NOx EMISSIONS OF A MILD COMBUSTION BURNER OPERATED WITH JET FUEL SURROGATES

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Abstract

In this work the sustainability of Mild combustion for jet fuel surrogates has been investigated using a dual-nozzle (DN) laboratory-scale burner. The experiments, carried out with different fuels, evidenced that the mild combustion characteristics seem more influenced by the physical state of the fuel than by its chemical composition. These findings support the idea that a DN Mild combustion burner can create a suitable environment for NOx, PAH and soot depression, allowing the use of a wide range of liquid wastes and low-BTU liquid fuels, even with unsteady composition or coming from different sources.

1. Introduction

Recently significant efforts have been made in order to obtain high thermal efficiencies in high temperature combustion processes without the adverse effect of, in particular, high NOx emissions caused by high temperature flames [1]. It was found that a massive exhaust gas recirculation coupled with a preheating of the combustion air generates relatively low flame temperatures. If the combustion air is diluted with a large amount of recirculated exhausts, the oxygen concentration in the main reaction region of the furnace is reduced to a lower concentration with respect to the case of undiluted air, allowing for a better control of the reactants kinetic and furnace average temperature. This combustion technology is commonly defined as flameless [2] or mild combustion [3,4]. The possibility to reach mild combustion conditions using gaseous fuels as methane or ethane [5-6], as well as mixtures of gaseous hydrocarbons and hydrogen [4,7], have been extensively studied; on the other hand, much less information are available concerning the sustainability of mild combustion for liquids and solids [8,9].

For this reason, an experimental study has been performed in a laboratory-scale burner in order to evaluate the sustainability of mild combustion for liquid hydrocarbons, such as surrogate fuels, using a two-nozzle feeding system. Therefore, the influence of different parameters, such as the fuel composition, the air preheating temperature and the combustion gas recirculation ratio (K_V), on the stability of mild combustion and pollutants formation, has been investigated.

2. Experimental Apparatus

In mild combustion processes, the burner geometry and the configuration of the nozzles for fuel and combustion air play a key-role allowing for obtaining high

turbulence and a strong recirculation of the exhausts inside the furnace, that are requirements to reach mild combustion conditions. A burner, designed and used in previous mild combustion studies on gaseous fuels [5], and provided by a single high-velocity jet nozzle has been modified to have the possibility to work with liquid fuels [9]. The burner, a flow rate control section for the reactants feed, and a sampling and measurement section for the detection of temperatures and exhaust gases compositions constitute the experimental apparatus. The laboratory-scale burner is a vertical quartz tube made by two sections: the combustion air preheating zone (filled by quartz pellets to enhance heat exchange), and the combustion chamber (height=350mm, ID=50mm); through the closed top of the burner, thermocouples and the gas sampling line enter the combustion chamber. The combustion air can be preheated up to 1600 K, while another oven reduces heat losses from the combustion chamber by keeping its wall temperature no more than about 150 K below the average temperature continuously detected in the combustion chamber by three type B thermocouples. Two thermocouples move along the combustion chamber 14 mm apart from the furnace axis, while another one moves along the axis.

Air and gaseous fuel can be fed through the bottom of the combustion chamber, as shown in fig. 1, using a single-nozzle (SN) configuration (ID=3mm). Since both fuel and primary air (together with diluting nitrogen when required, inlet A1+N_2) enter the same nozzle, a partial premix of air and fuel arises before they enter the combustion chamber. However, no fuel oxidation occurs inside the nozzle due to the short residence time. Fig. 1 also shows a secondary air inlet (on the left) that is used both for firing the burner as well as for changing the internal exhaust recycle as discussed in the following. This SN configuration is not suitable for liquid fuels because pyrolysis would arise plugging the nozzle in spite of the small residence time; moreover, firing the burner using a liquid fuel is quite cumbersome. This required changes both in the apparatus configuration and in the firing procedure [9]. The experimental equipment has been modified by implementing the double-nozzle (DN) inlet configuration, where the preheated air enters the combustion chamber through the bottom nozzle, while the liquid fuel is injected as a well-dispersed and homogeneous spray through a lateral water-cooled plain jet airblast atomizer (fuel feeding pipe ID=0,4mm). The two jets interact perpendicularly and mix to each other in a high turbulence region.

