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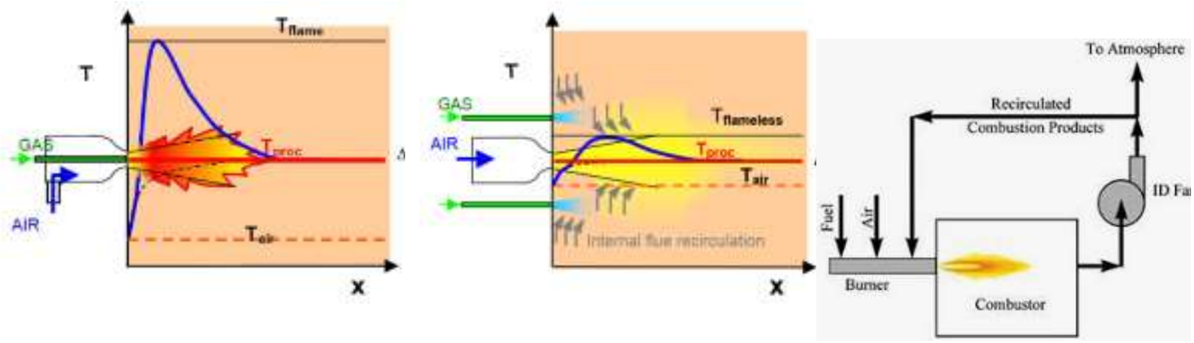
Abstract. Flameless combustion offers more promising results than conventional combustion, such as reduced NO_x emissions with enhanced thermal efficiencies. Flameless combustion of various gaseous fuels and furnace configurations have been fully investigated. However, the burning of liquid fuel flameless combustion is still scarce and not fully explored due to its complex processes such as atomization, evaporation, and mixture formation before combustion takes place. Despite the efforts and recent developments in this area, it is still essential to perform extensive studies on liquid fuel flameless combustion using various liquid fuels and flow configurations to improve the versatility of using liquid fuel as a source of energy. Several preliminary studies have reported numerous promising results of using liquid fuel in both small and complex designs. However, research in this area is still in the early stages, and thorough investigations are required, especially in simple and large burners to mimic industrial burners. This review paper aims to provide key findings from the latest development in liquid fuel flameless combustion with a thorough explanation of the combustion characteristics of liquid fuel flameless combustion. The end of this article highlights some possible contributions and research gaps.

INTRODUCTION

Combustion of fossil fuel remains the primary source of energy generation world widely, as it accomplishes up to 80% of the energy needs in industrial furnaces and power generation [1]. It plays an essential role in our modern technological society, both industrial and domestic applications, because of the high temperature associated with the burning of fossil fuels. However, its concurrently emitting high pollutant emissions and green gases that are detrimental to the environment and public health [2]. Since total elimination of fossil fuels is not achievable at our current knowledge and technology development stage. So, optimization of combustion processes is one of the possible ways to mitigate the adverse effect issue. These challenges drove interest in developing efficient and clean combustion techniques for a better future for humanity [3–5]. Many combustion technologies have been developed to minimize pollutant gas emissions through homogenous combustion. Flameless combustion is proven to be one of the most promising combustion techniques, which causes a more uniform temperature distribution within the reacting zone. In this way, high-temperature zones are eliminated, and simultaneously, the NO_x and CO production is reduced.

FLAMELESS COMBUSTION

Flameless combustion is one of the novel combustion techniques that enhances thermal efficiency and simultaneously lowers pollutant emissions [6–8]. Flameless combustion can be achievable through preheating and diluting the incoming reactants with internal (**FIGURE 1b**) or external recirculation **FIGURE 1c**) of the flue gases [9,10] To decrease the flame temperature of the furnace, Leading to a distributed reaction zone, less NOx formation, CO, and other pollutants such as soot and particulate matter [6,10–14]. Unlike the conventional flame (**FIGURE 1a**), where the temperature is higher at the burner exit due to the flame front at that point. Flameless combustion is characterized by a low peak temperature and uniform distribution through the combustor volume (**FIGURE 1b**), but above the fuel's auto-ignition temperature and below the dissociation temperature of N2 and O2 and accomplished with excellent combustion stability. The low oxygen concentration results in a distributed reaction zone; no visible flame; it produces less noise level and thermal stress for burners and fewer fuels restraint [15]. This form of combustion is desired in many industrial applications [6,15–17]. It is highly applicable in industrial burners that need high and uniformly distributed temperature, such as in metallurgical industries where energy saving is an issue, cement companies, waste treatment, boilers, gas turbines, or petrochemical [18,19]. The preoccupation of developing the flameless combustion technique in industries is for less NOx formation, increases heat transfer rate, and prolongs the equipment's lifespan, which is mostly damaged by extremely high heat flux [20]. The alternative names of flameless combustion include: Moderate and Intense Low Oxygen Dilution (MILD) combustion [9,21–23], High Temperature Air Combustion (HiTAC) [3,24], Colorless Distributed Combustion(CDC) [25], Stagnation Point Reverse Flow (SPRF) combustor [26], Flameless Oxidation (FLOX) [24,27], and High Intensity Low Emission (HILE) burner [28], fuel direct injection (FDI), and dilute combustion,[29].



(a) (b) (c)

FIGURE 1. Comparison between conventional flame (a), flameless combustion/ Internal EGR (b) and External EGR [30]

Flameless combustion has been widely studied and reviewed for gaseous fuel for different configurations without many difficulties as both fuel and oxidizer are in gaseous forms. However, the complexity of the Liquid fuel flameless combustion has obstructed its large-scale availability in the area of research and development, as it involves complex processes from atomization of the liquid fuel to droplets, evaporation, mixing before burning finally [12,31]. Hence, the combustion characteristics of liquid fuel in flameless need to be explored more in terms of various flow configurations in both axial and tangential air inlets. Still, liquid fuel flameless combustion is rarely reviewed to favor its understanding and popularization.

