TIME EVOLUTION OF TWO-DIMENSIONAL VELOCITY FIELDS IN GAS-PHASE REACTING AND NON-REACTING TURBULENT JETS

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ABSTRACT

The time evolution of two-dimensional (2-D) velocity fields in gas-phase reacting and non-reacting turbulent jets is experimentally observed using a newly developed kilohertz frame rate cinema Particle Imaging Velocimetry (cinema PIV) system. Up to 8000 instantaneous PIV images per second are obtained, with continuous sequence lengths exceeding 4000 images. The combination of high image acquisition rate and sequence length shows relatively long histories of time incremental changes in the velocity field, enabling observation of the time evolution of turbulent structures such as vortex convection, line and sheet formation, merging, and dissipation. Application of the method to a lifted turbulent jet flame reveals the interaction between turbulent vortex structures and the flame thermal boundary position. These results are uniquely suited to aid the development and validation of computational models used in simulation of turbulence and turbulent combustion, such as Large Eddy Simulation (LES).

INTRODUCTION

Obtaining meaningful measurements in turbulent flows is arguably the first step in gaining a scientific understanding of the physical phenomena of turbulence. However, information available from conventional experimental measurements or numerical simulations leaves unanswered many fundamental questions concerning the dynamics of turbulent velocity fields, for example:

- How fast do vortex structures travel?
- In what direction do vortex structures travel?
- How do vortex structures interact?
- What is the lifetime of turbulent vortex structures?
- How do vortex structures interact with flames?

Conventional single-point and 2-D instantaneous measurements of the velocity field provide little information concerning the above questions. Single-point measurement techniques offer statistical or even time resolved information concerning flow properties at a single point (Lewalle et al., 2000), but do not show 2-D time evolving flow structures. 2-D measurement techniques such as conventional PIV show instantaneous snap-shots of velocity fields (Adrian, 1991), but acquire images at insufficient rates compared to the characteristic length and time scales of these flows to observe the time evolution of the velocity field. The Reynolds numbers achievable with numerical experiments using Direct Numerical Simulation (DNS) are limited by the computational capabilities of today's computers (Moin and Mahesh, 1998), (Vervisch and Poinsot, 1998). Large Eddy Simulations (LES) are in an early stage of development and not yet used in a predictive sense (Meneveau and Katz, 2000).

In contrast, the cinema PIV method offers a sufficient combination of spatial and temporal resolution for quantitative measurements of the time evolution of vortex structures in laboratory-scale gas-phase reacting and non-reacting turbulent jet flows (Lecordier and Trinité, 1999). The film-based cinema PIV system employed was developed specifically for this study, and provides a previously unavailable combination of high resolution, image acquisition rate (up to 8000 images/second), and sequence length (more than 4000 images). We present several examples of short-lived transient events spanning 2-7 milliseconds, in which time the cinema PIV system captures 6-55 images showing the detailed time evolution of velocity fields. In comparison, the 33 millisecond image acquisition period of conventional PIV systems (operating at a maximum 30 Hz, typically) are capable of acquiring no more than one image during such time spans.

EXPERIMENTAL METHOD

The test flow apparatus was a 5.0 mm diameter turbulent jet tube surrounded by a 170 mm coaxial laminar coflow tube. Two test flow conditions were considered; a non-reacting turbulent air jet and a reacting methane/nitrogen jet. The non-reacting jet exit velocity, coflow velocity, and Reynolds number were 8.4 m/s, 0.265 m/s, and 2900, respectively. The reacting jet exit velocity, coflow velocity, and Reynolds number were 14.0 m/s, 0.265 m/s, and 4300, respectively. The reacting jet consisted of 77% methane and 23% nitrogen by volume. For these conditions the leading edge of the reaction zone is "lifted" or stabilized at some downstream distance from the jet exit.

Methods of high-speed photography were combined with traditional PIV methods to obtain up to 8000 instantaneous PIV images per second, with sequence lengths exceeding 4000 images. The test flows were seeded with micron sized ceramic particles that were illuminated by Q-switched light pulses from a pair of high repetition rate Nd:YAG lasers. The particle images illuminated by each laser pulse were recorded on sequential film frames using a high-speed 16 mm rotating-prism movie camera. The film images were digitized using a 2036 x 3060 pixel resolution digital camera. Each sequential pair of digitized particle images was cross-correlated to obtain a high-speed sequence of instantaneous PIV velocity field images. A small percentage (less than 5%) of erroneous vectors in the resulting raw vector fields were removed and replaced with interpolated values. No spatial or temporal smoothing of the resulting velocity vector fields was done. For the reacting jet, the flame thermal boundary was identified by the distinct drop in seeding number density accompanying the expansion of combustion products through the flame (Muñiz and Mungal, 1997). The flame thermal boundary was located using a computer code that calculated the seed particle number density and identified the boundary at a location having a predetermined number density.

