Experimental Analysis of Flame Stability in Mild Combustion Condition

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ABSTRACT

The analysis of flame stability is particularly important when low quality fuels have to be burned: in fact their combustion is more difficult to be kept stable. The work presented deals with the tests made on flames from low quality fuels combustion in mild condition, that is burning in a hot stream with moderate or intense oxygen dilution, achieved by flue gas external recirculation.

Near the burner outlet section, reactants temperature is higher then autoignition one so no external spark is needed the combustion to begin.

Oxygen dilution lowers combustion pick temperature with benefic effect upon thermal NOx formation; moreover the presence of CO_2 and H_2O within reactants, enhances radiative heat transfer between flue gases and furnace walls, due to higher values of monochromatic emittance of these species.

In mild combustion, high temperatures near burner outlet encourage diffusive phenomena inside the reactants stream; on the other hand, mixing is delayed by oxygen dilution. It isn't possible, a priori, to foresee which is the mean effect; for this reason an experimental analysis has been performed.

Tests have been made varying air ratio and reactants outlet velocity at the main burner; for each test condition, geometrical characteristics of the flame have been registered by an high speed CCD camera, in order to have to identify stable and instable working condition.

Results are reported by means of diagrams and acquired images and critically discussed , expressing the range of flame stability in terms of thermal and fluidynamic operating parameters.

FLAME STABILITY AND MILD CONDITION

Diffusion flames at atmospheric condition have been analysed. Just downstream the outlet section of such a burner, if we divide the area in little finite elements, we can find a very reach zone in the centre and a very lean zone all around, as shown in fig. 1.

To start combustion it's necessary that in subsequent section flammable condition take place so ignition is realized and heat production can spread through surrounding zone, generating the flame propagation.

In deflagration regime, flame front tends to proceed in the opposite direction with respect to fuel and air stream; on the other hand, fuel and gas stream tends to push the flame front away from the outlet section. In steady state condition, *flame stability* can be achieved when

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an equilibrium is established between these opposite phenomena. In this case flame is at a a fixed position in the combustion chamber.

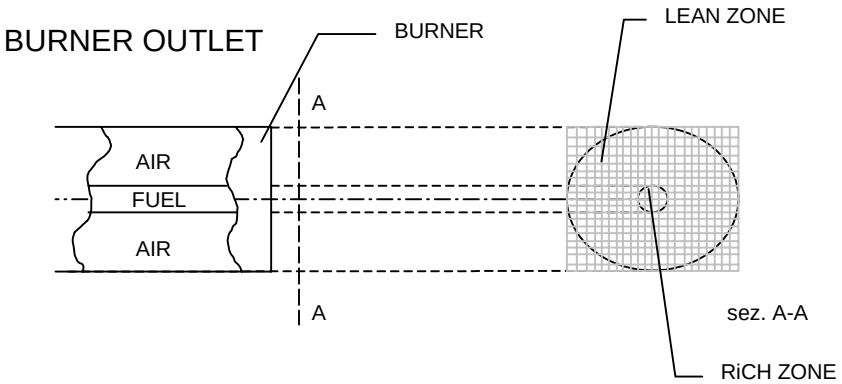

Fig.1: Non premixed flame burner configuration

Anyway, combustion is able to stay stable if reactants velocities vary in a limited range: if they decrease under lower limit, the flame die due to bad mixing: air and fuel diffuse too slowly for flammable condition to take place; on the other hand combustion stops if reactants are too fast: in this case reactants, even if well mixed, stay too little in the high temperature zone.

Consideration above reported are the fundamentals of Broadwell theory for mixing and combustion of liquid fuels in turbulent, non premixed flames: he says that during mixing, air penetrate inside the spray; in this phase and till macroscopic vortexes are created, chemical reactions and diffusive phenomena take place at the interface between air and fuel.

In the first phase, mixture, not yet homogeneous, is too rich, so combustion begins only on the external layers of the air-fuel mixture. After, mixture enriches of air and combustion starts to propagate inside

If t_m is the time for homogenization, it can be demonstrated that for big values of Reynolds, t_m is proportional to d/u ratio, where d is the local diameter of the spray, u is the local velocity of droplets distributed along the ring with diameter d. If t_c the minimum time for reactants ignition, t_c is proportional to k/S_l, where k is the thermal diffusivity of fuel and S_l the laminar combustion rate. Falme is in stable condition when

$$\varepsilon = \frac{t_m}{t_c} \propto \frac{d}{u}\frac{k}{S_l} > \varepsilon_{critic} \qquad [1]$$

In different terms flame can sustain itself until t_m/t_c ratio is fairly high, that is combustion can start not so far from stoichiometric condition zone.