PRINCIPLES OF FLAMELESS COMBUSTION

Flameless combustion is based on exhaust gas recirculation, which suppresses NO_x formation without compromising thermal efficiency. It is formed when the combustor reactants temperature is above the fuel's auto-ignition temperature, and the recirculation ratio is increasing gradually to 3 and above **(FIGURE 4)**. Suppose the fuel is injected directly into the furnace at particular turbulence and velocity levels and bypasses the mixer with combustion air. In that case, this produces an oxidation reaction that is not visible, smooth, and stable but still produces thermal energy [21]. **FIGURE 2** shows the flame mode While **FIGURE 3** shows the flameless combustion mode.

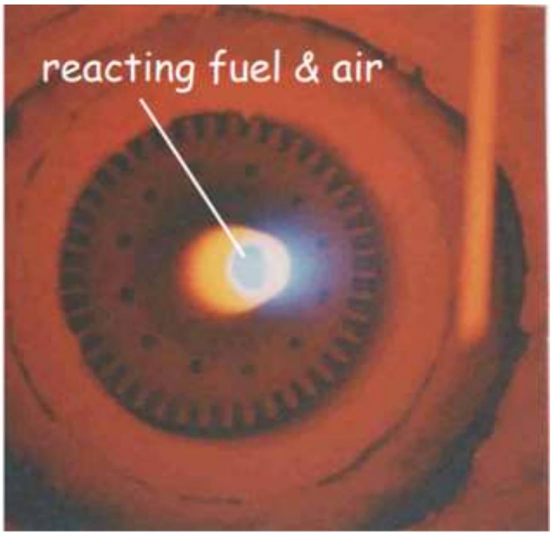


FIGURE 2. The reaction zone of flame mode

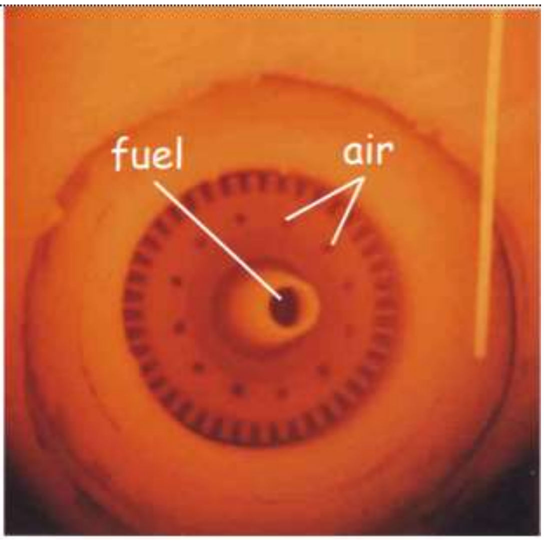


FIGURE 3. The reaction zone of flameless modes

In summary, the following points are of paramount important key points in achieving flameless combustion:

i. Recirculation of flue gases that dilutes the reactants is a crucial point in maintaining flameless combustion. Dilution widens the reaction zone into more volumetric distribution.
ii. Exhaust gas recirculation ratio (kv) of 3 and above.
iii. O_2 concentration of the reaction zone between 5%–10% is required and its temperature to be more than the autoignition of the mixture [32].
iv. Preheating of combustion air is no longer a requirement rather, it is advantageous.
v. recycling the flue gases through a regenerator increases the thermal efficiency of flameless combustion to about 30%, likewise reduces the harmful NO_x emission by about 70% [3]

The degree of reactants dilution by the flue gases can be measured by the recirculation ratio (k_v), which is defined as [24]:

$$K_v = \frac{M_E}{M_F + M_A} = \frac{(M_T + M_F + M_A)}{M_F + M_A} \tag{0}$$

Where: M_T: Total mass flow rate of flue gases entrained by air and fuel jets. It quantifies the influence of flue gas recirculation on mild combustion, M_E : Mass flow rate of recirculated exhaust gas, M_F : Mass flow rate of fuel and M_A : Mass flow rate of air.

FIGURE 4 shows the relationship between recirculation ratio and temperature in respect to the various combustion modes. Boundaries of different combustion modes were indicated. The flameless combustion mode occurred at K_v of about 3 and above. Khidr et al. [33] reported that different fuels require different K_v conditions for the establishment of a stable flameless mode.

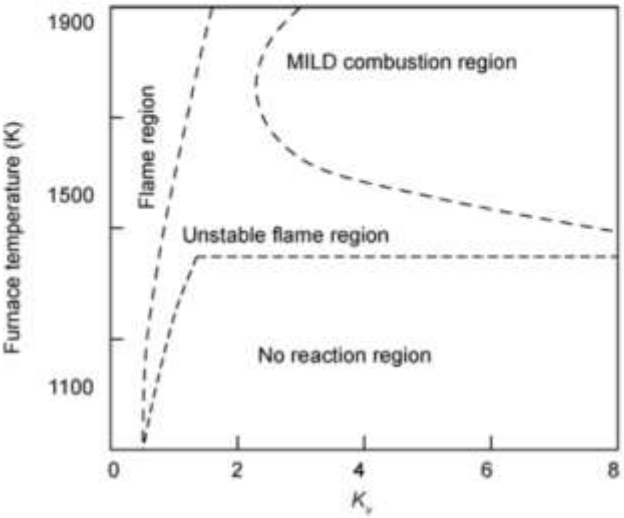


FIGURE 4. The relationship between Kv and temperature in methane non-premixed combustion

