociation of Nitrogen[12),83] and in some cases lead thermal fatigue and thermal shock cracking[84),85]. Variation in temperature inside combustion zone occurs due to fuel and oxidizer molecules concentrating more in one point, which makes the flame to be more intense in one point. In flameless combustion, there is no visible flame signature and the combustion takes place at a lower temperature which is below the dissociation temperature of Nitrogen[86], thereby reducing NOx formation. When the temperature is uniform, it provides an even dissipation of energy to the combustor by slowing the chemical reaction, widening the reaction zone and lowering peak temperatures in some areas around the combustor, there by suppressing the production of pollutant emissions such as NOx, which are associated with high uneven temperature within the combustion zone[87),88]. From the results shown in Figures 8, 9 and 10 below, which are all temperature against axial burner distance, it can be seen clearly that an asymmetric swirling combustor is capable of sustaining combustion up to a very high temperature irrespective of either in flame or flameless mode. Figures 8 and 9 that are in flameless mode show more uniformity in temperature compared Figure 10 which is in flame mode. The results obtained buttress the fact that the asymmetric combustor is very compliant to providing uniform temperature distribution inside the combustion zone of the combustor without the need for swirler. The uniform temperature distribution is as a result of the enhanced mixing of the fuel and oxidizer due to the shape of the combustor and tangential airflow which generates auto swirling inside the combustor.

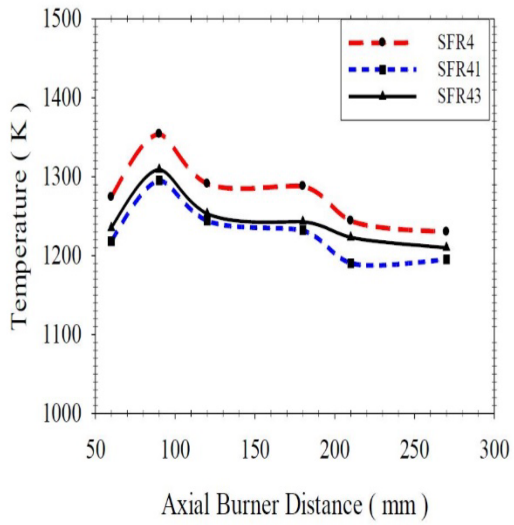

Fig. 8: Temperature distribution along the central axis of an asymmetric swirling combustor[10]

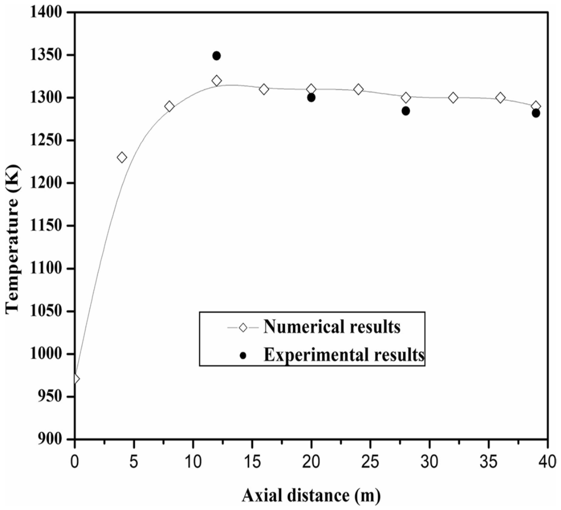

Fig. 9: Temperature distribution along the central axis of a micro asymmetric swirling combustor. Adapted with permission[40]. Copyright Springer

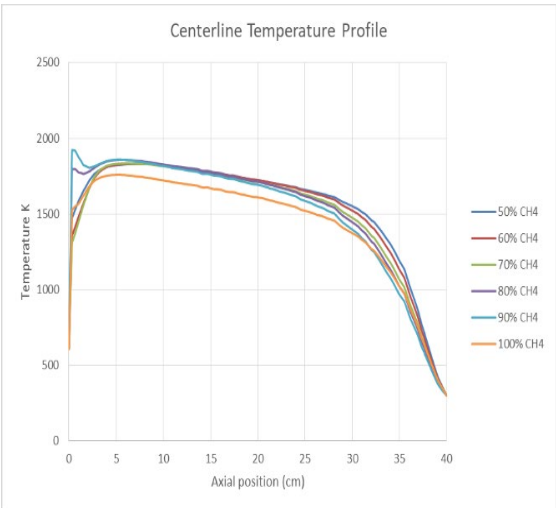

Fig. 10: Temperature distribution along the central axis of an asymmetric swirling combustor operated in flame mode[42]

