Flameless Combustion: A Review

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Abstract

This review paper presents the characteristics of flameless oxidation/FLOX. In this present paper, combustion characteristics and pollutant emissions are studied for various types of fuels, both liquid and gaseous fuels. For some fuels, oxygen enrichment had been done and its effect has been compared with the results without oxygen enrichment. For each case, pollutants emissions like NOx, CO and HC have been studied and tried to reduce it further. This review paper also focuses on the efficiency of the combustion.

Keywords: Flameless combustion, MILD combustion, HiTEC, CDC

I. INTRODUCTION

One of the important role in the survival of any humankind is energy. Energy can be generated from various sources among them a way of energy generation is by combustion of any fuel. Majorly dependence on combustion leads to development and improvement in combustion technology, improving the efficiency during these decades resulted in decrement in energy requirement for unit GDP growth. However, combustion causes the emission of various pollutants such as NOx, CO etc. which have adverse effects on human health as well as lead to greenhouse effect in the environment. The challenging task arises is to control the NOx formation and limit the amount of these Greenhouse gases [1].

![Fig. 1: Global energy consumption](image)

Figure 1 is showing the variation of global energy consumption during the period of 1980-2030. During these periods, a major fraction of total energy production is mainly based on the fossil fuels like coal, oil and natural gas etc. However, the renewable energy are improving its contribution, but still in very small fraction compared with the fossil fuels.

Various researches have been done to reduce the formation of such harmful gases and these researches lead to the development of various new methods and technologies for controlling pollution. One of superior method of reducing pollution up to large extent is flameless Oxidation (FLOX). In this method, the reactant temperature is raised to its self-ignition temperature due to which fuel starts to burn which produces the flue gases into furnace and the reactant temperature is raised above its self-ignition temperature. This flue gases gets intact with the other combusting fuel available, smoothing or diluting the combustion area reducing the peak adiabatic flame temperature during the combustion into the furnace. This reduced flame temperature is below 1900 K as estimated by Wunning et al. [2]. This method of reduction comes into action when the enthalpy of gases increases [3].

Various names are currently in trend to call this type of combustion. Some of these names are HiTAC (High-Temperature Air Combustion) [4], MILD (Moderate or Intense Low-Oxygen Dilution) [5] and CDC (Colorless Distributed Combustion) [6]. We put this in one category of control while another category to prevent the NOx formation by changing the design of burner which includes injection of low NOx [6]. This new technology leads to the less formation of pollutants and increases the efficiency simultaneously.
The important feature of flameless combustion is to reduce the pollutants emission. Plessing et al. [7] noticed low noise production during combustion and lower NOx formation than conventional combustion. It also assumed that OH is distributed uniformly along with the increase in temperature of flame. Results were found true when Szego et al. [8] reported the temperature measurement and flue-gas composition from MILD laboratory and also showed that pre-heating of air is not required to get required MILD combustion during the combustion process. Mi et al [9] reported the effect of air fuel injection momentum rate and air-fuel premixing on mild combustion in laboratory recuperative furnace. Luckerath et al. [10] investigated at elevated pressure up to 20 atm, flameless combustion in forward flow configuration for the application of gas turbine combustors. Suda et al. [11] investigated on the cylindrical shape furnace for characteristics of high temperature air combustion driven by pulverized bituminous and anthracite coal as a fuel. It had been found that 50% in NOx reduction is obtained when anthracite coal is used as a fuel while comparing with low NOx burners [12]. Ramona et al. & John et al. investigated the NOx formation using wood pellets as fuel in Flameless Combustion. The result showed that the level of NOx formation is proportional to the oxygen concentration in incoming air and to air combustion temperature [1]. Due to increase in momentum of gases, the level of turbulence gets increased due to which time of mixing gets reduced and simultaneously chemical time are increased due to dilution [13]. Damkohler No [14] approaches unity which states that both mixing and chemical kinetics are taken into account when studying the Flameless Combustion.

Various former studies had been done to visualize the effect of turbulence and evaluate the turbulence flame temperature characteristics and structures through various techniques such as Rayleigh scattering and Laser induced Fluorescence [15-16]. Figures 2 and 3 are clearly showing the difference between the flameless mode and flame mode of combustion [18].

![Fig. 2: Flame and flameless combustion](image1)

![Fig. 3: Flame and flameless combustion](image2)

### II. ADVANTAGES OF FLAMELESS COMBUSTION

The various advantages of flameless combustion over normal combustion are as follows [19-22]

1) Reduction in fuel consumption.
2) Stable combustion.
3) More efficient combustion.
4) Reduction in harmful pollutants like NOx, CO etc.
5) Lower combustion noise.
6) Improved heat transfer.
7) Uniform combustion throughout the combustion chamber
8) Better ignition and flame shape control
9) Greater turn down of the burners.