TECHNICAL AND PHYSICAL CHALLENGES OF LIQUID FUEL

Liquid fuels are used extensively in industries because of their advantages, such as high density and calorific value, smaller storage volume, and a much brighter flame. However, a particular challenge is to vaporize the liquid fuel to burn completely in a fraction of a second [34]. Therefore, the combustion of liquid fuels depends on effective atomization. To promote vaporization, mixing, and combustion with maximum efficiency and low emissions. In contrast, improper atomization produces high pollutant emissions and reduces fuel efficiency. Thus, liquid fuel flameless combustion combustors pose an additional challenge due to the many complex processes involved. Such as atomization and vaporization of various liquid fuels [35]. In addition, it requires high recirculation of combustion products by turbulence processes within the reaction zone through a very high swirl [6,30]. The higher density of liquid fuel makes it extremely difficult to entrain large quantities of hot combustion products within the reaction zone [36]. All the processes above must be considered and addressed when designing and developing a practical flameless combustor

SWIRL EFFECTS

Swirling or rotating is often used to intensify mixing due to the formation of a toroidal recirculation zone, which usually shortens the flame due to fast mixing and blocks flame impingement on the furnace wall, increasing the burner lifespan with minimum maintenance The disappearance of flame resulted in low fuel consumption and pollutant emissions combustion [37]. Swirl is a flow that contains both tangential and axial components of flow [38], It can be achieved by twisting either combustion air or fuel concerning the combustor axis (axial or radial). Swirl is often used in liquid and solid fuel combustion because these fuels are more difficult to mix with the combustion air and burn than gaseous fuels. It can be achieved either by the swirl nozzle or the tangential supply of air. Therefore, swirls can be used to reduce specific emissions, such as UHCs and particulates. Swirl enhances fuel burnout and reduces CO emissions[30].

UTILIZATION OF DIFFERENT LIQUID FUELS AND CONFIGURATIONS IN FLAMELESS COMBUSTION BY VARIOUS RESEARCHERS.

This section reports and discusses the available work made on the flameless combustion with liquid fuel in laboratory-scale furnaces as follows:

Ye et al. [39] conducted a comparative study of pre-vaporized ethanol, n-heptane, and acetone in a flameless reverse flow burner (5). The fuel nozzle is fixed at the bottom of the combustor and surrounded by concentric air inlet nozzles and exit holes, but the fuel nozzle projects 0.144 cm above the exit plane of the air nozzle. The reverse-flow design was employed to enhance the internal recirculation of exhaust gases. The top hemispherical shape is to guides the recirculation of flue gases. They achieved MILD combustion regimes with ultra-low CO and NO_x emissions with N_2 as the carrier gas for a range of Φ, as shown in **FIGURE 6**. The lean extinction limit was measured at $\Phi = 0.25$. **FIGURE 6**. Recorded ultra-low CO towards stoichiometry with a sharp rise toward lean extinction due to incomplete combustion. Contrariwise, NO_x emission shows a rapid increase towards stoichiometry conditions. **FIGURE 7.** showed the effect of fuel injection pressure on NO_x and CO. Interestingly, NOx emission increases with increasing injection pressure, from $\Phi = 0.4$ whereas the pressure does not affect CO emissions only at the lean extinction limit ($\Phi \leq 0.4$).

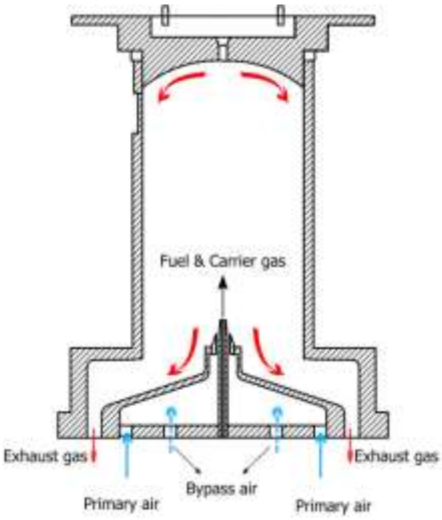


FIGURE 5. Reversed flow MILD combustor with prevopized liquid fuels

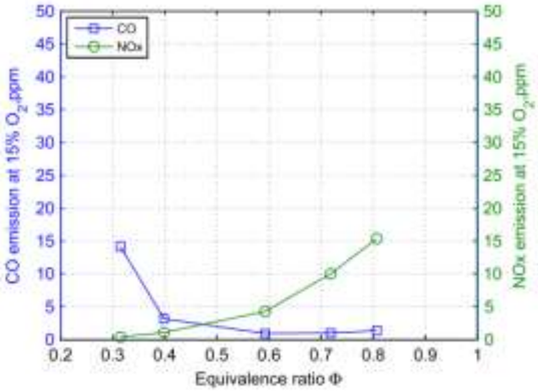


FIGURE 6. Mole fraction of NOx and CO emissions at 15% O2 by volume for ethanol plotted against the equivalence ratio at P = 1.0 bar

