Mild Combustion of Liquid Hydrocarbon Fuels

L. La Gamba, M. Derudi, R. Rota

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

1. INTRODUCTION

In the last decades, significant efforts have been made in order to obtain high thermal efficiencies in combustion processes without the adverse effect of high NOx emissions caused by flames at high temperatures [1]. It was found that a strong exhaust gas recirculation combined with air preheating generates relatively low flame temperatures. If the combustion air is diluted with a large amount of recirculated exhausts, the oxygen concentration in the reaction zone is reduced to a lower concentration with respect to the case of undiluted air allowing for a better control of the 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], as well as mixtures of gaseous hydrocarbons and hydrogen [4,6], have been extensively studied; on the other hand, much less information are available concerning the sustainability of mild combustion for liquids [7-9] and solids [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 n-octane and n-dodecane, using a two-nozzle feeding system. A common 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.

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 ($N_2$) 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 [4,6]. 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.

![Fig.1 Reactants feeding system: (a) single-nozzle gaseous fuel feeding; (b) dual-nozzle liquid and gaseous fuels feeding; (c) dual-nozzle liquid fuel feeding.](image)

The transition from the gas to the liquid fuel mild combustion (fig. 1c) is then reached reducing progressively the gas flow rate (say CH\textsubscript{4}) 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).

![Fig.2 Liquid pneumatic atomizer: liquid fuel flow (orange), cooling water flow (blue) and nitrogen flow for the atomization (grey).](image)

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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, two thermocouples have been located at different heights of the combustion chamber (close to the top and the liquid fuel injection port, respectively) to detect temperatures inside the furnace.

As previously mentioned, the combustion gas recirculation, the dilution ratio inside the combustion chamber, \(K_V\), 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 \(K_V\) can be computed as:

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

(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 $[10]$. 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 jet as a function of the distance from the burner nozzle for various jet velocities.

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 NO$_x$ emissions; moreover, in a previous study $[6]$, a clean flameless condition has been also defined, considering as upper threshold levels for the pollutants NO$_x$ < 30 ppm and CO < 50 ppm.

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 NO$_x$ region, where mild conditions can be sustained but thermal NO$_x$ 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 study of possible effects on the combustion conditions 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 fraction within 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 a good spray formation and an effective fuel droplets evaporation. However, the low temperature difference measured by the two thermocouples, one located close to the burner outlet and the other one at middle 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 pollutants trends (fig. 5b): NO emissions are increased but they are still below the mild clean threshold value (30 ppm), while practically no CO emissions have been detected, confirming that a complete fuel conversion occurred. Moreover, it can be noticed that clean mild combustion conditions were steadily sustained even if a drastic change was operated within the small lab-scale furnace; indeed, transition from methane towards n-octane involved the use of two fuels, in different phases and fed through separated nozzles, the production of fuel droplets to be evaporated and probably a partial alteration of the flow field inside the furnace.

![Fig. 5](image)

**Fig. 5** Temperature profiles (a) and emissions measured (b) during the transition from gaseous to liquid fuel feed (14% of O₂ excess, combustion air preheated at 950°C).

However, others experiments have been done to study the effect of the oxygen excess on the combustion regime, paying attention in particular to the CO formation (fig. 6a); it was observed that a reduction of the oxygen excess, until 10% by vol., makes the n-octane combustion more difficult but CO emissions were always well below the mild clean threshold value (50 ppm, red line in fig. 6a), except during a strong reduction of the air preheating or a

![Fig. 6](image)

**Fig. 6** Effect of the oxygen excess on the n-octane mild combustion (a) and n-octane mild clean operating map (b).
burner shutdown.

Considering all the experimental results, referred to the dilution ratio ($K_V$), it was possible to define the mild operating map (fig. 6b), for the n-octane: empty symbols indicate mild clean working conditions, while black and blue symbols represent conditions that are above the CO and NO threshold limits, respectively. As a consequence, it is possible to highlight a lower mild clean temperature limit (black line in fig. 6b) placed at about 840°C (below this temperature CO emissions are higher than 50 ppm, so the fuel conversion is reduced), and a lower $K_V$ limit at about $K_V=1.5$; below this value, dilution is not enough to effectively prevent NO formation, that reaches concentrations higher than 30 ppm. Finally, a high temperature mild clean limit (blue line in fig. 6b) at about 1010°C has been found; above this threshold both the thermal homogeneity and oxygen dilution are not enough to keep a low NO formation.

Once verified the possibility to obtain a mild clean combustion using a low molecular weight liquid fuel, such as the n-octane, a liquid hydrocarbon with a longer chain molecule, n-dodecane, has been briefly tested as a fuel. As reported in fig. 7, n-dodecane and n-octane showed a similar behaviour both for average furnace temperatures and NO concentration profiles. These tests were performed with the same air preheating temperatures, oxygen excess (10% by vol.) and liquid flow rates; the slightly larger molar flow rate used in n-dodecane run explains the temperature difference of about 50°C between the profiles (fig. 7a) but although the temperature increase is moderate higher NO emissions for the n-dodecane (fig. 7b) have been measured, evidencing a lower $K_V$ threshold of 2.5 for this fuel. Moreover, n-dodecane showed a lower temperature limit for the clean mild combustion at about 835°C.

![Fig. 7](image-url) Comparison between temperature profiles (a) and NO emissions trends (b) for liquid n-octane and n-dodecane mild combustion (air combustion preheated at 980°C).

In the last part of this work, 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 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. 8a). Lower CO emissions were found for lower preheating temperatures probably because these conditions allowed an increase of the reactants residence time within the combustion chamber, thus ensuring the complete fuel conversion. However, according to the results of fig. 8a, all the following experiments with kerosene were carried out using an oxygen excess of 20% by vol.

Pollutants emissions detected during the transition from the gaseous fuel (CH$_4$) to the liquid one, kerosene, are summarized in fig. 8b.
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. Moreover, several sulfur oxides traces (max 2 ppm), due to the possible presence of a low amount of sulfur-containing compounds in the fuel mixture, were found. Lastly, experimental results allowed for the definition of the operating mild clean map for kerosene (fig. 9); a lower dilution ratio, \( K_V = 1.7 \), and lower and upper mild clean temperature limits at about 855°C and 1055°C were identified, respectively.

4. REFERENCES