Flameless Combustion

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1.Theme description

In the light of the recent trend in regulations about greenhouse emissions and environmental protection and towards more cost-effective production systems, there is an increasing demand to develop combustion systems to reduce pollutant emissions and fuel consumption. In this frame, a breakthrough technology, called flameless combustion has appeared about thirty years ago. Firstly though for energy-efficient combustion in steel furnaces, is now a consolidated part of several research projects in matter of advanced combustion. During experiments with a self-recuperative burner in the fields of in 1989[1], a surprising phenomenon was observed: at furnace temperatures of 1000°C and about 650°C air preheated temperature, no flame could be seen, but the fuel was completely burnt. Furthermore, the CO and NO_x emissions from the furnace were considerably low[1] and, thanks to the air preheating, a great energy efficiency was reached. In order to define the conditions of flameless combustion, it can be said that, the reactants must exceed self-ignition temperature and must have entrained enough inert combustion products to reduce the final reaction temperature well below adiabatic flame temperature, so much that a flame front cannot be stabilized[2]. Figure 1 shows the conventional and flameless firing of heavy oil with preheated, vitiated air. The visible differences result in diverging reaction steps that follow chemistry paths different resulting in quite different pollutant formation and heat flux distribution of hot combustion products. The mixing of 2-4 recirculating volumes (low Damköhler number), has the double aim to preheat and to reduce the outlet temperature peaks. Other features of the technologies is that the fuel is oxidized in a low oxygen environment with a substantial amount of inert (flue) gases by spontaneous ignition with no visible or audible signs of the flames usually associated with burning; the chemical reaction zone is quite diffuse, and this leads to almost uniform heat release and a smooth temperature profile. All these factors result in an extremely efficient process as well as reduced emissions; furthermore the flame supervision may be dispensed with according to safety rules, as there is no danger of the reaction extinguishing and hence no risk of explosion.