In case of mild condition we have two opposite effects on combustion. The first is that , for the same oxidant stream rate, it is reasonable to expect that mixture will burn much easily because temperature near the burner are higher than traditional combustion one and higher than autoignition one; moreover it must be considered that exhaust gas recirculation represent an obstacle for fuel diffusion into the oxidant.

The first effect is preponderant on the second if oxidant stream is not so diluted and its velocity is not so high. On the contrary, if big velocities are required for a good mixing of reactants, flame stability could be compromised.

In this case only an experimental analysis can give fairly good information on combustion; in fact mathematical model of mild combustion have not yet achieved enough accuracy in foreseeing flame behaviour varying inlet conditions.

Flame stability is also influenced by fuel nature. The width of velocity range which guarantees stable combustion condition depends on fuel properties too.

In case of low temperature of reactants, valuable fuels guarantee better stability conditions; in fact in this case flame stability depends on capability to keep high the thermal level near the burner outlet. A valuable fuel, quickly diffusing, also in rich condition, keeps the flame stable due to good homogenization of heat locally generated. In this case the most flammable the fuel, the largest is the stability range of velocities.

In mild combustion instead, the situation is quite different: the least flammable the fuel, the largest the velocity range which guarantees stability. In such condition, when reactants temperature is higher than autoignition one, mixture ignition principally depends on fuel capability to diffuse into the oxidant. In low diffusion condition, in some points where mixture is into flammability limits, ignition points can be generated which encourage local diffusion motion and allow to keep a very irregular flame, which jumps locally from one primer to another. In fact in mild combustion, local temperature increasing is not finalized to keep thermal level higher than ignition temperature, but to increase diffusion motion. It means that with gaseous fuel reaction has low probability to be kept because critical conditions are uniformly reached; with liquid fuels instead, moreover with solid ones, it is easier to locally find aiding conditions.

In different words, for easy flammable fuels, the mixture burns well, in a uniform and complete way, or reaction stops; for not easy flammable fuels instead, there is also the chance that mixture burns not in a uniform and complete way, but fairly to keep a long and not so hot flame. In this last case perhaps it is not very correct to speak about “flame stability”: it is rather a transition zone between stable and instable conditions.

EXPERIMENTAL SETUP

The combustion plant at DIME laboratories is made principally of a long furnace (1m x 1m x 5m) with an external gas recirculation system, fed by a diesel oil main burner and a supplementary burner for start up phase. The plant allows to investigate a very large range of operating conditions and thermal power, from 50 to 1000 KW.

On the recirculation duct a fan (for high temperature) is mounted, driven by an electrical motor, regulated in its speed by an inverter system. Fan speed can arise up to 18.000 rpm, in fact it’s derived from a turbocharger. Furnace is monitored and controlled by a computerized interface which allows continuous data acquisition (see control panel in fig.2).

A first series of test has been performed, in which recirculation has been simulated by start-up burner continuous operation : it burns diesel oil with a fixed air/fuel ratio; its flue gas with a residual oxygen concentration (lower than 8%) are sent to the main burner.

With a fast acquisition CCD camera system it’s possible to investigate about flame stability condition, varying oxidant rate and so its velocity at main burner outlet section. Acquisition rate can be up to 1000 frame per second (1000 Hz) with a full frame resolution of 1024x512 pixels.

All the tests are managed by LABVIEW software, which is able to acquire temperature, pressure, oxygen and pollutant concentration (NOx, CO, SOx) in different points

of the plant, All data are collected and stored in EXCEL chart in order to be analysed in post process phase.

