Flameless Combustion Mode as a Promising Trend: a Review on Its Fundamental, Role Towards Emissions Reduction, Fuel Consumption and Performance Enhancement

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Flameless Combustion mode as a Promising Trend: A Review on its Fundamental, role towards Emissions Reduction, Fuel Consumption and Performance Enhancement

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Abstract. Flameless combustion techniques have created a huge opportunity in the patronizing high number of combustible fuel materials. This opportunity is connected with its potential in providing acceptable features of the combustion regime, mostly centered on mixing the working medium (reactants) above the temperature of auto-ignition of the fuel. Recent research has provided some potential of flameless combustion towards pollution reduction and energy generation. However, this technology still requires more attention to improve its versatility. The effect of flameless combustion on emissions reduction and its performance enhancement both on biofuels and fossil products is reported in this paper. Flameless combustion follows mixture before oxidizes in the combustion process, thus generates lower NOx emissions with clear and flameless of very little visible radiation. Similar values in the area of pollutant emissions for all studied fuels, especially with bio-fuel showed that flameless combustion yields good results both on conventional and diluted fuels. The review still points that flameless combustion regime modelling might not be capable of predicting intermediate species for reducing the emissions to zero level due to some inherited properties in the operation. Assessing the thermal performance of flameless combustion, showed similar temperature distribution for all the fuels studied, although bio-fuel temperature observed little below, due to the inert gases of CO_2 of large amount towards cooling the reactants. Challenges like wall-flame quenching and residence time were discovered on micro-scale combustors. The report suggests that little modifications on the flameless combustor in the area of wall-flame quenching will contribute to solving the NOx emission problems.

INTRODUCTION

In combustion, fossil fuels like coal, petroleum and natural gas are the most pronounced energy source globally, however, the full expectations from the patronage of those products are not satisfactory based on the associated emission. Consequently, considering the negative environmental effect from the use of fossil feedstock's turn out to be quite detrimental. Although other materials like biofuel of similar combustible properties of the fossil were brought as a substitute because of its eco-friendly features. Even with some good characteristics recorded from bio-fuel as a sustainable fuel, yet, challenges still occur. These confrontations emanate from low calorific values (LCV) (biogas about 30 MJ/kg to compare fossil of about 50 MJ/kg) [1,2], ignition temperature problem and need to be upgraded (purified) as to remove CO_2 from biomaterials [3] and some levels of emissions. During the Kyoto protocol summit in 1997, series of patent reports from many developed countries on the need and possibility of reducing the emissions accumulations in the environment as well as in the atmosphere [4,5]. Obvious that most of the industrial plants work at high operation temperatures resulting in emissions generation especially NO_X. Following the eminence of these pollutants, industries are the main source of emissions both for the lower and upper layer of the atmosphere [6,7]. In the analysis, the ecological catastrophes come from emissions from different pollutants like NO_X, CO, CO_2 hydrocarbon and soot from the consumption of fossil fuel that was not well combusted [7,8].

Therefore, there is a need for modification of techniques in the field of combustion that will control these emissions manifestation from the use of fossil and even biomass feedstock. One of the successful approaches and promising worldwide is flameless combustion mode, thus free from high operating temperature [9–11]. Flameless combustion was created to reduce thermal NO_X generation and improve combustion performance in burners that use heated combustion air to heat industrial furnaces. This is accomplished by preheating the combustion air in the furnaces, and then transferring energy from the exhaust gases back to the combustion air via regenerative or recuperative processes [12]. This combustion process is commonly used in gas turbines and boilers where high power production is required [12]. Flameless combustion burner can be designed for several applications with the flame front as the main confronting challenge resulting from humming or fluctuation which affects premix-base combustor [13].

FLAMELESS COMBUSTION

Flameless combustion [5,14,15] also known as high-temperature air combustion technology (HiTAC) combustion or moderate intensive low oxygen Dilution (MILD) combustion was designed owing to their ability to control the emissions and support the system with high output performance [16,17]. As the performance of combustion is temperature-dependent, the flame is stabilizing by hot peak temperature, meanwhile, the formation of thermal NO comes from the same peak temperature [14,18,19]. In the flameless burner, a combustion reaction takes place with the mixing of fuel/air, utilizing energy from recirculated combustion exhaust through a heat transfer mechanism while the flame front is avoided [20]. Generally, flameless combustion mode low emission is caused by fresh inlet air dilution by exhaust gasses like N_2 and CO_2 [2,21,22]. During the flameless mode operation, the inlet diluted oxidizer temperature is higher than the use of fuel self-ignition, thus ignition is eliminated [17,23,24]. In thermodynamics, plant combustion output and efficiency are a function of flame temperature as shown in Fig. 1. This revealed that higher flame temperature improves the system operation [12,25]. With long residence time for molecular constituents of nitrogen at temperature together with the high oxygen availability, result in the formulation of NO_X [19,26]. The new product species developed are from oxidation of the reaction free nitrogen in the combustion medium of air or fuel, otherwise known as NO_X. This generally depends on the stoichiometric adiabatic flame temperature of the combustion fuel (temperature of burning a theoretically correct mixture of fuel and air in an insulated vessel) [6]. To achieve a regime with a pure feature of flameless combustion mode, the incoming medium temperature must be higher than the auto-ignition temperature of the fuel [13]. Also, the auto-ignition temperature of the fuel must be higher than the difference between the incoming reactant medium temperature and the peak combustion temperature [16,19]. These conditions can be achieved simply by using the hot exhaust flue gas recirculation adopting regenerator [27] or by fluid dynamics conditions through internal gas recirculation.

Using stability limit diagram as illustrated in Fig. 1, shows different combustion mode boundaries. Stable combustion donated by zone A, due establish almost the entire system temperature with little recirculation rate window [25]. when recirculation rates of up to 30% (somewhat increased at higher temperatures). With higher recirculation rates, the flame will become unstable (zone B). Accordingly, when the operating temperature is lower than the temperature of self-ignition, the unstable flame is recorded resulting in extinguishment (NO reaction zone). Consequently, operation with high temperature beyond system self-ignition, alongside high recirculation gas exhaust, lead to stable and steady reaction without flame, referred to as flameless zone C. This is possible because, at a high recirculation rate, the system hot exhaust gas dilutes the oxygen concentration of the fresh inlet air and further preheat the air stream with an increase in chemical reaction time, finally yield a smaller Damkohler number as an essential characteristic for the formation of flameless combustion [12,28]. Table 1 summarizes some of the flameless combustion characteristics.

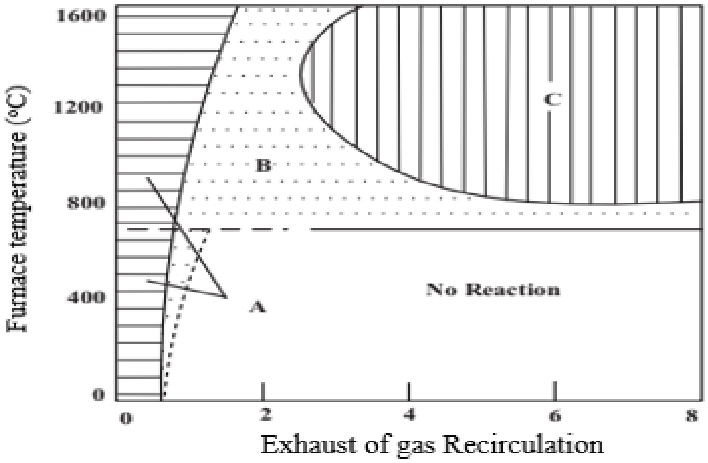

FIGURE 1. Stability limits diagram as Influence of temperature and flue gas recirculation rate: zone A - stable combustion, zone B - unstable combustion, zone C- flameless zone [12,25].

Temperature rise in flameless combustion mode is dispersed and moderate because of its heat release distribution, resulting in a significant reduction in NO_x emission. The various combustion regimes concerning inlet temperature (Tin) and temperature increase (ΔT) coordinate using methane as fuel (molar fractions $CH_4/O_2/N_2 = 0.1/0.05/0.85$) as shown in Fig. 2 (a and b) [29]. Numerical computation was applied to estimate self-ignition temperature (Tsi) (1000 K) as boundaries to map the various combustion zones. Adequate temperature referred to as traditional combustion for flame sustaining is guaranteed through the region of higher temperature ΔT as in feedback. Generally, the acceptable governing condition of ΔT<Tsi and Tin>Tsi as in Mild Combustion mode in Fig. 2 (a) fulfil flameless combustion formation

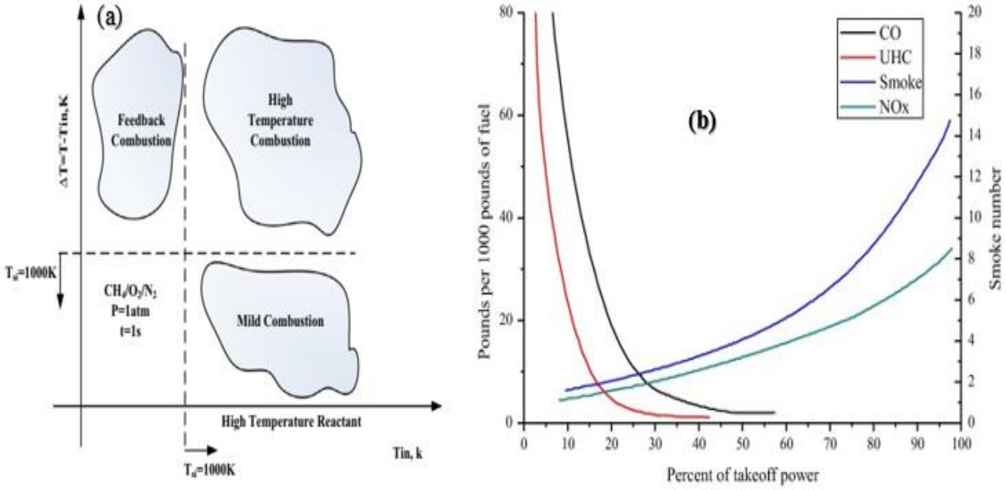

FIGURE 2. Combustion state distribution of inlet temperature with temperature raise(residence time=1s, atmospheric pressure) (a) [17] and Result between the power output of the plant and the emission generation (b) [6,29].

