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Influence of Acoustic Excitation upon the Entrainment Phenomenon in Combustion/Propulsion Applications

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***Abstract*— This paper presents the results of an experimental investigation performed about the entrainment phenomenon induced by an axisymmetric jet, which can be used for premixed combustion appliances or in free diffusion flames (for instance in propulsion applications). Particularly, the main goal of the research activity was a systematic analysis of the influence of an acoustic excitation upon the jet development and entrainment of the surrounding stagnant air. The analised jet presents a quite low Reynolds number (ReD • 3600), constituting a test case non yet thoroughly studied in literature, but peculiar of some technical appliances, for instance in the field of premixed gas burners. At first, the flow field generated by the stationary free jet has been characterised both through laser Doppler velocimetry, to estimate the global and local entrainment coefficient, and hot wire anemometry, to attain the natural frequency (Strouhal number) of the jet. Subsequently, the jet has been acoustically excited through an active loudspeaker placed in a stagnation chamber upstream the jet outflow, operating at a frequency corresponding to the natural one of the stationary jet (210 Hz). The flow field induced by the excited jet has been analised through laser Doppler velocimetry, comparing the jet development (mean axial velocity and turbulence intensity profile) and the entrainment phenomenon with respect to the stationary (i.e.: not-excited) jet. The results put into evidence that the excited jet presents, especially in the initial region, higher turbulence levels and a larger radial expansion, contributing to a noticeable reduction of the potential core length (backwarding of the jet virtual origin). Moreover, this induces an increase of the entrainment phenomenon with respect to the stationary jet (up to 25% of the entrained flow rate from the surrounding stagnant air).**

***Index Terms*— entrainment phenomenon, laser Doppler velocimetry, combustion.**

I. INTRODUCTION

The entrainment induced by an axisymmetric turbulent jet is a basic phenomenon studied from a long time [1, 2]. Entrainment is an intrinsic characteristic of a turbulent jet, mainly due to the formation of vortical structures at the jet boundary, which put in motion the surrounding ambient, "entraining" it towards the jet [3, 4] and generating the mixing process between the jet and the surrounding ambient. The importance of this process is strictly connected to its practical appliances in different industrial fields. In fact, a turbulent jet is an easy, low-cost methodology to obtain an efficient and rapid mixing between different streams (the jet and the surrounding ambient): in fact, it is often used in combustion processes (mainly premixed burners equipped with a nozzle + Venturi system, but also automotive and propulsion applications).

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However a quantitative and exhaustive analysis of this phenomenon has been attained only recently, by virtue of the development of optical diagnostic techniques (laser Doppler velocimetry and particle image velocimetry). In fact, to deepen the entrainment phenomenon induced by the jet it is necessary to investigate both the jet and the surrounding flow field, with the lowest intrusivity. The entrainment efficiency of the jet is usually identified by the value of the entrainment coefficient K_e, which depends on Reynolds number Re_D of the outflowing jet, at least for $Re_D<25000$ [1]. Entrainment efficiency can be enhanced by acoustic excitation of the jet flow: many studies [5 –9] report the behaviour of a pulsed jet, especially at high Mach and Reynolds number (M>0.3; $Re>10^4$). In fact, acoustic forcing of a jet can strictly influence its development and interaction with the surrounding ambient, mainly promoting the generation of vortical structures at the jet boundary and favouring the entrainment. Moreover, acoustic modulation has been already used in combustion applications [10] in order to improve lean premixed flame stability by interaction of the modulated flow field with heat released by the combustion reactions.

This paper presents the results of an experimental investigation performed about the entrainment phenomenon induced by an axisymmetrical jet, characterised by a quite low Reynolds number ($Re_D \cong 3600$): this constitutes a test case non yet thoroughly studied in literature, but peculiar in the field of premixed gas burners equipped with a nozzle+Venturi mixing system or free diffusion flames [11]. The low value of Reynolds number of this jet yields a slow mixing process with the surrounding ambient, due to low turbulence intensity at the jet boundary. Therefore, the analysis has been focused on the influence upon the entrainment process of an acoustic excitation applied to the jet outflowing in stagnant air.

In the present paper, the flow field generated by the stationary free jet has been at first characterised through laser Doppler velocimetry, to estimate the entrainment phenomenon induced by the jet. Hot wire anemometry has been used to attain the natural frequency (Strouhal number) of the jet [12]. Subsequently, the jet has been acoustically excited through an active loudspeaker placed in a stagnation chamber upstream the jet outflow, forced with a sinusoidal waveform at the same frequency of the natural one of the stationary jet (210 Hz). The forcing amplitude has been selected in order to obtain the maximum value of peak amplitude in the power spectrum obtained by FFT of the hot wire anemometry signal, measured at the jet boundary downstream the efflux.