Since firing the laboratory-scale burner in the DN configuration with liquid fuels is not easily done in practice, the burner has been always fired with a gaseous fuel in the SN configuration; once mild conditions have been attained in this configuration, the transition from the SN gas-fuel configuration to the DN liquid-fuel one has been carried out by reducing progressively the gas flow rate fed to the bottom nozzle while increasing the liquid flow rate from the atomizer; for this reason, during the transition from a SN to a DN configuration two different fuels have been fed contemporarily to the burner, a gas from the bottom nozzle and a liquid from the lateral injection point, reducing step-by-step the gas to liquid ratio.

Exhaust have been sampled, dried and analyzed with two on-line instruments, namely a gas analyzer Horiba PG-250 (for NOx, O_2, CO and CO_2 measurement) and a GC-FID Perkin Elmer Clarus 500 (for C1-C6 unburned hydrocarbons measurement); maximum deviations of about 1 ppm and 2 ppm from the mean value have been estimated for NOx and CO concentrations, respectively.
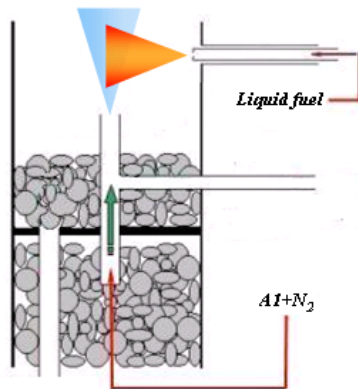

Figure 1. Reactants feeding strategy in the dual-nozzle (DN) configuration.

As previously mentioned, to obtain Mild combustion conditions the exhaust gas recirculation, or in other words the dilution ratio inside the combustion chamber, K_V, has a paramount role determining mild combustion working conditions. As a consequence of several numerical simulations performed with a general–purpose code for computational fluid dynamics [5] and accounting also for both internal and external recycle as well as the presence of a secondary air inlet, which flow rate is lower than the entrained one, the K_V can be computed as:

$$Kv = \frac{R - S/A}{1 + S/A} + \frac{(I/A)\cdot(R+1)}{(1 + F/A)\cdot(1 + S/A)} \qquad (1)$$

where A and S are primary and secondary air, respectively, I is the inert gas flow rate (nitrogen in this case), F the fuel flow rate and R the maximum value of the recirculation factor imposed by the main jet of the burner; R can be estimated as the ratio between the flow rate of recirculated exhausts and the inlet jet flow rate. When neither secondary air nor inert gas are fed to the lab-scale burner, the previous relation leads to $K_V=R$. As reported in a previous work [5], the maximum R value is equal to about 5; this value is reached at about 5.5 cm from the bottom nozzle tip, where the lateral spray-jet has been located. Therefore, in the dual nozzle setup, with the atomizer for the liquid fuel, this jet enters practically to the centre of the combustion chamber, interacting with the incoming air jet where the maximum aerodynamic recirculation is created.

The identification of mild conditions boundaries requires the definition of some threshold values either for pollutant emissions or for temperature gradients in the

combustion chamber. Following previous studies [4,7], clean mild conditions have been defined as characterized by NOx < 30 ppm and CO < 50 ppm in the exhaust.