TABLE 1. Summary and results of some flameless combustion

Type of fuel	Combustion Type	Operation Conditions	Atomization	Study of Methods	Remarks	Ref.
Methane	Non premixed	Air tempt. 425 K Air flow rate 0.01-0.025 m3 /s. Fuel flow rate 0.2-0.43 g/s. Equivalence. ratio 0.24-0.28	No need	Chemkin (Chemical Reactor Modeling). Experiments with LDV, gas temperature, and emissions measurement	The flameless combustor is experimented and exhibits stable operation over a relatively wide range of operating conditions	[30] [31] [32]
Propane	Premix	Air temperature 523-823 K Air mass flowrate10-35 g/s (Φ 100 mm) Equivalence ratio 0.3-0.55	No need	Experiments with PIV, ICCD Camera for flame images, emissions measurement	The transition to flameless mode from regular combustion was gradual and cannot be well defined	[33]
Gaseous fuel	Partial premix	Tangential airflow rate 0-12 g/s Axial airflow rate 0-12 g/s Main airflow rate 47.2 g/s Air temperature 298 K Equivalence ratio0.59-0.78	No need	Experiments with PIV, pressure spectra, flame images, and emissions measurement	Cavity air injection pattern and the cavity equivalence ratio were identified as the major parameters for flameless combustion controlling	[34]
Butane and propane	Partial premix	O_2 mass fraction 6.7 -7.3% Oxidant pressure 200 kPa Oxidant temperature>1300 K Oxidant mass rate70-102 g/s (Φ 160 mm) air excess factor 0.95-1.5	No need	House CFD code ($k - \varepsilon$ model, laminar flamelet joint PDF), Experiments	Validated and supplied CFD code from the Mechanical Engineering Department at Imperial College London	[35]
Liquid kerosene and Methane	Non-premixed	The velocity of fuel 20 m/s Velocity of inlet air 40-100 m/s Inlet air pressure 30 atm Equivalence ratio 0.5-0.69	No mention	Fluent (RANS and LES, EDM and EBU)	The outflow temperature is not uniform, therefore, the characteristics of flameless are not obvious	[36]
Methane	Partial premix	The initial temperature 1000 K The initial pressure 1 bar Reference Velocity 12 m/s Combustor	No need	Experiments with PIV, OH* chemiluminescence images, pressure pulsating,	Both frequency and amplitude of the pulsation are specific for each equivalence ratio, which have a strong impact on NOx emissions	[37]

		diameter 10 mm Equivalence ratio 0.57-0.8		emissions measurement		
Liquid diesel	Non-premixed	O_2 mass fraction 0.23 Oxidant temperature 323 K Oxidant flow rate 0.5 m^3 /h Equivalence ratio 0.25-0.5	The SMD is between 30-60 µm	Fluent (Realize k-ε). Experiments with outlet gas analyser, thermocouples	There is a critical injection momentum from the air blast atomizer for the combustion mode is converting	[38] [39]
Liquid Kerosene	Non-premixed	Reactants dilution ratio >2.71 Fuel mass flow rate 28.67 g/s at 9 bar injection pressure Equivalence ratio 0.6-1	A pressure swirl fuel injector provides SMD 17-23 µm	Fluent (RSM and P1 and PDF). Experiments with outlet gas analyser, thermocouples	The outstanding performance of the burner with very low chemical and acoustic emissions at high heat release rates	[10] [40] [11]
Liquid biofuels	Lean premixed	O_2 mass fraction 0.17-0.23 Oxidant temperature 905 K Oxidant flow rate 0.808 kg/s Fuel mass flow rate 0.0065 kg/s	No mention	Fluent (Realize k-ε and EDC)	Building the relationship between the emissions and recirculation ratio	[41]
Liquid Kerosene	Non-premixed	Reference Velocity 12-22 m/s Oxidant temperature >560 K Equivalence ratio 0.2-0.36	No mention	Chemkin and Fluent (Realize k-ε& DO & PDF).	Trapped-vortex is used as the gas generator and flame stabilizer	[42] [40]
Syngasfue l	Premixed	Inlet air pressure 20 bar Inlet air temperature 700K Inlet air velocity 62-75 m/s Equivalence ratio 0.2-1.4	No need	Chemkin and Fluent (Realize k-ε, LES and P1, EDC)	The preliminary optimization of geometry causes different flows in perfect balance and a vortex filling the entire volume	[43] [44]
Biomass gas	Partial premix	O_2 mass fraction 0.17-0.23 Oxidant pressure 270 kPa Oxidant temperature 723 K Oxidant rate 90 g/s (Φ 110 mm) Equivalence ratio 0-1	No need	Chemkin and Experiments (without further information)	A 3 staged combustor for micro-gas turbine	[45]
Natural gas and H_2	Non-premixed	Inlet air pressure 20 bar Inlet air temperature 600-735K Inlet air velocity 40-160 m/s	No need	Experiment with PLIF, temperature, pressure and emissions measurement	A successful operation of the FLOX® combustor with low emissions could be the first time at high pressure	[46] [47]

Liquid hydrocarbons	Non-premixed	Oxidant temperature >600 K Oxidant flow rate 355 g/s Equivalence ratio 0.25-0.75	Pressure atomizer with 0.8 Flow Number	Experiment with SPIV, PLIF, temperature, and noise and emissions measurement	All fuels except for n-butane showed very similar combustion characteristics	[48]

MICRO FLAMELESS COMBUSTION

As to solve the problem from the demand of small scale electricity generation, different small scale called micro combustor power source has been designed and developed. Although some challenges were associated with the system during operation and investigations [9]. However, its combustion features lead to system improvement and design optimization. Modification of old EU burner version with development of improved concept adopting swirl approach for high turbulence intensity was tested both for flameless and pollution reduction, thus yielded huge success [31,33]. A new combustor was investigated under experiment, observed to be stable over a wide range of subjected conditions [49]. At air inlet temperature of 425 K, equivalent ratio 0.24-0.28, the emission on NO_x level was found lower than 10 ppm. The CO level was measured as relatively high of about 700-1200 ppm, indicating more possibility for improvement especially on the design geometry as to increase the combustion efficiency without affecting the performance[6]. According to [9,50,51], on an investigation of bluff-body micro-flameless combustion. The analysis involved two cases of different diluents with different corresponding concentrations (case one: O_2 of concentration of 7% and N_2 diluent applied while case two: O_2 of concentration of 7% and CO_2 diluent applied, as shown in Fig. 3 [9].

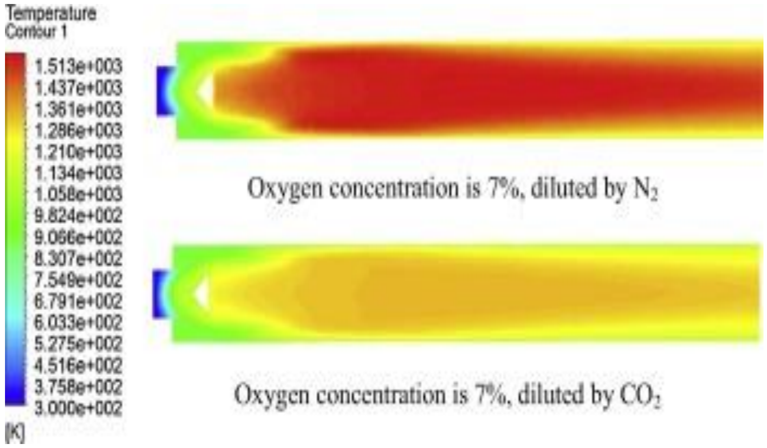

FIGURE 3. Effect of various diluents on the temperature distribution in the micro flameless mode [9].

The investigation indicated a maximum temperature of 1551 °K and 1345 °K for N_2 and CO_2 diluent application respectively, but show the better result with N_2 diluent, hence reported better performance in achieving higher temperature. Also conducted with and without bluff body using the same concentration and diluent cases, the structure of flameless micro-combustion in the cases indicated distribution along the mid axis or centreline, demonstrating the wall temperature of various conditions of micro-flameless mode as in Fig. 4 (a) [9].