6.2 Fuel Flexibility

Fuel flexibility in a combustor is a situation where by the combustor can be operated with different types of fuel. The need to have a combustor that is compatible with different forms of fuel i.e. renewable and non-renewable is becoming necessary in order to have efficient energy systems that produces lower level of pollutant emission in order to meet up with the global standard in power systems. This has pushed combustion engineers to create several novel combustion techniques that operate with several forms of fuel[89,90]. They are looking at ways to achieve extremely low emissions of pollutants like NOx and CO, as well as low flame fluctuations, reduced combustion instability, and high levels of efficiency. This section's main goal is to assess the swirling flameless combustion system's fuel adaptability without altering any of its geometrical characteristics. As a result of this, flameless combustion has been used by several researchers using different fuel in order to determine the limit of which fuel can be used for that type of combustion with an asymmetric swirling combustor. From several results obtained by different researchers, it was discovered that different types of fuel such Ethanol, Propane, Butane, Biogas etc. can be used for this type of combustion in other to achieve flameless in asymmetric swirling combustor. Hence, this makes it flexible with fuel because of its accommodating nature of different fuel. Abdulrahman[5] operated a circular combustor using a liquid fuel (ethanol), the result shows that flameless combustion was achieved and has a very wide limit of fuels that can be utilized. Figures 11 and 12 shows the plot of temperature against burner distance using an asymmetric swirling combustor both for micro and standard size. The combustors were operated with biogas, natural gas, propane and the results obtained showed a moderate level of uniformity in the temperature in both figures 11 and 12. As the trend now is to use renewable form of energy such as biogas due to its importance, figure 12 used synthetic biogas on a micro asymmetric combustor can be operated using a renewable energy.

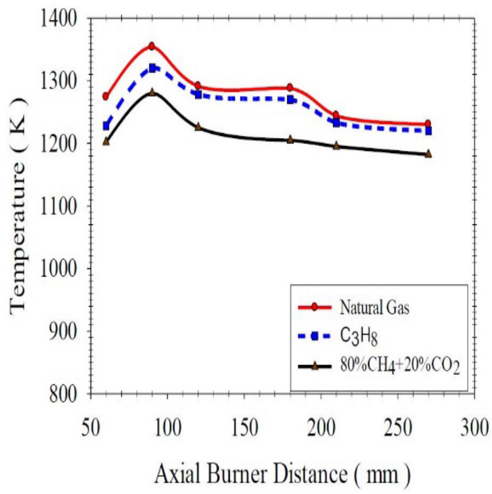

Fig. 11: Temperature distribution along central axis of an asymmetric swirling combustor operated with three (3) different fuels[10]

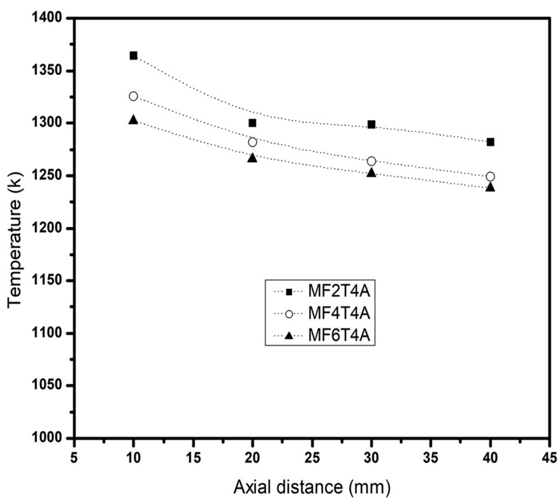

Fig. 12: Temperature distribution along central axis of a

micro asymmetric swirling combustor operated with biogas. Adapted with permission[76]. Copyright Springer

