Influence of a rotating flow created by an acoustic excitation on a premixed flame

Ducruix, S., Durox, D., Candel, S.

Laboratoire EM2C, École Centrale Paris,
92295 Châtenay-Malabry Cedex, France
ducruix@em2c.ecp.fr

Key words : premixed combustion, acoustics, rotating flows.

Experiments on conical premixed flames stabilized above a burner, submitted to acoustic forcing are numerous ([1], [2], [3]). In these configurations, a loudspeaker, placed at the bottom of the burner, creates a periodic axial modulation of the velocity field at the burner exit. The frequency and amplitude of the acoustic excitation induce different responses of the flame ([3], [4]).
Using the same kind of bunsen burner as [4], a system, in which rotating acoustic modes of the duct placed before the burner exit could be excited, has been developed. These are vanishing modes, due to the burner geometry, and are converted, under certain conditions, to a rotating flow in the convergent nozzle. Creating a rotating motion with this device is interesting because no modification of the fresh gas inlet is required.
The new setup is presented in section 1. Visualizations and velocity measurements are then given in section 2. A model based on the perturbed G-equation is finally proposed to explain the shape of the flame in section 3.

1 Experimental Setup

Experiments were carried out in the configuration shown in Fig.1. The burner consists of a convergent nozzle of 22 mm exit diameter, followed by a cylindrical end piece 3 cm long. A cylindrical tube, 120 mm long, containing various grids and honeycombs to produce a laminar flow at the exit is placed upstream from the convergent nozzle.

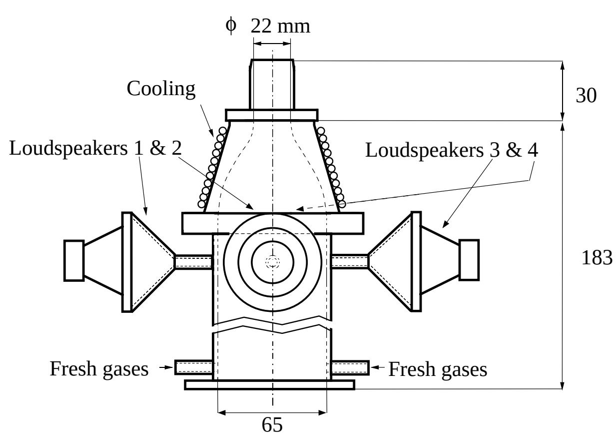

Figure 1: experimental setup

Forcing Device
Four holes are drilled in the lower tube, at a height of 45 mm from the top, and at 90^o from each other. Four loudspeakers are mounted on this duct. The connecting tubes have 10 mm in diameter. The distance between the loudspeakers and the duct wall may be varied. These driver units are fed by a frequency generator, a four-channel delay generator, and a pair of two-channel amplifiers. This device delivers to each loudspeaker the same signal with a different phase. A phase delay of 90^o is chosen between a loudspeaker and the following one.

To determine the excitation frequency, consider, in first approximation, a cylindrical cavity closed at each end by a rigid wall. A cylindrical coordinate system (r,θ,z) in which the z axis coincides with the longitudinal axis of the cavity is used. In linear acoustics, assuming that there are no noise sources or volume forces, the pressure fluctuation p' satisfies the wave equation. Taking into account the boundary conditions, it is possible to obtain a general description of the acoustic modes in the cavity. In the particular case of the fundamental tangential mode, p' can be written ([5, section 15.4]):

$$p'(r,\theta,z,t) = J_1\left(\frac{\pi\alpha_1 r}{R}\right)\left[M\cos\left(\theta+\omega_1 t-\delta_1\right)+N\cos\left(\theta-\omega_1 t-\delta_2\right)\right] \tag{1}$$

where t is the time, R the radius of the cavity, J_1 the Bessel function of the first kind of first order, and α_1 equals 0.586. ω_1 is the angular frequency given by $\omega_1 = 2\pi f_1$. $f_1 = c_0\alpha_1/2R$ (c_0 is the speed of sound). M, N, δ_1, and δ_2 are constants depending on the initial conditions. The cylindrical tube used in this study has an inner diameter of 65 mm (Fig.1). For $c_0 = 355$ m/s (stoichiometric premixed methane/air flow), one obtains : $f_1 = 3200$ Hz.

Experimental conditions and diagnostics

Experiments were carried out with a methane-air mixture at a fixed equivalence ratio of 1.05, corresponding to a laminar burning velocity, S_L, of 0.39 m/s. The space-averaged flow velocity is equal to 0.92 m/s. Gas velocities were measured by Particle Imaging Velocimetry (PIV), and Laser Doppler Velocimetry (LDV). Oil droplets, with a mean diameter of 2.5 μm, were used to seed the flow.

