Generation of two-dimensional vortices in a cross-flow

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1. Motivations and objectives

The present report is concerned with an experimental study on the generation of plane two-dimensional vortices in a cross-flow. The purpose of this work is to address the problem of the feasibility of a two-dimensional experiment of flame-vortex interactions.

The interaction of a laminar flame with a vortex pair is a model problem in which several questions relevant to turbulent combustion may be addressed such as transient and curvature effects. Based on direct numerical simulation (DNS) of flame-vortex interactions, Poinsot *et al.* (1991) have shown the existence of different types of interaction from the wrinkling of the flame front to local quenching of the reaction zone (Fig. 1). The authors emphasized the importance of heat losses in the quenching process. Studying the interaction of a freely propagating flame with a vortex ring, Roberts & Driscoll (1991) confirmed the existence of the different regimes of flame-vortex interaction. These works have extended the validity of flamelet models for premixed combustion.

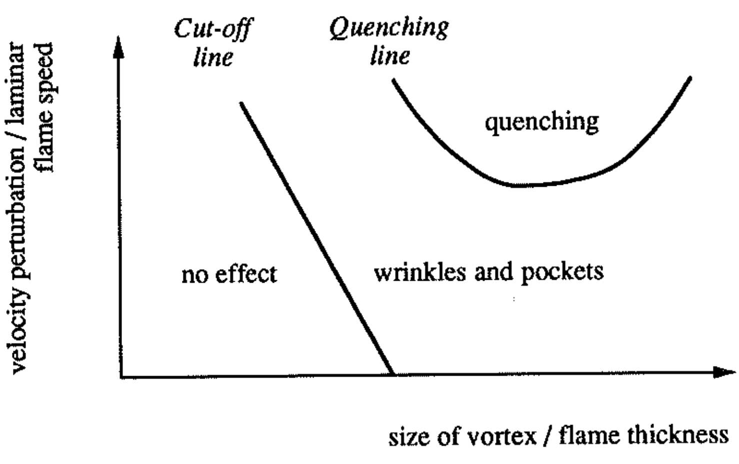


FIGURE 1. The different types of flame-vortex interaction (Poinsot *et al.* 1991).

Recent experimental studies have focused on the quenching of the flame front by a vortex ring: OH fluorescence imaging was applied to track the flame front and identify the occurrence of quenching (Roberts *et al.* 1992) and two-color Particle Image Velocimetry to obtain instantaneous planar cuts of the velocity field through the vortex ring (Driscoll *et al.* 1993). Such studies have allowed a remarkable insight in the quenching process although some problems remain. First, the role of heat losses, which are believed to be one important ingredient, has not been addressed yet. An estimate of the heat losses can be obtained by measurements of the temperature field. Secondly, using OH fluorescence to study flame quenching is questionable since OH molecules persist long after their creation in the flame zone and, hence, do not mark the region of chemical reaction accurately. An alternative approach is the line-of-sight imaging of spontaneous light emission from species such as C_2 or CH that have extremely short lifetimes in the flame and, as such, are very good indicators of the reaction zone. Thirdly, bias of the results due to a misalignment of the vortex trajectory with the laser sheet might occur and introduce significant errors in estimating velocities. In this respect, a planar two-dimensional experiment appears as an attractive solution for the study of flame-vortex interactions.

Computations of two-dimensional and three-dimensional turbulent premixed flames using DNS have investigated the behavior of a flame front submitted to a homogeneous and isotropic turbulent field (Rutland & Trouvé 1990, Trouvé 1991, Haworth & Poinsot 1992). These studies have shown that two parameters play an essential role in the dynamics of the flame sheet: the local curvature of the flame front and the Lewis number. All these numerical studies have a common idealization: they are based on a simplified chemical model (one-step irreversible reaction). Whether or not this assumption is valid is an open question. It clearly depends on the objectives: it is certainly inappropriate for the prediction of pollutant formation, but it could be satisfactory for the study of the dynamics of the flame front. This problem needs to be addressed in order to determine the validity of previous DNS studies. One way of achieving this goal is a project involving an experimental and numerical study of flame-vortex interaction. Comparison of numerical and experimental results would serve as a test for the validity of the chemical model.