RESULTS

Non-reacting turbulent air jet

A 130-image cinema PIV sequence of the non-reacting turbulent air jet (Re=2900) was obtained at 1000 images/second. Figure 1 shows a six-image excerpt from the full sequence. The time delay between each image shown is 1 millisecond. The field of view is 23 mm (lateral) x 40 mm (axial), centered 160 mm from the jet exit along the jet axis. The horizontal and vertical axes represent the radial and axial position from the jet exit, respectively. The vectors represent velocity, with length scaled to the relative velocity magnitude. The maximum velocities in the laboratory coordinate frame are 2-3 m/s. The mean velocity has been subtracted to aide visualization of turbulent vortex structures. Shading contours represent vorticity, which has been calculated from the measured velocity fields using a three-point central differencing scheme. Peak vorticity levels are represented by dark shading, with peak counterclockwise vorticity regions being distinguished from clockwise regions by light perimeter shading. The velocity vector field shows obvious circulation patterns that correspond to the darkly shaded high vorticity regions.

A high degree of similarity between sequential images is evident, indicating that the time separation between successive images is short enough to show incremental changes in the time-evolving velocity field. Approximately 20 isolated high vorticity regions or turbulent "eddies" may be identified. Both the velocity and direction of movement of individual eddies may be determined by comparison of successive images. A single turbulent eddy is identified at the bottom-center of the first image in the sequence and tracked as it moves downstream. This eddy is identified by a single black dot on each image, which is connected by a line to the corresponding eddy location on sequential images. This counterclockwise rotating eddy is initially isolated but in close proximity to another counterclockwise eddy just above it. These eddies gradually merge to form an elongated region of high vorticity or vortex sheet in the last image at t=106 ms. Just to the right of this counterclockwise vortex sheet is a clockwise vortex sheet that persists throughout this six-image sequence. Several other instances of paired eddies of opposite rotation are evident, such as at t=104 ms at the lower left of the field of view at radial position 10 mm, axial position 155 mm.

It is evident from careful inspection that most of the turbulent eddies persist throughout this sequence, giving an indication of the lifetime of vortex structures in a gas-phase turbulent jet flow. However, several instances of gradual dissipation of turbulent eddies are apparent. For example, a clockwise rotating eddy initially at the top-left of the first image at radial position 7 mm and axial position 171 mm gradually weakens and disappears by the fourth image at t=104 ms. The disappearance of this eddy could be due to dissipation, out of plane motion, or shifting of its axis of rotation toward the cinema PIV image plane.

Reacting turbulent methane/nitrogen jet

A 1097-image cinema PIV sequence of a reacting methane/nitrogen jet (Re=4300) was obtained at 8000 images/second. Figure 2 shows a twelve-image excerpt from the full sequence. Only every fifth image is shown, for brevity. The time delay between each image is 0.625 milliseconds. The field of view is 32 mm (lateral) x 51 mm (axial) centered 80 mm from the jet exit and 17 mm radially from the jet axis, in a plane containing the axis. Only the upper half of the field of view is shown. The jet axis is along the left edge of the images. The white region extending from the top of the images is the hot combustion product zone, and its border is the thermal boundary of the leading edge of the flame. The mean velocity has been subtracted to aide the visualization of turbulent vortex structures. This sequence shows the interaction of a turbulent vortex structure with the flame thermal boundary. A relatively strong, isolated turbulent eddy is identified within the boxed region and tracked as it interacts with the flame. The eddy appears a significant distance upstream of the flame boundary in the first image at t=112 ms, and little change in the boundary is evident until the eddy approaches closer to it at t=114.5 ms. At t=115.125 ms the eddy is immediately adjacent to the flame boundary and its velocity field begins to influence the shape of the boundary, pushing it inward. From t=115.125 ms to the end of the sequence at t=118.875 ms, the eddy curls the flame leading edge into a hooked shape. This interaction is consistent with the clockwise eddy rotation direction evident from the velocity vector field. The eddy appears to be completely absorbed into the flame boundary by the last image in the sequence at t=118.875 ms. The entire interaction spans only 6.875 milliseconds, in which time 55 images are acquired by the high speed cinema PIV system.