3. Results and Discussion

Due to the presence of fuel droplets that are not fed to the burner premixed with the combustion air and considering the fact that the liquid fuel must evaporate before its vapors will be properly distributed within the gaseous reactants, several tests have been dedicated to properly evaluate the effects of both the atomizer and the liquid fuel injection on the burner thermal field. For this reason, preliminarily to the use of jet fuel surrogates, n-octane has been used to perform few experiments, at a constant thermal input, with the aim to clarify if some deviations from the clean Mild conditions can be observed during the transition from gas (SN layout) to liquid fuel (DN configuration). Fig. 2 reports a comparison among the average furnace temperature profiles collected for the clean Mild combustion of methane (SN), n-octane (DN) and in the middle of the gas to liquid transition; error bars have been used to indicate the maximum temperature deviation measured in the radial direction at a given distance from the burner top (corresponding to the axial distance=0 mm). The temperature profiles show a similar shape but it can be noticed that during a methane mild combustion the fuel oxidation is more concentrated close to the burner nozzle (axial distance=330 mm), while the reaction is more spread within the combustion chamber when the liquid progressively substitutes the gaseous fuel, thus leading to a reduced temperature gradient along the burner. Fig. 2 highlights also a temperature reduction close to the nozzle for the n-octane case; this should be ascribed to the fact that the liquid fuel droplets evaporation requires some energy to be completed.
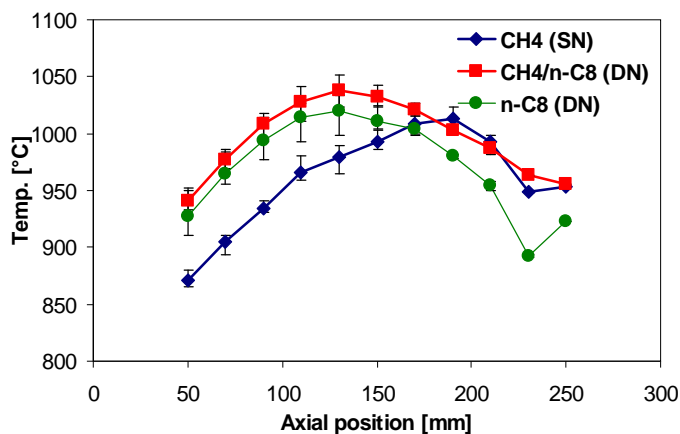

Figure 2. Average temperature profiles measured at different steps of the gas to liquid fuel transition (fuel input =0.3 kW, $T_{preheat}$=1050°C).
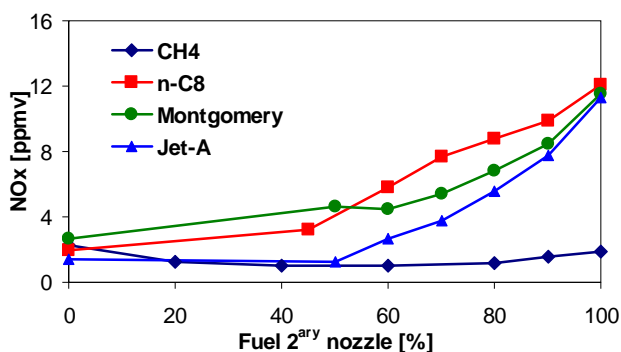
Figure 3. NOx trends measured during the transition (0% = SN; 100% = DN). Fuel input =0.3 kW, $T_{preheat}$=1050°C.

Then, the possibility to sustain Mild combustion conditions for different jet fuel surrogates, proposed in the literature [10,11], has been investigated. As an example, NOx emissions have been recorded during the transition to the liquid fuel feed for the Montgomery (42% n-dodecane, 33% n-decane, 14% butyl-benzene and 11% methylcyclohexane, by vol.) and a Jet-A surrogate (48% n-decane; 28% i-octane and 23% toluene) and compared with the corresponding emissions found for n-octane and methane (fig. 3). Both the surrogates, independently from their chemical composition and different molecular weight, evidenced NOx trends very similar to the one obtained for pure n-octane; NOx emissions are increased but they are still below the Mild clean threshold value (30 ppmv), while negligible CO emissions has been detected, confirming that a complete fuel conversion occurred.

A previous study [9] evidenced that the mild combustion characteristics seem more influenced by the physical state of the fuel (that is, gas or liquid) than by the chain length of the paraffins (that is, C1–C4 or C8–C10). These results seem to expand this assumption also to other hydrocarbons classes, such as cycloalkanes and aromatics. With the aim to support this idea, experiments with other jet fuel surrogates have been carried out; in particular, the following surrogates have been used: Stanford Mix-A (65% n-dodecane, 22% i-octane, 7% methylcyclohexane, and 6% toluene, by vol.); Cooke (28% n-tetradecane, 36% n-dodecane, 9% i-octane, 4% tetralin, 13% methylcyclohexane, and 10% m-xylene); Aachen 1 (40% n-dodecane, 40% n-octane, and 20% trimethylbenzene); Aachen 2 (60% n-dodecane; 20% methylcyclohexane, and 20% o-xylene).