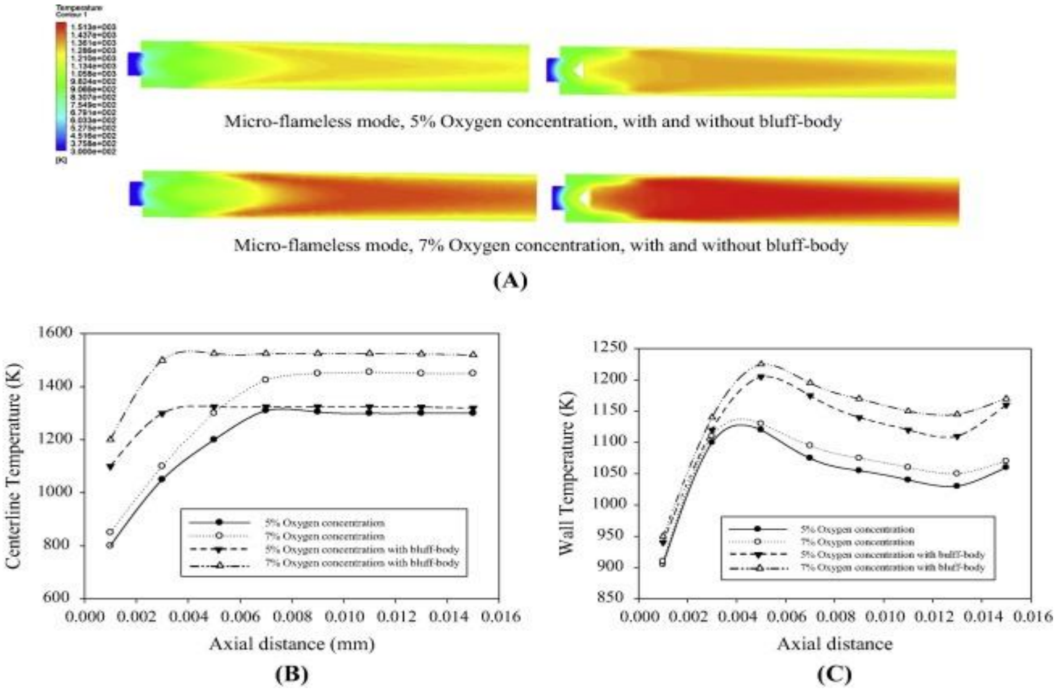

FIGURE 4. Micro flameless combustion mode: (A). Temperature contour of micro-flameless, (B), Temperature distribution along the centerline, (C), wall temperature of the micro-flameless mode [9]

A better explanation of micro-flameless combustion was obtained in terms of temperature distribution and flameless stability when used with the bluff body at the inlet combustor. The shift in the peak temperature to the inlet of the micro flameless combustor with an oxygen concentration of 5% and 7% using bluff body was illustrated in Fig. 4 (B) and (C). With the bluff-body, the maximum temperature of the flameless combustion of CH_4 was 1551 ^oK and 1376 ^oK at 7% and 5% oxygen content in the oxidizer respectively. According to [22,52,53], CO_2 and N_2 were applied as a diluent (oxidizer) in flameless combustion and found eligible.

COMBUSTION IN ASYMMETRIC VORTEX CHAMBERS

Asymmetric vortex chamber is another recommended approach of reducing NO_x emission from the combustion process. This technique improves combustion and is capable to keep a stable flame for a wide range of equivalence ratios [54–56]. The vortex flame is created by injecting air via a tangential port in a cylindrical combustor. The first operation of this kind was in 1998 by Gabler [57]. The use of two methods like asymmetric and axisymmetric for applying fuel was adopted as shown in Fig. 5. During the use of this mode, the developed flam like conventional swirl was found stabilized if introduced axisymmetric fuel inlet thus gives different combustion characteristics if asymmetric fuel inlet was applied. The technology of vortex provide good characteristic for burner combustion [54,55]. Among the huge benefit, it permits operation at excess air premixed regime, provides use of different fuel type for combustion as well as improve flame stability through the opportunity of extending the flammability limits. The most important one is the provision of ultra-low pollutant emission without post-combustion treatment or dilution method [58]. The stabilize combustion and recirculation mode is achieved through swirl flow that recirculates the hot exhaust gas back to the flame root thereby provide optimal mixing and combustion [59,60].

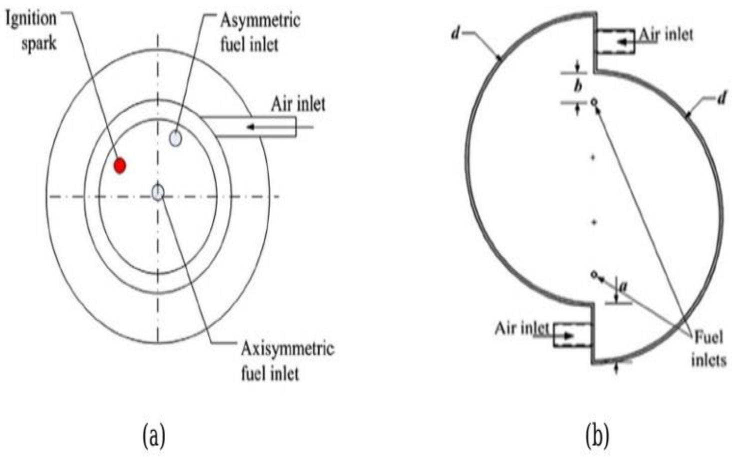

FIGURE 5. Schematic of the Asymmetric vortex combustor presented by a), Gabler [57] and b)Saqr [54,56]

Because of zero-emission combustion analysis, an experiment was conducted by [56,57] on asymmetric combustion compared to axisymmetric mode, thus revealed significant NO_x emissions reduction rate. As NO_x emission strongly depends on oxygen concentration and system temperature, this implies that a decrease in oxygen concentration and temperature reduces NO_x formation [53,61]. In vortex combustion, high swirl intensity and low temperature lead to low NO_x when compared with conventional combustion mode [27,62]. Again, NOx emission is found lower with rich combustion to compare stoichiometric and lean combustion, due to the generation of low temperature from incomplete combustion [63]. However, the experimental data result is higher than predicted NO_x due to the condition of under-prediction of temperature as shown in Fig. 6.

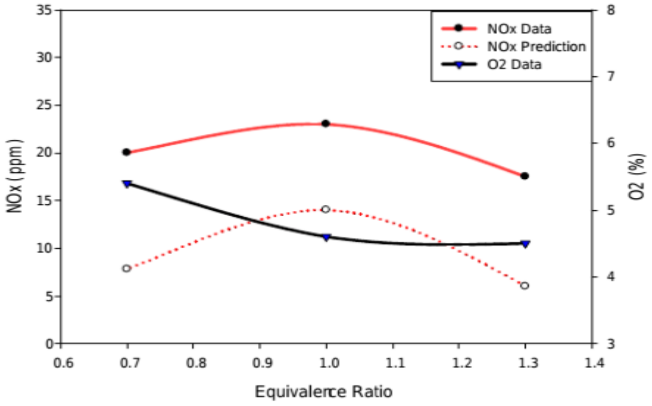

FIGURE 6. Variation of NO_x and oxygen concentration at different equivalence ratio [63]

In the study, visible low NOx emissions and uniform thermal distribution with all equivalence ratios if compare to the counterpart of conventional combustion were achieved. The analysis further detected greater NO_x emission under the condition of stoichiometry, followed lean before the condition of the rich system, hence occur the same in simulation and in experimental. A trapped vortex combustion model of flameless was designed, a very significant reduction in NO_x was recorded with high-performance systems [42,64].

In another new flameless combustion approach called asymmetric whirl combustion as an improved method of NOx reduction was conducted [54,65]. The operation was done using methane fuel, air injection rate from 100 to 200 litres/minute, the fuel flow rate of 1 to 4 litres/minute. In the combustion, the lean fuel-air mixture adiabatic flame temperature rose from 564 to 1389K with the overall equivalence ratio increased from $\phi = 0.095$ to 0.38 NO as a result of the developed Zeldovich mechanism by ϕ increase. Further observed that increase in equivalent ratio brings about excess of HO_2 that help in converting NO to NO_2 [66]. At the same time, with higher equivalence ratios, high concentration of reacting radical species, like H, O and OH atom shows rapid destruction of NO_x to NO. Since the formation of NO_x is ϕ ratio-dependent as shown in Fig. 7, at Q_{air}=100 litres/minute, NO_x<15 ppm was recorded for ϕ <0.18. However, at the same air inlet working condition (Q_{air}=100 litres/minute), NO_x < 25 ppm for ϕ<0.38. Reports from other researchers discovered similar results on rapid quenching of combustion gases that could promote the conversion of NO to NO_2, both in probe walls and gas phase. [67,68]

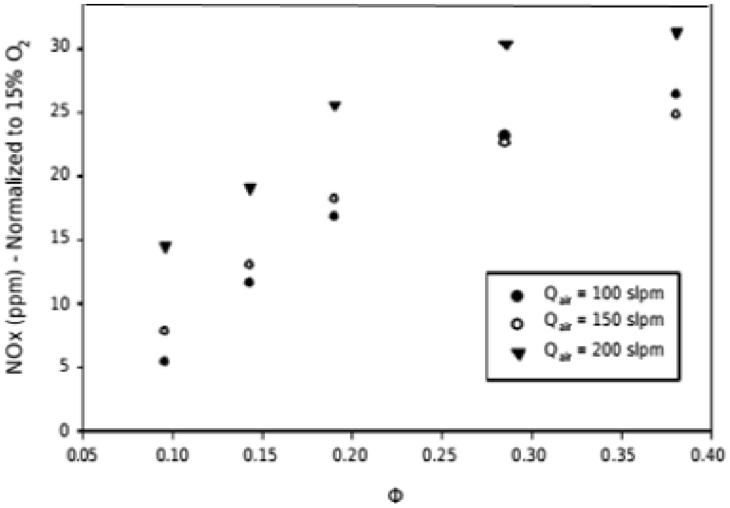

FIGURE 7. NO_x Emissions versus Equivalence ratio, insulated combustor without Air Preheat [65]

Since the reaction of NO and NO_2 gives the summary of all the major nitrogen oxides irrespective of their formation mode. Also, the formation of NO and fuel oxidation are strongly temperature-dependent, lower NO and increased CH_4, CO emissions will be generated as illustrated in Fig. 8 and 9. In a combustion reaction, CO oxidation rates due occur only with temperature however, significant oxidation is mostly observed at temperatures below 1100 K [69–71].

