EVALUATION OF FUEL FLEXIBILITY IN A CYCLONIC BURNER.

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Abstract
Stabilization of distributed combustion regimes adopting cyclonic flow fields has been proven to be challenging. In fact, the establishment of a toroidal flow field within a combustion chamber may ensure the recirculation of mass and sensible enthalpy required to simultaneously dilute the fresh reactants and increase the temperature above the autoignition one. The combination of reactants dilution and preheating may greatly increase system energy efficiency and lower pollutants production producing very peculiar combustion regime (MILD Combustion). At the same time this strategy can be compromised if the sensible enthalpy is not high enough to promote the auto-ignition process of diluted mixtures. The paper aims at exploiting the performance of a small-size cyclonic burner for a conventional fuel (CH_4) and low calorific fuel (synthetic biogas) or ammonia through the characterization of the process stabilization and pollutant emissions as a function of the mixture equivalence ratio and the nominal thermal power of the inlet mixture (from 2 to 10 kW), with the aim of identifying the optimal operating condition of the system. Results suggest that the system has to be exercised with mixtures with compositions slightly under the stoichiometric conditions for methane or biogas mixtures and in a well identified temperature range to minimize both NOx and CO emission. On the other hand, ammonia/air mixtures have to operate under slightly rich conditions. The burner can be easily exercised also with low calorific fuels or with ammonia-based ones for higher thermal powers according to the low LHV. However, it results that an efficient recirculation of the exhausts produces a robust MILD combustion condition also when low calorific fuels are used.

Introduction
In the consolidated and fast evolving concept of smart energy grid, the leading renewable, alternative energy sources are however integrated with (and supported by) combustion based energy production systems. However, to fit the grid criteria and meet load following requirements, combustion based energy systems at different scales are required to use both fossil and alternative fuels. This latter class includes many fuels produced by means of a wide variety of processes with the general aim of maximizing the renewability of sources and/or find a suitable way of storing the energy excess from renewable sources.
Fuel and power flexibility is not a simple task to pursue in a single combustion

unit. Based on a substantially different combustion regimes, new paradigms of combustion processes, such as MILD combustion [1], give the opportunity to explore the possibility of using a wide palette of fuels in a wide range of power in a single unit. Several configurations have been conceived and studied for practical applications [2,3].

In this framework, the present paper aims to move a further step forward in the knowledge about MILD Combustion application. The results here reported have been obtained using a very simple MILD burner that realizes an internal recirculation scheme. Following the approach already used in previous works from the same research group [4], a systematic experimental study has been carried out to explore the feasibility of fuel and power flexibility. Methane, a surrogating biogas mixture (methane/CO_2) and ammonia have been used as fuels. The combustion effectiveness as a function of thermal power has been evaluated at different equivalence ratio by measuring process temperature and exhaust gas composition.

Experimental setup and methodology

The experimental campaign was carried out in the Laboratory Unit CYclonic (LUCY) burner. It consists of an alumina prismatic (2000 cm^3) chamber mounted inside an AISI 310s stainless case. Several shielded thermocouples (type N) are used to monitor the combustion process inside the burner. Details of the experimental plant can be found elsewhere [5].

Flow rates can be easily changed in a wide range resulting in a nominal thermal power interval from 0.1 up to 10 kW. In all the cases here reported, both the T_{in} and the fuel inlet temperature are kept at environmental temperature.

The exhausts are sampled at the outlet section center by means of a cooled probe and are analyzed through a portable micro-GC analyzer that allows to measure O_2, CO, CH_4 and C_2-species. NO and NO_2 (NO_x) are measured by means of both a flue gas analyzer (TESTO 350) and a ABB analyzer. All the gas concentrations reported in the followings are all normalized to a 15% O_2 in the exhausts.

Results and discussions

The experimental tests were realized, first of all, for methane/air mixtures at ambient conditions (T_{in}=300K, P=1 Atm) by monitoring the temperature and pollutant emissions (CO, NO_X) as a function of the equivalence ratio at two values of the nominal thermal power (4 and 10 kW), as reported in Figure 1.

The equivalence ratio Φ ranged between 0.5 and 1. As shown in previous works [6], such range ensures reasonably low pollutant emissions in the exhausts.