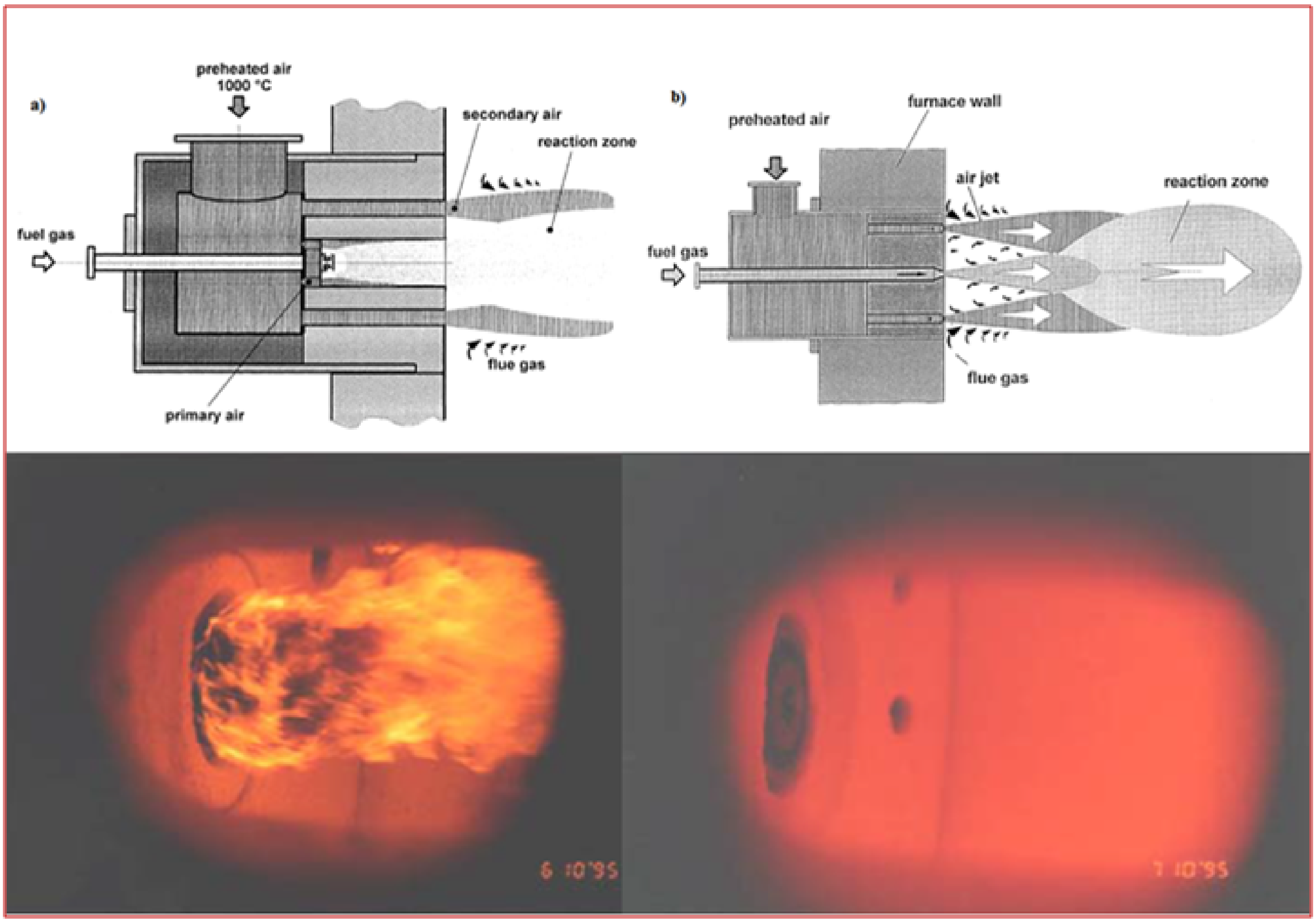

Figure 1 – Flame and flameless firing of heavy fuel oil (left: flame mode – right: flameless)

A steady flame front is reached in conventional combustion systems and the local temperature approaches the adiabatic one. The front is characterized by a sharp gradient of temperature and composition due to the radical reactions and quenching by convection. Hot peak temperatures stabilize the flame, but at the same time cause the the formation of thermal NO. On the contrary, in a flameless burner, the flame front is avoided and combustion reactions occur at the mixing of fuel, air and recirculated combustion products; the mixing is also controlling mechanism for the heat transfer and consequently for the temperature profile. This last, consequently, cannot deviate too much from the temperature of the recirculated combustion products. A characterization of temperature peak regime in flameless combustion is given by Oberlack et al., 2011[3] and shown in Figure 2 reported by Cavaliere and de Johannon in 2004.

The consequence of reduced temperature peaks in lower emission of thermal NO is shown in figure 3, where data from natural gas burners were reported for the purpose of direct comparison[4] (right side).

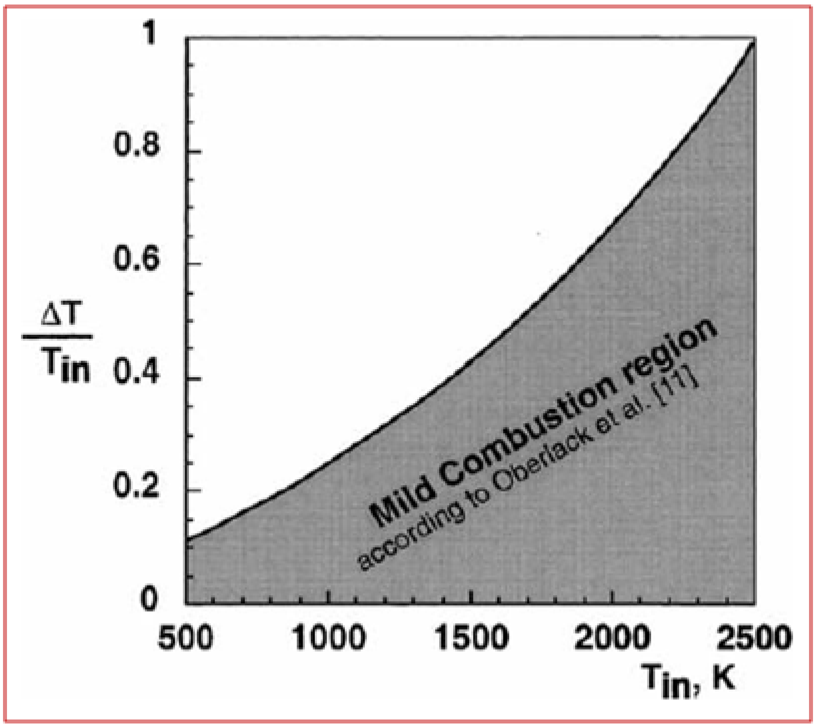

Figure 2 – Typical region of Mild Combustion in relation to temperature differences, according to Oberlak et al., 2011.