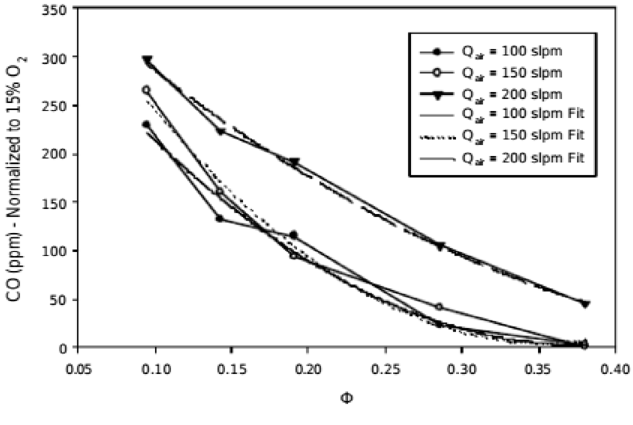

FIGURE 8. CO emissions versus Equivalence ratio, insulated with combustor without Air Preheat [65].

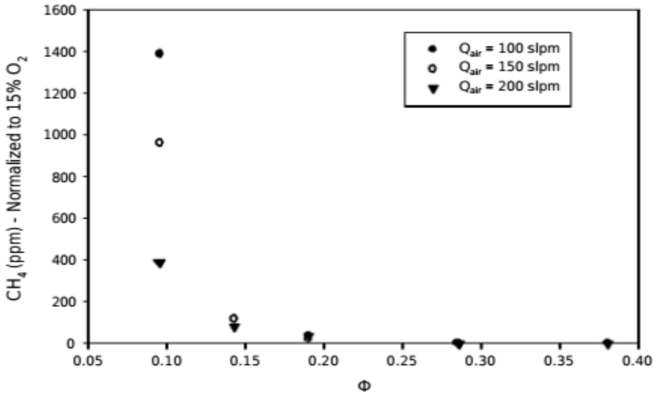

FIGURE 9. CH_4 emissions versus Equivalence ratio for insulated combustor without Air Preheat [65]

The CH_4 and CO mole fractions were found to be high during the leanest investigation with 1389 ppm 230 ppm respectively on $\phi = 0.095$ at O_2 at lowest air inlet rate, without air preheat. Continuously, increased ϕ, fuel oxidation rates accelerated and fuel emission level decreases. With 100 litres/minute, complete consumption of CH_4 was established with $\phi = 0.28$ and CO level with a significant drop to 3 ppm by $\phi = 0.38$ [72]. In addition, oxidation of CO to CO_2 possibly can be achieved through quenching at a system cool wall surface[73]. As the system combustor flame zone is positioned close to the combustor wall in the turbulent shear layer. As a result of this, the temperature of the quartz combustor wall was observed to be cool if compared to normal combustion temperature [74,75]. In the application of preheated inlet air, NO formation and CO oxidation rates are completely dependent on system operating temperature. With that, minimizing one of the species automatically affects the other specific condition. More so, in the kinetic study of the compounds (CO and NO), the two may exist within temperature regime 1700 K, the threshold for NO formation [64,76], and 1100 K, the threshold for CO oxidation [77,78]. This may yield burnout of CO with no significant record of NO formation [78]

BIOMASS FLAMELESS COMBUSTION AND NO_X EMISSION

As mentioned earlier of having some NOx emission confrontations from the utilization of biomaterials. Going flameless combustion mode is because of its significant effects on emission reduction as well as system operation performance enhancement. According to [17,79] on the experiment conducted using biomaterial, observed that the temperature of the furnace was about 1000 ºC, while the preheating combustion air was around 650 ºC. The reaction and image displayed showed a complete breakdown of the reactants with a pronounced image of flame [80] as shown in Fig. 10. The analysis results further indicate stable combustion, low carbon monoxide in exhaust flue gas (<1 ppm) and NO_x emission approximately zero [80].

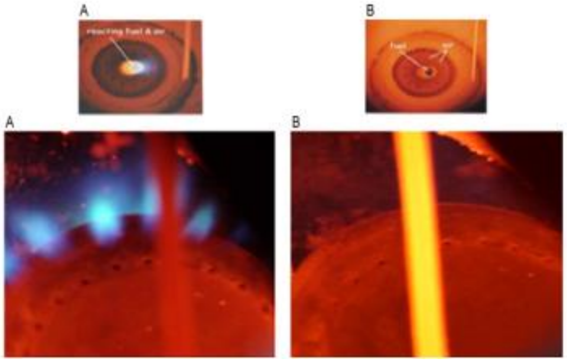

FIGURE 1. Various combustion modes: (a). The flame mode A: conventional flame. B: flameless Combustion. (b). Direct photographs of "A" of visible flame, and "B" of flameless combustion modes using HIREF apparatus [81].

According to [82] on numerical investigation of the asymmetric vortex combustion running on biogas with a component of methane (CH_4), carbon dioxide (CO_2), water (H_2O), Oxygen (O_2), Nitrogen (N_2), Hydrogen sulphide (H_2S) and Hydrogen (H_2) [83]. Application of 80% and 90% methane fuel compositions yielded higher values of NOx compared when using pure methane and other compositions. Again, less or no formation of NO x when 50% and 60% methane compositions were used, hence because of low flame temperatures. Generally, the NO_x emissions were found to be ultra-low as the greatest concentration was of $3.45*10^{-5}$ mole fraction with equivalent to less than 1 ppm. Ultra-low NO_x emission is achieved at 25 ppm [84], this is possible due to the vortex combustor low flame temperature. On the other hand, analysis by [85] 50% methane composition possess the greatest of CO_2. This is because CO_2 is already present as a component of biogas.

Pure methane indicates much CO concentration, with other samples showed lower CO constituents though close to each other if compared. With vortex combustion, high CO emission was recorded near the combustor bottom, reduced close to about 0.002 mass fraction of CO because of oxidation of CO to CO_2 in the vortex flame [86]. According to[1] emissions were found to be low and similar during flameless combustion of NG and biogas, thus measured only residual values of CO and NO from the chimney. Indicate that dilution of NG fuel using inert gases like CO_2 of about 40% gives infinitesimal effect on emissions [87]. More so, dilute fuel with inert gases lead to a reduction of NO_x emission, yielding cooling of inert gases that further lower the operating temperature of the burning zone [22]. NO_x emission formation during flameless combustion using wood pellets as fuel was conducted by [88] The result pointed oxygen element in the mixture to be the influencing parameter. Indicate that the level of oxygen concentration in the reactant inlet air and combustion air temperature is proportional to NOx emission [89]. This is to say that at the increase in combustion air temperature (1000 ^{O}C), the formation of NO_x increases simultaneously with combustion air oxygen concentration, as in Fig. 11 (a) and (b).

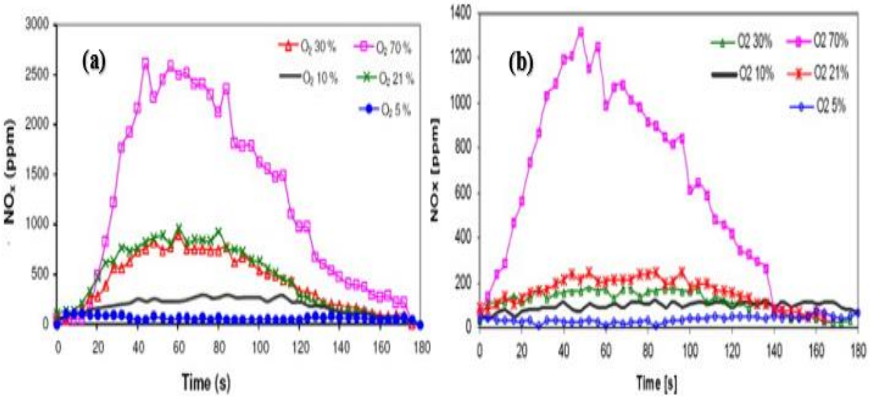

FIGURE 11. Effect of O_2 concentration with time on NO_x emission at 1000 °C and 800 °C [81,90]

The comparison on the formation of NO_x under different oxygen concentration and combustion air temperature of 1000 °C and 800 °C, clearly show the strength of oxygen content in the reaction mixture towards NO_x emission generation [89]. In the analysis, the oxygen concentration of 70% yield the greatest level of NO_x emission and recorded maximum in the two different air temperatures (1000 and 800 °C) and resulted from nitrogen rounded within fuel matrix and excess oxygen (1000 °C) and oxygen and nitrogen from the air (800 °C). In another work conducted by [91,92], on the effect of high preheats air combustion on NO_x emission. The result depicts low NO_x emissions even when conducted under high temperature, thus pointed to be one of the most benefits from using flameless combustion mode [91,93]. The operation still achieved recommended result using an exhaust diluent approach to yield NO_x emissions of about 50 ppm [91]. When temperature increases in traditional combustion approaches, experiences thermal NO_x which is in contrast with the flameless combustion mode [47,94]. Furthermore, in the application of biomass as fuel, when the recirculation ratio of exhaust gas increases [95], certainly, NO_x emission decreases after the increase at the starting and drastically decreases and maintain it as shown in Fig. 12 [81].

