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THE INTERACTION OF A LAMINAR FLAME WITH ITS SELF-GENERATED FLOW DURING CONSTANT VOLUME COMBUSTION

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ABSTRACT

The formation of cusp shaped or "tulip" flames during closed tube flame propagation has been recorded by combustion researchers for nearly sixty years. Flame instability, pressure wave/flame interaction, and large scale circulation in the unburned gas have been suggested as explanations for the "tulip" flame phenomenon, but the cause of the "tulip" flame has not been conclusively determined. This work uses laser Doppler anemometer measurements of the flow field during flame propagation in a closed tube to describe the combustion generated flow and to support a fluid mechanical explanation for the "tulip" flame formation. The flame behaves as a fluid mechanical discontinuity which deflects the velocity of the gas passing through it. As the flame quenches at the side walls of the combustion vessel, the flow deflection generates a vortex in the burned gas. The vortex remains in the proximity of the flame and modifies the unburned gas field such that the flame propagates more quickly near the wall than at the center. The discrepancy in propagation rates leads to the "tulip" flame.

INTRODUCTION

Flame propagation in tubes has been a subject of combustion research for more than a century (Mallard and LeChatlier, 1883), and the formation of "tulip" flames during combustion in closed tubes has been recorded for nearly sixty years (Ellis, 1928, Guenoche, 1964, Smith, 1979, Steinert et al., 1982, Wakai et al., 1984, Dunn-Rankin, 1985). However, the cause of the "tulip" flame has eluded researchers. An example of the "tulip" flame phenomenon is shown in Figure 1. The photograph is a sequence of frames extracted from a high speed schlieren movie of a stoichiometric methane/air flame propagating in a closed rectangular duct (38 mm x 38 mm x 155 mm). The flame is initiated by a point igniter near one endwall of the combustion vessel. The "tulip" flame phenomenon is relatively insensitive to tube cross-section geometry, combustible mixture composition, and ignition source geometry (Dunn-Rankin, 1985). Detailed descriptions of the development of "tulip" flames for many different experimental conditions are in the references mentioned above.

Historically the "tulip" flame phenomenon has been attributed to a flame/pressure wave interaction (Guenoche, 1964), or a flame instability (Strehlow, 1984). Recently, however, the authors have used laser Doppler anemometry (LDA) to explore the possible role of combustion generated flow in "tulip" flame formation (Dunn-Rankin et al., 1984). The present study extends the earlier exploratory work by providing a complete mapping of the flow field during the "tulip" formation. LDA measurements of the fluid velocity near the flame front suggest a fluid mechanical explanation for the formation of "tulip" flames.

APPARATUS

The experimental apparatus, Figure 2, consists of a laser Doppler anemometer, a high-speed schlieren cinematographic system, a closed combustion vessel, a spark ignition source, a gas mixing device and a data logging computer. A detailed description of the experimental apparatus and methodology can be found in an earlier report (Dunn-Rankin and Sawyer, 1985); only a brief outline is repeated here.

The schlieren system records the changes in flame shape and position during the combustion process. The system is arranged in a standard Z-configuration. Details of the schlieren apparatus are described by Smith (1977).

The single component LDA system is arranged in a standard forward scatter configuration. The LDA system is described in detail by Dunn-Rankin and Sawyer (1985). A pair of Bragg cells provide differential shifting to resolve the directional ambiguity of the LDA signal.

The combustion chamber, Figure 3a, is a closed rectangular duct 38 mm square by 155 mm long. It is constructed of 12.7 mm thick plexiglas. The ignition site is a single spark gap (approximately 3 mm) located on the duct axis 10 mm from one endwall. The combustible gas is a stoichiometric mixture of methane and air.

METHODOLOGY

Figure 3b indicates the coordinate convention adopted and the 42 LDA measurement locations. The LDA separately measures two components (axial and radial) of the unsteady velocity at each of these locations. Positive radial velocity is away from the centerline of the duct; positive axial velocity is away from the igniter. The axial (X) and radial (Y) velocity from different experiments provide a time history of the vector velocity at each measurement point. Details of the data acquisition and vector generation are described in Dunn-Rankin and Sawyer (1985).

The experiment is repeated five times at each measurement location for each velocity component to determine the run-to-run variability. Earlier studies (Dunn-Rankin et. al., 1984, Dunn-Rankin and Sawyer, 1985) have shown that both the flow field and the flame shape are quite reproducible.

Noticeable LDA data rate reduction coincides with passage of the flame front through the LDA probe volume, Figure 4. The data rate reduction results from the nearly discontinuous change in both the fluid velocity and gas density which occurs at the flame front. The time of noticeable LDA data rate drop out, which is also the time of flame arrival, for each experiment is shown in Figure 5. The time of the data rate drop from all experiments can be combined to determine an approximate flame shape and position. The approximate flame shape history generated from this information, Figure 6, agrees with high speed schlieren cinematographic records of the flame shape evolution.

RESULTS

The time history of the experimentally determined vector velocity field during the flame propagation is shown in Figure 7. The vectors with a dot at their origin represent negative velocity. The flow field is assumed to have cylindrical symmetry except in the corners of the chamber. Individual frames from a high-speed schlieren movie of the flame propagation indicate the flame shape and location, and the solid line in the vector plots represents the flame location determined from LDA data rate reduction.

While the flame is convex toward the unburned gas ($t < 15$ ms), the entire flow field is positive. However, by the time the flame flattens ($t = 20$ ms) the burned gas flow field is entirely negative. At the same time the unburned gas velocity has dropped to a very small almost constant value. Previous studies have indicated that the decrease in unburned gas velocity is due primarily to a decrease in flame area (Dunn-Rankin and Sawyer, 1985). The reversal of the direction of the burned gas motion and the decrease in unburned gas velocity occurs very rapidly, which suggests that the "tulip" transition is a very rapid process. As the "tulip" continues to grow ($t > 25$ ms) a stagnation region develops in the burned gas behind the vertex of the "tulip" cusp. Furthermore, a small reverse flow appears in the unburned gas just within the confines of the "tulip". This flow pattern and the "tulip" flame shape persist for the remainder of the combustion process, which indicates that the "tulip" configuration is a relatively stable flame shape in closed tube combustion.

DISCUSSION OF FLAME/FLOW INTERACTION

Interpretation of the velocity field is simplified by adopting a flame sheet model for the closed tube flame. The flame is assumed to be an infinitely thin interface where unburned gas is instantaneously and irreversibly converted to high temperature burned gas. With this assumption, classical deflagration analysis predicts deflection of the flow as it passes through the flame sheet from the unburned to the burned side (Strehlow, 1984).

The component of gas velocity parallel to the flame front is continuous across the front. The component of gas velocity perpendicular to the reaction front, however, changes discontinuously across the flame as the unburned mixture is converted to higher temperature, lower density burned gas, Figure 8a,

$$S_b = \sigma S_u,$$

where S represents the normal velocity relative to the flame sheet, subscripts b and u refer to the burned and unburned gas respectively, and σ is the density ratio ρ_u/ρ_b (also referred to as the expansion ratio). S_u is the fundamental flame speed of the mixture. The discontinuous normal velocity change is,

$$\Delta V = S_b - S_u = (\sigma - 1)S_u.$$

The jump condition applies in the laboratory frame of reference as well, but there is a convective component added to the burned and unburned gas velocities, Figure 8b. The velocity jump only occurs in the component of velocity normal to the flame front. The discontinuous change in the velocity across the flame is apparent in the measurements of the centerline velocity. The measured velocity jump as the flame passes the centerline measurement locations closely approximates the predicted value of the jump for stoichiometric methane/air flames ($\Delta V \approx$ 2.0 m/s: $\sigma \approx 6.75$, $S_u \approx 0.35$ m/s, $\Delta V = (\sigma - 1)S_u$), Figure 9.