2 Visualizations and Measurements

Fig.2 and 3 show the deformation of the flame caused by an acoustic excitation at a frequency $f_{ex} = 3220$ Hz. The deformation does not develop continuously as the frequency is increased or decreased to f_{ex}, but appears quasi instantaneously at this frequency. Moreover, when the phase delay between the loudspeakers is modified, there is no perturbation on the flame. The frequency of the signal delivered to the four loudspeakers, f_{ex}, is very close to f_1, calculated in section 1.

Figure 2: front view of the excited flame

Figure 3: top view of the excited flame

The perturbed shape of the flame features a helicoidal pattern, as clearly seen in Fig.3. Four cells, which are crescent-shaped and completely steady, appear on it. PIV results are shown in Fig.4 to 7. Velocities, in a vertical cut including a diameter of the burner, and in several horizontal cuts have been obtained.

A slight deflection of the axial velocity is detected in Fig.4. Using the LDV system, it was possible to show that the rms axial velocity is almost zero for several points in the fresh gases, and no 3000 Hz fluctuations could be observed at the burner exit. Comparing this velocity field to the one obtained when the excitation is not present, no fundamental difference was observed. The horizontal cuts are placed at $z = 1.5$, 10, 20 mm above the burner exit (Fig.5 to 7). A rotating movement of the flow can clearly be seen. This rotation is present up to the top of the flame. At $z = 1.5$ mm, the intersection between the planar cut and the flame front still gives a circle. For $z \geq 5$ mm, there is a perturbation of this shape due to the four cells appearing on the flame.

Fig.8 displays the tangential velocity along a diameter for $z = 1.5$ mm. In a disk of about 5.5 mm diameter, the fresh gases feature a solid body rotation. The angular frequency is approximately 160 rad/s, and is maintained up to the top of the flame. Around this inner disk, a boundary layer, due to the burner exit wall has developed. This cylindrical rotating flow is detected several diameters above the burner exit, even when the flame is not present. It appears that the rotating acoustic mode in the cavity gives birth to the rotating flow, which is then convected by the main axial flow. This streaming may

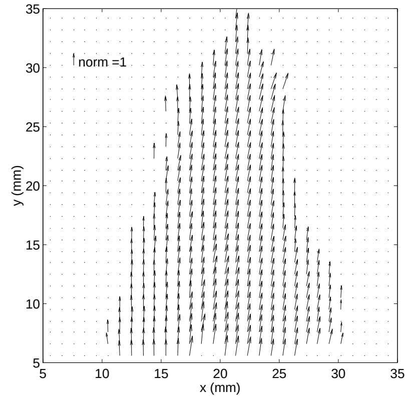

Figure 4: velocity field, vertical cut

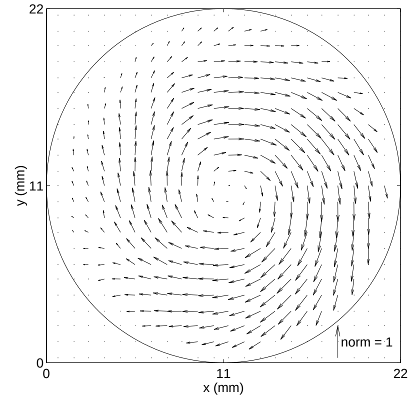

Figure 5: velocity field, $z = 1.5$ mm

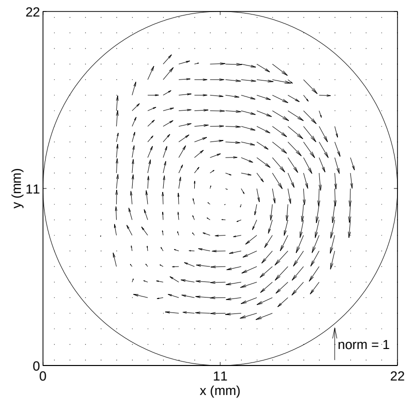

Figure 6: velocity field, $z = 10$ mm

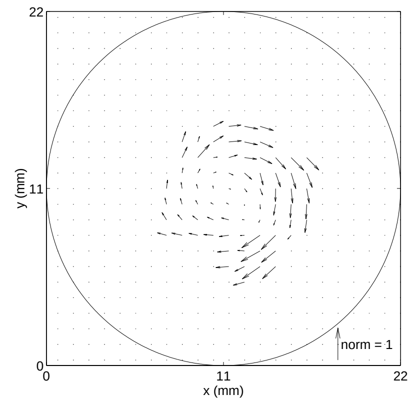

Figure 7: velocity field, $z = 20$ mm

result from both the very high amplitude of the acoustic excitation, and the vanishing behavior of the rotating modes, leading to nonlinear acoustic effects ([6]).

