Experimental Analysis of Mild Combustion of Liquid Fuels

M. Derudi, R. Rota

Politecnico di Milano - Dip. di Chimica, Materiali e Ingegneria Chimica “G. Natta” / CIIRCO, Milano – ITALY

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 [8] and solids [8].

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 n-octane and n-dodecane, using a two-nozzle feeding system. A practical liquid fuel with a mixed composition, namely kerosene, largely used for domestic heating applications and turbo reactors, was also considered. Therefore, the influence of different parameters, such as the oxygen excess and the combustion gas recirculation ratio ($K_V$), on the stability of mild combustion and pollutants formation has been investigated, as well as the temperatures trends inside the furnace for different operating conditions.

2. EXPERIMENTAL SECTION

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 used in this work. The burner, a flow rate control section for the reactants feeding, 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). The air preheating is performed in the lower section of the equipment by an electric oven, while another oven prevents heat losses from the combustion chamber.

The combustion chamber bottom is provided by a gaseous reactants feeding system, showed in fig. 1a, into which fuel is fed perpendicularly through a capillary pipe. It is possible to notice the positions of other reactants inlets for the incoming flow rates of primary air (A1), inert gas (N₂) and for the secondary air flow rate (A2). This single high-velocity nozzle configuration have been successfully used to reach mild combustion conditions using gaseous
fuels such as methane or ethane [5] and mixtures of gaseous hydrocarbons and hydrogen [4,7]. Because of possible pyrolysis phenomena, a liquid fuel cannot be however fed through the capillary pipe used for the gaseous fuel and the burner cannot be directly operated from the beginning of a run using the liquid fuel. This one is fed only when the burner reaches stable mild conditions using the gaseous fuel (methane or ethane), as showed in fig.1b. Therefore, the liquid fuel is fed by means of a peristaltic pump and injected within the combustion chamber as a fine and homogeneous spray by a water-cooled pneumatic atomizer.

The transition from the gas to the liquid fuel mild combustion (fig. 1c) is then reached reducing progressively the gas flow rate (say CH₄) fed to the burner nozzle while increasing the liquid flow rate into the atomizer. This means also a transition from a single nozzle feeding system designed for gaseous fuels (fig. 1a), to a dual nozzle feeding system with the liquid fuel (fig. 1c), where only the combustion air is fed through the burner nozzle, while the liquid is fed through the lateral atomizer (sketched in fig. 2).

Gas sampling has been performed by an on-line gas analyzer (HORIBA PG–250), which allows for measuring the concentrations of nitrogen and sulfur oxides, oxygen, carbon monoxide and carbon dioxide. Moreover, three thermocouples have been located at different heights of the combustion chamber to detect temperatures inside the furnace.

As previously mentioned, the combustion gas recirculation, the dilution ratio inside the combustion chamber, KV, plays a key-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 KV can be computed as:

\[
KV = \frac{R - S / A}{1 + S / A} + \frac{(I / A) \cdot (R + 1)}{(1 + F / A) \cdot (1 + S / A)}
\]  

(1)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>c₀</td>
<td>1.59</td>
</tr>
<tr>
<td>c₁</td>
<td>3.17</td>
</tr>
<tr>
<td>c₂</td>
<td>6.35</td>
</tr>
<tr>
<td>c₃</td>
<td>9.52</td>
</tr>
</tbody>
</table>
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. Assuming an incoming high velocity jet of the reactants at 1073 K, as shown in fig. 3, results highlight that R values do not change significantly in the investigated velocity range resulting in a maximum value of R equal to about 5, reached about 5.5 cm far from the nozzle tip.

In the latter configuration, 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.

Fig. 3  Dilution factor values induced by the main jet as a function of the distance from the burner nozzle for various jet velocities (without the secondary air feed).

Mild conditions can be practically identified by both the flame disappearing and the reduction of temperature gradients inside the furnace, that means a reduction of NOx emissions; moreover, in a previous study [7], a clean mild condition has been also defined, considering as upper threshold levels for the pollutants NOx < 30 ppmv and CO < 50 ppmv.

According to this criterion it is possible to build, for each fuel, usual $T$ vs. $K_v$ diagrams which represent the influence of $K_v$ on the combustion characteristics as shown, for the sake of example, in fig. 4. This diagram reports five main areas: a mild clean combustion region (B), where mild conditions can be easily maintained without any significant pollutant emission; a mixed zone (A), where both low-emissions and mild conditions can be achieved depending on the experimental conditions, such as a selection of a suitable combustion air preheating temperature; a thermal NOx region, where mild conditions can be sustained but thermal NOx production becomes significant; a no combustion (or extinction) zone and a traditional flame combustion region.