When the flame sheet is oblique to the unburned gas flow the discontinuous change in the velocity component perpendicular to the flame causes a deflection of the flow direction across the flame, Figure 10. V_f is the flame velocity in the laboratory reference frame. V is the magnitude of the vector velocity with the subscripts u and b denoting unburned and burned gas as before. The additional subscript n refers to the normal component. The angle of incidence between the upstream flow and the flame sheet is denoted θ_i. The deflected angle, θ_d, is the angle between the unburned gas velocity vector and the burned gas velocity vector. Simple geometric and algebraic considerations produce the following relationships between the unburned gas flow speed, V_u, the angle of incidence, θ_i, the deflected angle, θ_d, and the burned gas flow, V_b:

$$\theta_d = \theta_i + \arctan\left(\frac{V_u \sin(\theta_i) - (\sigma - 1)S_u}{V_u \cos(\theta_i)}\right)$$

$$V_b = \sqrt{(V_u \cos(\theta_i))^2 + (V_u \sin(\theta_i) - (\sigma - 1)S_u)^2}$$

When θ_d is greater than 90 degrees the burned gas velocity is negative in the laboratory reference frame. The above relationship between θ_i, θ_b, V_u, and V_b explains the dependence of the burned gas motion on both the flame shape, which enters the above expression as θ_i, and the unburned gas velocity, which enters the expression as V_u. Particle track photographs of flow through open bunsen burner flames (Lewis and Von Elbe, 1943) and flow through steady flames in open tubes (Uberoi, 1959) show the deflection phenomenon. The deflection is also apparent in the velocity vector measurements of the nonsteady flow field associated with closed tube combustion, Figure 11. When the flame is convex toward the unburned gas the deflection is toward the centerline, and when the flame is concave toward the unburned gas the deflection is away from the centerline. The deflection away from the centerline is responsible for the stagnation region behind the "tulip" cusp.

When the flame front is curved, the deflection phenomenon described in the previous paragraph can create a vortex in the burned gas. The generation of a vortex by a curved flame front is shown schematically in Figure 12. The unburned gas velocity, V_u, is assumed constant and parallel. The burned gas velocity is not constant or parallel because θ_i varies along the flame front. The LDA measurements show a vortex structure behind the flame as the "tulip" forms which is similar to the predicted circulation, Figure 13.

EXPLANATION FOR THE "TULIP" FORMATION

The features of the flow field associated with the formation of the "tulip" flame occur very rapidly during a transition period of the combustion process (from t = 14 ms to t = 17 ms). During the transition process the flame shape changes rapidly as the extended portions of the flame near the sidewalls of the combustion vessel are quenched. This leaves only the flatter domed section of the flame, and greatly reduces the flame area. The reduced flame area causes a dramatic decrease in the unburned gas velocity because the decreased burning rate reduces the expansion contribution to the unburned gas motion (Dunn-Rankin and Sawyer, 1985). As a consequence of the reduced unburned gas velocity and the velocity jump condition, the burned gas changes direction. These events are evident in the vector velocity field during the transition period, Figure 14.

The measured velocity field and the deflection analysis of the previous section indicate a vortex just behind the flame as the wall quench occurs. Immediately following the the generation of this vortex the flame becomes nearly planar, and the vortex remains in close proximity to the planar front. However, the vortex, planar flame shape, and unburned gas motion are not compatible because the vortex requires a curved flame front. The flow field and flame shape must change to accomodate the new conditions. The change occurs very rapidly and appears as the flame curvature associated with the onset of the "tulip" cusp. Once the cusp begins, the natural burning behavior extends the "tulip" and maintains this shape. Numerical support for the vortex caused "tulip" flame has been obtained by Hsiao (1985). He demonstrated that a vortex in the burned gas behind a planar flame front will cause the flame to "tulip".

SUMMARY

The fluid mechanical aspects of closed tube combustion are investigated using laser Doppler anemometry (LDA). In particular, the interaction between the flame sheet and the fluid motion is discussed. This interaction leads to the "tulip" flame formation.

The LDA measurements show that the flame behaves as a nonsteady gasdynamic discontinuity with a jump in the component of velocity normal to its surface. The velocity jump causes a deflection of the streamlines passing through the flame. When the flame is sufficiently curved, and the proper unburned gas motion is present, a vortex appears in the burned gas. The velocity jump, flow deflection, and vortex generation all appear in the experimental results.

The features of the flow field associated with the formation of the "tulip" shape occur during a transition period of the combustion process. These features appear when part of the flame is quenched by the sidewalls of the combustion vessel. The quench reduces the flame area which decreases the overall velocity of the unburned gas flow. The flame area decrease is also accompanied by a change in flame shape that generates a strong circulation in the burned gas near the flame. This circulation, or vortex, affects both the flame shape and the unburned gas, causing the flame to propagate more quickly at the walls than at the center. The ultimate effect of the different flame propagation rates is the "tulip" flame.

ACKNOWLEDGEMENTS

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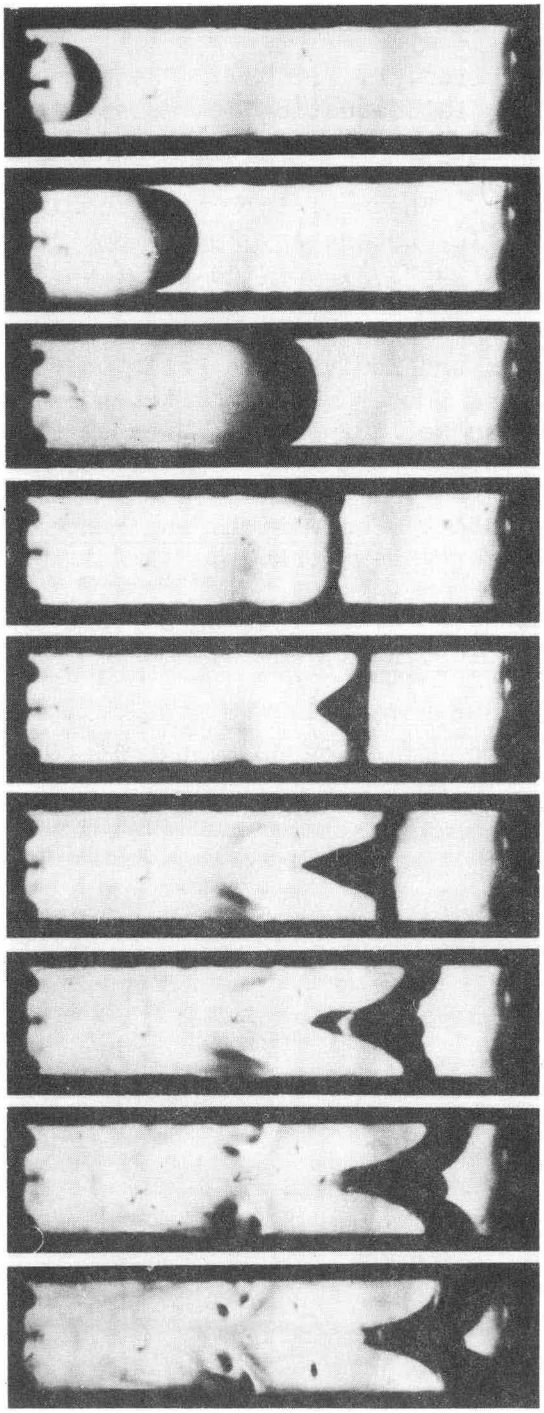

Figure 1. An example of the "tulip" flame formation. Stoichiometric methane/air flame initiated by a spark. Square cross-section vessel (38 mm x 38 mm x 155 mm).