3 Rotationally perturbed G-equation

To understand the mechanisms leading to this peculiar shape of the flame, it is convenient to examine the perturbed G-equation to analyze the propagation of perturbations on a conical flame surface. Writing the unperturbed and the perturbed G-equation, respectively for $G_0(r, z)$ and $G(r, \theta, z, t)$, it is possible to introduce $g = G - G_0$, and to retain only first order terms in the equation derived for g. Considering the unperturbed flame surface as a perfect cone, with an half angle α, one finally obtains :

$$\frac{\partial g}{\partial t} - S_L \cos(\alpha) \frac{\partial g}{\partial r} + \frac{v_\theta}{r} \frac{\partial g}{\partial \theta} + (v_z - S_L \sin(\alpha)) \frac{\partial g}{\partial z} = 0 \tag{2}$$

Steady perturbations propagate along characteristic lines defined by a differential system, which may be integrated as follows :

$$r = r_0 - \frac{S_L cos(\alpha)}{\omega}(\theta - \theta_0) \tag{3}$$

$$z = \frac{r - r_0}{\tan(\alpha)} \tag{4}$$

where (r_0, θ_0, z_0) are the initial coordinates of the perturbation, and ω the angular frequency of the flow. These expressions indicate that the perturbation remains on the cone and travels along the line defined by (3). Four lines, created from four points located at 90^o from each other, are represented in Fig.9. The perturbation sources, still unknown, are problably linked with the location of the loudspeakers. The modified shape is in perfect agreement with Fig.3.

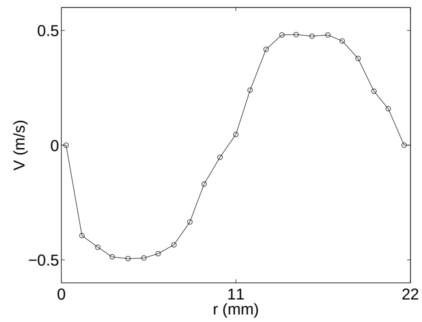

Figure 8: tangential velocity along a diameter, $z = 1.5$ mm

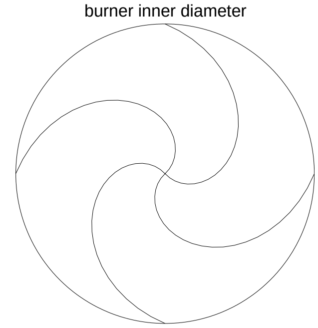

Figure 9: characteristic lines of the rotationally perturbed G-equation, top view

Conclusion

A new setup, devised to study the forcing of a rotating flow on a conical premixed flame, has been built. The excitation frequency which gives a strong modification of the flame shape ($\simeq$ 3000 Hz) is in good agreement with the frequency of the fundamental tangential mode of the burner cavity. A rotating movement at the burner exit is observed, with an angular frequency of about 160 rad/s. The flame shape features a helicoidal pattern and four crescent-shaped steady cells appear on it. No 3000 Hz fluctuations could be observed at the burner exit. A possible explanation for the peculiar velocity field could be the streaming of the flow due to nonlinear acoustic effects. A model based on the perturbed G-equation has been proposed, and describes the modification of the flame shape.

References

[1] H. Von Hahnemann and L. Ehret. Über den Einfluß starker Schallwellen auf eine stationär brennende Gasflamme. *Zeitschrift für Technische Physik*, 24:228–242, 1943.

[2] G. De Sœte. Etude des Flammes Vibrantes. Application à la Combustion Turbulente. *Revue de l'Institut Français du Pétrole et Annales des Combustibles Liquides*, 19:766–785, 1964.

[3] F. Baillot. *Etude expérimentale et modélisation théorique de flammes de prémélange. Application à la flamme soumise à un champ vibratoire.* PhD thesis, Paris VI, 1989.

[4] D. Durox, S. Ducruix, and F. Baillot. Strong acoustic forcing on conical premixed flames. In *Twenty-Seventh Symposium (International) on Combustion*, Boulder, Co., U.S.A., 1998.

[5] M.J. Zukrow and J.P. Hoffman. *Gas Dynamics*, volume 2. 1976.

[6] J. Lighthill. *Waves in Fluids.* Cambridge University Press, 1978.