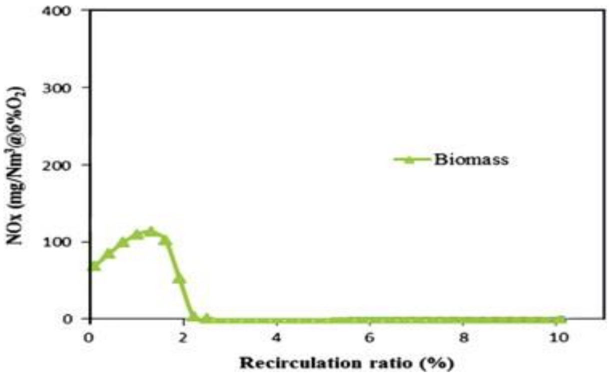

FIGURE 12. Effect of the recirculation ratio on NO_x emission using biomass [81]

In addition, the CO and CO_2 effects due to manifest from values of temperature and oxygen concentration in exhaust combustion gases. As temperature changes from 800 °C to 1000 °C, with 5% oxygen dilution, CO emissions rises from 10.1% to 11.0%. In the case of CO_2 generation, only pronounced at higher oxygen concentration and lower temperature [81]. This shows that CO emissions can be detected in the diluted condition of 5% oxygen. At preheated air combustion when biomass was used as fuel, observed that ignition time decreases as combustion air temperature rises from 350 °C to 800 °C and the same with fossil fuel of coal [24]. A study has it that ignition delay increases with decreasing oxygen concentration and decreases oxidizer temperature thus very important in NO_x emission study [96,97].

FLAMELESS COMBUSTION PERFORMANCE

One of the most advantages of combustion under flameless conditions is their ability to burn fuels of changing and fluctuating quality (LCV of the fuel). Currently, there is serious interest in the combustion flameless regime using fuels from biomass with some reports from researchers concerning their phenomenological features of burning fuels of (LCV) under Mild combustion mode [22,87]. An investigation has been conducted in detail within the European R$D project BIO-PRO [98] on (LCV) liquid and gases under flameless mode. Although a few assessments work on the performance of industrial operations with bio-fuels has been conducted [99]. Performance of a flameless combustion furnace using biogas and natural gas was conducted [1]. On the temperature profile of the fuels (NG and biogas), the left and right axis are not well pronounced because of their similarity with the central axis profile while on flameless mode. Burning with biogas, a slight reduction of temperature of 907 °C was recorded at the mid-plane while the average temperature in mid-plane for NG was observed at about 953 °C. Generally, the temperature reduction when fuelled with natural gas was about 4.8% to the temperature of the burner. The various temperature profile of different fuel used during combustion operations is shown in Fig 13.

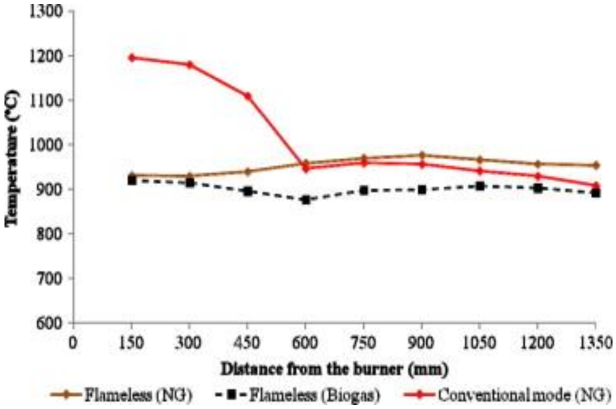

FIGURE 13. Operation Temperature profile along the central axis (Biogas and NG on flameless) and (NG on conventional mode) [1]

Also, there was an observation of excess fumes corresponds to the mass fraction of CO_2 in the biogas, thus increase the amount of the fumes by 8.5% if compared to the overall fumes generated by natural gas [1,22]. With this result, CO_2 possesses better cooling than N_2 because of its characteristics in high heat capacity (C_p) ($Cp\ CO_2/C_pN_2 = 1.28/1.20$ at 1200 °K) at high temperatures [1]. These properties promote radiation features to absorb greater radiation within the reaction zone. This suggests replacing the burning of NG with biogas product, which will not affect the temperature field inside the chamber [22].

The side of energy balance during flameless combustion using a different type of fuel are shown in Table 2. Temperature and mass flow rates measurements of air leaving the cooling tubes and entering air were used to calculate the amount of energy removed by air-cooled tubes. During combustion with biogas in flameless mode, the hot exhaust products together energy loss through chimney was estimated 26 % under the temperature of about 851 °K. Under flameless mode, the energy loss from the chimney fuelled with biogas is found higher compared that loss from the use of NG from the same chimney, also recorded higher efficiency of the regenerative system [72,100].

TABLE 2. Energy balance of combustion (flameless and conventional) using biogas and NG [100].

Combustion mode (fuel)	Flameless mode (biogas)	Flameless mode (NG)	Conventional mode (NG)
Energy input (fuel+ comb air + cooling air)	21.13	21.31	21.02
Energy removed by the cooling tubes (kW)	14.39	14.99	8.71
Energy losses through the wall (kW)	3.00	3.07	3.2
The energy of the combustion products after the regenerative system (kW)	1.01	1.36	0
Energy output through the chimney (kW)	2.72	1.39	8.25
Efficiency (%)	68	70	41.4

In Table. 2, more energy losses found in the use of biogas fuel through the chimney, are from higher CO_2 concentration with more absorption capacity heat radiation. When fuelled with NG, 15% of the combustion products under 881 ° C were escaped through the exhaust path with an energy loss of 6.5 % of the operation total energy input [100]. In flameless combustion, the application of dilute gasoline leads to improvement in managing fuel consumption. This is true because of low combustion temperature product at partial loads thereby losing less heat if compared to ordinary conventional combustion mode [19]. In addition, a flameless combustion engine utilizes an adequate fuel injected to regulate the operating load, instead of restricting the system throttling (inlet airflow) to regulate operation. Generally, as the combustion products are at their optimal levels, it allows the engine to work more efficiently than conventional mode[72,100].

CHALLENGES OF MICRO-SIZE COMBUSTOR

Thermodynamically, it has been proven that combustion performance enhancement is theoretically possible through the turbine burner, mostly with higher compression ratios and bypass ratios projected for future designs. It is essentially important to understand these changes by addressing the combustion difficulties inside the combustion system stages. As the size of the combustor is reduced, the surface of the combustor to volume ratio significantly increases, thus generating high thermal and chemical interactions within the structure of the combustor, flame, and flame-solid interface. To understand heat loss, the effect on the flame extinction in a channel was conducted [101–103] to ascertain the flow velocity applying Lewis number and width of the channel of the flame propagation. The outcome indicated that the near wall-flame quenching together with the flame curvature exhibited a significant role in flame extinction. Another challenge to micro-combustion is how to complete reaction combustion in a micro-scale combustor

which is called residence time [68,104]. To sustain combustion in any combustors, residence time should be larger than chemical reaction time. In general, the residence time is a significant factor that plays an essential role to achieve complete combustion. Supporting the finding, the investigation was carried out by [68,104] to ascertain the heat transfer in the solid phase and also in the system coupling flames. The findings further show that the coupling flame-wall thermal provide a quenching limit, thus led to the manifestation of a new flame regime. In addition, an increase in flame temperature, result in an increase in material strength at elevated pressure and high temperature is another problem incurred. In analysing the effect of excess enthalpy in a Swiss-roll design burner stabilization [105,106], independently for the impact of heat recirculation coming from the burned flue gas to the unburned reactants as shown in Fig. 14, adopting the counter-propagating mode in two parallel techniques.

