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Development of Hairpin Vortices in Turbulent Spots and End-Wall Transition

The end-stage phase of boundary layer transition is characterized by the development of hairpin-like vortices which evolve rapidly into patches of turbulent behavior. In general, the characteristics of the evolution from this hairpin stage to the turbulent stage is poorly understood, which has prompted the present experimental examination of hairpin vortex development and growth processes. Two topics of particular relevance to the workshop focus will be covered: 1) the growth of turbulent spots through the generation and amalgamation of hairpin-like vortices, and 2) the development of hairpin vortices during transition in an end-wall junction flow. Brief summaries of these studies are described below.

Using controlled generation of hairpin vortices by surface injection in a critical laminar boundary layer, detailed flow visualization studies have been done of the phases of growth of single hairpin vortices, from the initial hairpin generation, through the systematic generation of secondary hairpin-like flow structures, culminating in the evolution to a turbulent spot. The key to the growth process is strong vortex-surface interactions, which give rise to strong eruptive events adjacent to the surface, which results in the generation of subsequent hairpin vortex structures due to inviscid-viscous interactions between the eruptive events and the free stream fluid. The general process of vortex-surface fluid interaction, coupled with subsequent interactions and amalgamation of the generated multiple hairpin-type vortices, is demonstrated as a physical mechanism for the growth and development of turbulent spots.

When a boundary layer flow along a surface encounters a bluff body obstruction extending from the surface (such as a cylinder or wing), the strong adverse pressure gradients generated by these types of flows result in the concentration of the impinging vorticity into a system of discrete vortices near the end-wall juncture of the obstruction, with the extensions of the vortices engirdling the obstruction to form "necklace" or "horseshoe" vortices. Recent hydrogen bubble and particle image visualization have shown that as Reynolds number is increased for a laminar approach flow, the flow will become critical, and a destabilization of the necklace vortices results in the development of an azimuthal waviness, or "kinks," in the vortices. These vortex kinks are accentuated by Biot-Savart effects, causing portions of a distorted necklace vortex to make a rapid approach to the surface, precipitating processes of localized, three-dimensional surface interactions. These interactions result in the rapid generation, focussing, and ejection of thin tongues of surface fluid, which rapidly roll-over and appear as hairpin vortices in the junction region. Subsequent amalgamation of these hairpin vortices with the necklace vortices produces a complex transitional-type flow.

A presentation of key results from both these studies will be done, emphasizing both the ubiquity of such hairpin-type flow structures in manifold transitional-type flows, and the importance of vortex-surface interactions in the development of hairpin vortices.