III. CONCEPTS OF FLAMELESS COMBUSTION

It had been seen during an experiment in 1989 that for the combustor temperature of 1000°C and preheated air temperature of about 650°C (above the self-ignition temperature of the fuel), the fuel is completely burnt without the visibility of the flame. The results also confirmed that the NOx formation was very low, lower noise and CO content was lower than 1ppm [23].

The early concepts of the excess enthalpy combustion was discussed by the Weinberg et al. [24]. They elaborated both the positive and negative limitations about the flame combustion temperature. As explained, heat recirculation is the major factor. High efficiency heat exchanger together with heat circulation factor was implemented to produce higher combustion temperature and energy saving. Nevertheless engineers require to lower the combustion temperature to reduce the emissions and other limitations affiliated the materials used in combustor.

The total enthalpy of the combustion system is associated with the enthalpy associated with the pre-heated air, fuel gas and chemical energy of the fuel. In flameless mode of combustion, the total enthalpy of the reaction zone is greater than the total enthalpy of the conventional flame combustion as the circulated fraction of the energy (thermal) from the combusted products rise the combustion temperature [25].

![Fig. 4: A typical flameless combustor](image_url)

A flameless combustion can be synthesized by the external or internal recirculation and very rigorous mixing inside the chamber. Thus, it can only have achieved with almost uniform distribution of the reactants and temperature in a large volume. In this chamber, fuel burns under high temperature with lower oxygen concentration and because of which combustion takes place within whole volume with the lower peak temperature and higher thermal efficiency.

In the figure 4, it can be clearly seen that the flue gas recirculation is primarily internal recirculation in which fuel and air have been injected at pre-mixed temperature. It is also pointed out that reaction zone occur at the downstream from injection ports. Because of this reason, the lower flame temperature and oxygen concentration happen in that zone which leads to the formation of lower NOx and invisible flame [27-28].

IV. DESIGN AND CHARACTERIZATION OF FLAMELESS COMBUSTION SYSTEMS

One of the major challenge faced is during the designing of the burner and chamber. It is most critical part as the design decides the effectiveness during the flameless mode, controlling the propagation timing of the combustion. It also maintains uniformity and limits emission of pollutants. Hence, it is crucial to discuss various designs of the combustion chamber for the various fuels used for the flameless mode of combustion.

Szegő et al. [29] experimented on MILD combustion using the 20 kW single MILD combustion burner to analyze the stability criterion and performance. At IFRF research station in Netherlands, a burner, consisting a pair of 1000 kW NFK-HRS-DL4 regenerative burners capable to fire Coke Oven Gas (COG) [30]. A multi-burner system comprises of two pairs of NFK-HRS-DF burners has been planted at the KTH, Sweden which is capable of 200 kW thermal intake [31]. A different kind of combustion
chamber had been developed in NKK Corporation in Japan. It consisted of a slab reheat burners. These burners are of four pairs, consisting of 2919 kW total power [32].

Cho et al. experimented with multi-burner furnace consisting of three pairs of regenerative FLOX burners, firing simultaneously generating total thermal power of 300 kW. Fig. 5 shows the schematic diagram used by them [33].

V. NOx FORMATION AND EMISSION THROUGH FLAMELESS MODE OF COMBUSTION

During normal combustion with flame leads to the formation of large amount of NOx which is later released in the atmosphere. During combustion, three different types of the NOx is formed in the combustion as mentioned by Abuelnuer et al. [25] in his paper

1) Thermal NOx: Due to direct oxidation of the nitrogen molecules at higher temperature, thermal NOx is formed.
2) Prompt NOx: This type of NOx is formed in the hydrocarbon rich zone. It is formed by the interaction of the nitrogen molecules and hydrocarbon rich flame zone.
3) Fuel NOx: Some of the solid and liquid fuels contain nitrogen in its contents. This type of NOx is formed by the oxidation of the nitrogen molecules contained in the fuel itself.

Raman et al. [34] worked out with the wood pallets as the solid fuel for the flameless combustion and studied for the NOx emission during the study. They confirmed that the level of NOx emission is proportional to the oxygen concentration in the incoming air and maximum combustion air temperature. Figures 6 & 7 show the variation of the NOx emissions with the time at 1000°C and 800°C respectively.
Both graphs show that at higher O₂ concentration maximum concentration of the NOx was reported and it was found at 70% O₂ concentration. Choi et al. [35] studied about the effects of high preheat air combustion on NOx emission. They explained two types of combinations- one with the nitrogen molecules surrounded in fuel matrix and oxygen in excess and other one with direct reaction of nitrogen molecules with the oxygen molecules from air.

VI. CONCLUSIONS

This review paper focuses on the developments and benefits involved in using flameless mode of combustion. This paper also summarizes the reasons for the emission of the NOx and its remedies. The various design models which are currently in use are also summarized. In addition, paper also confirmed that flameless combustion reduces NOx emission in huge amount compared with the conventional combustion. The flameless combustion can be achieved in large volume and after a pre-defined temperature of the combustion chamber and preheated air.

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