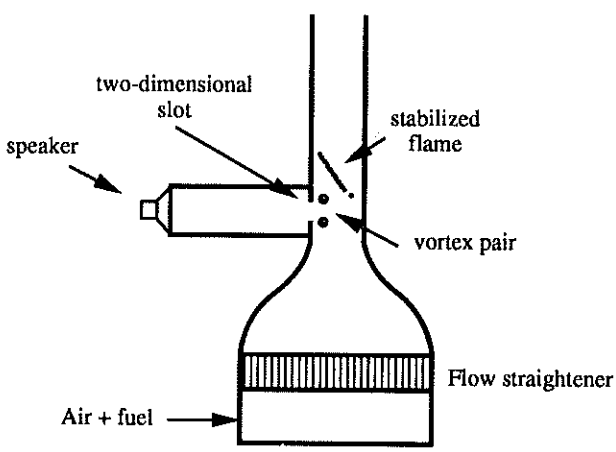


FIGURE 2. Sketch of the proposed two-dimensional geometry.

	r/d	u_{max}/S_l
Poinsot *et al.*	1 to 10	4 to 100
Roberts and Driscoll	6 to 50	0.5 to 20

Table I. Values of r/d and u_{max}/S_l used in the works of Poinsot et al. (1991) and Roberts & Driscoll (1991). r is the size of the vortex pair (size of orifice in Roberts and Driscoll 1991), d the flame thickness, S_l the laminar flame speed and u_{max} the maximum rotational velocity.

The proposed experimental geometry is a two-dimensional tunnel in which the flame is anchored to a stabilizer (for example a heated wire). Since the flame speed of a hydrocarbon flame is of the order of a few tens of centimeters per second ($\sim 40\, cm/s$ for stoichiometric mixtures), the flow speed must be of the order of $1\ m/s$ to achieve flame stabilization. A vortex pair would be generated through a slot located on one lateral wall and would eventually interact with the oblique flame sheet (Fig. 2). While it is possible to stabilize such flames (see for example Boyer & Quinard 1990), the generation of a two-dimensional vortex pair (through a boundary layer) and its propagation is questionable. Various mechanisms may make it difficult: end wall effects (Gerich & Eckelmann 1982, Auerbach 1987), Crow instability (Crow 1970), columnar instability (Leibovich & Stewartson 1983), etc.

The slot width prescribes somehow the size of the vortex pair r. Since the flame thickness d ranges between 1 and 4 millimeters for hydrocarbon flames at ambient conditions (d can be varied by varying the equivalence ratio) and since the ratio r/d must remain small enough ($r/d < 20$) to allow future comparison with DNS, r must remain smaller than a few centimeters and, hence, the slot width. Furthermore, following the values of u_{max}/S_l given in Table 1, u_{max} must range somewhere from a few centimeters per second to a few tens of meters per second in order to address various kinds of interactions (Table I summarizes the values of r/d and u_{max}/S_l in the works of Poinsot *et al.* 1991 and Roberts & Driscoll 1991).

In order to determine whether or not it is possible to generate two-dimensional vortex pairs in these conditions, a preliminary non reacting flow experiment, which is the purpose of the present paper, has been carried out. It involved the construction of a whole set-up: test section, flow controls, smoke generator, timing circuit. The experimental apparatus and the main results are presented and discussed in the following section.

2. Accomplishments

2.1 Experimental apparatus

The test section is a vertical tunnel with an inner square cross-section of 63.5 ×

63.5 mm^2 and a height of 381 mm (Fig. 3). The vortex pair is generated by acoustic forcing through a horizontal nozzle-shaped slot spanning over one lateral wall. The slot width can be adjusted by shifting the upper part of the wall.