6.3 Pollutant Emission

One of the most important pollutant emission produced during combustion is NOx emission[91,92]. The NOx emission is categorized into three (3) different forms depending on what causes it. The thermal NOx is as a result of excessive temperature above the dissociation temperature of Nitrogen inside the combustion zone which causes oxidation of Nitrogen, Prompt NOx which occurs due to presence of Nitrogen in the oxidizer and finally Fuel NOx which is associated with bounding of Nitrogen with fuel[93,94]. In order to have a low NOx combustion system, we need to carefully select the appropriate fuel to use and control the combustion process by lowering the temperature of the combustion zone, oxygen concentration and residence time through flue gas recirculation, water or steam injection, flameless combustion. When using an asymmetric swirling combustor, it is expected that ultra-low NOx emission of about less than 30ppm will be achieved and when used in flameless mode, a single digit NOx of less than 9ppm to 1ppm will be achieved. The results below in figures 13, 14 and 15 from the works of Alwan[10], Muhsin[42] and Asmayou[95] shows that an asymmetric swirling combustor produces low level of NOx emission in all the cases due to enhanced mixing between fuel, oxidizer and exhaust gases, thereby reducing oxygen concentration. Figures 13 and 14 which were operated in flameless mode, produced NOx of 3ppm and less than 1ppm while figure 20 that was operated in flame mode produced 25ppm. The low NOx produced in figures 18 and 19 were achieved due to the low operating temperature of flameless combustion that is well below the dissociating temperature of Nitrogen while in the case of figure 15, the combustion took place at a higher temperature, therefore aiding the production of NOx.

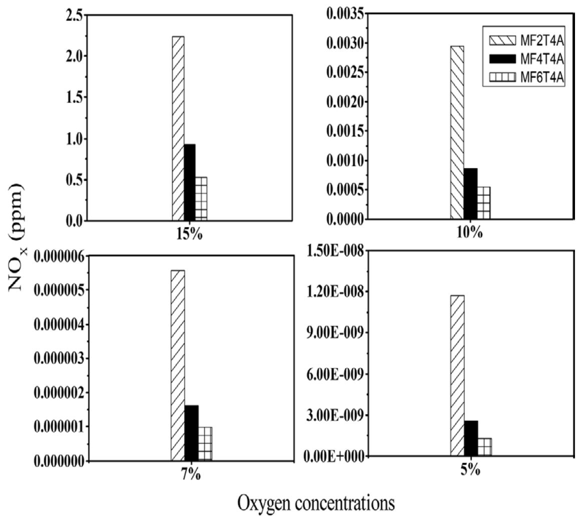

Fig. 13: NOx emission for different air entry configurations and oxygen concentration at exhaust location in a micro asymmetric swirling combustor. Adapted with permission[76]. Copyright Springer

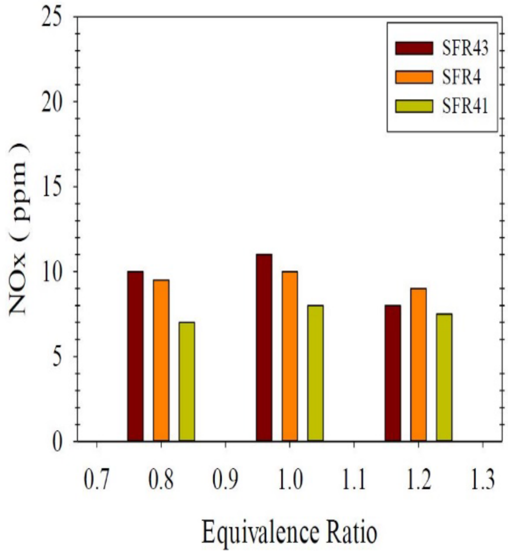

Fig. 14: NOx emission at different equivalence ratio for (3) different cases in an asymmetric swirling combustor[10]