The flow field generated by the excited jet has been analised through laser Doppler velocimetry, comparing the jet development (mean axial velocity and turbulence intensity profile) and the entrainment phenomenon with respect to the stationary (i.e.: not-excited) jet. The results put into evidence that the excited jet presents, especially in the initial region, higher turbulence levels and a larger radial expansion, contributing to a noticeable reduction of the potential core length (backwarding of the jet virtual origin). Moreover, this induces an increase of the entrainment phenomenon in the initial region of the jet development (up to 25% of the entrained flow rate from the surrounding stagnant air), with respect to the stationary jet. It is an important result, if extended to practical appliances: in fact, acoustic excitation of the jet can be a low-cost and easy solution to improve mixing efficiency in a reduced length.

II. Experimental set-up

Fig. 1 reports a schematic view of the experimental apparatus.

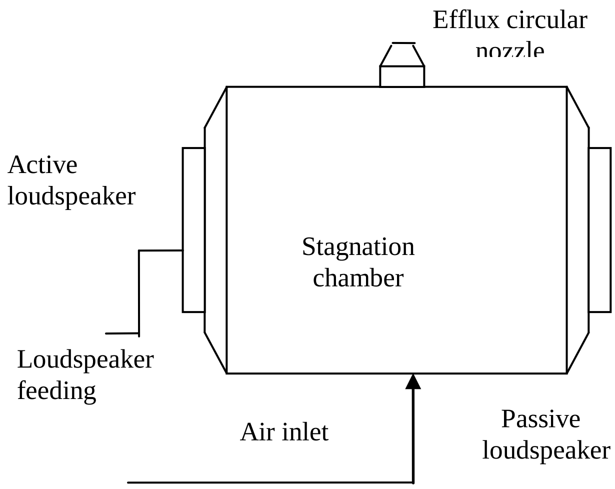

Fig. 1: the experimental apparatus.

As it can be seen, the set-up is basically constituted by a cylindrical stagnation chamber

(D=190 mm; L=300 mm) equipped with pressure and temperature transducers and fed with air whose flow rate is metered and stabilised by a calibrated thermal mass flowmeter and controller. In fact, in the experiments, the fuel has been replaced by air, studying the entrainment phenomenon in isothermal (i.e., in non-reactive) conditions. At the top of the chamber, it is positioned the outflow circular nozzle (D_0=3 mm). The air jet outflows from the chamber in stagnant air. Moreover, the chamber is equipped with two loudspeakers (only one active). In fact, the active loudspeaker is fed by a function generator (Wavetek mod. 164), able to generate many waveforms in a wide amplitude-frequency range (0.03 – 30 MHz). The generated function is amplified and supplied to the active loudspeaker, the passive one constituting an elastic wall, preventing reflection and distorsion of the exciting wave inside the chamber. Tab. 1 reports the operating conditions of the investigated jet.

Efflux diameter D_0 [mm]	3
Efflux temperature [K]	296
Jet flow rate [kg/s]	$1.608*10^{-4}$
Mean efflux velocity [m/s]	19.1
Efflux Reynolds number Re_{D0}	≅3600
Efflux Mach number	0.055

Tab. 1: operating conditions of the analised jet.

As previously outlined, different experimental techniques have been applied to characterise the jet and the surrounding flow field.

For the optical measurements, sub-micrometric oil droplets have been dispersed alternatively in the jet flow or in the surrounding stagnant air and used as flow tracers. Laser Sheet Visualization (LSV) provided qualitative informations about the flow morphology: in this case the laser sheet is derived from a copper vapour laser with nominal power of 15 W, pulse duration 15 ns, maximum pulse repetition frequency 10 kHz. The light sheet has been obtained by virtue of a cylindrical lens and the light scattered by the droplets has been collected by a CCD camera (minimum exposure time=1 μs). The obtained images have been subsequently processed with Image ProPlus software. Laser Doppler Velocimetry (LDV) has been used to measure mean velocity and turbulence intensity profiles downstream the jet efflux, to quantify the entrainment phenomenon. In this case, velocity fields were measured using a two-component fiber optics Laser Doppler Velocimeter equipped with an Argon ion laser and a Bragg cell with 40 MHz frequency shift for directional ambiguity resolution. The optical system was operated in the backscatter mode and the signal processors were two Burst Spectrum Analysers (BSA – Dantec). At least 10000 instantaneous velocity data were acquired for statistical analysis, with estimated statistical errors of less than 2% in the mean values and 5 % in the r.m.s. fluctuations.