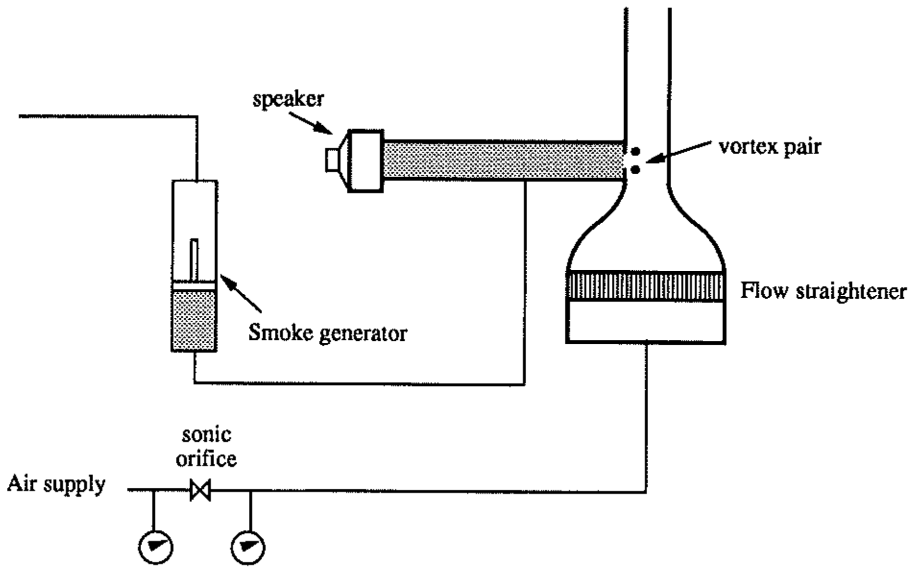
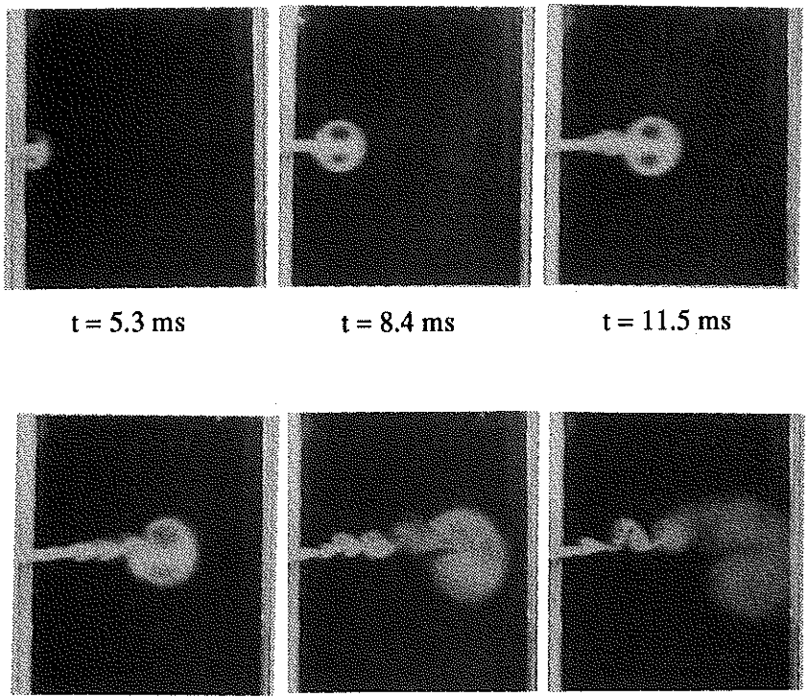


FIGURE 3. Schematic view of the set-up used for visualization of the non-reacting flowfield.

The air flow is metered by a sonic orifice and is supplied to the test section through a plenum chamber. The bulk velocity of the flow in the vertical tunnel can be varied from 0.25 to 1.0 m/s corresponding to Reynolds numbers (based on the tunnel width) ranging from 1060 to 4240.

The vortices are visualized with cigarette smoke. For this purpose, the wave guide is filled with smoke issuing from a smoke generator. When the speaker is actuated, a puff of smoke illuminated by a 100 *Watts* lamp or a strobe lamp is pushed into the tunnel. The smoke pattern, used to trace the vortex pair evolution, is recorded on video tape and photographs and then analyzed.

Velocity measurements were performed using a hot-wire anemometer DISA in order to investigate the flow in the tunnel.



t = 5.3 ms t = 8.4 ms t = 11.5 ms

t = 14.6 ms t = 17.9 ms t = 21.0 ms

FIGURE 4. Sequence of photographs showing the vortex pair evolution without cross-flow. Slot width = 3 mm. Time $t = 0\,ms$ corresponds to the speaker excitation.