As n-octane evidenced the possibility to operate in clean Mild conditions above a K_V value equal to about 1.5, the influence of the reactants dilution, K_V, on the Mild combustion sustainability for the above mentioned surrogates has been investigated. As reported in Fig. 4a, at low Kv, NOx emissions slightly exceeded the clean threshold limit of 30 ppmv for few surrogates, but this behavior depends also on the air preheating temperature; since a decrease of the dilution ratio involves a reduction of the air jet momentum, a lower reactants dilution is realized,

thus leading to a local increase of temperatures in the lower part of the combustion chamber (close to the nozzles); as a consequence, at low K_V, the surrogate fuel oxidation is still complete but NOx emissions are progressively increased. Very low CO emissions have been detected in the investigate range of dilution ratios K_V and practically no emissions of unburnt hydrocarbons have been found.
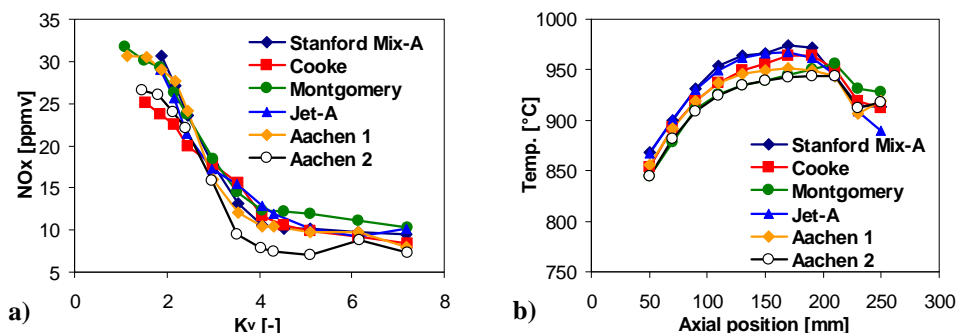

Figure 4. Emissions trends as a function of the dilution ratio (a) and average furnace temperature profiles along the burner axis (b) for the investigated liquid fuels (K_V=7); Fuel input =0.3 kW, $T_{preheat}$=1050°C.

All the investigated surrogates evidenced similar trends, both qualitatively and quantitatively, for temperatures (fig. 4b) and emissions at different K_V. Therefore, Mild combustion evidenced a great flexibility for what concern fuel properties, leading to the conclusion that it is possible to realize a clean Mild combustion at low K_V values for almost any kind of liquid jet fuel surrogate.

References

[1]   Choi, G.M., Katsuki, M., *Proc. Combust. Inst.* 29:1165-1171 (2002).
[2]   Wünning, J.A., Wünning, J.G., *Prog. Energy Combust. Sci.* 23:81-94 (1997).
[3]   Cavaliere, A., de Joannon, M., *Prog. Energy Combust. Sci.* 30:329-366 (2004).
[4]   Derudi, M., Villani, A., Rota, R., *Ind. Eng. Chem. Res.* 46:6806 (2007).
[5]   Cavigiolo, A., Galbiati, M.A., Effuggi, A., Gelosa, D., Rota, R., *Combust. Sci. Technol.* 175:1347-1367 (2003).
[6]   Effuggi, A., Gelosa, D., Derudi, M., Rota, R., *Combust. Sci. Technol.* 180:481-493 (2008).
[7]   Derudi, M., Villani, A., Rota, R., *Proc. Combust. Inst.* 31:3393-3400 (2007).
[8]   Weber, R., Smart, J.P., Kamp, W., *Proc. Combust. Inst.* 30:2623-2629 (2005).
[9]   Derudi, M., Rota, R., *Proc. Combust. Inst.* 33:3325-3332 (2011).
[10]   Ranzi, E., *Energy Fuels* 20:1024-1032 (2006).
[11]   Honnet, S., Seshadri, K., Niemann, U., Peters, N. *Proc. Combust. Inst.* 32:485–492 (2009).