It is possible to note that for P = 10 kW, the temperature increases linearly with Φ, from 1400 K to 1500 K in the considered Φ range. Temperatures are generally higher than the ones recorded at P = 4 kW. For P = 4 kW, the residence time (t) increases with Φ from 0.22 to 0.37s, while for the P = 10 kW, from 0.11 to 0.13s. Because of an increase of system temperatures at higher Φ, t diminishes with Φ,

but as much as Φ increases less air is introduced in the system, thus τ increases.
Figure 1b shows the concentration, normalized at 15% O_2, of CO and NOx, as a function of the equivalence ratio, at fixed power values. In general, it is possible to note that the CO concentration exhibits a non-monotonous trend. At low Φ it is relatively high because of low system temperatures, that does not allow a full conversion of CO to CO_2. As matter of fact, for P = 4 kW and Φ = 0.5, CO value are 166 ppm with a system working temperature equal to 166 ppm. A further decrease of Φ causes a decrease of temperature with an increase of CO with the occurrence of the process extinction. On the contrary, as Φ increases, CO reaches a minimum value and it starts increasing when the equivalence ratio value approaches the stoichiometric condition. For P = 4 kW the minimum CO value occurs around Φ = 0.7, while for P = 10 kW the minimum value occurs at Φ equal to about 0.75.

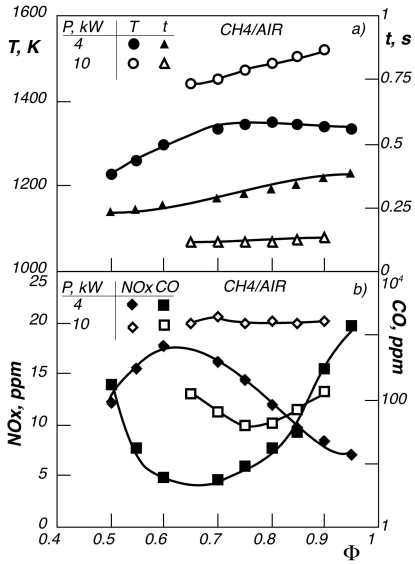

Figure 1. Temperature measurements, characteristic residence time (a) and pollutant emissions (b) for CH_4-air mixtures as a function of Φ for different thermal power values.

The concentration of CO becomes lower than 100 ppm, respectively for 0.55 < Φ < 0.85 for P = 4 kW, and at 0.7 < Φ < 0.85 for P = 10 kW.
NO_x concentrations show a non-monotonous trend at P = 4 kW. In particular, they reach a maximum value of 18 ppm at Φ = 0.6 and then slightly diminishes down to 7 ppm when the mixture composition moves towards the stoichiometric value. This last effect may be correlated to the onset of NO reburning chemistry for temperatures higher than 1200 K [7]. For P = 4 kW, the optimal condition is at Φ = 0.85, while for P= 10 kW it is at Φ = 0.75.
In order to verify the fuel flexibility of the cyclonic burner for small scale

applications, further experimental campaigns were performed with a synthetic mixture (60% CH_4, 40% CO_2 [8], mimicking a fuel with lower LHV.
Similarly to methane/air campaigns reported in previous sections, the experimental tests were realized, for biogas/air mixtures at ambient conditions (T_{in}=300K, P=1 Atm) by monitoring temperature and pollutant emissions (CO, NO_x) as a function of the equivalence ratio (in the same 0.5-1 range) at the same nominal thermal powers (4 and 10 kW).

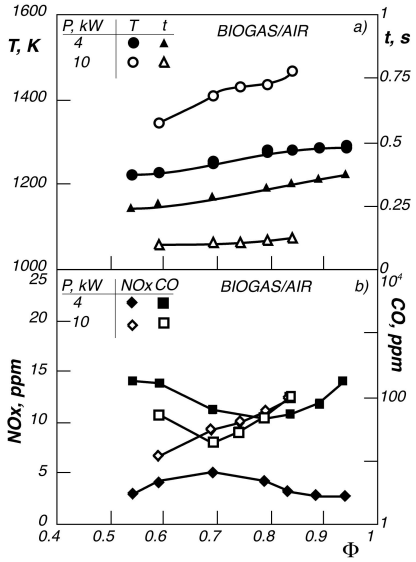

Figure 2. Temperature measurements, characteristic residence time (a) and pollutant emissions (b) for biogas-air mixtures as a function of Φ for different thermal power values.