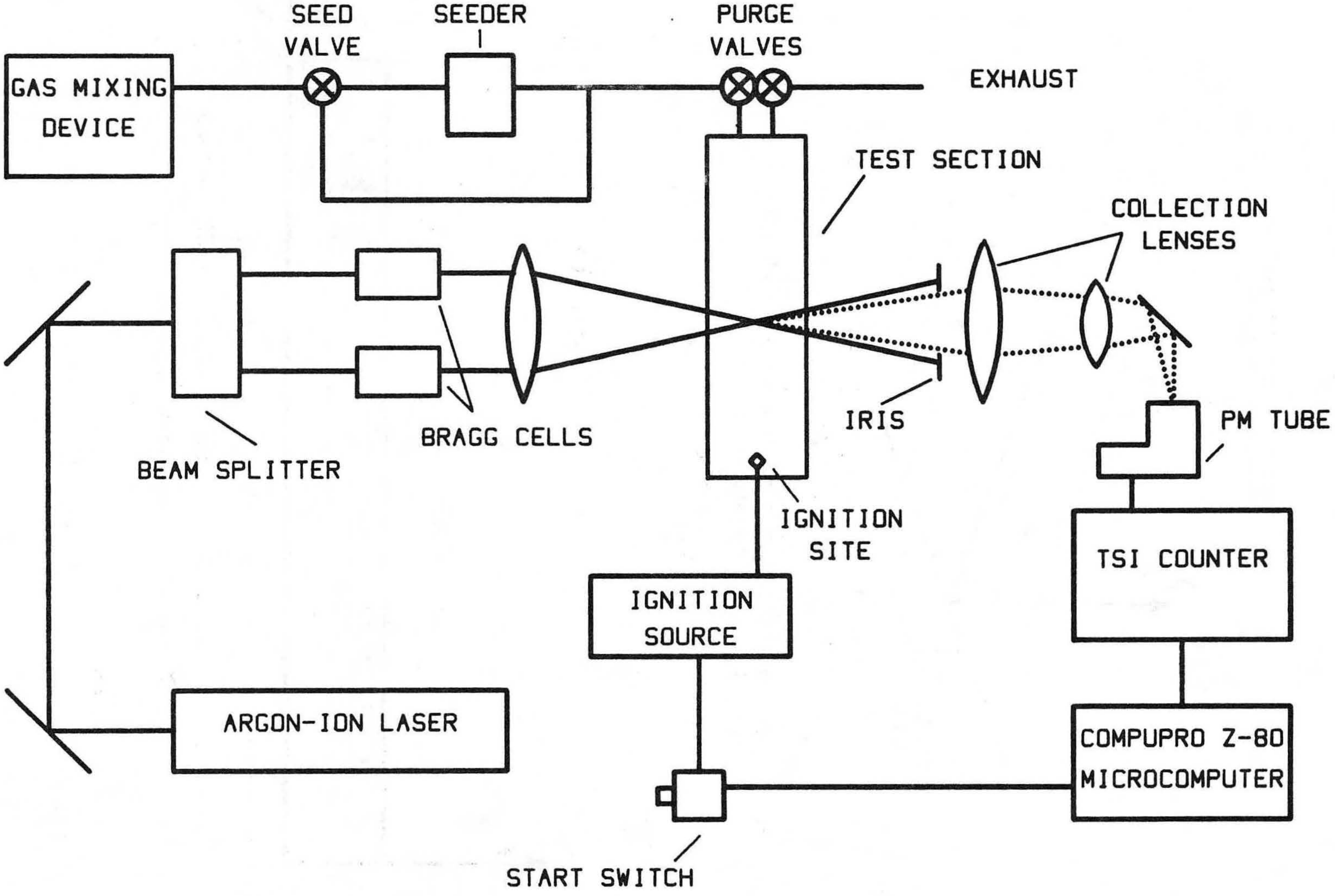

Figure 2. Schematic of experimental apparatus.

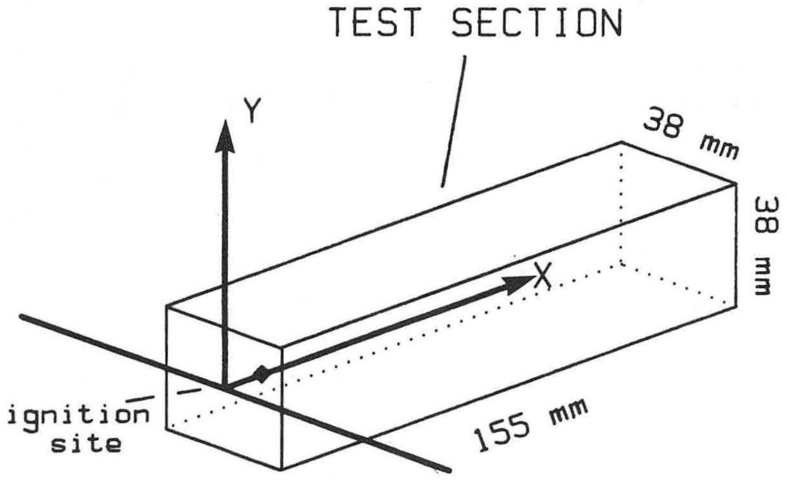

Figure 3a. Coordinate layout of the combustion vessel showing the ignition location.

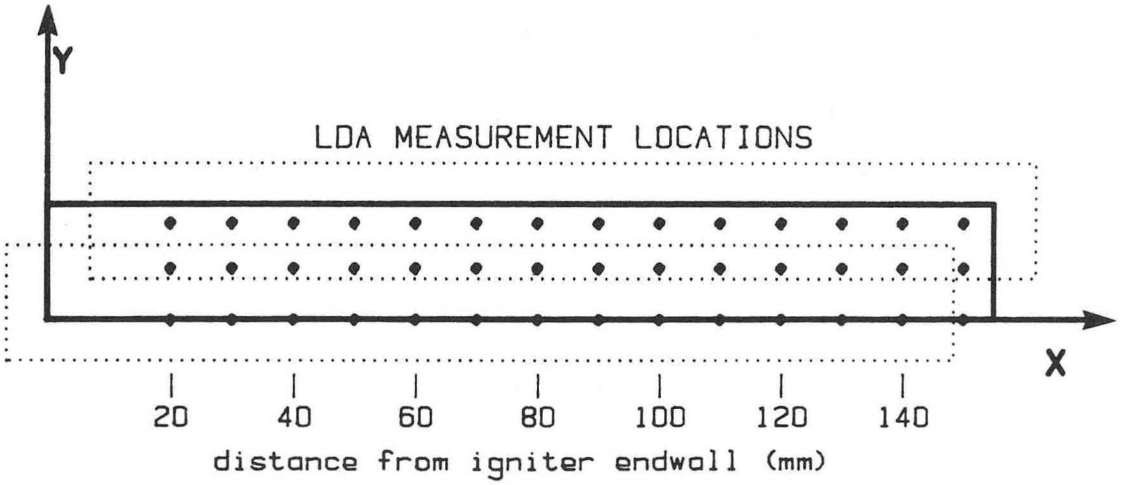

Figure 3b. Matrix of LDA measurement locations.