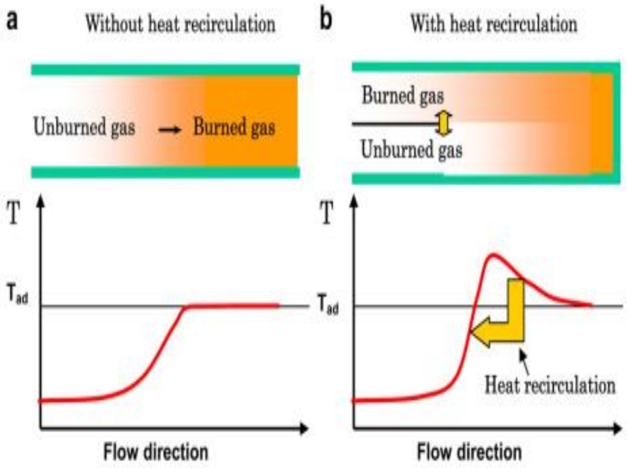

FIGURE 14. Distributions of temperature in the micro swirling burner and heat recirculation burner[107].

Fig. 14, explained that the limit of flammability increased through burned flue gas heat recirculation also, indicated that the flame temperature and flame position due affected by the heat recirculation. Further observed that sub-limit flame due manifest with an increase in flow velocity. In micro combustion future design, the fuel distribution should seriously consider because of the temperature profile, as a more homogeneous profile allows a preferable combustion chamber temperature without affecting the stress on the turbine parts and system load. Therefore, adequate distribution of temperature and inlet flow of the fuel vapour and the air is very essential. Because of solving these confrontations, many micro-thrusters incorporated with different combustor materials, length scales, ignition methods and propellants have been carefully designed and tested with recommendable results [108–110]. Also, to maintain good thermal and chemical sustainability, various micro and mesoscale thrusters designed with high melting point materials were produced and tested using ceramic and quartz tubes, micro-scale combustor of two stages comprises of mesoscale quartz combustor of 10 mm in diameter and sub-millimetre scale catalytic reactor was fabricated and tested successfully[111].

CONCLUSION

Flameless combustion shows great characteristics towards substituting the conventional combustion mode of any form. Avoiding the high adiabatic flame temperature conditions contribute to reducing the associated combustion high NOx emission. These features make flameless mode worthy of attention and further investigation. Operation utilizing trapped vortex, micro flameless, asymmetric vortex chambers etc. combustor provides intrinsic nature of improving the mixing of hot combustion gases and fresh mixture that represents a prerequisite for diluted combustion and at the most flameless combustion regime. Several advantages were offered from various modified flameless burners like an extension of the flammability limits, burning low calorific value fuels, and extremely low NOx emissions. In most of the flameless combustion, pollutant emissions of NO_x and CO were found to be very low at about 3 ppm and 16 ppm respectively during the burning of biogas and natural gas. Operating with biogas fuel, the system efficiency was 2 % lower with little reduction in exhaust temperature. With this, flameless combustion using biogas stands to hold thermal load constant than natural gas but yet better to practice than conventional mode. The performance of the system flameless combustion furnace remains almost constant with all fuel types, thus recorded more advantage over the counterpart. The overall approach in achieving flameless with high pollutants reduction is to design the flow field of the combustor to have a dilution of fresh reactants and high-temperature flue gas recirculation. The outcome of a flameless combustion regime permits consumption or interchangeability among combustion fuels of different compositions.

Although flameless proves promising technology, yet, some challenges due arise in flameless combustion mode like predicting the most efficient mixing approach (fuel/air), resulting from fuel spry characteristics, port geometry/configuration and others. An issue like uncontrolled combustion and explosion from a stochastic misfire and knock due arise. Most of these issues emanate from the combustion design and flameless phenomena analysis. Difficulties are still found in flameless operation which is not understood from the experiment and numerical studies. Due to behaviour exhibited by some fuels during chemical reactions, additional work is seriously required during the computational simulations to predict suitable parameters (flow) before computational fluid dynamics modelling to solve the problem of uncertainty. Capturing accurate mass flow rate, pressure, high enthalpy states and temperature is very difficult with the experimental approach due to some errors during data reading. However, flameless mode advantages in emission control, performance optimization and fuel economy make it a more interesting and worthy technology.

REFERENCE

1. A. F. Colorado, B. A. Herrera, and A. A. Amell, “Performance of a Flameless combustion furnace using biogas and natural gas,” *Bioresour. Technol.*, 101(7), 2443–2449 (2010).
2. M. Mörtberg, W. Blasiak, and A. K. Gupta, “Combustion of normal and low calorific fuels in high temperature and oxygen deficient environment,” *Combust. Sci. Technol.*, 78(7), 1345–1372 (2006).
3. A. A. A. Abuelnuor *et al.*, “Characteristics of biomass in flameless combustion: A review,” *Renew. Sustain. Energy Rev.*, 33, 363–370 (2014).
4. A. Gupta, “Clean energy conversion from waste fuels using high temperature air combustion technology,” *Asian J. Energy Env.*, 5 (4) 223–266 (2004).
5. A. K. Gupta, “Thermal Characteristics of Gaseous Fuel Flames Using High Temperature Air,” 126(1) 9-19 (2018).
6. F. Xing *et al.*, Flameless combustion with liquid fuel: A review focusing on fundamentals and gas turbine application, 193 28-51 (2017).
7. S. E. Hosseini, M. A. Wahid, and N. Aghili, “The scenario of greenhouse gases reduction in Malaysia,” *Renew. Sustain. Energy Rev.* 28 (12) 400–409 (2013).
8. S. E. Hosseini, M. A. Wahid, and S. Salehirad, “Environmental protection and fuel consumption reduction by flameless combustion technology: A review,” *Appl. Mech. Mater.*, 388 (45) 292–297 (2013).
9. S. E. Hosseini and M. A. Wahid, “Investigation of bluff-body micro-flameless combustion,” *Energy Convers. Manag.*, 88, 120–128 (2014).
10. V. Mahendra Reddy and S. Kumar, “Development of high intensity low emission combustor for achieving flameless combustion of liquid fuels,” *Propuls. Power Res.*, 2 (2) 139–147 (2013).
11. V. M. Reddy, A. Katoch, W. L. Roberts, and S. Kumar, “Experimental and numerical analysis for high intensity swirl based ultra-low emission flameless combustor operating with liquid fuels,” *Proc. Combust. Inst.*, 35 (3) 3581–3589 (2015).
12. A. A. Abuelnuor, M. A. Wahid, H. A. Mohammed, and A. Saat, “Flameless combustion role in the mitigation of NOx emission : a review,” *Int. J. ENERGY Res.*, 38, 827–846 (2014).
13. S. E. Hosseini and M. A. Wahid, “Enhancement of exergy efficiency in combustion systems using flameless mode,” *Energy Convers. Manag.*, 86 1154–1163 (2014).
14. S. Zhu, A. Pozarlik, D. Roekaerts, H. C. Rodrigues, and T. van der Meer, “Numerical investigation towards HiTAC conditions in laboratory-scale ethanol spray combustion,” *Fuel*, 211 (5) 375–389 (2018).
15. S. Lille, W. Blasiak, and M. Jewartowski, “Experimental study of the fuel jet combustion in high temperature and low oxygen content exhaust gases,” *Energy*, 30 (2-4) 373–384 (2005).
16. Y. Tu *et al.*, “MILD combustion of natural gas using low preheating temperature air in an industrial furnace,” *Fuel Process. Technol.*, 156 72–81 (2017).
17. A. Cavaliere and M. De Joannon, *Mild combustion*, Progress in Energy and Combustion Science 30 (4) 329-366 (2004).
18. A. Sobiesiak, S. Rahbar, and H. A. Becker, “Performance characteristics of the novel low-NOx CGRI burner for use with high air preheat,” *Combust. Flame*, 115 (1–2) 93–125 (1998).
19. G. Sorrentino, P. Sabia, M. De Joannon, and P. Bozza, “Influence of preheating and thermal power on cyclonic burner characteristics under mild combustion,” 233(6) 207–214 (2018).
20. P. Li, B. B. Dally, J. Mi, and F. Wang, “MILD oxy-combustion of gaseous fuels in a laboratory-scale furnace,”

Combust. Flame, 160 (5) 933–946 (2013).