2.2 Results and discussion

2.2.1 Visualization

Figure 4 is a sequence of photographs showing the evolution of a vortex pair in the absence of cross-flow. The time step between the photographs is 3.1 ms. In this case, the slot width is set at 3 mm, and a voltage of 3.2 $Volts$ is suddenly applied through the speaker coils at $t = 0\,s$. The whole smoke puff is illuminated so that the photographs show the smoke pattern integrated over a line of sight. Consequently, a two-dimensional structure would result in a well-defined pattern, and a three-dimensional structure would correspond to a fuzzy pattern.

Although the pictures are slightly blurred, one can easily identify a vortex pair structure propagating rightward at approximately 3 m/s, followed by a "wake". The blur can be attributed to a relatively too long exposure time (1 ms) and to the effect of perspective. In the first instance, as inferred from the smoke pattern, the vortex pair is well-defined and remains self-similar. Two cores, symmetric with respect to the vortex trajectory, are clearly visible. Later, as small spanwise counter-rotating vortices appear in the "wake", the smoke pattern within the vortex cores becomes non-symmetric and fuzzy.

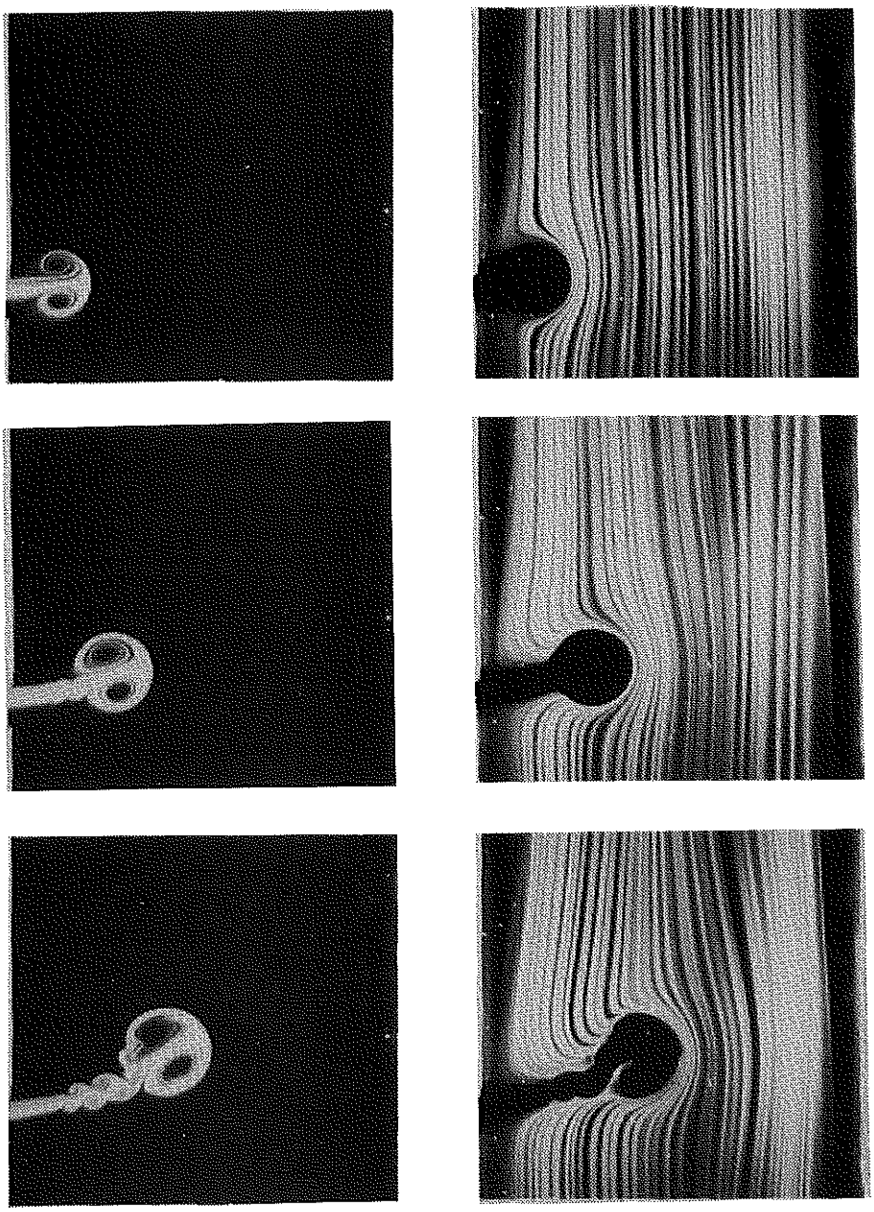
It can be concluded that the vortex pair is initially two-dimensional and propagates at its self-induced velocity. The smoke trailing the vortex pair (referred previously to as a "wake") may be interpreted as a plane jet resulting from the remainder (or excess) of the fluid pushed out by the speaker membrane. This jet would underlie a Kelvin-Helmholtz instability, resulting in a sinuous mode and giving rise to an alley of counter-rotating vortices. These vortices eventually interact with the vortex pair in a way similar to a pairing process (see time $t = 14.6\,s$). During this process, the vortex pair loses its symmetry and becomes less coherent: this phenomenon can be viewed as a mechanism for transition to three-dimensionality.