Hot Wire Anemometry (constant temperature anemometer) and subsequent FFT of the obtained signal have been used to investigate the natural frequency of the jet (Strouhal number of the jet) and to select the amplitude of the forcing waveform in order to obtain the maximum amplitude in the power spectrum of the velocity signal measured at the jet boundary.

III. Experimental analysis

3.1 – Introduction

As previously outlined, the behaviour of the air jet has been studied especially as for the entrainment phenomenon induced by the jet towards the surrounding stagnant air. The entrainment process has been quantified through a procedure already used and described in [13]. The jet has been confined inside a large cylindrical transparent chamber (D=500 mm) and this chamber has been saturated with oil droplets. Then, laser Doppler velocimetry has been used to measure the radial velocity component of the surrounding air entrained by the jet inside the lateral surface of a virtual cylinder, whose axis concides with the jet axis (Figgs. 2, 3). The radius of the virtual cylinder has been selected as a compromise in order to have low turbulence intensity (far from the jet boundary), granting at the same time significant radial velocity values (about 0.15-0.2 m/s). For the excited jet (Fig. 3), owing to the higher radial expansion of the jet, it has been necessary to increase progressively the radius of the virtual cylinder. The lateral surface of the virtual cylinder has been divided in several circular crowns and, through the measurement of the radial velocity component by LDV, it has been possible to quantify the air flow rate m_i entering each crown, by the expression:

$$m_i = \rho \cdot u_i \cdot A$$

where:

ρ=air density; u_i=radial velocity measured by LDV; A=lateral surface of the circular crown= 2π R Δz; (Δz=10 mm in the analised case).

Thus, it has been possible to obtain the global entrained flow rate $m_{global}=\Sigma m_i$ and, consequently, to evaluate the entrainment coefficient K_e, as defined in [1].

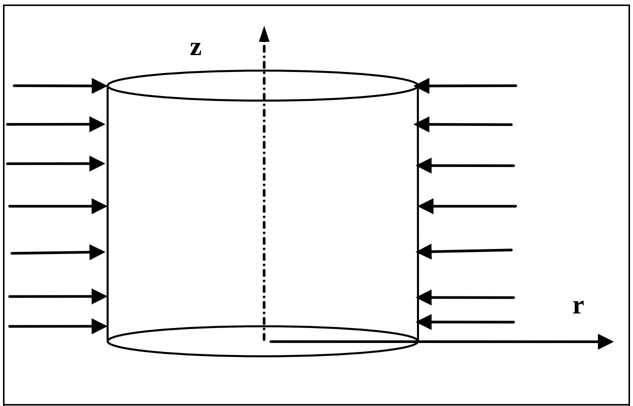

Fig. 2: virtual cylinder for the stationary jet.

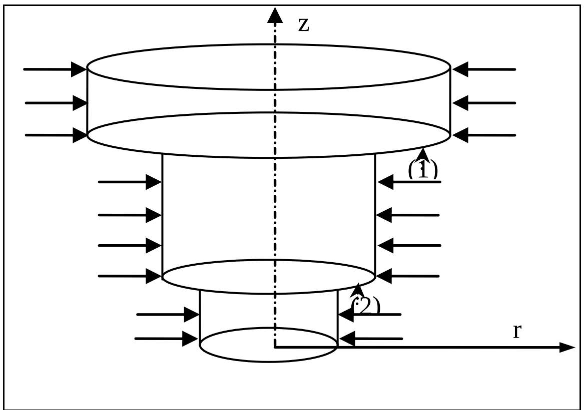

Fig. 3: virtual cylinder for the excited jet.

The jet has been acoustically modulated by a sinusoidal waveform imposed to the active loudspeaker, whose frequency and amplitude have been selected by the analysis of the jet behaviour by hot wire anemometry and subsequent FFT of the measured signal. To discover the natural frequency of the stationary jet, the hot wire has been positioned normally to the jet axis, close to the presumed position of the jet boundary, where the highest turbulence intensities are measured. The power spectrum of the velocity signal put into evidence the natural frequency of the jet (f=210 Hz), corresponding to a Strouhal number=0.033 ($St = f{*}D_0/v$). Consequently, the forcing frequency has been set to the value of 210 Hz. The forcing amplitude has been selected in order to obtain the maximum value of peak amplitude in the power spectrum obtained by FFT of the hot wire anemometry signal, measured at the jet boundary downstream the efflux. Fig. 4 reports the link between the peak amplitude in the power spectrum of the forcing and the peak amplitude in the power spectrum of the velocity signal acquired by HWA.