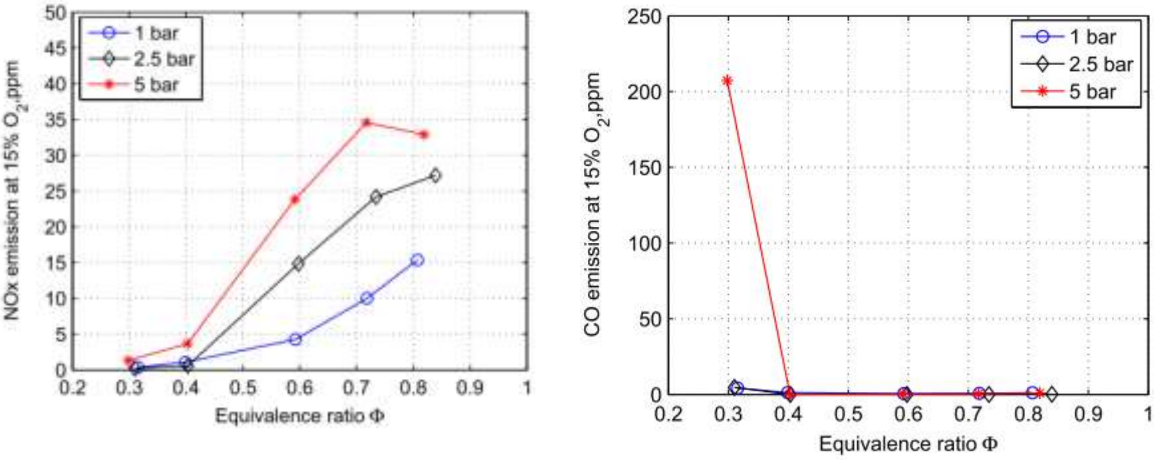
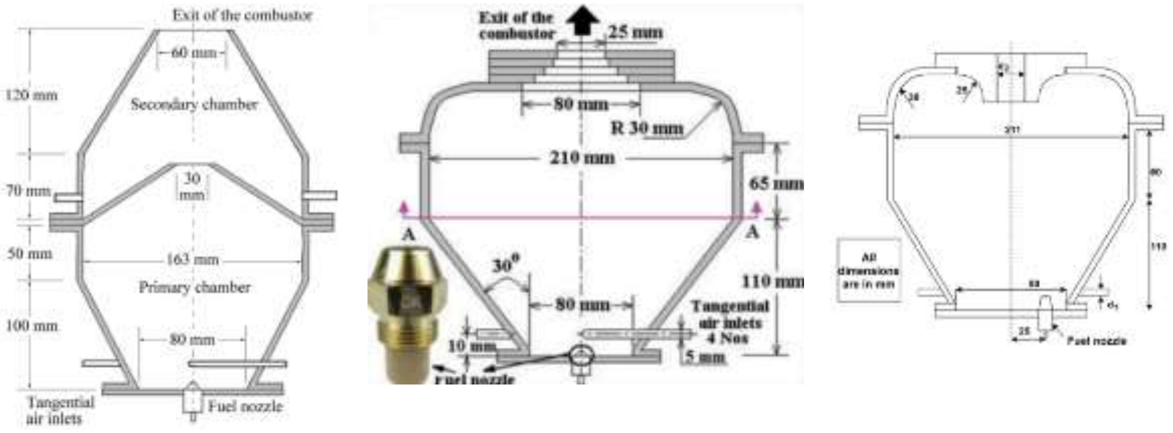


FIGURE 7. Variation of NO_x and CO for ethanol carried by N_2 plotted against the equivalence ratio at various pressures [39].

Reddy et al. studied two-stage [6,40] and single-stage [14,41] divergent conical burners fired with kerosene, diesel and gasoline in flameless combustion. The two-stage vertical burner is shown in **FIGURE 8a**. Air is introduced into the burner through four tangential air inlets near and perpendicular to the fuel injector, creating a swirl flow pattern, and liquid fuel is introduced through a centrally located swirl injector. Both the fuel and the oxidant are fed under ambient conditions. The air and fuel injection is believed to affect the fuel spray by increasing the shear force and leading to better mixing and vaporisation of the droplets. The results show that the two-stage burner is not ideal for flameless combustion. Therefore, further investigations were carried out using a single-stage [14,41] burner with a swirl-based and a chamfer at the top of the combustor **(FIGURE 8b)**, which is the better choice due to the improved droplet residence time and recirculation rate. They found that the NO_x and CO emissions decreased steadily from 56 to 6 ppm, and from 300 to 15 ppm, respectively, as the exhaust port diameter is reduced from 80 mm to 25 mm as presented in **FIGURE 9a** The decrease in the exhaust gas opening diameter indicates the transition from the conventional to the flameless combustion mode by improving the internal recirculation of the hot combustion products.



(a) (b) (c)

FIGURE 8. Schematic diagram of experimental combustor with detailed dimensions: (a) two stage, (b) one stage symmetric and (c) one stage asymmetric [2,14,40]

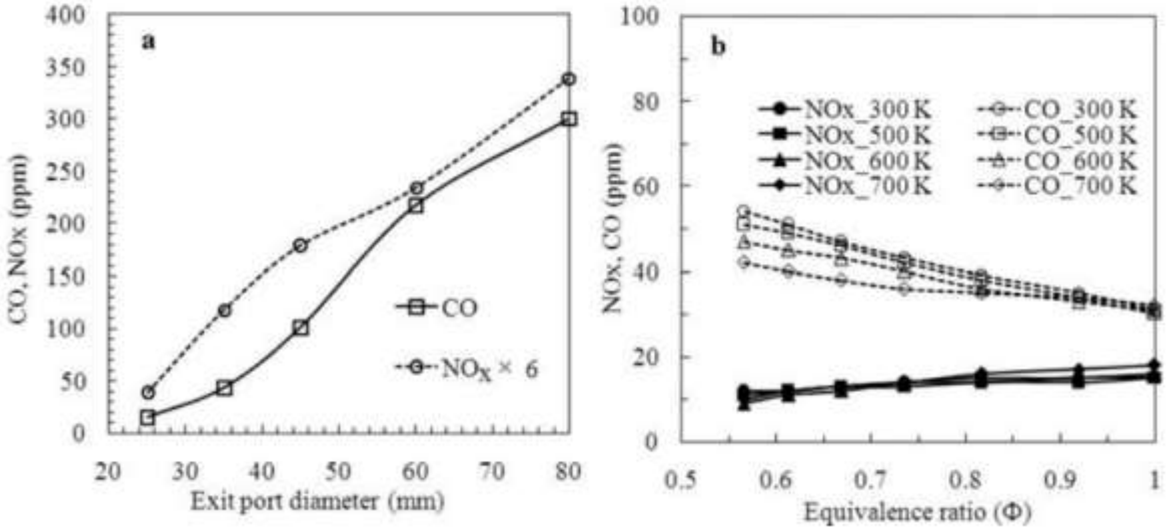


FIGURE 9. (a) Variation of CO and NO_x emissions with combustor exhaust diameter varied from 80 to 25 mm (at $\Phi = 0.92$). (b) Variation of CO and NO_x (ppm) with global equivalence ratio for the case of 20 kW thermal input and different air preheat temperatures [14].