Figures 5a and 5b shows a sequence of photographs of a vortex pair generated in a cross-flow of 0.50 m/s. The left column is smoke patterns illuminated by a light sheet of 1 cm thickness centered on the mid-plane of the cavity. The right column shows images of smoke wire visualization taken at same instants after the speaker excitation. The wire was located upstream of the slot at 6 mm from the opposite wall of the tunnel relative to the camera in order to investigate end wall effects. These photographs were taken using a strobe lamp as a light source. The duration of the light pulse (50 μs) is short enough to freeze the flow.

This sequence shows the same trends as Fig. 4: generation of a two-dimensional vortex pair, onset of an instability in the "wake" of the vortex pair, coalescence and rupture of symmetry. Later the smoke pattern becomes fuzzy. Other results indicate that the vortex evolution is repeatable until time $t = 10.5\,ms$ for this particular set of operating conditions (slot width, voltage, cross-flow velocity). After this time, the smoke pattern differs from one run to another. This is attributed to the unsteadiness of the cross-flow in the center of the cavity as revealed by other smoke-wire visualization.

The role of the lateral walls as a source of three-dimensionality is evidenced in Fig. 5. The vortex pair structure appears to be first disrupted near the end walls at time $t = 14.7\,ms$ (see the right column) while it keeps a coherent structure near the mid-plane of the tunnel. Later, the whole vortex pair is affected and degenerates into small-scale structures. Although the Crow instability (or other instabilities such as the columnar instability) may play a role, it seems that the dissipation of the vortex pair is controlled by the coalescence with vortices located in its "wake". This phenomenon is observed both in the cases with and without cross-flow.

One difference between these two cases is the presence of boundary layers along each wall (Fig. 6). Particularly, the presence of a boundary layer along the slot causes the starting vortex pair to be non-symmetric. The boundary layer is characterized by a distributed vorticity of one sign (either positive or negative depending on the reference frame): it has the same sign as the upper vortex vorticity and opposite sign to the lower vortex vorticity. During the roll-up process, fluid from this boundary layer is engulfed in each vortex core, and this results in a strengthening of the upper vortex and in a weakening the lower vortex. As a consequence, the