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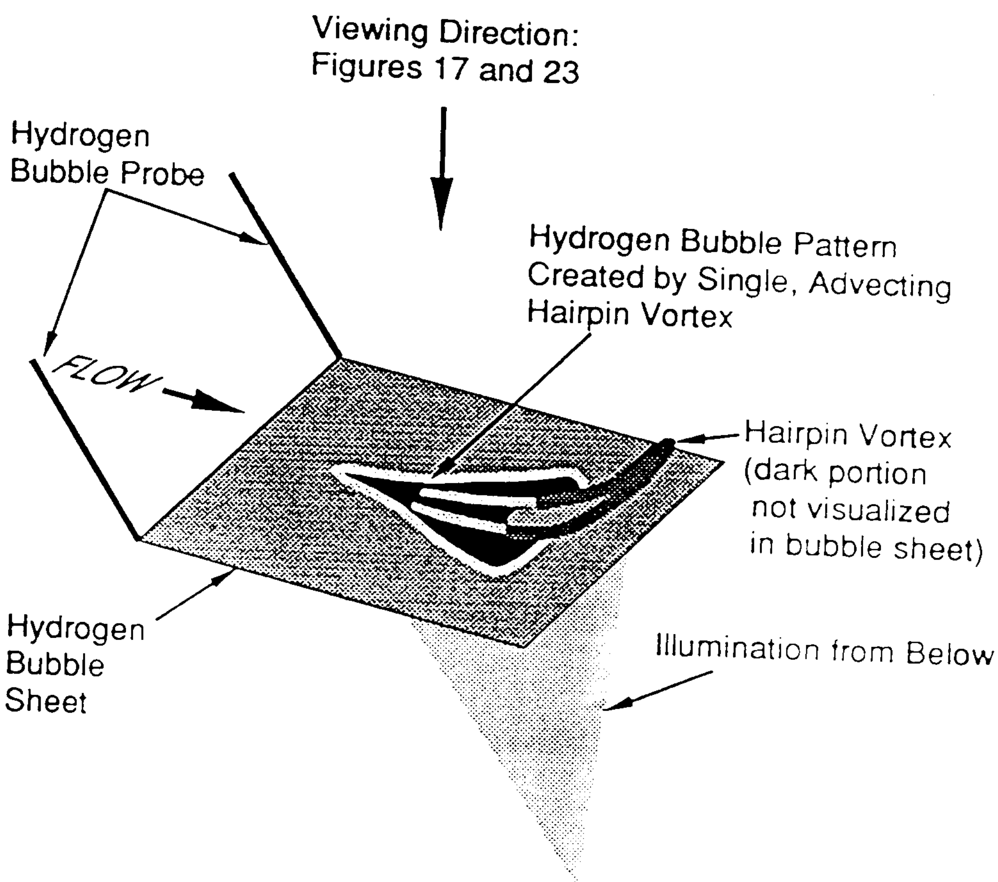
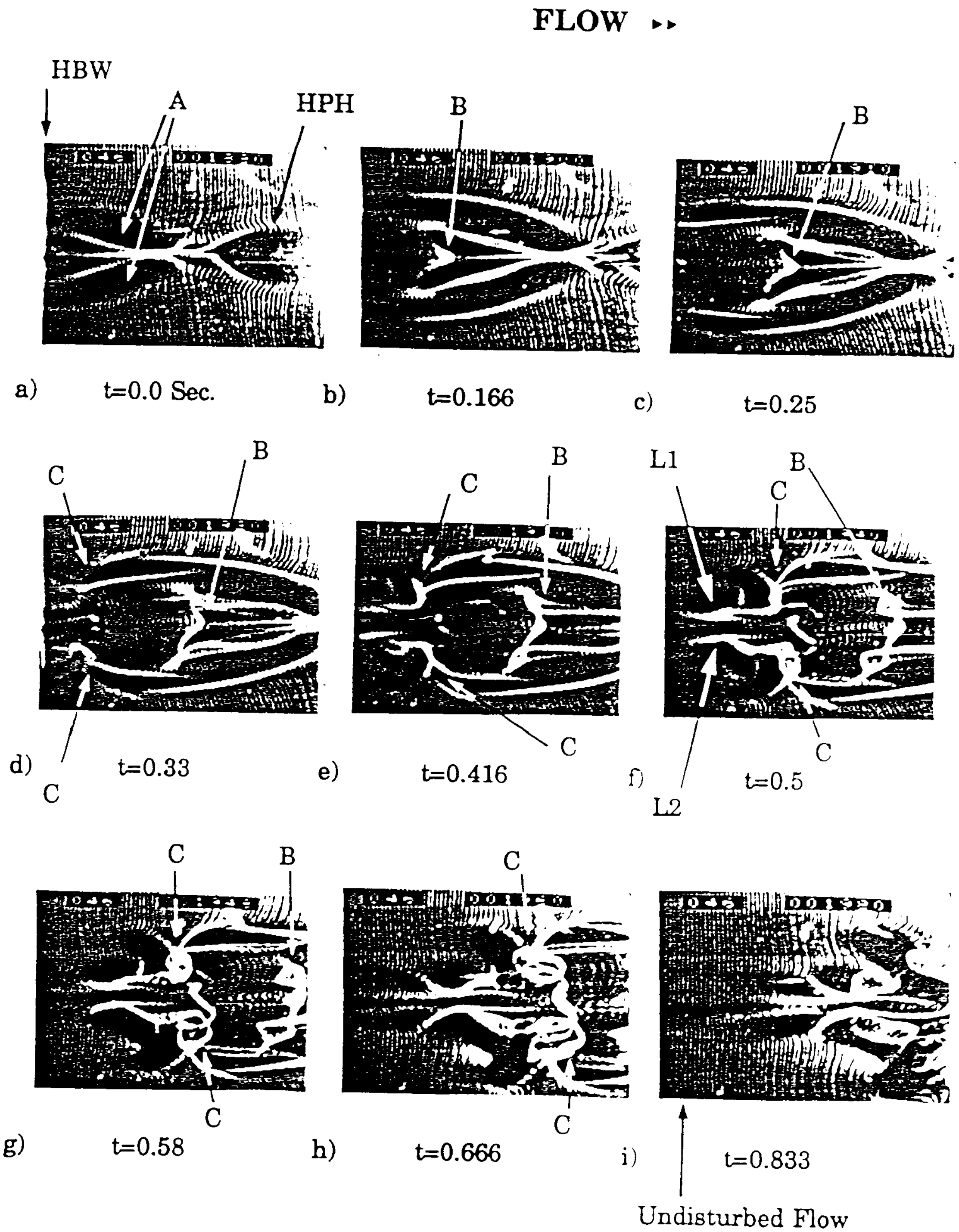
Topics :