FIGURE 9 shows the NO_x and CO variation with the Φ for different air preheating conditions at 20 kW heat input. For lean mixtures, the average temperature in the combustor decreases with a decrease in the Φ. This leads to a reduction in NO_x emissions. Conversely, the CO emissions increase slightly for all preheat temperatures, as seen in the **Figure**. For higher preheating temperatures, the average chamber temperature increases compared to 300 K. Therefore, the CO emissions decrease with increasing preheat temperature. Nevertheless, the effect of air preheating on NO_x emissions is insignificant as the peak temperature is below 1800 K. This clearly shows that despite a large change in the mixture Φ and air preheating, it is possible to maintain the flameless combustion mode with uniform temperature distribution and extremely low NOX and CO emissions.

Sharma et al. [2,36] investigated flameless combustion of kerosene in a single-stage laboratory scale burner, previously used by Reddy [14], under symmetric (**FIGURE 8b**) and asymmetric (**FIGURE 8c**) fuel injection. They [36] reported that CO emissions increase with decreasing Φ **(FIGURE 10**) and similarly decrease with increasing injection pressure. This suggests that higher injection pressure facilitates vaporization, mixture formation, and complete combustion of kerosene droplets in flameless combustion mode with very low CO emissions. It was also observed **(FIGURE 10**) that NO_x emissions decrease with a decrease in Φ. At lower Φ, leaner mixtures lead to lower temperatures in the combustion chamber, resulting in lower NO_x emissions.

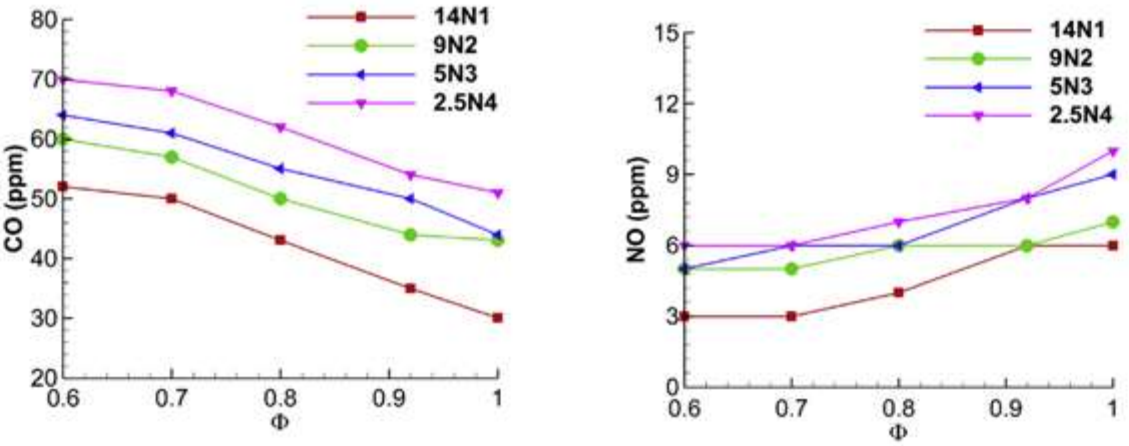


FIGURE 10. CO and NO_x emissions variation for a fixed fuel flow rate (2.5 kg/hr) at different injection pressures, for the symmetric combustor. Note 14N1 means 14 bar fuel injection pressure for nozzle N1 [36].

They [2] observed increased flame stability with asymmetric fuel injection up to Φ = 0.2 compared to Φ =0.6 with symmetric fuel injection. The variation of CO and NO_x emissions for asymmetric fuel injection with preheated and non-preheated combustion air is shown in **FIGURE 11** and compared with symmetric injection [36]. The flameless operation was stable up to Φ = 0.4 with non-preheated air and Φ = 0.2 with preheated air for asymmetric injection, compared to Φ =0.6 for symmetric injection (**FIGURE 10**). The preheated air resulted in very low CO emissions because CO oxidizes faster at higher temperatures. It was also observed that asymmetric injection resulted in significantly lower CO emissions compared to symmetric injection. Moreover, lower NO_x emissions were observed with asymmetric injection at higher heat release densities for a similar geometry. Extending the combustion stability limits to Φ = 0.4 and 0.2 for non-preheated and preheated air, respectively, further reduced NO_x emission levels due to the reduction of peak temperatures in the combustion chamber. NO_x values increase with heat input and Φ due to the increase in peak temperature. Higher NO_x values were measured for preheated air (800 K) compared to non-preheated air (300 K). Slightly higher NO_x values were observed for symmetrical compared to symmetrical injection [36], which can be attributed to a higher peak temperature in the center of the combustion chamber.