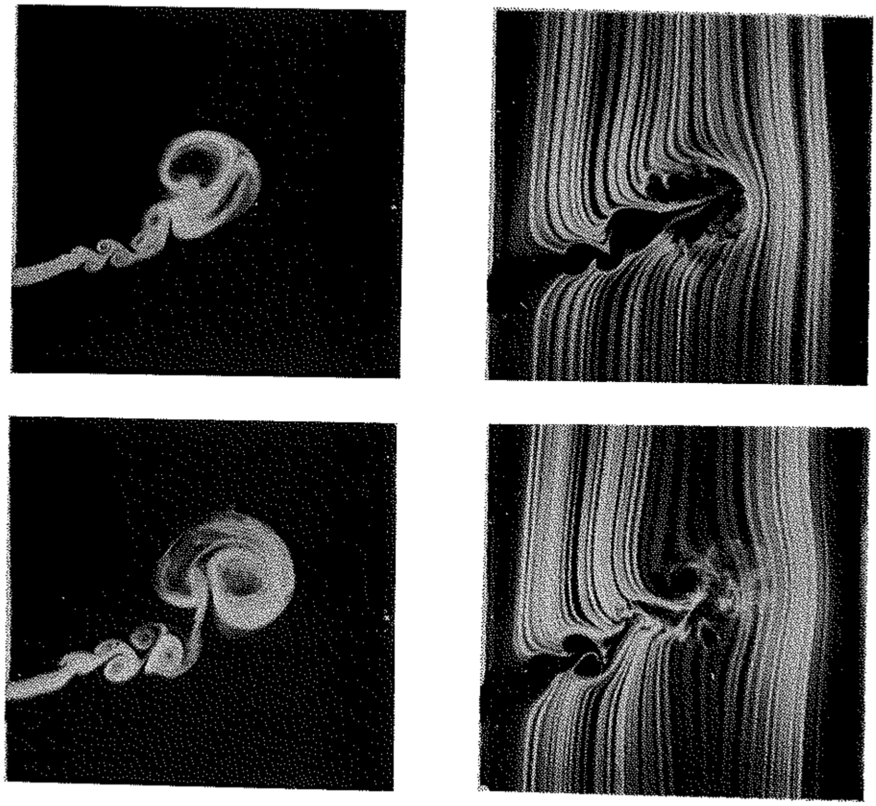


t = 8.4 ms

t = 10.5 ms

t = 12.6 ms

FIGURE 5A. Sequence of photographs showing the vortex pair evolution with a cross-flow of 0.5 m/s. Slot width = 3 mm. Time $t = 0\,ms$ corresponds to the speaker excitation.



t = 14.7 ms

t = 16.8 ms

FIGURE 5B. Sequence of photographs showing the vortex pair evolution with a cross-flow of 0.5 m/s. Slot width = 3 mm. Time $t = 0\,ms$ corresponds to the speaker excitation.

vortex pair has an upward circular trajectory as shown by the sequence of Fig. 5 (Batchelor 1967).

2.2.2 parametric study: effect of voltage ΔV and slot width w

These effects have been studied using flow visualization in the absence of cross-flow. The vertical tunnel was replaced by two walls of Plexiglass so that impingement of the vortex pair on the opposite wall was avoided.

For given operating conditions (ΔV and w), a series of vortex sheddings was recorded on video tape. The axial position x and size r of the vortex pair at different moments after the roll-up were measured on the monitor screen. Fig. 7 shows a typical result for the evolution of the axial position and size of a pair vortex obtained from three different vortex sheddings ($\Delta V = 0.65\,Volts$ and $w = 3\,mm$,

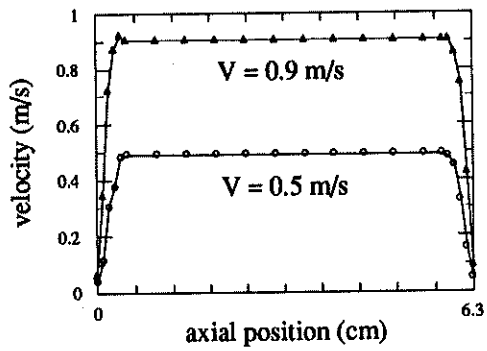


FIGURE 6. Velocity profiles at the exit of the plenum chamber for two different bulk velocities.

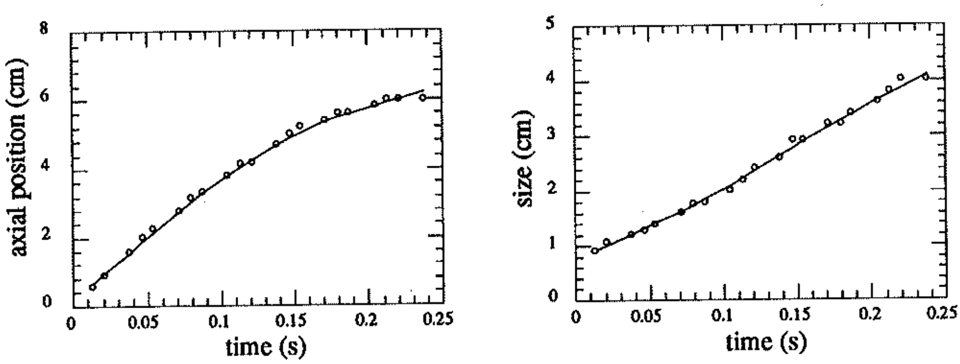


FIGURE 7. Time evolution of the position and size of a vortex pair. Slot width = 3 *mm*, tension applied to the speaker = 0.65 *Volts*. Time $t = 0\,ms$ is an arbitrary origin. It does not correspond to the speaker excitation.