21. T. Marco, S. M. Camporeale, and B. Fortunato, “Diluted combustion in a aerodynamically staged swirled burner fueled by diesel oil,” *Process. Technol. a Sustain. energy,* 27 (30) 1–9 (2010).
22. B. B. Dally, E. Riesmeier, and N. Peters, “Effect of fuel mixture on moderate and intense low oxygen dilution combustion,” *Combust. Flame,* 137 (4) 418–431 (2004).
23. P. Sabia, M. De Joannon, A. Picarelli, and R. Ragucci, “Methane auto-ignition delay times and oxidation regimes in MILD combustion at atmospheric pressure,” *Combust. Flame,* 160 (1) 47–55 (2013).
24. P. Sabia, M. de Joannon, G. Sorrentino, P. Giudicianni, and R. Ragucci, “Effects of mixture composition, dilution level and pressure on auto-ignition delay times of propane mixtures,” *Chem. Eng. J.,* 277 324–333 (2015).
25. J. A. Wuenning and J. G. Wuenning, “Flameless Oxidation to Reduce Thermal {NO}-formation,” *Prog. Energy Combust. Sci.,* 23 81–94 (1997).
26. A. Di Benedetto, V. Di Sarli, and G. Russo, “Effect of geometry on the thermal behavior of catalytic micro-combustors,” *Catal. Today,* 155 (1–2) 116–122 (2010).
27. R. A. Alwan, “Thermal and Fluid Flow Analysis of Swirling Flameless Combustion,” 39 (3) 561–563 (2016).
28. D. Tabacco, C. Innarella, and C. Bruno, *Theoretical And Numerical Investigation On Flameless Combustion*, 174 (6) (2002).
29. C. V. Lieuwen, *Gas Turbine Emissions. Cambridge*. 2013.
30. M. J. Melo, J. M. M. Sousa, M. Costa, and Y. Levy, “Flow and combustion characteristics of a low-NOx combustor model for gas turbines,” *J. Propuls. Power,* 27 (6) 1212–1217 (2013).
31. Y. Levy, G. A. Rao, and V. Sherbaum, “Chemical kinetic and thermodynamics of flameless combustion methodology for gas turbine combustors,” *Collect. Tech. Pap. - 43rd AIAA/ASME/SAE/ASEE Jt. Propuls. Conf.,* 6 (7) 6099–6116 (2007).
32. Y. Levy, V. Sherbaum, and P. Arfi, “Basic thermodynamics of FLOXCOM, the low-NOx gas turbines adiabatic combustor,” *Appl. Therm. Eng.,*24 (11–12) 1593–1605 (2004).
33. G. Li *et al.*, “Experimental study of flameless combustion in gas turbine combustors,” *Collect. Tech. Pap. - 44th AIAA Aerosp. Sci. Meet.* 9, 6619–6633 (2006).
34. M. D. Guyot, “Pollutant and Noise Emissions in a Flameless Trapped-Vortex Reheat Burner (FTVRB),” in *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*,. 8–11 (2007).
35. I. O. Awosope, N. H. Kandamby, and F. C. Lockwood, “Flameless oxidation modelling: On application to gas turbine combustors,” *J. Energy Inst.,* 79 (2) 75–83 (2016).
36. M. Losurdo, C. Bruno, and L. Patrignani, “Numerical simulations of trapped vortex combustors. Feasibility study of TVC integration in traditional GT combustion chambers,” in *Collection of Technical Papers - AIAA/ASME/SAE/ASEE 42nd Joint Propulsion Conference,* 10 7846–7860 (2012).
37. E. Varea, S. Kruse, H. Pitsch, T. Albin, and D. Abel, “Actuation studies for active control of MILD combustion for gas turbine application,” *Proc. ASME Turbo Expo,* 4B 1–5, (2014).
38. Y. Jing and Q. Zhao, “Realization of Flalemess Combustion of Liquid Fuel,” pp. 2088–2092 (2012).
39. Y. Cui, T. Ye, and Q. Lin, “Effect of fuel air equivalence ratio on the flameless combustion of liquid hydrocarbon,” *J. Univ. Sci. Technol. China,* 42 325–334 (2012).
40. V. M. Reddy, D. Sawant, D. Trivedi, and S. Kumar, “Studies on a liquid fuel based two stage flameless combustor,” *Proc. Combust. Inst.,* 34 (2) 3319–3326 (2013).
41. M. C. Cameretti, R. Tuccillo, F. Reale, and R. Piazzesi, “Liquid bio-fuels in an EGR equipped micro gas turbine,” *Proc. ASME Turbo Expo,* 3, 909–918 (2011).
42. P. Z. Zang, “Numerical simulation of flameless combustor based on trapped-vortex,” *Combust. Flame,* (2) 3–14 (2012).
43. A. Di Nardo, G. Calchetti, S. Giammartini, G. Ingrassia, and C. Mongiello, “Design and analysis of a gas turbine trapped vortex combustion chamber operating in MILD regime,” *rocesses Technol. a Sustain. energy,* (1) 27–30 (2010).
44. A. Di Nardo, G. Calchetti, and C. Mongiello, “Non-premixed syngas MILD combustion: The trapped-vortex approach,” *Proc. Int. Symp. Turbul. Heat Mass Transf.,* (9) 787–796, (2012).
45. M. Hiramatsu, Y. Nakashima, S. Kaneko, Y. Yamasaki, and S. Adachi, “Combustion characteristics of small size gas turbine combustor fueled by biomass gas employing flameless combustion,” in *Proceedings of GT2007 ASME Turbo Expo 2007: Power for Land, Sea and Air* 1–7 (2007).
46. M. A. Rainer Lückerath, W. Meier, “Combustion at High Pressure With Different Fuel Compositions,” *J. Eng. Gas Turbines Power,* 130 (1) 1–7 (2008).

47. R. Sadanandan, R. Lückerath, W. Meier, and C. Wahl, “Flame characteristics and emissions in flameless combustion under gas turbine relevant conditions,” *J. Propuls. Power*, 27 (5) 970–980 (2012).
48. E. Guillou, M. Cornwell, and E. Gutmark, “Application of ‘Flameless’ combustion for Gas Turbine Engines,” *47th AIAA Aerosp. Sci. Meet. Incl. New Horizons Forum Aerosp. Expo.*, (1) 1–10 (2009).
49. C. L. Cha, H. Y. Lee, and S. S. Hwang, “An experiment analysis of MILD combustion with liquid fuel spray in a combustion vessel,” *J. Mech. Sci. Technol.,* 33 (8) 3717–3724 (2019).
50. G. Bagheri, S. E. Hosseini, and M. A. Wahid, “Effects of bluff body shape on the flame stability in premixed micro-combustion of hydrogen-air mixture,” *Appl. Therm. Eng.,*67 (1–2) 266–272 (2014).
51. A. Fan, H. Zhang, and J. Wan, “Numerical investigation on flame blow-off limit of a novel microscale Swiss-roll combustor with a bluff-body,” *Energy*, 123, 252–259 (2017).
52. T. Hiroshi Tsuji, Ashwani K. Gupta, M. M. Hasegawa, Masashi Katsuki, Ken Kishimoto, and Search, *High Temperature Air Combustion: From Energy Conservation to Pollution Reduction*. pp.424 (2001).
53. J. Zhang, J. Mi, P. Li, F. Wang and B. B. Dally, “Moderate or Intense Low-Oxygen Dilution Combustion of Methane Diluted by CO2 and N2,” *energy fuel,* 4576–4585 (2015).
54. R. A. Alwan, M. A. Wahid, A. A. A. Abuelnuor, and M. Suardi, “Combustion in asymmetric vortex chambers Combustion in asymmetric vortex chambers,” (10) 1–6, 2015.
55. M. Khaleghi, S. E. Hosseini, and M. A. Wahid, “Emission and combustion characteristics of hydrogen in vortex flame,” *J. Teknol. (Sciences Eng.,* 66 (2) 47–51 (2014).
56. K. M. Saqr, H. S. Aly, M. M. Sies, and M. A. Wahid, “Computational and experimental investigations of turbulent asymmetric vortex flames,” *Int. Commun. Heat Mass Transf.,* 38 (3) 353–362 (2011).
57. H. C. Gabler*, An experimental and numerical investigation of asymmetrically-fueled whirl flames* . 1998.
58. K. Adam and M. A. Wahid, “On the effects of tangential air inlets distribution configurations to the combustion characteristics of a direct injection liquid fueled swirl flameless combustor (Sfc),” *Evergreen,* 8 (1) 117–122 (2021).
59. A. E. E. Khalil and A. K. Gupta, “Distributed swirl combustion for gas turbine application,” *Appl. Energy,* 88 (12) 4898–4907 (2011).
60. S. Archer and A. K. Gupta, “Effect of swirl on flow dynamics in unconfined and confined gaseous fuel flames,” in *42nd AIAA Aerospace Sciences Meeting and Exhibit*, , 9236–9241 (2004).
61. A. K. Gupta and T. Hasegawa, “The effect of air preheat temperature and oxygen concentration in air on the structure of propane air diffusion flames,” *37th Aerosp. Sci. Meet. Exhib.*, 121(9) 209–216 (1999).
62. A. E. E. Khalil and A. K. Gupta, “Swirling distributed combustion for clean energy conversion in gas turbine applications,” *Appl. Energy,* 88 (11) 3685–3693 (2011).
63. N. Burner, R. A. Alwan, M. A. Wahid, M. Fairus, and M. Yasin, “Effects of Equivalence Ratio on Asymmetric Vortex Combustion in a Low NOx Burner,” *Int. Rev. Mech. Eng.,* 9(5) 1970–8734 (2015).
64. K. I. Khidr, Y. A. Eldrainy, and M. M. El-kassaby, “Towards lower gas turbine emissions : Flameless distributed combustion,” *Renew. Sustain. Energy Rev.*, 67, 1237–1266 (2017).
65. H. Gabler, R. Yetter, and I. Glassman, “Asymmetric Whirl Combustion : A New Approach for Non-Premixed Low NOx Gas Turbine Combustor Design Joint Propulsion Conference & Exhibit,1-2 (1998).
66. V. K. Arghode and A. K. Gupta, “Investigation of distributed combustion for gas turbine application: Forward flow configuration,” *Am. Soc. Mech. Eng. Power Div. POWER,* 88, (1) 57–70 (2010).
67. Y. Saiki and Y. Suzuki, “Effect of wall surface reaction on a methane-air premixed flame in narrow channels with different wall materials,” *Proc. Combust. Inst.*, 34 (2) 3395–3402 (2013).
68. M. J. Lee, S. M. Cho, B. Il Choi, and N. Il Kim, “Scale and material effects on flame characteristics in small heat recirculation combustors of a counter-current channel type,” *Appl. Therm. Eng.* 30 (14–15) 2227–2235 (2010).
69. F. L. Dryer and C. K. Westbrook, “Simplified Reaction Mechanisms for the Oxidation of Hydrocarbon Fuels in Flames,” *Combust. Sci. Technol.*, 27 (1–2) 31–43 (1981).
70. F. Delacroix, “‘ The Flameless Oxidation Mode’: An Efficient Combustion Device Leading Also To Very Low Nox Emission Levels,” in *French Agency for energy and environment management,* 1–20 (2004)
71. D. Ristic, “Feasibility and NOx Reduction Potential of Flameless Oxidation in Pulverised Coal Combustion,” *Feasibility NOx Reduct. Potential Flameless Oxid. Pulverised Coal Combust.*, 49 , 0–10 (2012).
72. S. E. Hosseini and M. A. Wahid, “Development of biogas combustion in combined heat and power generation,” *Renew. Sustain. Energy Rev.*, 40, 868–875 (2014).
73. A. Quinqueneau *et al.*, “‘Flameless Oxidation’ Applied to High Temperature Process, Overview of Gaz De France R & D Activities On the Subject ”,” 1-141 (2002).