Fig. 4  $T$ vs. $K_v$ diagram sketching boundaries and peculiar regions identified in this work.
3. RESULTS AND DISCUSSION

The first part of this work concerned the evaluation of the effects on the combustion stability during the transition from a gaseous to a liquid fuel feed. A liquid fuel with a low molecular weight, such as the n-octane, was used. As reported in fig. 5a, an increase of the liquid n-octane percentage in the fuel mixture leads to an overall raise of the temperatures within the furnaces; this behavior was expected because the transition involved also a moderate increase of the thermal input of the burner, in order to ensure an effective spray formation and a complete evaporation of fuel droplets. However, the low temperature difference measured by the thermocouples, one located close to the burner outlet and the other one at half height of the combustion chamber, confirms that a mild combustion regime is steadily maintained during and after the fuel transition. This fact is also confirmed by the trends of the emissions (fig. 5b): NOx emissions are increased but they are still below the mild clean threshold value (30 ppmv), while a small amount of CO emissions has been detected during the first step that involves the liquid fuel injection (CH₄:n-octane = 80:20), confirming that a complete fuel conversion occurred. Moreover, it can be noticed that clean mild combustion conditions are steadily sustained even if a drastic change occurs inside the small-scale furnace due to the transition from methane towards n-octane, that involved the use of two fuels (a gas and a liquid), fed through separated nozzles, the production of fuel droplets to be evaporated, the presence of a carrier gas for the liquid atomization and probably a partial alteration of the flow field inside the furnace.

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 define which were the optimum operating conditions in terms of oxygen excess and preheating temperature for the air in order to ensure the sustainability of a clean mild combustion with, in this case, a particular attention on CO formation. In Fig. 6a the measured trends of CO emissions (dry ppmv) have been summarized as a function of the oxygen excess for few representative preheating temperatures; it is possible to notice that the preheating temperature has a slight influence on the CO formation, since the clean threshold for CO (that is 50 ppmv) has been always reached for an oxygen excess of about 8%. For this reasons, all the following runs have been performed at O₂ excess levels higher than 10% for n-octane.

Concerning the influence of the reactants dilution, KV, on the mild combustion emissions, n-octane evidenced the possibility to operate in clean mild conditions above a KV value equal to about 1.5, that is significantly lower than the reference values commonly found for methane or natural gas, which correspond to about KV=3 [2,5]. As reported in Fig. 6b, very low CO emissions have been detected in the investigate range of dilution ratios KV and practically no emissions of unburnt hydrocarbons have been found.

Fig. 5 Temperature profiles (a) and emissions measured (b) during the transition from gaseous to liquid fuel feed (20% of O₂ excess, combustion air preheated at 1100°C).
On the other hand, at low $K_v$, NOx emissions can exceed the clean threshold limit of 30 ppmv (Fig. 6b). Depending on different operating conditions, after the transition from the gaseous towards the liquid fuel, a NOx level higher than 10 ppmv is commonly found; 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 n-octane oxidation is still complete but NOx emissions are progressively increased.

Once verified the possibility to obtain a mild clean combustion using a low molecular weight liquid fuel, such as the n-octane, a real fuel, kerosene, constituted by a mixture of different hydrocarbons has been used. A gas-chromatography coupled with mass spectrometry (GC-MS) analysis showed that the selected kerosene was mainly a mixture of linear hydrocarbons ranging from C$_{10}$ up to C$_{13}$. Preliminary tests have been carried out to estimate, also for this fuel, the necessary air flow rate and, in particular, the optimal air excess able to sustain mild clean combustion conditions for this fuel, with particular attention to CO emissions. Results showed that low CO emissions are possible for an oxygen excess higher than 18-19% by vol., depending on the preheating of the combustion air (fig. 7a). With kerosene, pollutants emissions and temperatures detected during the transition from the gaseous fuel (CH$_4$) to the liquid one, evidenced trends similar to those previously reported for n-octane. This fuel, similarly to n-octane, showed NO emissions below 30 ppm and CO negligible emissions during the complete transition from the single-nozzle gas-based mild combustion towards the dual-nozzle liquid fuel mild combustion.

Considering all the experimental results, referred to the dilution ratio ($K_v$), it was possible to define the mild operating map (fig. 7b), for both fuels: red line indicates the boundaries of the mild clean working region for n-octane, while the blue one the corresponding region for kerosene; in particular, solid lines represent conditions that lead to CO emissions above the threshold limit, while the dotted lines the threshold limit values for NOx emissions. As a consequence, it is possible to highlight a lower mild clean temperature limit for n-octane, set at about 840°C (below this temperature CO emissions are higher than 50 ppmv, so the fuel conversion is reduced), and a lower $K_v$ limit at about $K_v=1.5$; on the other hand, kerosene evidenced a better sustainability at high temperatures with an upper temperature mild clean limit (blue dotted line in fig. 7b) at about 1070°C.

Lastly, preliminary measurements have been carried out with a new system of temperature detection, which allowed us to change the vertical position of three thermocouples hosted inside the combustion chamber also during the experimental run; in this way, it was possible to collect temperature profiles for different operating mild clean conditions, as summarized in Fig. 8 for several $K_v$ values. Both fuels showed similar trends but with differences in the
temperature gradients found across the burner length; in particular it was observed that increasing the $K_v$ value the main reaction region is progressively shifted towards the upper part of the furnace. The intermediate $K_v$ values ($K_v = 4.7$, Fig. 8b) always evidenced lower thermal gradients along the burner axis and lower peak temperatures with respect to other cases, evidencing once again the good thermal homogeneity of stable mild clean conditions.

**Fig. 7** CO vs. oxygen excess for kerosene as fuel (a) and operating mild clean maps defined for n-octane (red line) and kerosene (blue line), respectively (b).

**Fig. 8** Examples of temperature profiles measured along the burner (0 mm is the burner exit while 350 mm is the burner bottom) for erosene (a,b,c) and n-octane (d) respectively.

4. REFERENCES