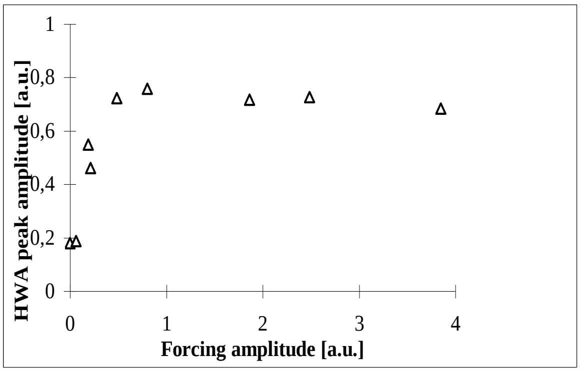

Fig. 4: peak amplitude in the power spectrum of the forcing Vs peak amplitude in the power spectrum of the velocity signal.

It can be noticed that, after an initial almost linear and steep increase, for a forcing amplitude > 0.9 the amplitude of the velocity peak saturates. Therefore, the forcing amplitude has been set to the value of 0.9, in any case obtaining the maximum modulation of the jet velocity (modulation can be defined, in this case, as the ratio between turbulence intensity and mean velocity at the jet outflow).

Finally, it has been verified that the acoustic modulation imposed to the flow is transmitted without distortion to the outflowing jet. For this purpose, it has been compared the power spectrum of the velocity signal measured for the excited jet just downstream the efflux with the power spectrum of the forcing signal (Fig. 5). The coincidence of the peaks in the two signals confirms that the forcing is transmitted from the loudspeaker to the jet without distortion.

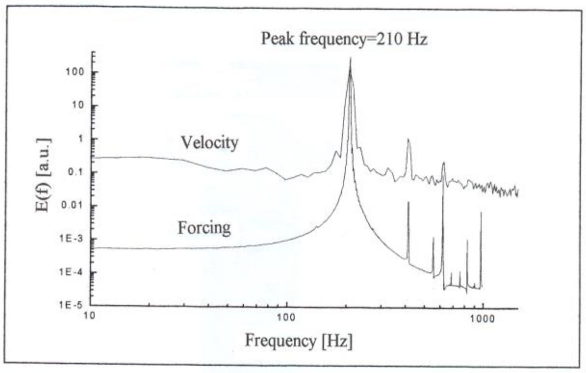

Fig. 5: comparison of the power spectrum of the forcing and of the velocity signal.

3.2 – Main Results

Fig. 6 a, b and Fig. 7 a, b report the comparison of the qualitative behaviour of the jet and of the surrounding flow with and without acoustic excitation, obtained by laser sheet visualization (exposure time of the CCD camera=5 ms).

It is immediately evident that the presence of the acoustic modulation increases the formation of vortical structures at the jet boundary, contributing to a sensitive reduction of potential core length (up to 60%) and jet radial expansion. This anticipates the entrainment of the surrounding air in the region just downstream the efflux. Fig. 8 and 9 report, respectively, the radial semi-profile of mean velocity and turbulence intensity, measured by LDV for the axial component, as a function of the distance from the jet efflux. The results are adimensionalised to the mean exit velocity U_e and to the nozzle radius R_0. It can be noticed that the mean jet flow field (Fig. 8) is almost unchanged by the acoustic modulation; at the contrary, the turbulence intensity levels clearly increase for the excited jet, especially in the jet core just downstream the efflux, contributing certainly to the development of the vortical structures observed in Fig. 6b.