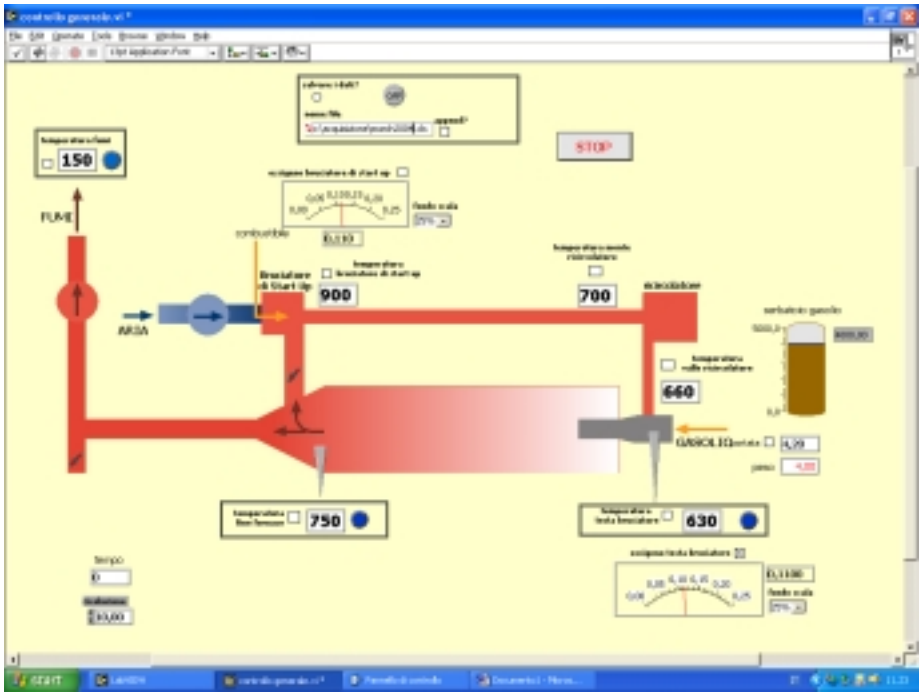

Fig.2: Front panel of control and monitoring system

Varying fan speed and air ratio it's possible to generate different inlet condition at the main burner in terms of oxidant temperature, velocity and oxygen concentration. For each condition, by means of the fast CCD camera, stable or unstable condition can be recognized. If flame base has a negligible oscillation with respect to its distance from burner outlet, flame can be considered stable; on the contrary, for large oscillation flame is unstable.

While temperature and composition of oxidant stream at the burner outlet can be directly measured by thermocouples and gas analysers, velocity instead is calculated by Δp measured between upstream and downstream the main burner final duct, composed of 72 little straightners in ceramic fibre, collected in a ceramic fibre cylinder (see fig. 3).

Fig.3: Main burner outlet section (not. the nozzle in the centre and the straightners around it)

RESULTS ANALYSIS

Each test condition has been considered reached when all parameters, especially temperature and concentration, were stable after switching from one condition to another. This situation has been evaluated by the analysis of temperature trends stored by data acquisition system.

For each test condition, two CCD acquisitions were performed in order to confirm the data acquired. In stable condition, as written, flame base oscillation must be negligible with respect to distance from the burner outlet section. In fig. 4 and 5 stable and instable condition are represented, reporting this distance vs time.