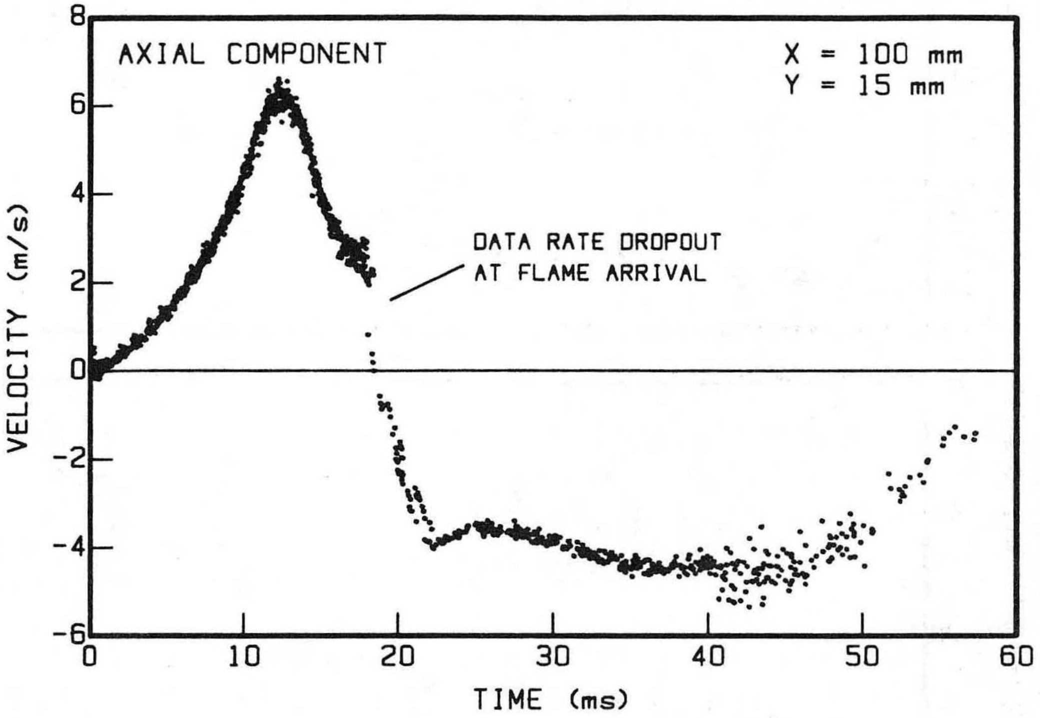

Figure 4. Overlayed raw data from five consecutive experiments.

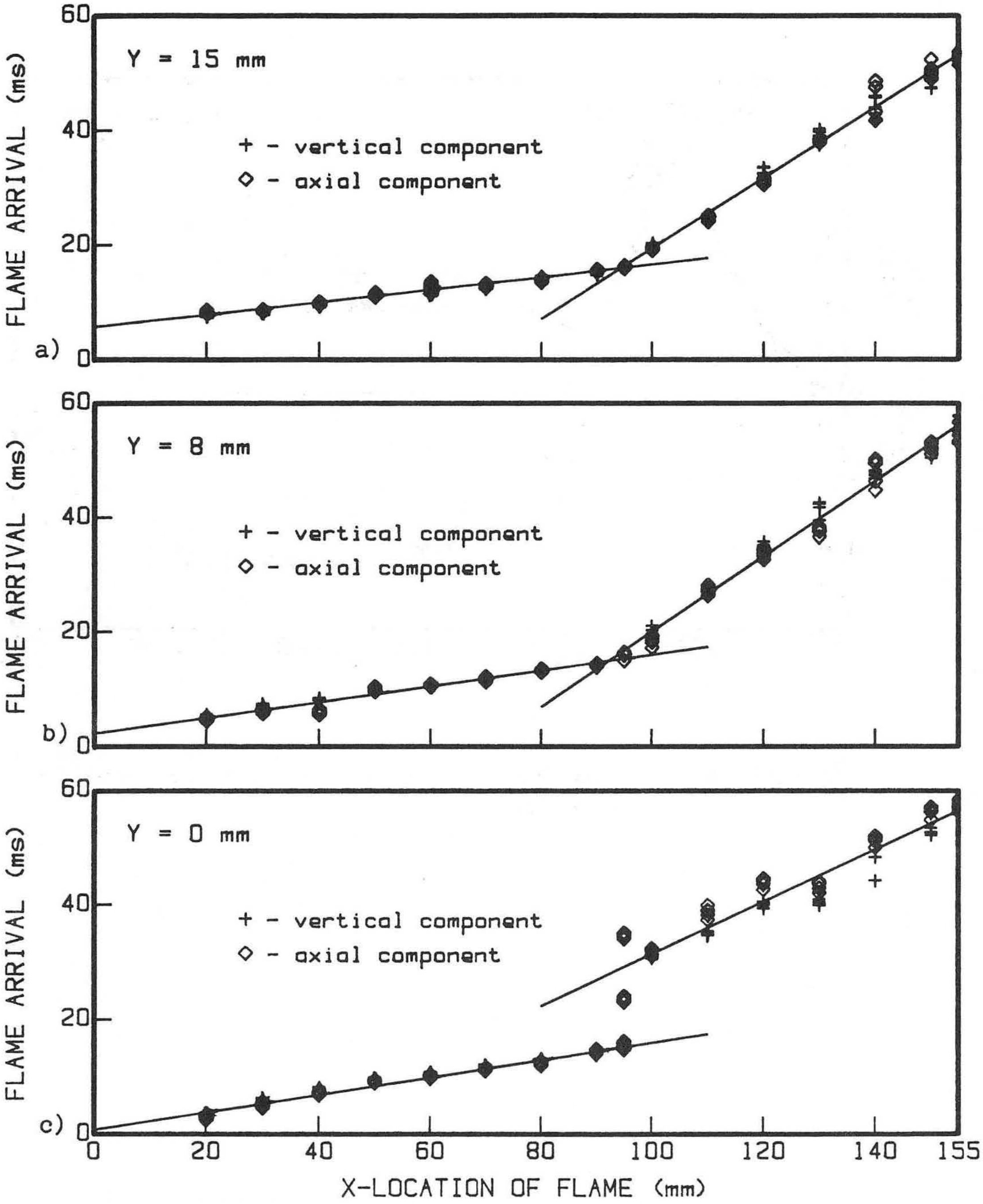

Figure 5. Flame arrival deduced from LDA dropout.
a) Near the sidewall (Y = 15 mm)
b) Half-radius location (Y = 8 mm)
c) At the centerline (Y = 0 mm)

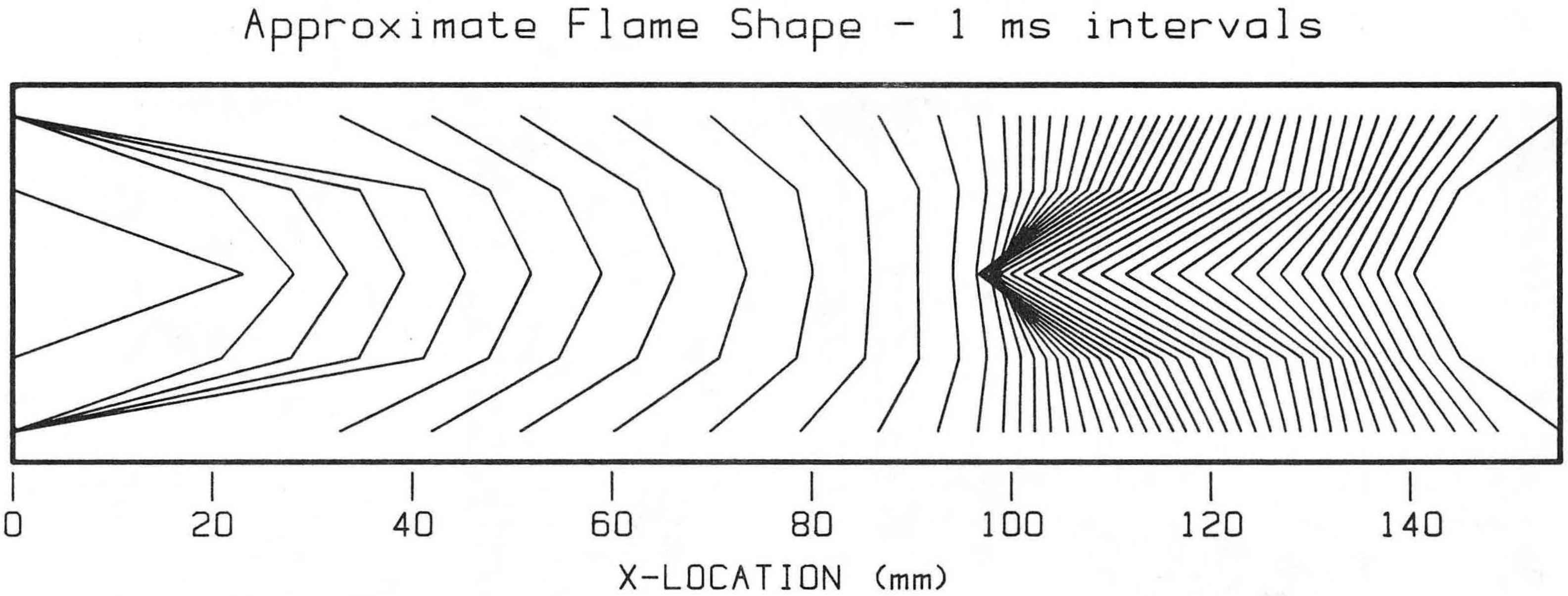

Figure 6. Flame shape history generated from flame arrival information.