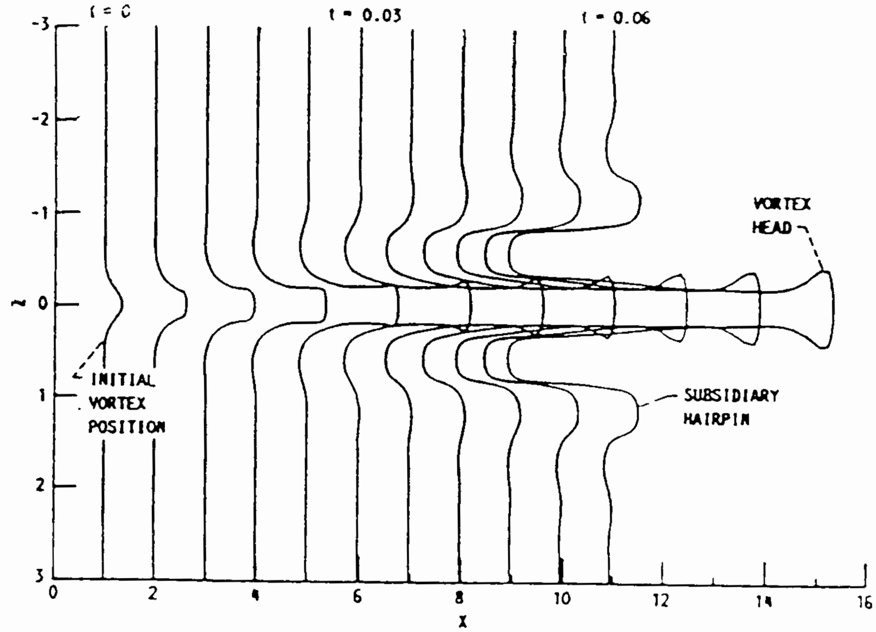
- Growth of a turbulent spot from a single hairpin vortex
    - ➡ generation by slot injection in laminar BL
    - ➡ evolution via vortex-surface interaction
- Development of hairpin-like vortices during transition in an end-wall junction flow.
    - ➡ transition in a strong pressure gradient environment