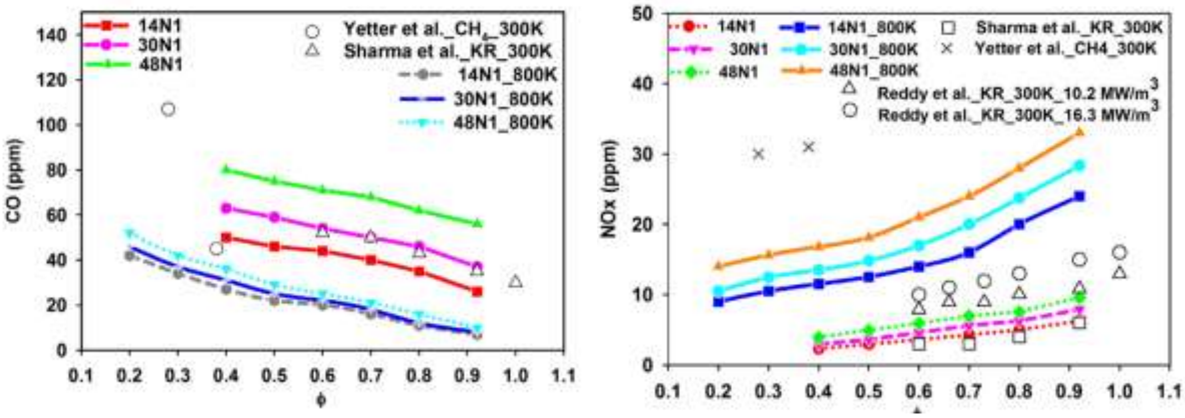


FIGURE 11. Variation of CO and NOx emissions (corrected to 15%O_2) for kerosene with non- preheated and preheated air [2].

Sharma et al. [42] investigated the effects of dilution (CO_2 & N_2) on kerosene combustion characteristics in flameless combustion numerically and experimentally in an asymmetric single-stage burner (**FIGURE 8c**). They reported that: An improved reaction flow field is observed under dilute flow conditions due to the lower oxidant concentration (**FIGURE 12).** CO_2 dilution reduces the maximum temperature at the center due to the high heat capacity of CO_2 and the lower concentration of oxidant due to dilution **(FIGURE 13**). However, N_2 dilution increases the temperatures compared to CO_2 dilution for all operating conditions **(FIGURE 14**). They further pointed out that CO emissions do not show any significant change with CO_2 dilution, while NO_x decreases significantly. However, NO_x emissions increase significantly with N_2 dilution in the oxidant stream. The authors also pointed out that CO_2 dilution in the preheated air has no effect on the velocity and thermal field but increases CO and decrease NOx emissions. On the other hand, N_2 dilution led to high NOx levels, which contradicted the behavior of inert gases even at temperatures lower than its dissociation (1200°C).

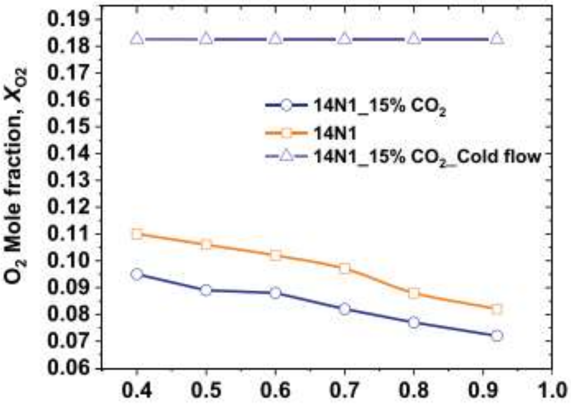


FIGURE 12. Comparison between O_2 of diluted and non-diluted cases [42]

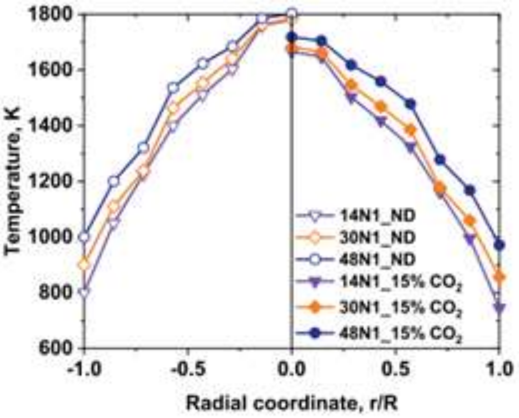


FIGURE 13. combustion chamber temperature of diluted and non-diluted cases [42]

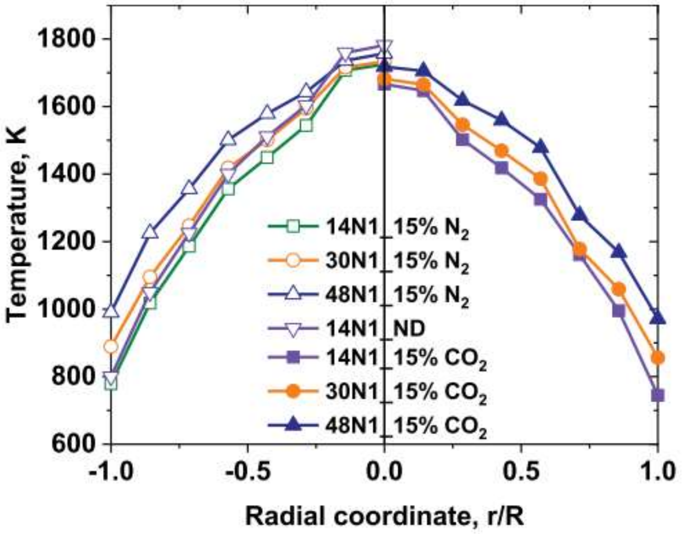


FIGURE 14. Variation of the measured temperatures at Tair = 300 K for, (a) 15% N2 dilution (left) and (b) 15% CO2 dilution (right); ND: No dilution.