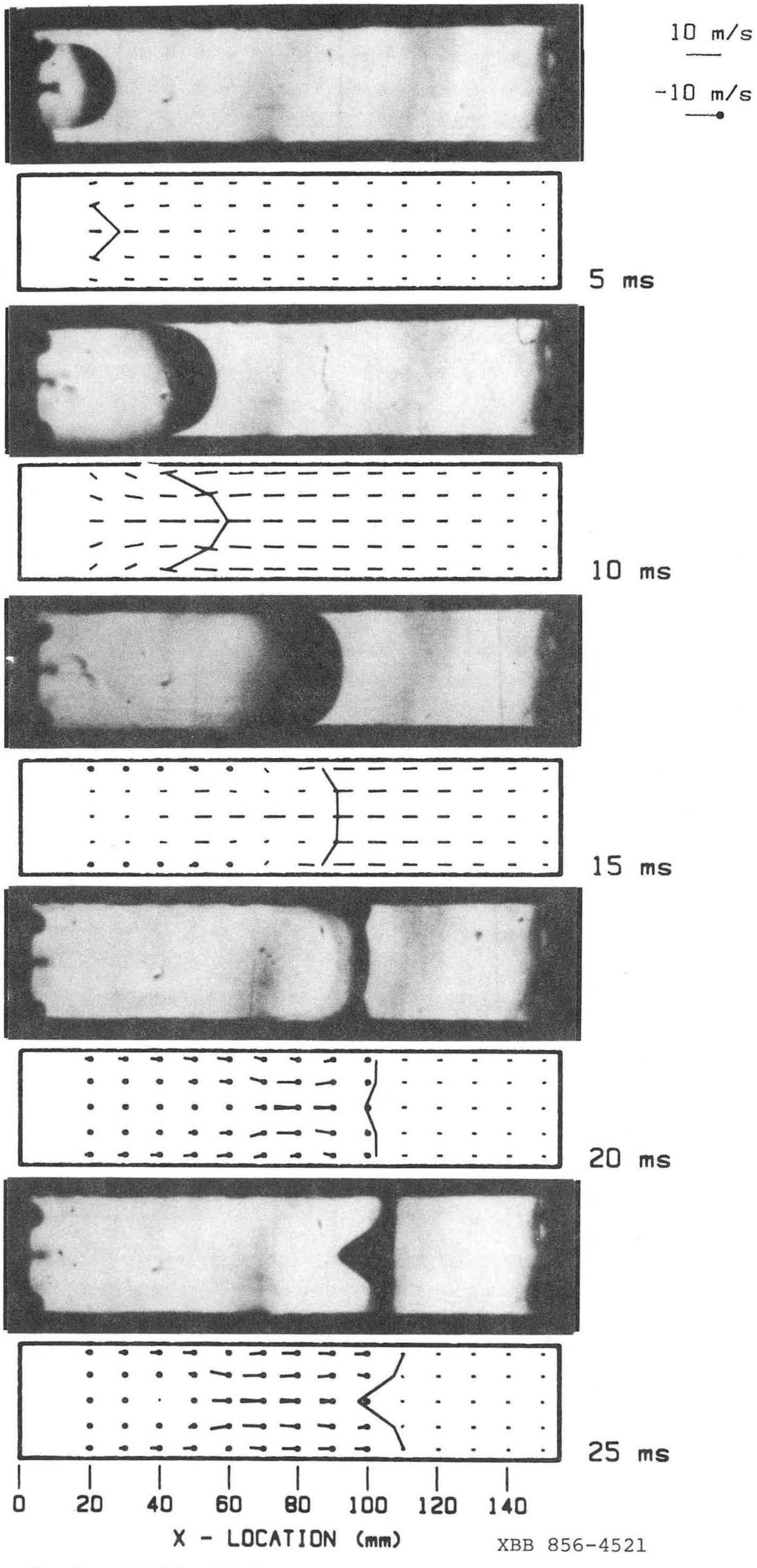

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Figure 7a. Vector velocity field and flame shape during constant volume combustion.