Figure 3a is a single full field of view velocity vector field showing flow reversal in the reacting turbulent jet flow. The vectors represent the absolute velocity in the laboratory coordinate frame and are scaled proportionally to the velocity magnitude. The maximum velocities are 5-6 m/s. The thick line shows the flame thermal boundary, while the thin lines are streamlines. An isolated region of flow reversal is evident within the boxed region just below the flame boundary. Streamlines turn upstream through this region before continuing downstream. Figure 3b is a close-up of the boxed region in Figure 3a, showing the isolated region of flow reversal just upstream of the flame leading edge. The flow reversal region is completely bordered by regions with streamwise flow, suggesting that the reversal is induced by the flame. This incidence of flow reversal persists for approximately 5 milliseconds.

Figure 4 is a 12-image excerpt from the full sequence showing an extremely rapid upstream movement of the flame thermal boundary. Only the top half of the field of view is shown and only every other image is shown, for brevity. An isolated pocket of the boundary appears suddenly upstream of the previous flame leading edge. This pocket quickly grows and connects with the downstream portion of the boundary. The physical mechanism behind this event could be out of plane propagation and/or convection of the flame boundary. This event spans less than 3 milliseconds.

CONCLUSIONS

1. A newly developed high-speed cinema PIV technique providing time-resolved velocity field sequences of gas-phase reacting and non-reacting turbulent jet flows is demonstrated. Up to 8000 images/second are obtained, with sequence lengths exceeding 4000 images.
2. The combination of high image acquisition rate and long sequence length provided by cinema PIV yields finely time-resolved 2-D measurements of transient turbulent flow phenomena.
3. Unique observations of short-lived transient events provided by the cinema PIV technique are presented. These events span from 2-7 milliseconds, and are captured in sequences of 6-55 cinema PIV velocity field images. Conventional PIV systems operating at a 30 Hz acquisition rate capture no more than one image during such time spans. Observations of transient turbulent flow phenomena include:
    - Turbulent vortex structure convection, merging, sheet formation, pairing and dissipation
    - Interaction of a turbulent vortex structure with a flame thermal boundary
    - Flame-induced flow reversal
    - Extremely rapid upstream motion of a flame thermal boundary