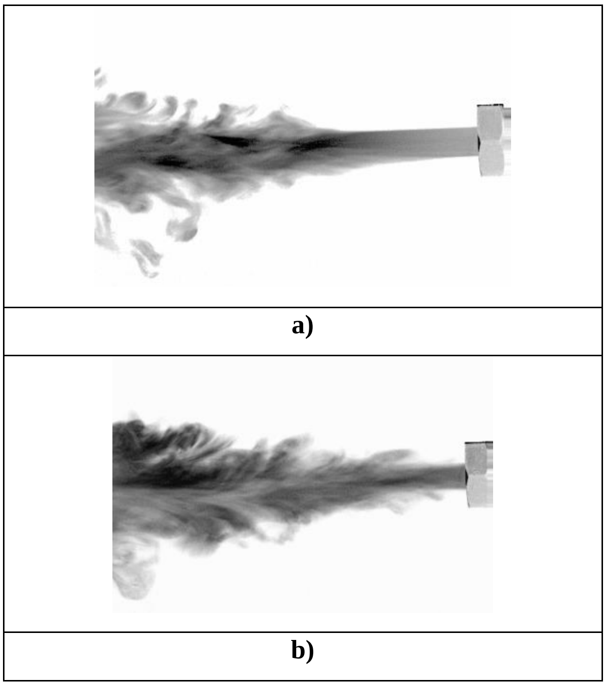

Fig. 6: visualization of the jet flow field. a) stationary jet; b) excited jet.

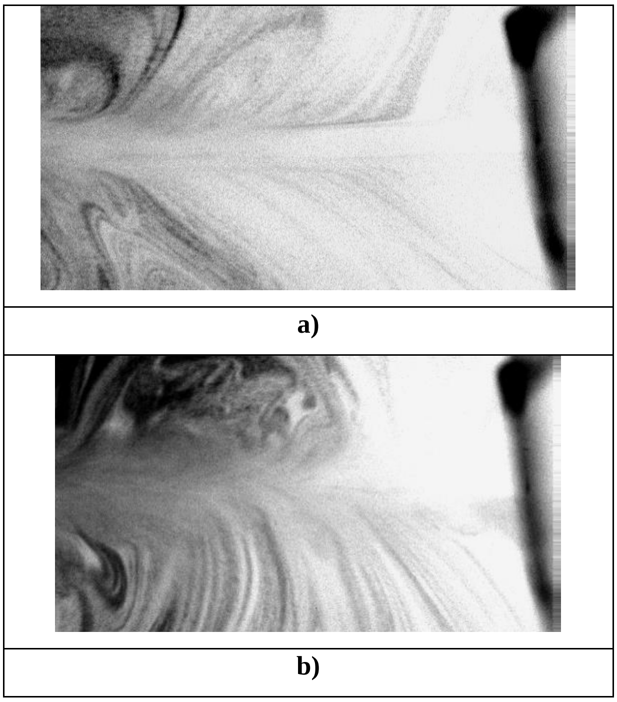

Fig. 7: visualization of the flow field surrounding the jet. a) stationary jet; b) excited jet.

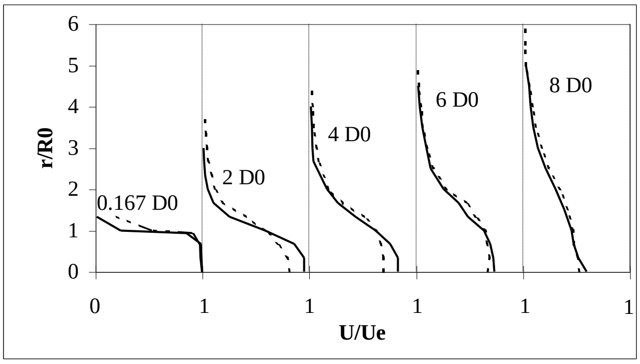

Fig. 8: mean axial velocity radial semi-profiles measured by LDV, as a function of the distance from the efflux. Stationary jet: continuous line; Excited jet: dashed line.

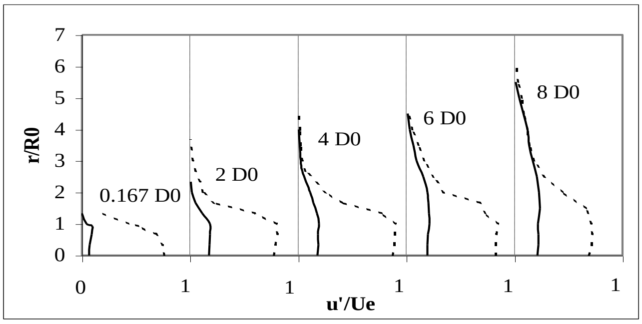

Fig. 9: turbulence intensity radial semi-profiles measured by LDV, as a function of the distance from the efflux. Stationary jet: continuous line; Excited jet: dashed line.