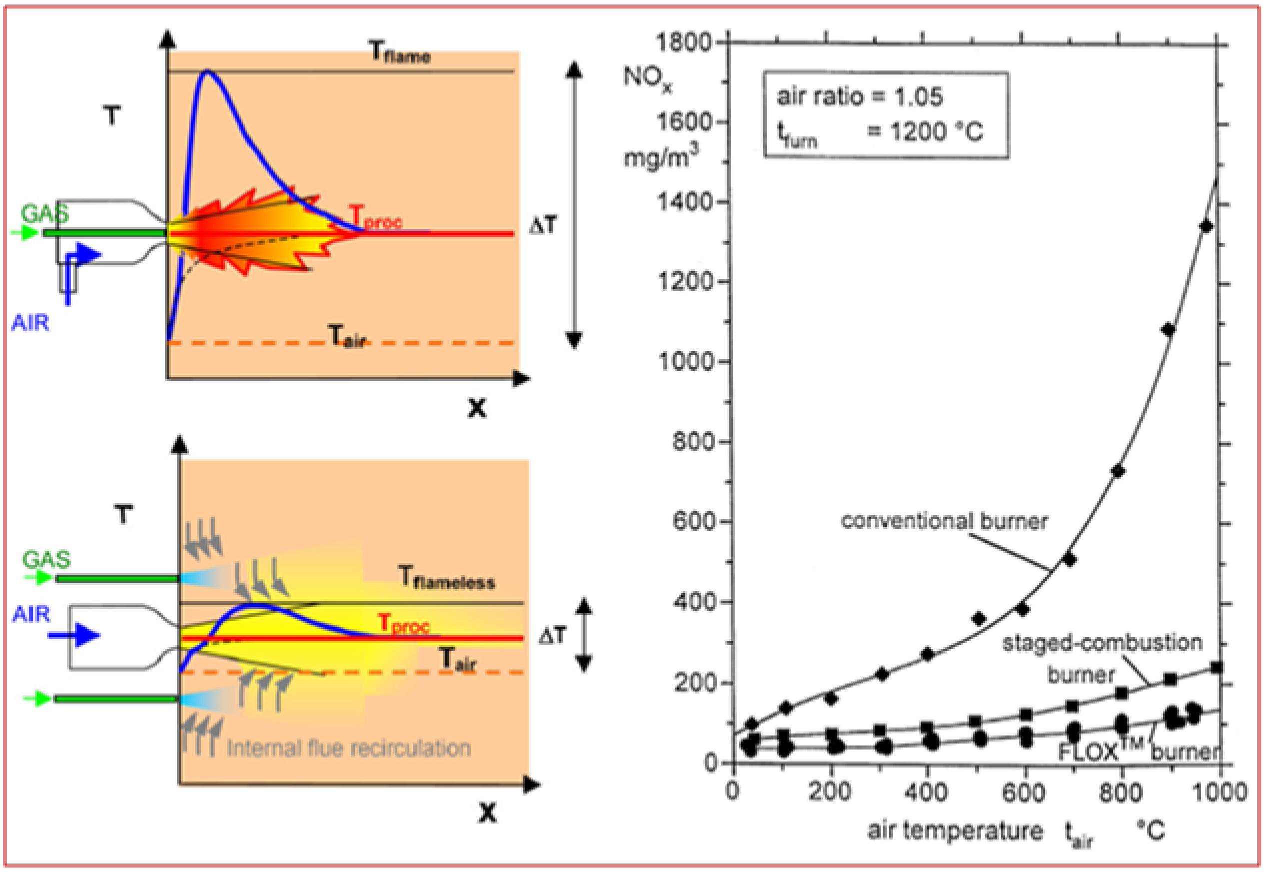

Figure 3 – Typical flameless and conventional temperature profile [5](left) and NOx concentration in conventional and flameless burners (right)[6].