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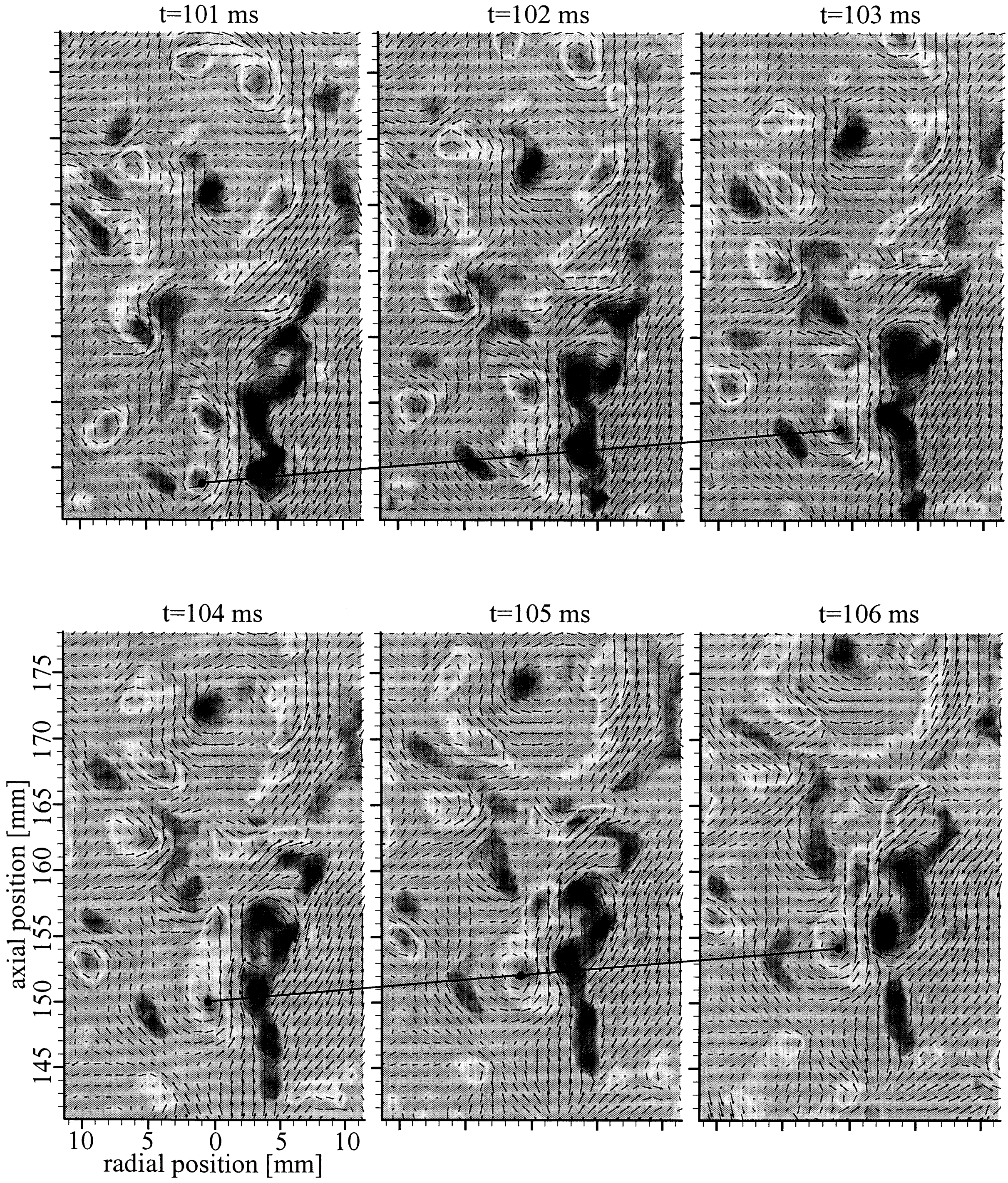

t=101 ms t=102 ms t=103 ms

t=104 ms t=105 ms t=106 ms

Figure 1: Cinema PIV sequence of a non-reacting turbulent air jet showing the time evolution of turbulent vortex structures:

- Convection speed
- Convection direction
- Interaction of vortex structures, including sheet formation and pairing
- Lifetime and dissipation