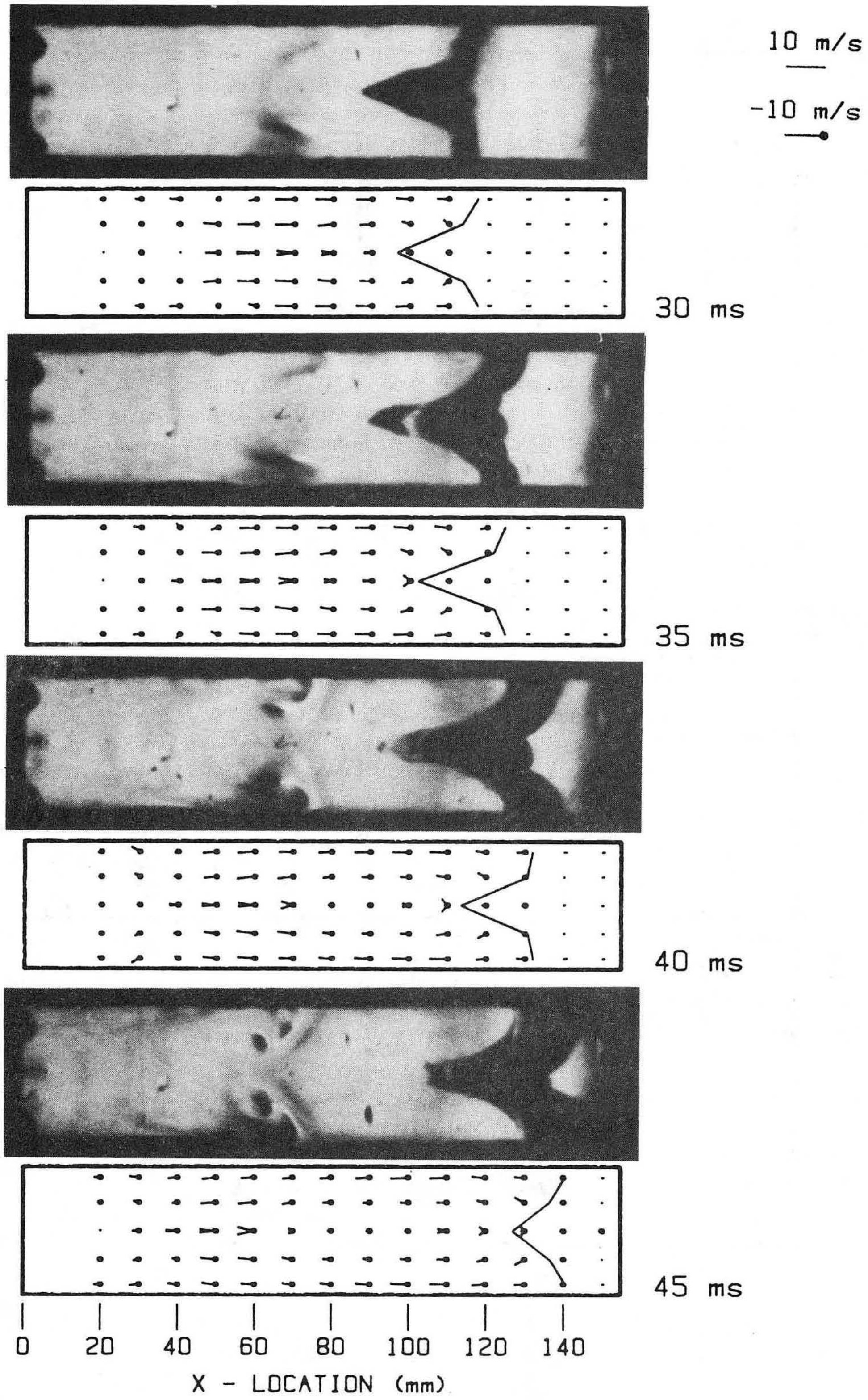

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Figure 7b. Vector velocity field and flame shape during constant volume combustion. Stoichiometric methane/air flame.

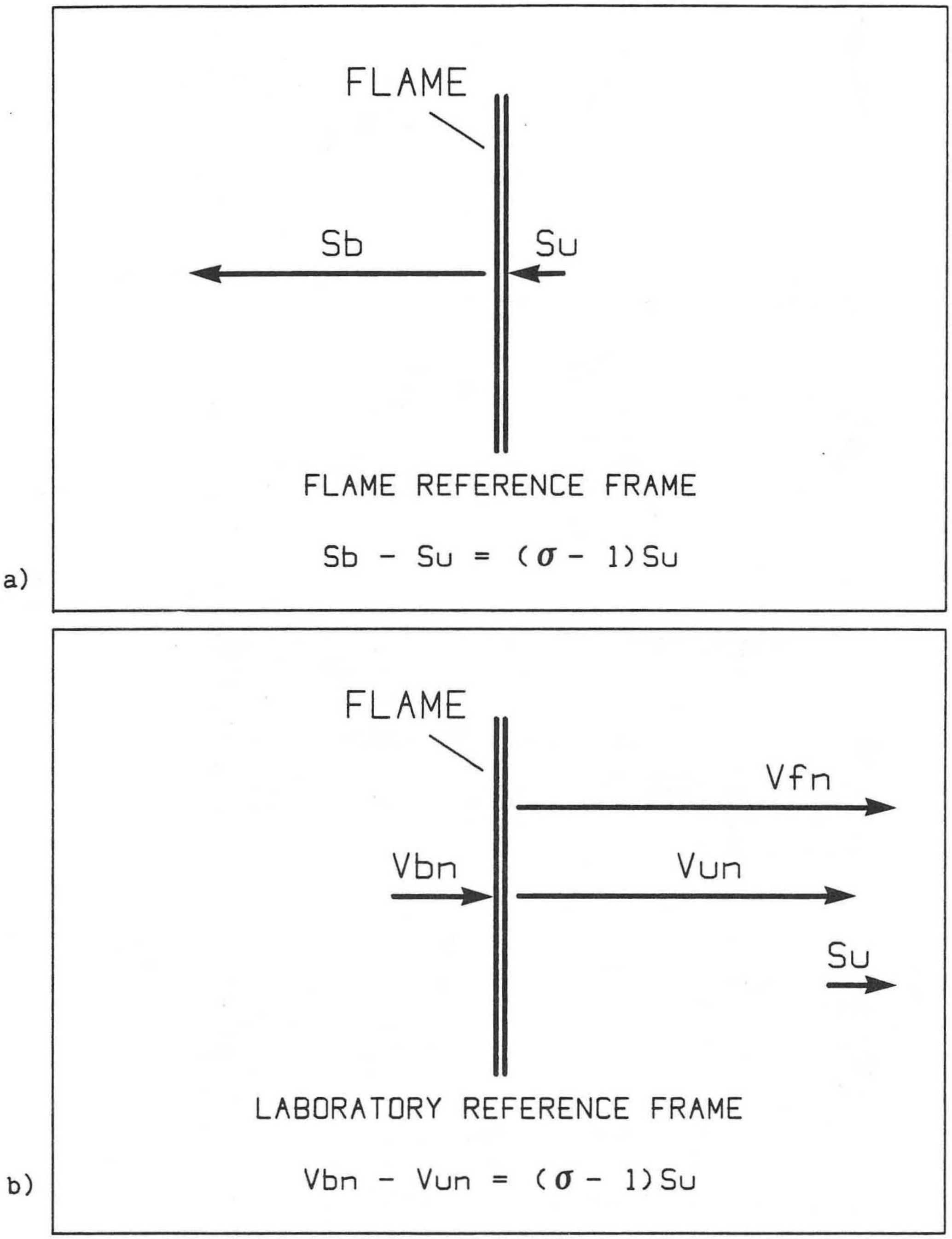

Figure 8. Velocity jump at the flame interface.
a) Flame reference frame
b) Laboratory reference frame

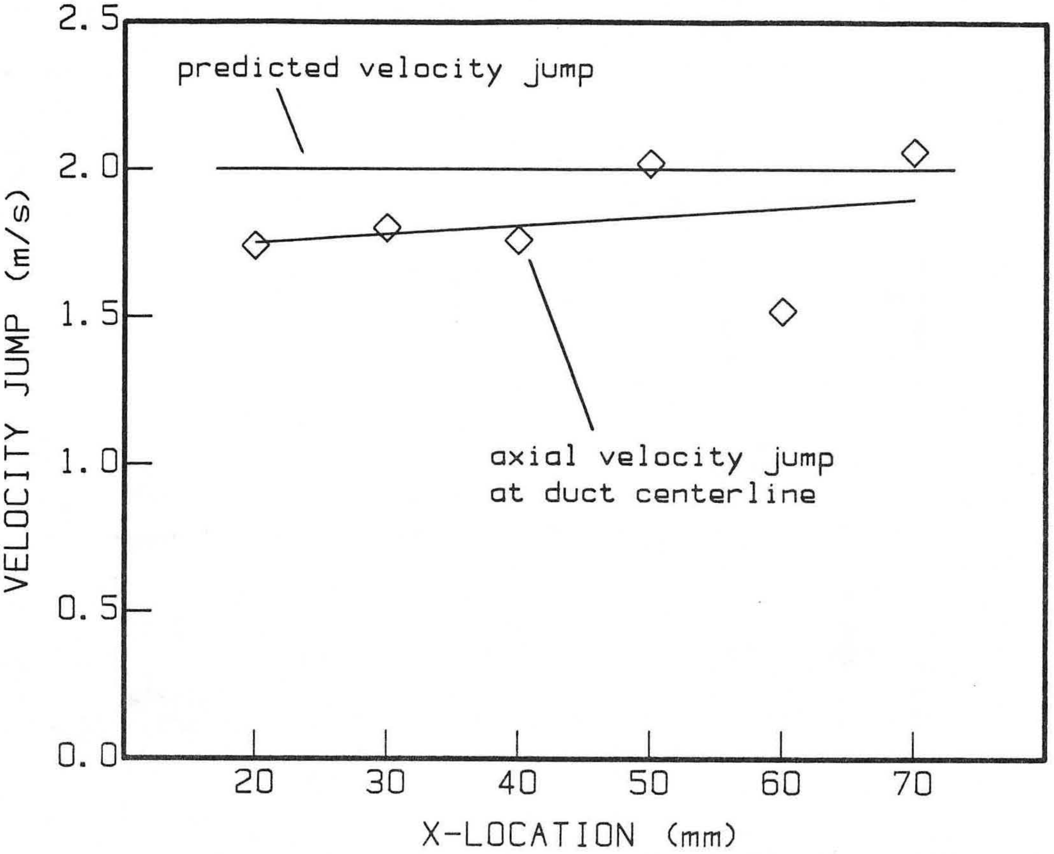

Figure 9. Comparison of measured velocity jump of the axial component of the centerline velocities to the predicted value.