Torresi et al.[43] Experimentally tested and numerically simulated flameless combustion of diesel oil in an aerodynamically staged swirled burner under dilute (with CO_2 and H_2O) and strongly preheated combustion air (673 K), where the O_2 concentration is 12.59%. A double coaxial air inlet achieves the staging with the same swirl orientation. The fuel is injected through a central atomizing nozzle, which is characterized by a very high range. The numerical and experimental results are in good agreement, confirming that under the correct operating conditions the burner exhibits flameless combustion with a uniform thermal field, as shown in **FIGURE 15.**

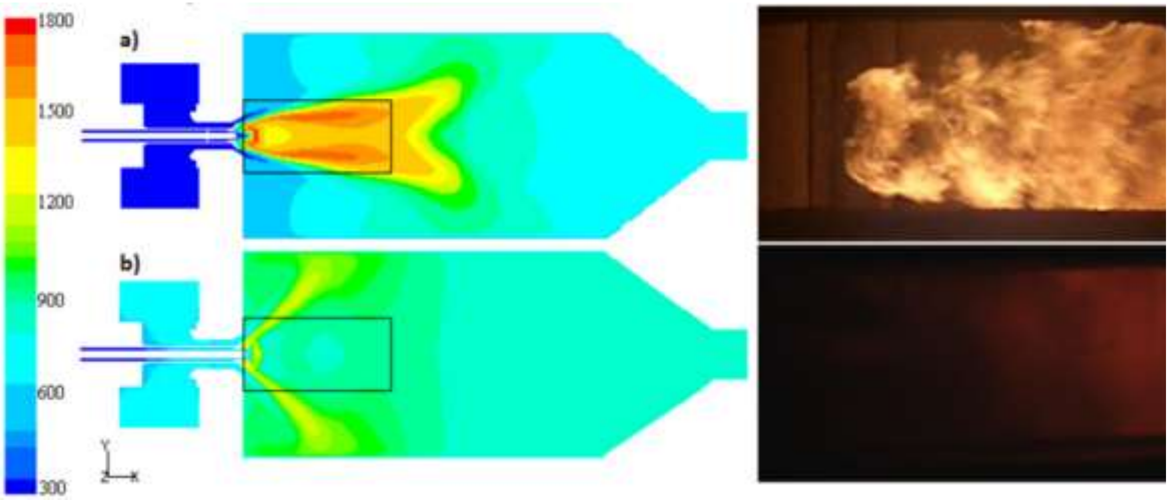


FIGURE 15. Contours of temperature for flame (a) and flameless (b) conditions with the relative experimental images [43]

Cui et al.[44] Realized flameless combustion in a cubic burner fueled by diesel and pointed out that air preheating is not an essential requirement for flameless combustion and that the rate of air supply is more important to lower the overall reaction rate. The burner was designed with a recirculation structure as shown in **FIGURE 16.** Air1, Air2 and Air3 are air inlets while Air0 is an optional swirl air nozzle. The numbers 1 to 10 denote the positions of the thermocouples. The red rectangle is the observation window. **FIGURE 16a, 16b** and **16c** show the flow field in the combustion chamber in flame, transition and flameless modes.

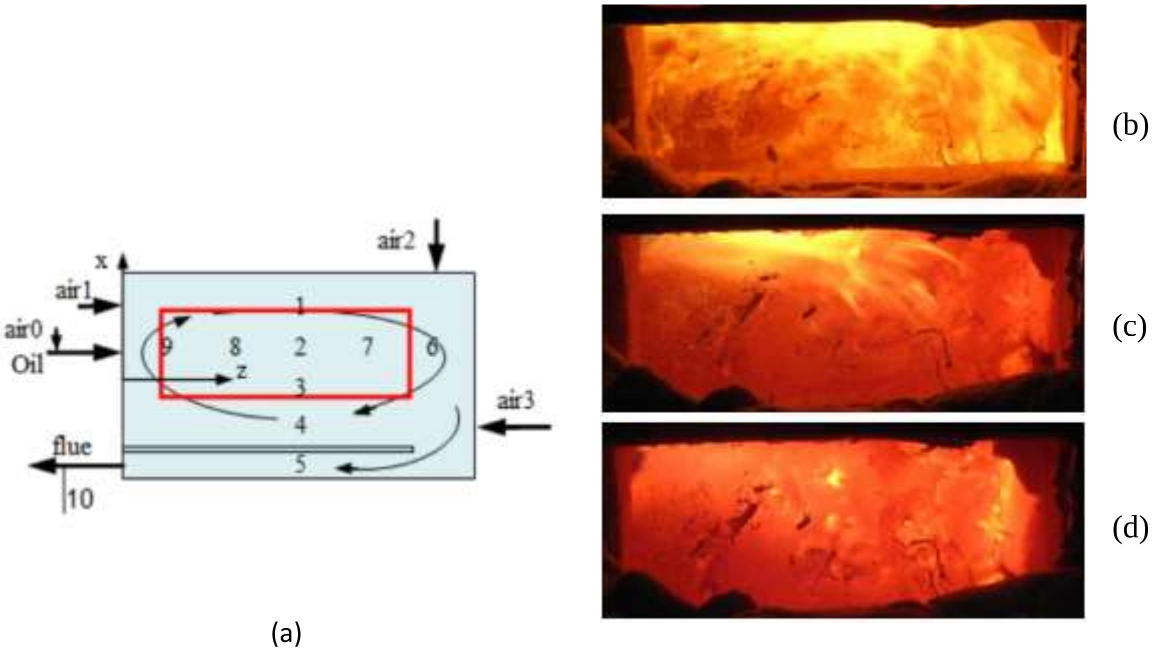


FIGURE 16. Combustor configuration and thermocouples layout (a), flame(b), transition (c) and flameless [44]