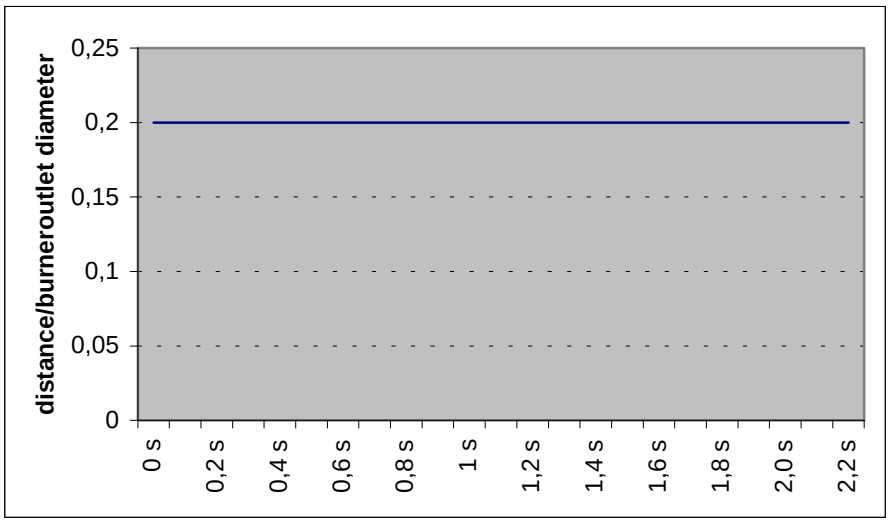

Fig.4: Stability condition

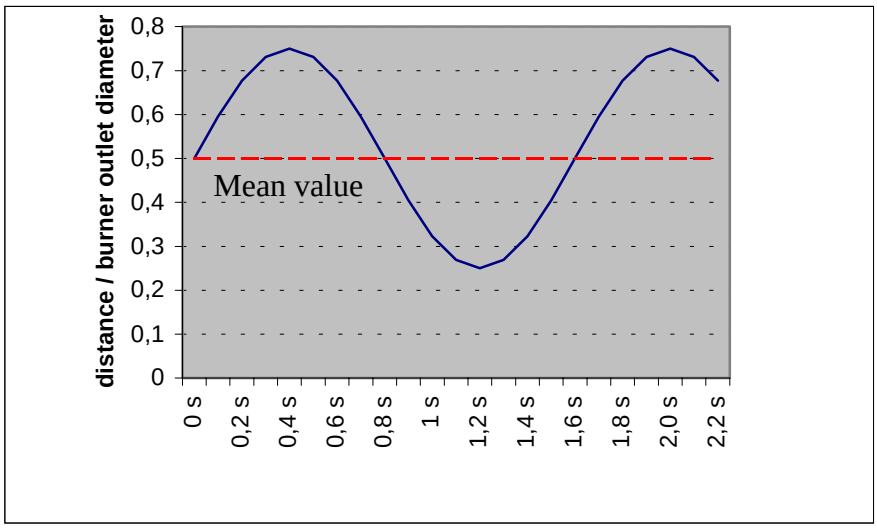

Fig. 5: Instability condition

FIRST RESULTS AND CONCLUSIONS

Test have been performed varying fan speed from 1000 to 4000 rpm, acquiring image sequences of 500 frames at 250 Hz, so the time elapsed from one frame to another is 4 ms. Obviously there aren't here presented the whole sequences but only some significant image from CCD camera. A colour camera with 25 Hz acquisition rate (not so fast as the CCD) has

been used too in order to characterized the colour of the flame (an example is reported in fig.3.

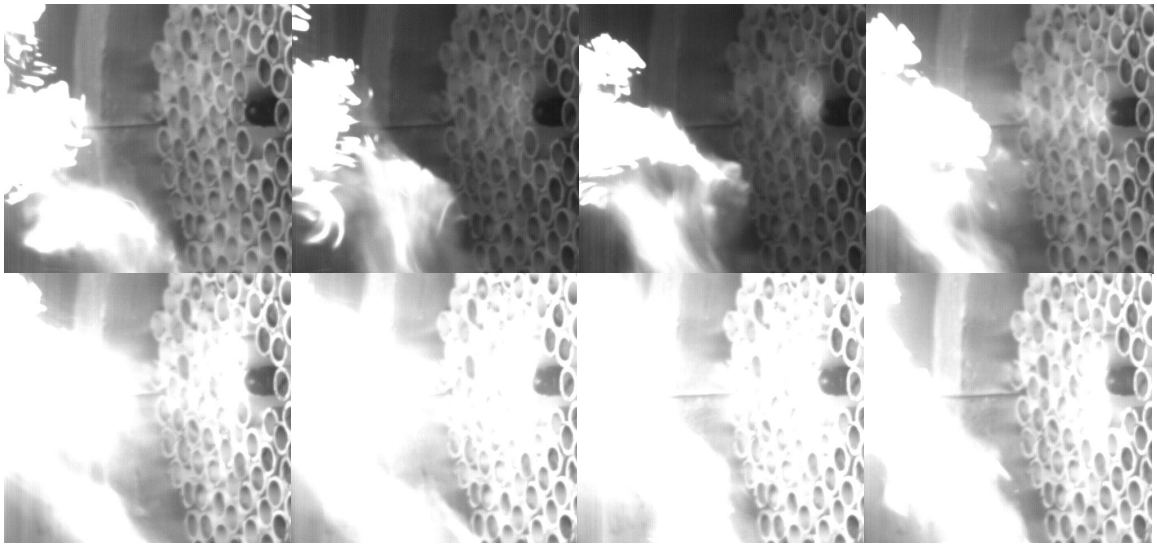

Fig.6: A sequence of frames at 250 Hz, in case of unstable flame

In fig. 6 a typical sequence of frames is reported, in case of unstable flame. Each frame represents 4 ms of the period of inspection; it can be noticed as from the frame is possible to detect the amplitude and the frequency of oscillation of the flame front and amplitude can be compared with burner diameter. So each sequence allows to analyse the stability or instability of flame in that condition.

In the tests performed not yet all the range of variation of operating parameters has been analysed, because the main goal has been the validation of the analysis procedure.

Many advances must to be yet realized on the plant in order to have more chance to vary different parameters for the tests.

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