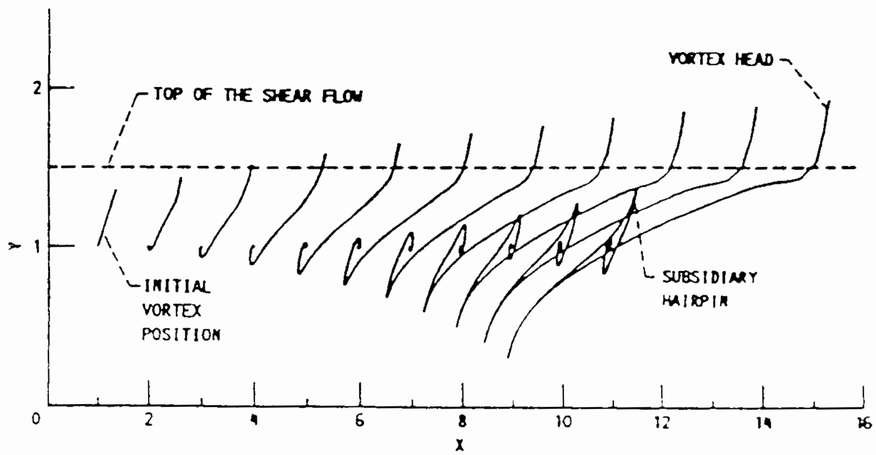
Schematic diagram of technique employed to visualize flow development associated with a single hairpin vortex



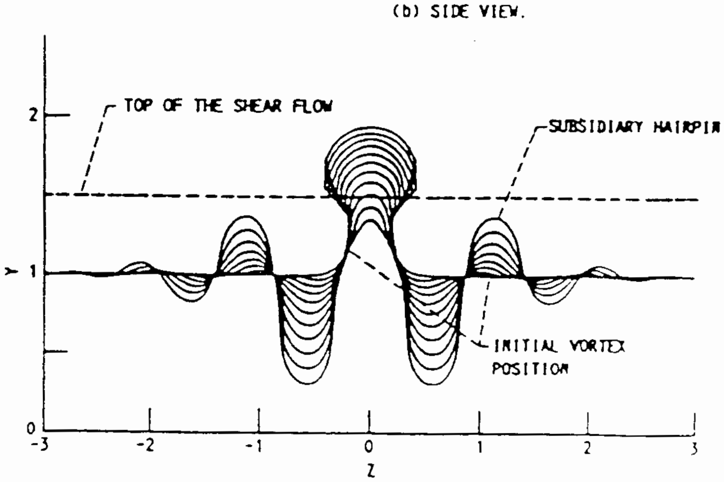
Plan-view hydrogen bubble wire visualization sequence illustrating the development of secondary vortices near the surface as a primary hairpin vortex passes a fixed streamwise location. HBW denotes the position of the hydrogen bubble wire, HPH is the location of head of primary vortex, A the location of the trailing legs of primary vortex, B the development of a secondary vortex behind head of primary, C the development of secondary vortices adjacent to the legs of the primary vortex, and L1,L2 the legs nearest the symmetry plane for the secondary vortices indicated by C.



(a) TOP VIEW.