This fact is evident in Fig. 10, which reports the trend of turbulence intensity (for the axial velocity component) along the jet axis, as a function of the distance from the efflux. The stationary jet behaves as a classical axisymmetric jet [14] (low turbulence level in the potential core, with a slight increase till $z/D_0=12$); the excited jet presents higher turbulence levels already close to the efflux, with the maximum value at $z/D_0=4$, followed by a slight decrease.

Fig. 10: turbulence intensity (for the axial velocity component) along the jet axis, as a function of the distance from the efflux.

Finally, the entrained flow rate and the entrainment coefficient have been evaluated following the procedure described in 3.1. Fig. 11 reports the trend of the total flow rate (m_{global}=entrained flow rate; m_0=injected flow rate) as a function of the distance from the efflux. The entrained flow rate presents a quasi linear trend, for $z/D_0>10$, in agreement with similar cases reported in literature [1]. It is important to notice that the acoustic modulation induces an increase up to 25% of the entrained flow rate, due to reduction of potential core length and jet radial expansion. This gain is evident mainly for $z/D_0<5$, that is in the initial jet development, where the presence of the excitation gives rise to more noticeable morphological and fluid dynamic differences with respect to the stationary jet. Downstream, for $z/D_0>5$, the two curves are almost parallel, and the influence of the modulation is no more present.

The influence of the acoustic modulation upon the jet is clear also in Fig. 12, which resumes the trend of the local entrainment coefficient. In this case too, the increase of entrainment phenomenon induced by the modulation is noticeable just downstream the jet outflow, reaching in large advance (already at z/D_0=5-7) the asymptotic value 0.32 of the entrainment coefficient [1] and inducing a noticeable backwarding of the virtual origin of the jet. Therefore, the influence of the acoustic modulation upon the jet morphology and the entrainment process is intensive particularly in the initial region of the jet, which is downright the most critical for technical appliances involving the use of a jet as a mixing device.

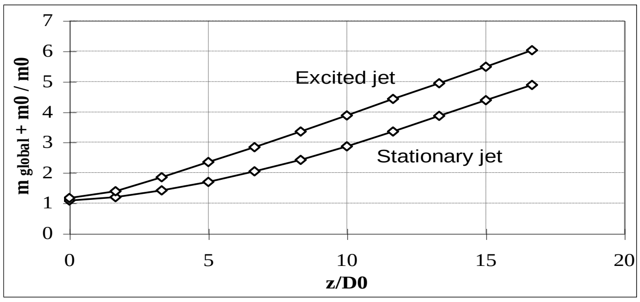

Fig. 11: entrained flow rate as a function of the distance from the efflux.

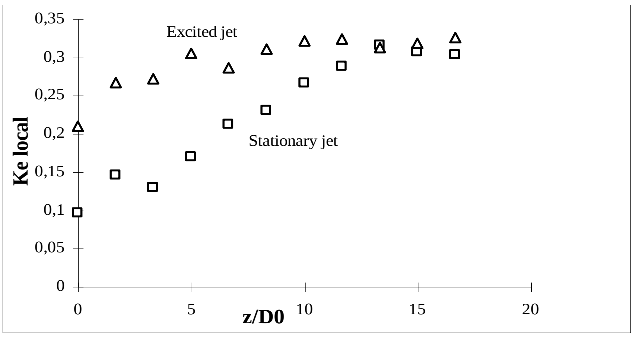

Fig. 12: local entrainment coefficient as a function of the distance from the efflux.

IV. Conclusions

The research activity reported in this paper was mainly finalised to the analysis of an axisymmetric jet at low Reynolds number (~3600), which can be considered as a test-case for premixed combustion appliances in domestic field or free diffusion flames. The low value of Reynolds number of this jet yields a slow mixing process with the surrounding ambient, due to low turbulence intensity at the jet boundary. Therefore, the analysis has been focused on the influence upon the entrainment process of an acoustic excitation applied to the jet outflowing in stagnant air. The acoustic modulation is imposed at the same natural frequency of the stationary jet. The experimental results put into evidence that the modulation induces a noticeable increase of turbulence levels and of the entrained flow rate (up to 25% with respect to the stationary jet) just downstream the jet efflux ($z/D_0<5$). Moreover, the excitation reduces the potential core length, backwarding the jet virtual origin. Even if the effect of acoustic modulation is concentrated in the jet initial region, it is downright the most critical zone for the technical appliances that exploit a jet as a mixing device, such as premixed gas burners equipped with nozzle+Venturi system or free diffusion flames. Concluding, the acoustic excitation can be considered an useful methodology to obtain a rapid mixing in a reduced length, also at low turbulence levels of the outflowing jet.

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