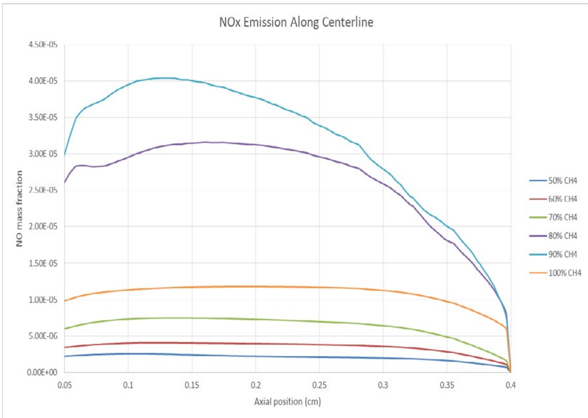

Fig. 15: Temperature distribution along central axis of an asymmetric swirling combustor operated in flame mode[42]

7. Knowledge Gap and Future Research

In the recent time, researchers have investigated new methods on how to improve our combustion processes. The idea of flameless combustion was discovered and since then combustion engineers have been working on the fundamentals of the process in order to understand it better especially using both renewable and non-renewable energy sources such as LPG, Biogas, Propane etc. A new combustor, asymmetric combustor was later proposed and from experiments performed with it, the combustor possess high potentials in both flame and flameless modes. From the literature analyzed, it was discovered that no researcher has used the combustor in both forward and reverse configurations with different fuels (renewable and non-renewable) in order to make comparism between them. The reverse flow configuration is an arrangement whereby the exhaust of the combustor is at the side of the fuel-oxidizer inlet, there is likelihood that it might improve the residence time of the combustor, internal recirculation of exhaust gas and diluting the reactant mixture in order to suppress the temperature of the combustor below the dissociation temperature of Nitrogen. Hence there is need for future research to investigate the asymmetric flameless combustor under the reverse flow configuration in order to check if we can have higher residence time, better mixing, complete combustion which will all enhance the performance of the combustor. In conclusion, the asymmetric flameless combustor needs to be studied using biogas under different flow configuration (forward and reverse) in order to have better understanding of the combustor.

8. Conclusion

This review paper presented the fundamentals of the combustion characteristics of an asymmetric swirling combustor operating in flameless mode. The flameless technology has brought about revolution in the field of combustion due to its advantages and huge prospects. There is no doubt that scientist and combustion engineers have contributed immensely in flameless combustion, but there is still need to explore the area more especially the combustion process so as to understand it better. The reviewed investigations confirm that an asymmetric swirling combustor is capable of being operated in flameless mode with excellent uniform temperature field and lower pollutant emission which are critical in any combustion process. The uniform temperature field is associated with the absence of flame signature, which proffers a wider combustion zone. The low NOx emission is likely due to low temperature inside the combustion zone that is lower than the dissociation temperature of Nitrogen, there suppressing thermal NOx emission. The targeted maximum NOx level when operating an asymmetric swirling combustor in flameless mode is 5ppm, this is as a result of the Nitrogen content in air which oxidizes to form NOx while other forms. The shape of the combustor (asymmetric) enhances mixing between fuel and oxidizer, there by having a more complete combustion with low CO emission. Also, the combustor has proved to be flexible with fuel, it has been operated with different fuels (renewable and non-renewable) successfully without the need for changes in the design of the combustor.

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Nomenclature

MILD	Moderate and intensive low oxygen dilution
HiTAC	High temperature air combustion
FLOX	Flameless oxidation
CDC	Colorless distribution combustion
NO	Nitrogen oxide
P	Static pressure
U	Axial velocity
UV	Ultra-violent
W	Tangential velocity
NOx	Oxides of Nitrogen
N2	Nitrogen
Ppm	Parts per million
CO	Carbon monoxide
CTRZ	Center toroidal recirculation zone
AVC	Asymmetric vortex combustor
CRZ	Center recirculation zone
DFI	Direct fuel injection
HRS	High cycle regenerative system
IFRF	International flame research foundation
CGRI	Canadian Gas Research Institute
CAGCT	Centre for advanced gas combustion technology
FODI	Fuel/Oxidant direct injection (FODI)
EU	European Union
COSTAIR	Continuous staged air combustion
Da	Damkohler number
SFC	Swirling flameless combustor
LPG	Liquefied petroleum gas
PPCC	Pressurized pulverized coal combustor

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