74. V. K. Arghode and A. K. Gupta, “Effect of confinement on colorless distributed combustion for gas turbine engines,” *45th AIAA/ASME/SAE/ASEE Jt. Propuls. Conf. Exhib.*, 2 (8) 1–10 (2009).
75. W. Yang, C. Deng, J. Zhou, J. Liu, Y. Wang, and K. Cen, “Experimental and numerical investigations of hydrogen-air premixed combustion in a converging-diverging micro tube,” *Int. J. Hydrogen Energy*, 39 (7) 3469–3476 (2014).
76. A. Parente, A. Cuoci, C. Galletti, A. Frassoldati, T. Faravelli, and L. Tognotti, “NO formation in flameless combustion : comparison of different modeling approaches,” 1–6, (2009).
77. A. S. Veríssimo, A. M. A. Rocha, and M. Costa, “Importance of the inlet air velocity on the establishment of flameless combustion in a laboratory combustor,” *Exp. Therm. Fluid Sci.*, 44, 75–81 (2013).
78. A. S. Veríssimo, A. M. A. Rocha, and M. Costa, “Operational , Combustion , and Emission Characteristics of a Small-Scale Combustor,” 2011.
79. Z. Shu, C. Dai, P. Li, and J. Mi, “Nitric oxide of MILD combustion of a methane jet fl ame in hot oxidizer co fl ow : Its formations and emissions under H_2O , CO_2 and N_2 dilutions,” *Fuel*, 234 (6) 567–580 (2018).
80. A. A. Abuelnuora, M. A. Wahida, A. Saata, “Characterization of a Low NO x Flameless Combustion Burner Using Natural Gas,” *J. Teknol.*, 2, (x) 121–125 (2014).
81. A. A. Abuelnuor *et al.*, “Characteristics of biomass in flameless combustion : A review,” 33, 363–370 (2014).
82. S. Hoon, S. Hyun, and S. Lee, “Reduction in nitrogen oxides emissions by MILD combustion of dried sludge,” *Renew. Energy*, 65 (x) 29–35 (2014).
83. T. Suda, M. Takafuji, T. Hirata, M. Yoshino, and J. Sato, “A Study of combustion behavior of pulverized coal in high-temperature air,” in *Proceedings of the Combustion Institute*, , 29 503–509 (2002).
84. Z. Peiyong Ma, ZhiguoTang, “Research on an Approach to High Temperature Flameless Combustion Technology of Biomass. Challenges of Power Engineering and Environment,” 1094-1198 (2018).
85. J. Li, W. Yang, W. Blasiak, and A. Ponzio, “Volumetric combustion of biomass for CO_2 and NOx reduction in coal-fired boilers,” *Fuel*, 102 624–633 (2012).
86. M. M. Sies and M. A. Wahid, “Numerical investigation of the asymmetrical vortex combustor running on biogas,” *J. Adv. Res. Fluid Mech. Therm. Sci.*, 74 (1)) 1–18 (2020)
87. P. Taylor, A. Effuggi, D. Gelosa, and M. Derudi, “Mild Combustion of Methane-Derived Fuel Mixtures : Natural Gas and Biogas,” *Combust. Sci. Technol.*, 180 (3) 481–493 (2008).
88. A. A. Abuelnuor, “Thermal Characteristics and Emissions Of gaseous Fuel Flameless Combustion With Tangential air Inlet.,”1-156 (2014).
89. R. Dinu, “Wood pellets combustion with rich and diluted air in HTAC furnace; The Royal Institute of Technology – Stockholm Wood,” 1-22 (2006).
90. G. M. Choi and M. Katsuki, “Advanced low NOx combustion using highly preheated air,” *Energy Convers. Manag.*, 42 (5) 639–652 (2001).
91. H. S. Zhen, J. Miao, C. W. Leung, C. S. Cheung, and Z. H. Huang, “A study on the effects of air preheat on the combustion and heat transfer characteristics of Bunsen flames,” *Fuel*, 184 (x) 50–58 (2016).
92. R. K. M. Nishimura, T. Suzuki, “Low-NOx Combustion Under High Preheated Air Temperature Condition In An Industrial Furnace,” *Energy Convers. Mgmt*, 38 (10–13), 1353–1363 (1997).
93. J. Richter, J. D. Gounder, C. Naumann, and W. Meier, “Exhaust Gas Recirculation at Elevated Pressure Using a FLOX(R) Combustor,” in *Turbomachinery Technical Conference and Exposition*, , 1–12 (2017).
94. M. M. Sies, M. O. Abdalla, and S. E. Hosseini, “Effects of Firing Mode on the Performance of Flameless Combustion : A Review,” *Appl. Mech. Mater.*, (5) 2014 1–9, (2013).
95. Y. Furutani, K. Norinaga, S. Kudo, J. I. Hayashi, and T. Watanabe, “Current situation and future scope of biomass gasification in Japan,” *Evergreen*, 4 (4) 24–29 (2017).
96. A. Cavaliere, M. De Joannon, and R. Ragucci, *Highly Preheated Lean Combustion*.1-120 (2008).
97. M. Mehregan and M. Moghiman, “A numerical investigation of preheated diluted oxidizer influence on NOx emission of biogas flameless combustion using Taguchi approach,” *Fuel*, 227 (7) 1–5 (2018).
98. R. S. G. W. Berger, “Neue Brennersysteme für Bio-Raffinerien: New burner systems for bio-refineries,” (6) 1-4 (2006).
99. S. Kalisz, M. Pronobis, and D. Baxter, “Co-firing of biomass waste-derived syngas in coal power boiler,” *Energy*, 33 (12) 1770–1778 (2008).
100. S. E. Hosseini, M. A. Wahid, and A. A. A. Abuelnuor, “Biogas Flameless Combustion : A Review,” *Appl. Mech. Mater.*, 388, 273–279 (2013).
101. J. Daou and M. Matalon, “Influence of conductive heat-losses on the propagation of premixed flames in channels,” *Combust. Flame*, 128 (4) 321–339 (2002).

102. J. Daou and M. Matalon, "Flame propagation in Poiseuille flow under adiabatic conditions," *Combust. Flame*, 124 (3) 337–349 (2001).
103. J. Daou, J. Dold, and M. Matalon, "The thick flame asymptotic limit and Damköhler's hypothesis," *Combust. Theory Model.*, 6 (1) 141–153 (2002).
104. F. Richecoeur and D. C. Kyritsis, "Experimental study of flame stabilization in low Reynolds and Dean number flows in curved mesoscale ducts," *Proc. Combust. Inst.*, 30 (2) 2419–2427 (2005).
105. P. D. Ronney, "Analysis of non-adiabatic heat-recirculating combustors," *Combust. Flame*, 135 (4) 421–439 (2003).
106. Y. Ju and C. W. Choi, "An analysis of sub-limit flame dynamics using opposite propagating flames in mesoscale channels," *Combust. Flame*, 133 (4) 483–493 (2003).
107. Y. Ju and K. Maruta, "Microscale combustion: Technology development and fundamental research," *Prog. Energy Combust. Sci.*, 37 (6) 669–715 (2011).
108. C. M. Miesse, R. I. Masel, C. D. Jensen, M. A. Shannon, and M. Short, "Submillimeter-scale combustion," *AIChE J.*, 50 (12) 3206–3214 (2004).
109. M. H. Wu, R. A. Yetter, and V. Yang, "Development and characterization of ceramic micro chemical propulsion and combustion systems," *46th AIAA Aerosp. Sci. Meet. Exhib.*, no. January, pp. 1–14 (2008).
110. D. H. Lewis, S. W. Janson, R. B. Cohen, and E. K. Antonsson, "Digital micropropulsion," *Sensors Actuators, A Phys.*, 80 (2) 143–154 (2000).
111. P. Galie, B. Xu, and Y. Ju, "Kinetic enhancement of mesoscale combustion using a novel nested doll combustor," *Collect. Tech. Pap. - 45th AIAA Aerosp. Sci. Meet.*, 10 (1) 6993–6999, (2007).