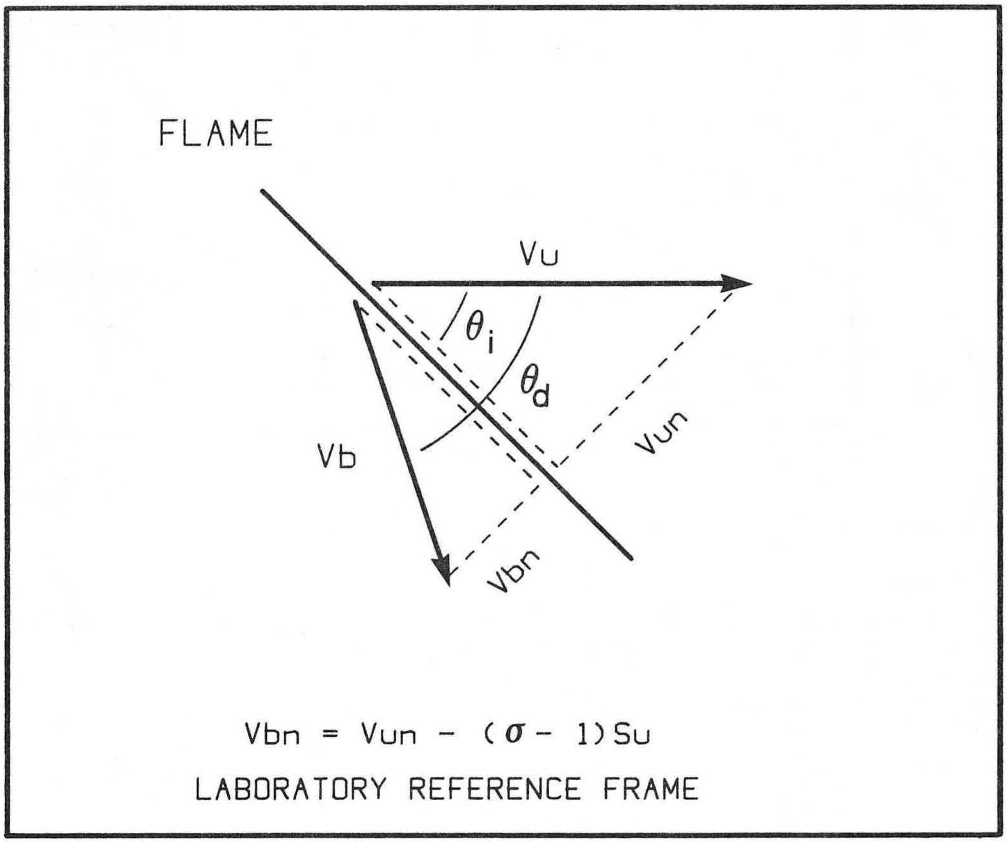

Figure 10. Schematic of flow deflection caused by a flame sheet oblique to the incoming flow.

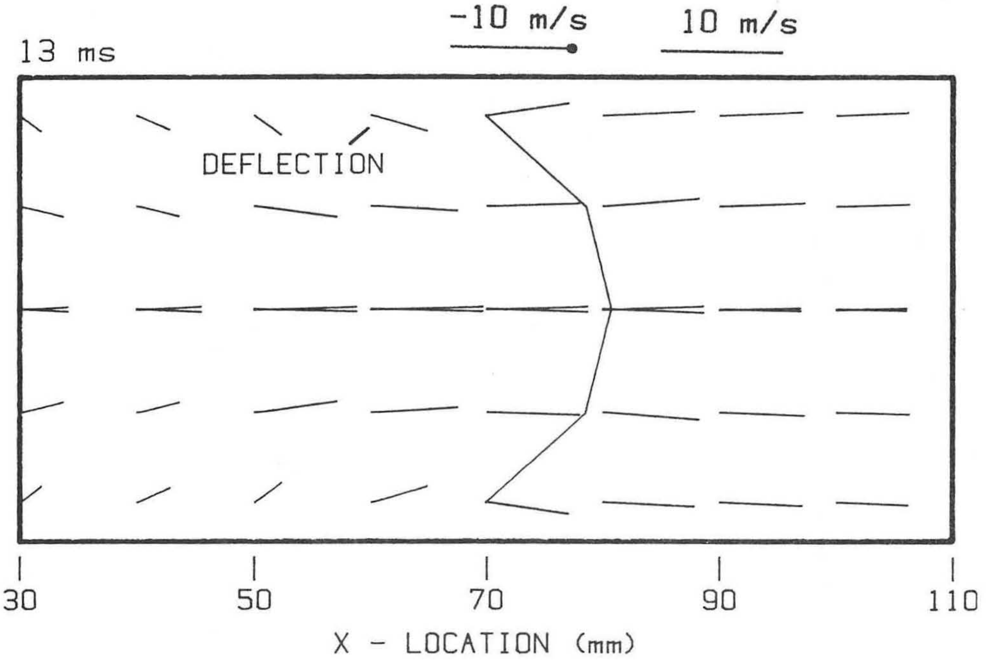

Figure 11a. Measured velocity deflection early in the transition phase as the flame passes.

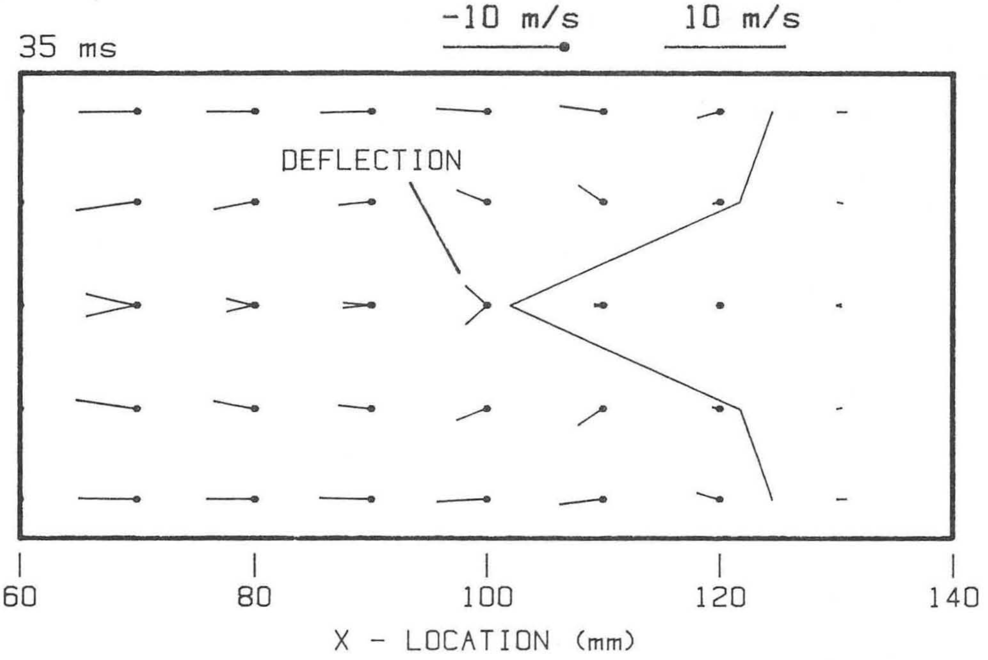

Figure 11b. Measured velocity deflection during the "tulip" phase as the flame passes.