The regime of flameless combustion can be individuated through some well-consolidated maps. Different combustion zones against rate of dilution and oxygen content are depicted in the Figure 4: in the typical flameless regime, the oxidation of fuel occurs with a very limited oxygen supply at a very high temperature.

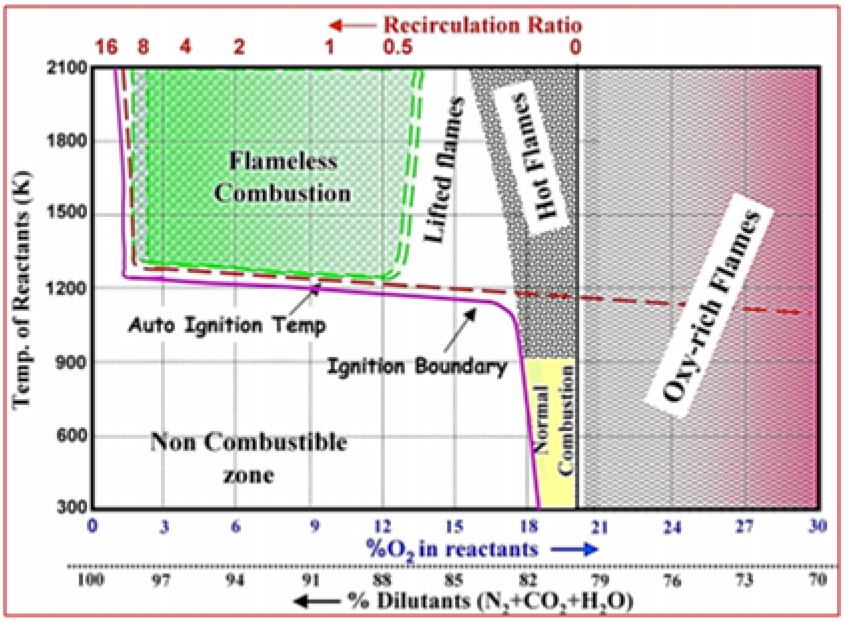

Figure 4 – Combustion regimes in relation to the dilution and reactants' temperature

The geometry of burners varies according to the fuel characteristics and the need of assuring flameless regime conditions. The concept of high swirl flows has been widely adopted to achieve internal recirculation rates for increasing the dilution of the fresh reactants. Two examples of properly designed geometries for liquid fuel combustion are depicted in Figure 5. The trapped vortex combustor (TVC) (a) is based on mixing hot combustion products and reactants at a high rate by a cavity stabilization concept[7] and has been implemented mainly for aircraft combustors. The name "trapped" came from the cavity that contains the injected reactants for realizing typical flameless regime and providing significant reduction of the pressure drop. A two stage combustor design (b) was proposed for an experimental campaign conduced with liquid fuels (diesel, Kerosene, gasoline) for different thermal heat inputs of 20-60 kW and heat release density of 5–15 MW/m^3, showing very low pollutant and sound emission[8].