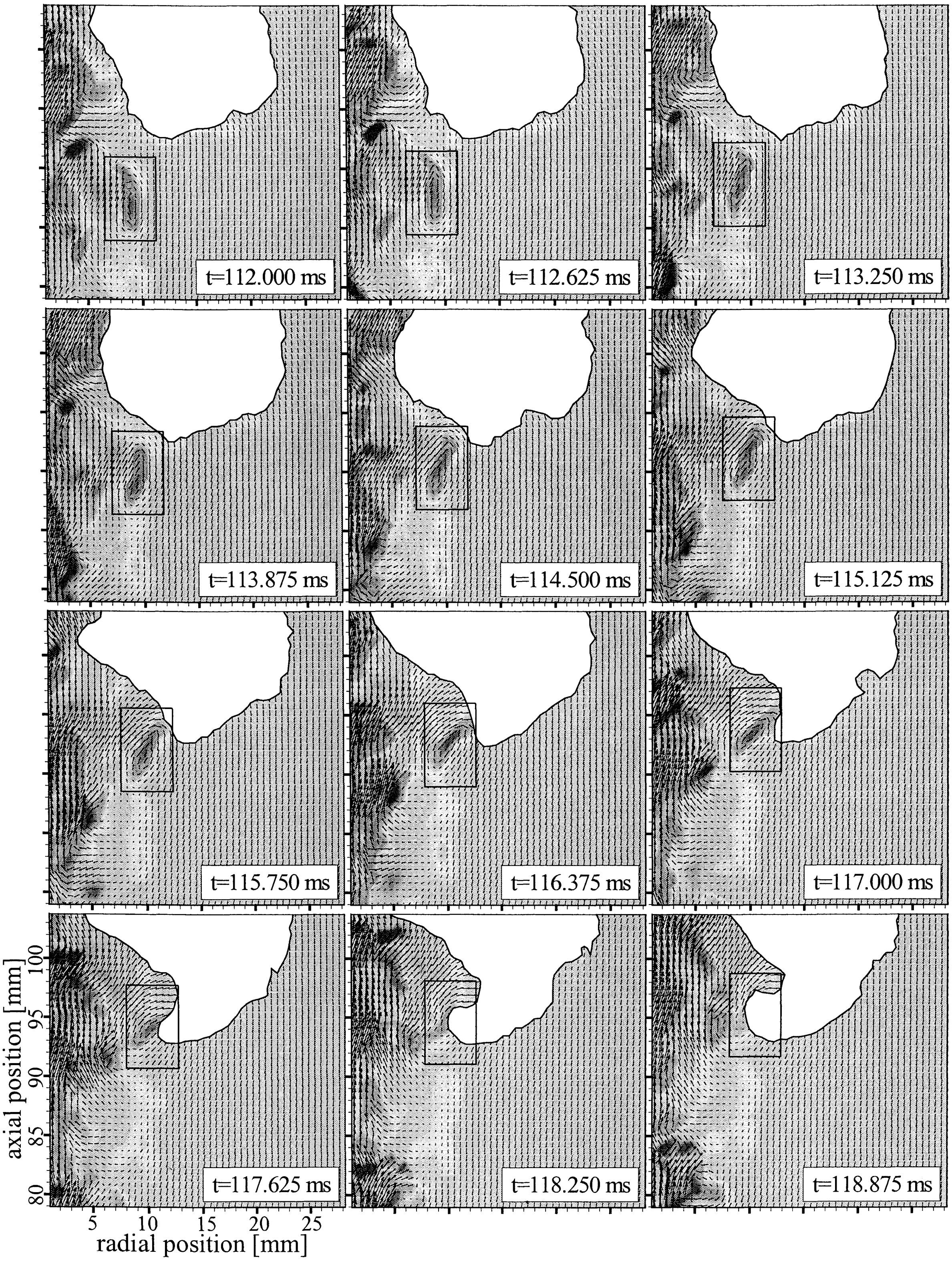

Figure 2: Cinema PIV sequence showing a time history of the interaction between a turbulent vortex structure (boxed) and the flame boundary in a lifted turbulent jet flame. The white region represents the flame thermal boundary. Vectors represent gas velocities, with the mean velocity subtracted. Shading contours represent vorticity, with dark shading corresponding to peak values.