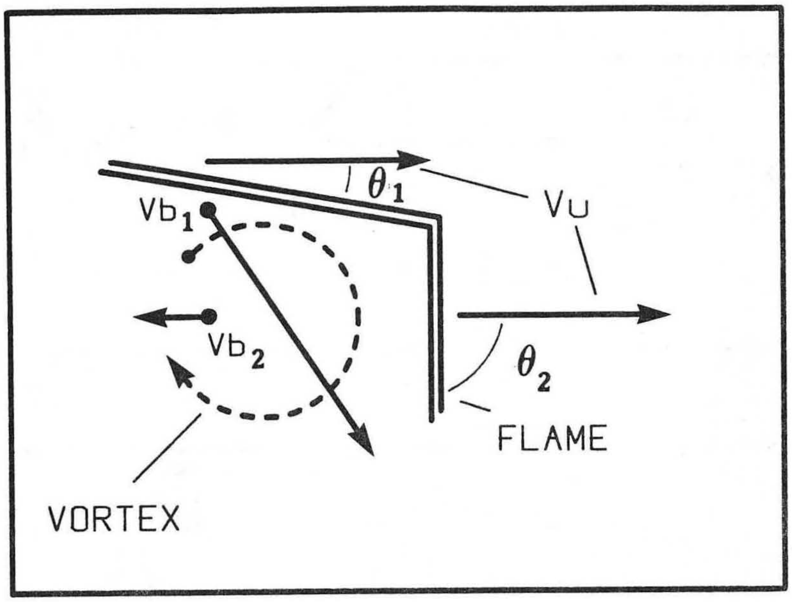

Figure 12. Schematic showing generation of regions of circulation by a curved flame front.

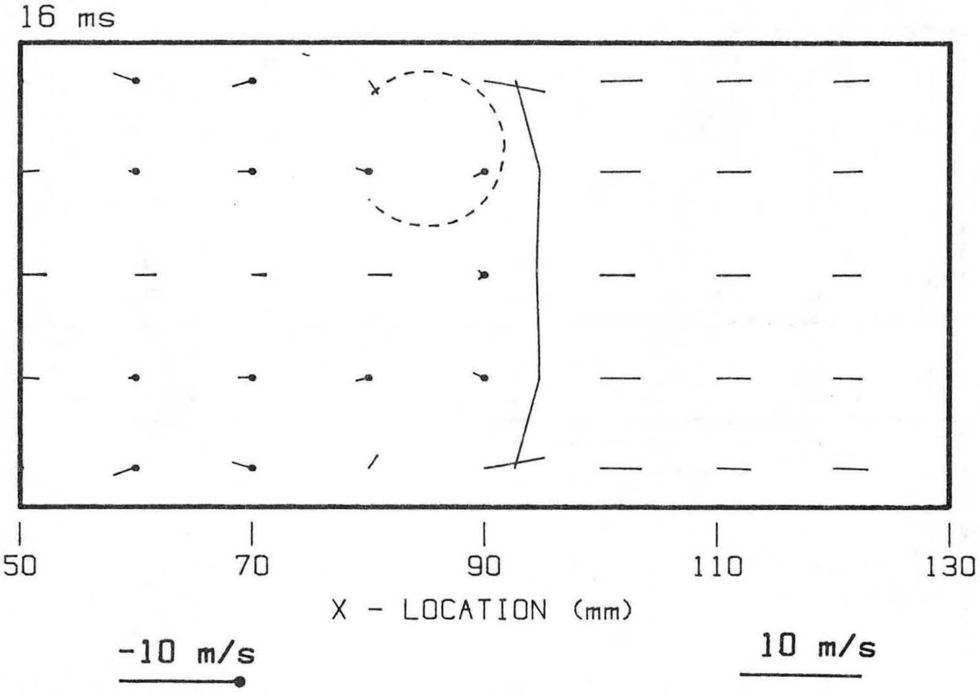

Figure 13. Measured velocity field showing vortical structure generated behind the flame during the transition phase.

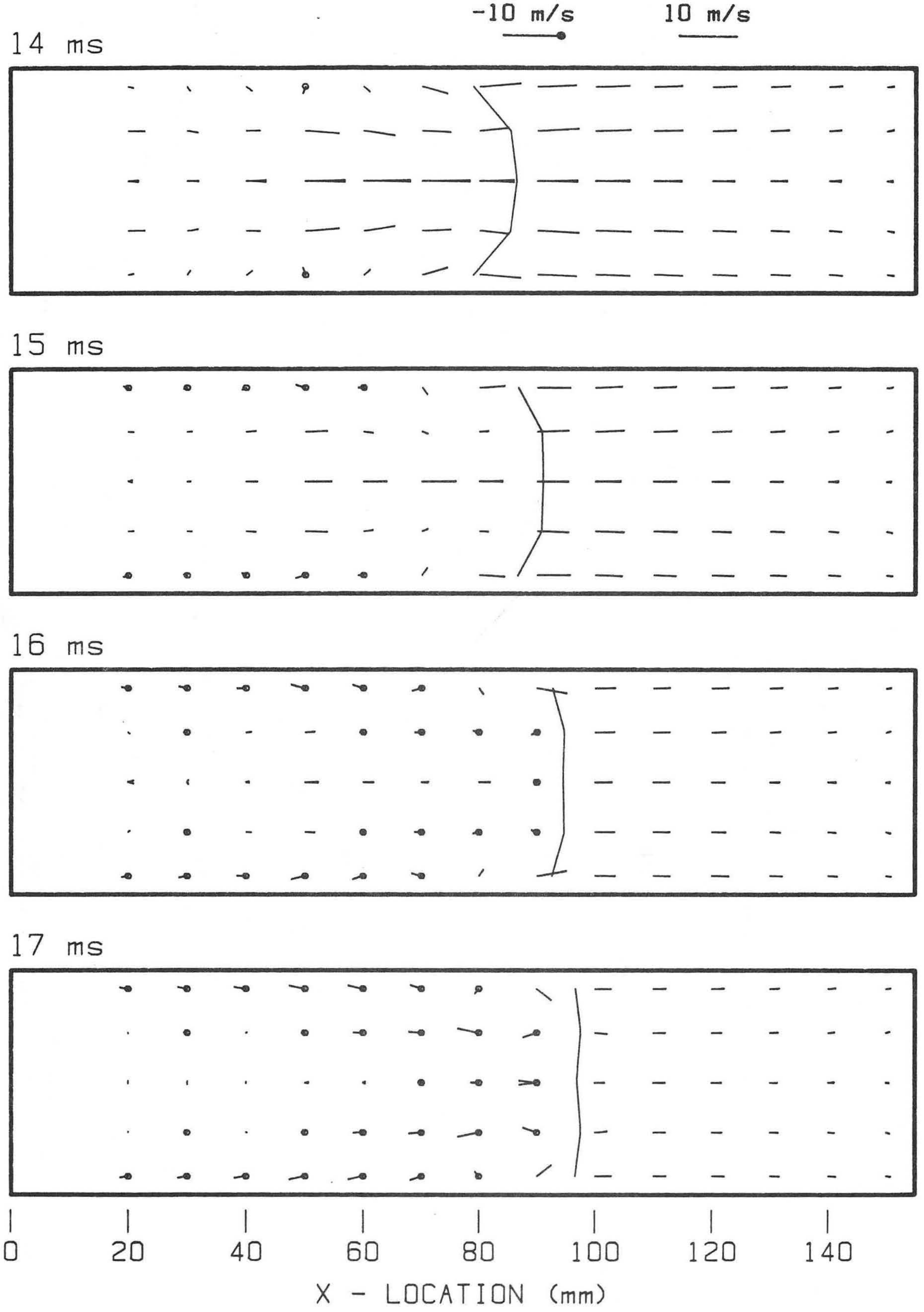

Figure 14. Close-up of vector field during the transition phase of flame propagation.