Temperatures were reported in Figure 2a as a function of the equivalence ratio for biogas-air mixtures. At P = 4 kW, the temperatures profile exhibits a monotonous trend and it increases with Φ, passing from T=1220K at Φ=0.55 to about 1300K at Φ=0.95. They reach higher values for P=10 kW, as expected.
The emissions of main pollutants (CO and NO_x) were reported in Figure 2b, for biogas-air mixtures as a function of the equivalence ratio, on curves parametric in P. CO concentrations show a non-monotonous trend in log-scale in the Φ range considered. The minimum CO value is 50 ppm at Φ = 0.8 for P=4 kW, whereas for P = 10 kW the minimum value is lower and it occurs about at Φ = 0.7. CO emissions are below 100 ppm, respectively for Φ < 0.8 for P = 10 kW, and at 0.65 < Φ < 0.8 for P = 4 kW. On the basis of the showed results it is possible to infer that the reactor performance, in terms of CO emissions, are enhanced for higher values of the thermal power when Φ < 0.8. NO_x concentrations show a non-monotonous trend at P = 4 kW and they are always in the single-digit limit. They reach a maximum value of 6 ppm at Φ = 0.7 and then slightly diminishes up to 3 ppm when the mixture composition moves towards ultra-lean conditions or in the

opposite direction. On the other hand, NO_x emissions for P = 10 kW slightly increase from 6 ppm at Φ=0.6 to 13 ppm at Φ=0.85. They exceed the single-digit value when Φ>0.75.

Finally, experimental tests were realized, for ammonia/air mixtures at ambient conditions (T_{in}=300K, P=1 Atm) by monitoring temperature and pollutant emissions (NO_x) as a function of the equivalence ratio by changing the thermal power from 5 to 10 kW.

As it is possible to note from Figure 3 the process sustainability is ensured when temperature is higher than 1300 K for all P values. On the other hand, the oxidation process is not sustained when the equivalence ratio is lower than 0.7. Results demonstrated the flexibility in terms of fuel of the cyclonic burner also when ammonia is used as fuel, making it implementable in applications such as gas turbines [9].

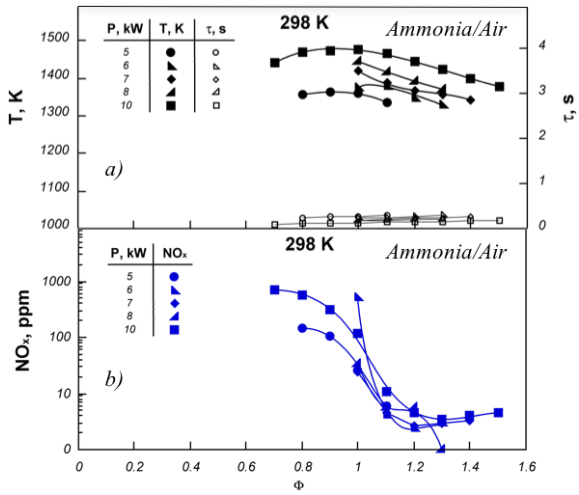

Figure 3. Temperature measurements, characteristic residence time (a) and pollutant emissions (b) for ammonia-air mixtures as a function of Φ for several P values.

In particular, NO_x levels are decreased from high values (up to 1000 ppm at 10 kW) to single digit ones when the equivalence ratio increases from ultra-lean to stoichiometric or slightly rich values.

Conclusions

The experimental results confirmed that the cyclonic burner has shown similar and very good performance for several fuels such as methane, biogas or ammonia.

With respect to the optimal operating conditions, the results have shown that the system has to be exercised with mixtures compositions slightly under the stoichiometric conditions for methane or biogas/air mixtures. In case of the methane/air mixtures the system can be operated with emissions of CO lower than 100 ppm. NO_x emissions can be lowered down to 1 digit values by keeping the

system temperature lower than about 1400 K.
In the case of biogas/air mixtures the optimal equivalence ratio to minimize emissions are slightly lower than the one identified for the methane mixtures. Results have suggested that in this case it is convenient to use higher nominal thermal power to optimize the system in order to contrast the effect of temperature reduction induced by the CO_2 thermal sinking effect. On the other hand, the presence of CO_2 has beneficial effects to contain the NO_x emissions.
Finally, the use of pure ammonia as fuels decreased the operability range of the burner in terms of temperatures and equivalence ratio ranges. Despite that the burner showed very good performance in terms of NO_x when the equivalence ratio is higher than the stoichiometric value.

References

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