Cha et al. [45] conducted an experimental study on the mild combustion of kerosene in a two-stage burner consisting of a premixed first burner and a second burner (**FIGURE 17**). **FIGURE 19a** shows the chamber temperature during the warm-up period of about 2 hours before the temperature rises to equilibrium. **FIGURE 19b** shows the exhaust emissions measured in real-time during combustion MILD. The effects of combustion gas velocity and O_2 concentration on the formation of liquid fuel MILD combustion is shown in **FIGURE 19b**. They pointed that the color of the flames changes from yellow to light blue when the combustion gas velocity through the nozzle becomes higher, and the flames become very short (**FIGURE 18)**. The local high-temperature region decreases as the combustion gas velocity increases and the flame temperature become spatially uniform. CO and NO_x emissions by 1 ppm and 10 ppm were measured, respectively, with an overall equivalence ratio of 0.8 to 0.98 when the diameter of the velocity control nozzle is 40 mm or less.

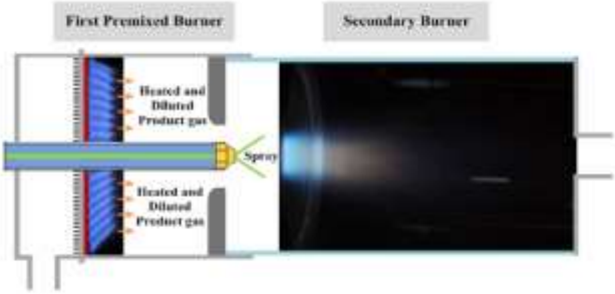


FIGURE 17. The concept of the 2 stages MILD combustor for liquid fuel.

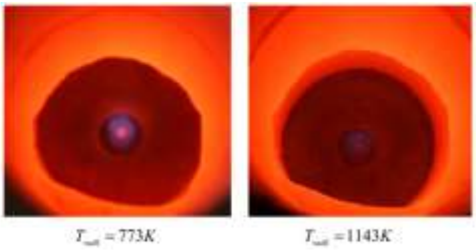
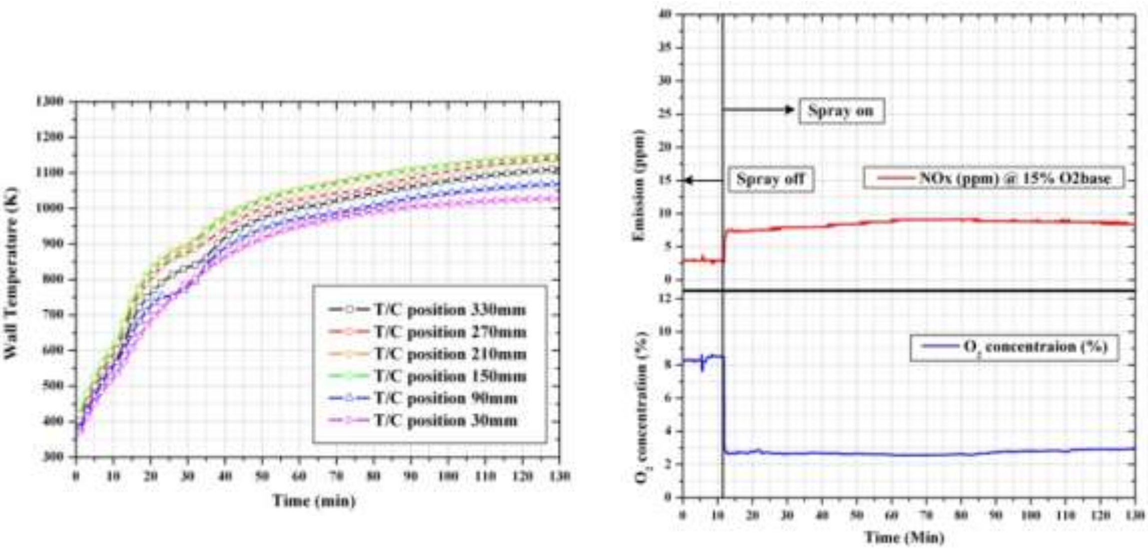


FIGURE 18. Images of the reaction zone of kerosene MILD combustion at different wall temperature.



(a) (b)

FIGURE 19. Transient trend of (a) chamber temperature; (b) NOx emission for MILD combustion in combustion chamber [45].

FIGURE 18 shows the direct flame images collected through the visualization window at different chamber temperatures. The flame became increasingly invisible at higher temperatures in the chamber. Increasing the temperature in the reaction zone accelerates the vaporization of the injected kerosene and provides a strong radiation from the furnace wall, resulting in a more uniform temperature distribution. It is postulated that more perfect MILD combustion could occur in a real combustion system with the low thermal conductivity insulating material [45]

CONCLUSIONS

Despite decades of research in flameless combustion, there are still many challenges in the analysis of flameless combustion phenomena and the design of combustion chambers. Therefore, there are still many unexplored phenomena, particularly in liquid fuel flameless combustion. This review gathered useful and relevant literature review information to understand flameless combustion's basic concepts and principles using liquid fuel for further studies by combustion scientists and engineers.

Air preheating is not an essential condition to realize flameless combustion, instead of additional advantage. In contrast, air and fuel injection schemes are of paramount importance for controlling reaction rate, which thus affects NOx emissions and combustion efficiency. Several parameters, including fuel properties, droplet distribution, vaporization, mixture formation, and subsequent combustion with preheating and diluting reactants, need to be discussed and developed.

Flameless combustion undoubtedly presents itself as a technology that combines high efficiencies and low pollutant emissions. These aspects make flameless combustion worthy of further study and attention.

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