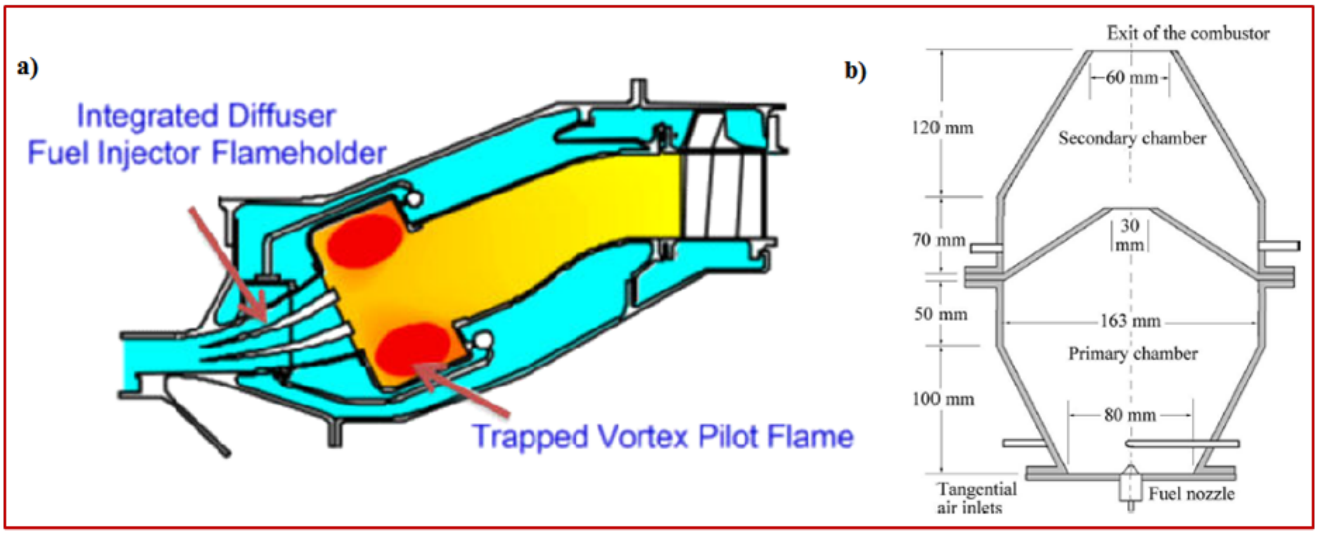

Figure 5 – Flameless burner geometries

2.Applications

The most noticeable advantages of flameless conditions are the contemporary use of hot preheated air for avoiding uncontrolled NOx emission and thermal stress to materials (ENEA). Since the early experiments of 90’, such benefits justified further research under different “names” in relation to the specific applications or to the chronological and geographical “birth”. In the last decade several research papers have appeared in the field of modelling and simulating this kind of combustion applied in several fields[9],[10]'[11]. A remarkable scientific review by Cavaliere & De Joannon gave a comprehensive analysis of the development and all the related fundamental phenomenological aspects.

The technology is often named as FLOX (a registered trademark belonging to the company WS) in Germany or Low NOx Injection (LNI) in the USA. Similarly, the High Temperature Air Combustion (HiTAC), born in Japan, a leading country in during the early stage of developing, refers to increase the air temperature by preheating systems such as regenerators and was originally named Excess Enthalpy Combustion. The technology is also known as Moderate and Intensive Low oxygen Dilution (MILD) or Colorless Distributed Combustion (CDC) combustion in

Italy where radiant tube as well as flameless burner application in the **steel industry** have represented a pioneering application of flameless combustion. An example is the Regemat®, a single regenerative burner which can replace self recuperative burner, being applied at the steel plant of AST-Terni (Figure 6) and Acc. Pietra di Brescia.

***Figure 6 – Regenerative burners in an annealing and pickling line installed at Terni** (11)*

The applied research also concerned the field of **power generating** equipment, from gas turbine combustors to small reformers for decentralized H_2 production. In particular, in the utilization of gas mixtures H_2-rich, some problem may arise because of the hydrogen combustion peculiarities (high laminar flame speed, high adiabatic flame temperature and heating value, large flammability range, high reactivity and short delay time) which make the performances of conventional burners unsatisfactory. Moreover, the intrinsic flameless temperature found an ideal application in steam reformers for hydrogen production thanks to the proven temperature uniformity, the easy control and the minimized thermic stress outside of the tubes thanks to the low front temperature gradients.

Globally, the flameless oxidation burners can be designed for every application, where the flame front stabilization is a critical issue, for overcoming the problem of fluctuations or “humming” that affects premix-based combustors; other applicative fields worth of mention are the ceramic and glass industry as well as the chemical industry[11]. In particular, this last has representative examples in petrochemical and reformer processes where Oxy-Flameless is a valid alternative in order to further reduce CO_2 emissions. *Furthermore, fewer studies have been carried out on the use of solid fuels, including biomass under flameless combustion conditions. The combustion characteristics and emissions under high temperature air combustion as well as innovative boiler design, are described in several papers for convention fuels (as in the case of the oxycoal technology)* [12],[13] *and biomass*[14]. The growing interest in biofuel is in fact pushing the FLOX technology forward in order to overcome the issue related to their inhomogeneous nature: several EU research projects born with this aim[15], as the BOFcom®, aimed to develop low-carbon option in cola fired plant by integrating oxyfuel and flameless combustion to coal-biomass co-firing[16].

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