corresponding to $V_1 = 0.42\,m/s$). Moreover, as it travels on, the vortex pair slows down and grows in size. This evolution can be explained by entrainment due to viscosity of surrounding fluid into the vortex cores and by interdiffusion of vorticity across the symmetry plane (Maxworthy 1972, Cantwell & Rott 1988).

Figure 8 shows the evolution of r/w with x/w for two different slot widths ($w =$ $3\,mm$ and $5\,mm$) and for various vortex Reynolds numbers ranging from 314 to 7540 ($Re = \Gamma/\nu$ with $\Gamma = 4\pi w V_1$, where ν is the kinematic viscosity and V_1 the initial displacement speed of the vortex pair as estimated from the video sequences). All the data seem to collapse on one quadratic-like curve. This indicates that x/d and r/d are strongly correlated and that a similarity law underlies the behavior of the vortex pairs. It can be deduced that the distance through which the vortex pair remains two-dimensional scales with the slot width (this distance is about ten times the slot width as indicated by the photographs). It can also be noticed that the initial size of the vortex pair is approximately 4 times the slot width.

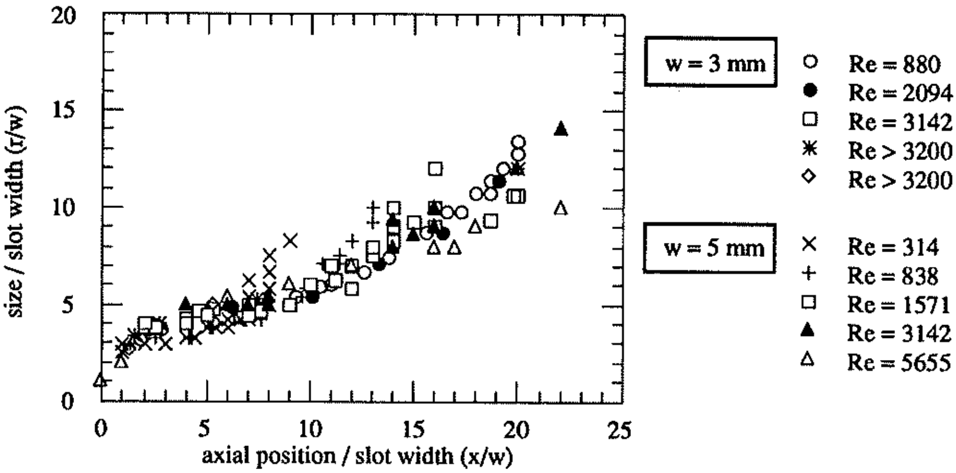


FIGURE 8. Correlation between the non-dimensionalized size and position of vortex pairs for different Reynolds numbers and two slot widths.

2.2.3 On the feasibility of a two-dimensional experiment

The present results indicate that it is possible to generate two-dimensional vortex pairs through a boundary layer. These structures remain two-dimensional over a significant distance (about 10 times the slot width). Since the flame front can be placed as close to the slot as needed by moving the flame stabilizer, it is possible to meet the conditions for a two-dimensional interaction between a flame front and a vortex pair.

3. Future plans

As a consequence of this work, an experimental facility designed for combustion will be set up. Diagnostic tools to monitor the flowfield will be developed. Two-dimensional instantaneous velocity fields will be determined using particle image velocimetry (PIV) or particle tracking velocimetry (PTV). The instantaneous location of the flame front, and possibly the distribution of the reaction rate along the flame front, will be obtained by line-of-sight imaging of radical emission (C_2 or CH). A technique to characterize the heat losses will also be devised.

These data will be used as initial condition for DNS. Comparison between computations and experiments will serve as a test for the quality of the chemical model used in the code.

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