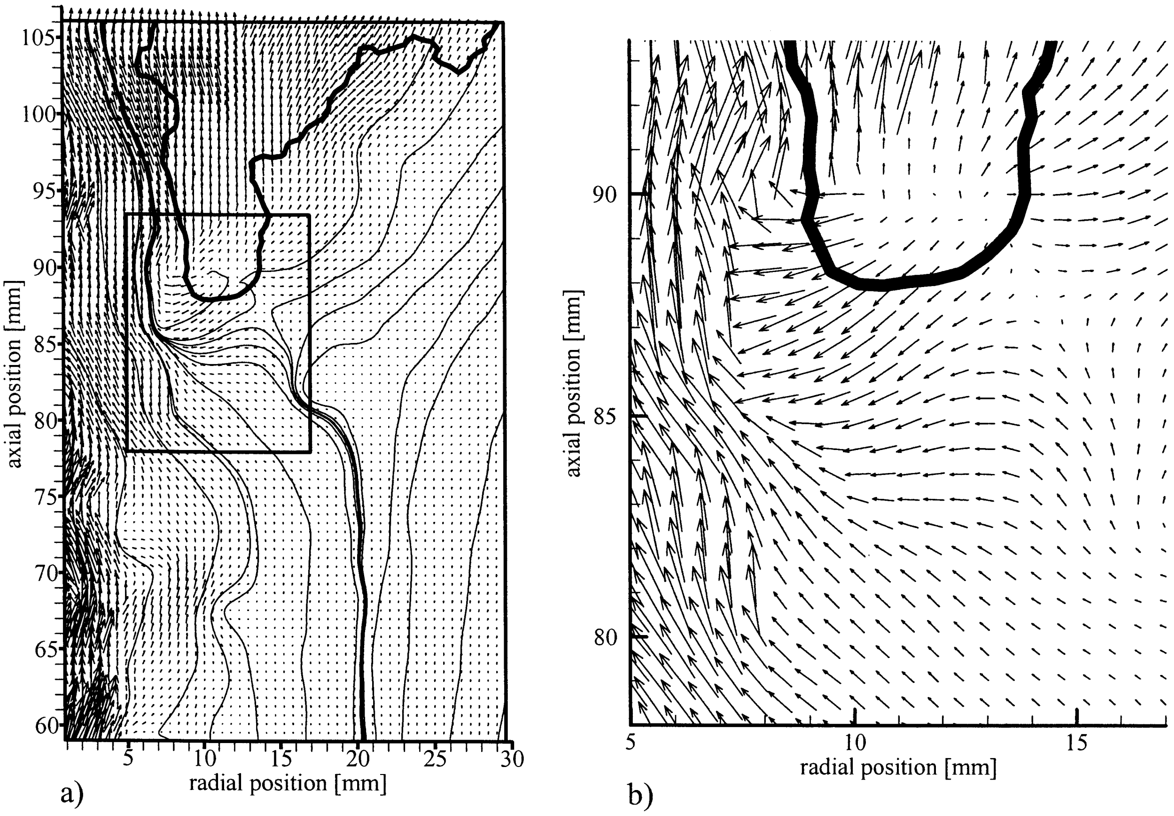

Figure 3 : Cinema PIV image showing gas velocities, the flame thermal boundary (thick line) and streamlines (thin lines). Entire field of view (a), close-up of boxed region (b). An isolated region of flow reversal is evident within the boxed region.

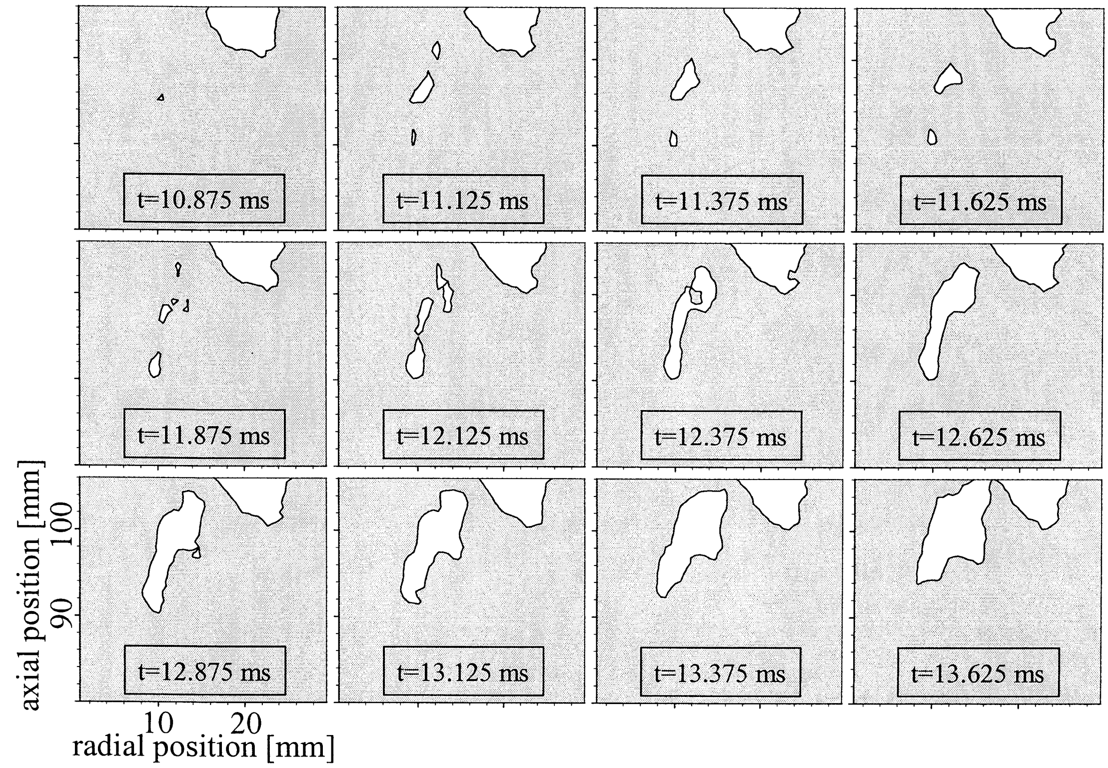

Figure 4 : A time history of the flame thermal boundary showing appearance and growth of an isolated pocket.