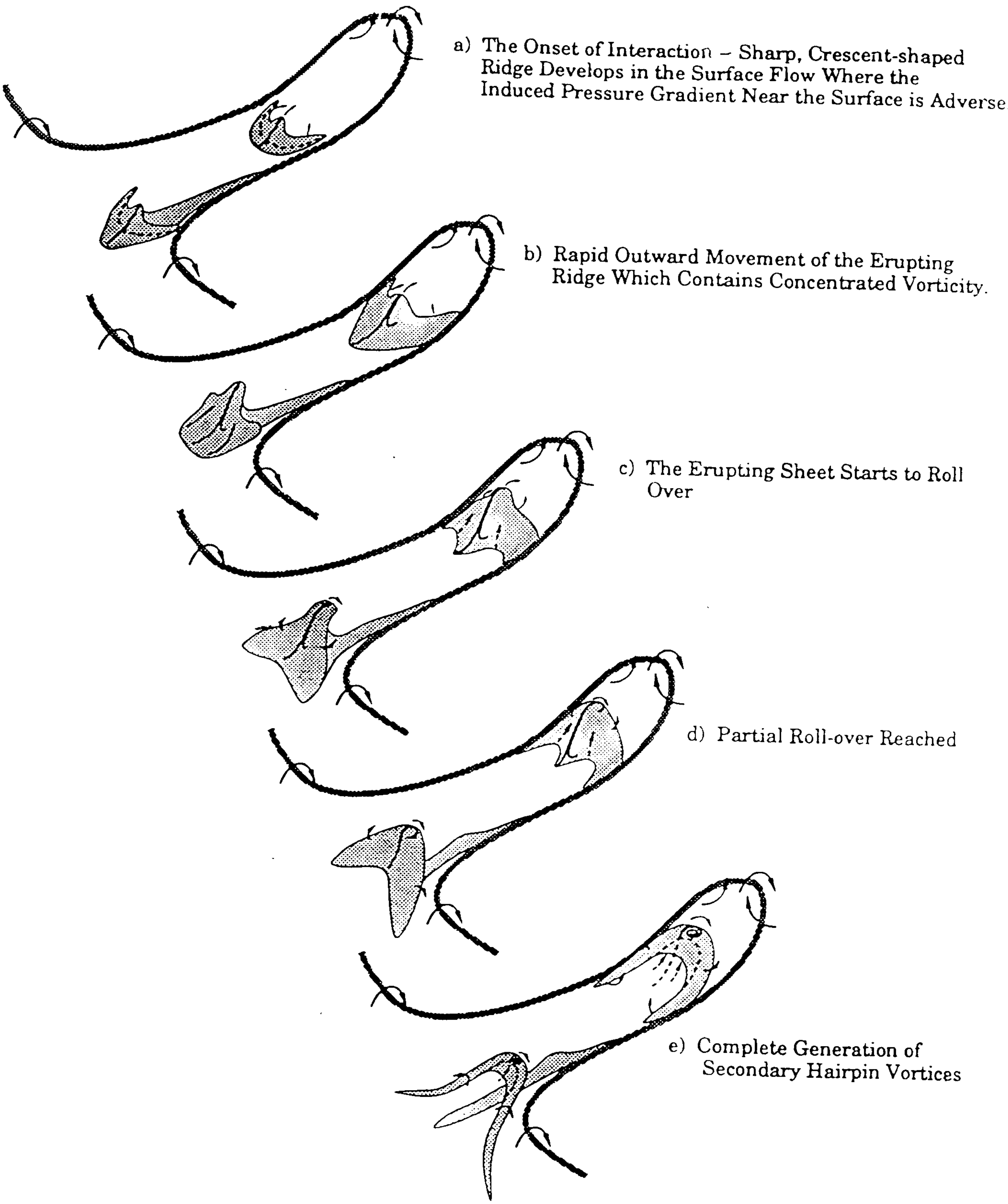


(b) SIDE VIEW.

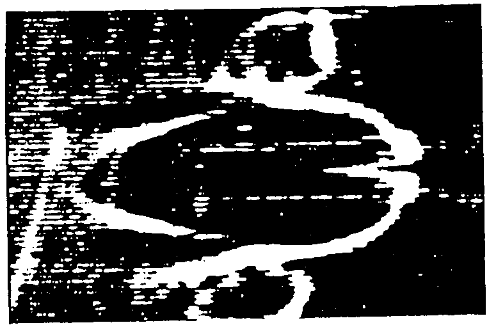


(c) END VIEW.

FIGURE 4. - TEMPORAL DEVELOPMENT FOR A HAIRPIN VORTEX IN A SHEAR FLOW; THE VORTEX POSITION IS PLOTTED EVERY 30 TIME STEPS (Δt = 0.0002).



The generation of secondary vortices via surface interaction for a symmetric hairpin vortex

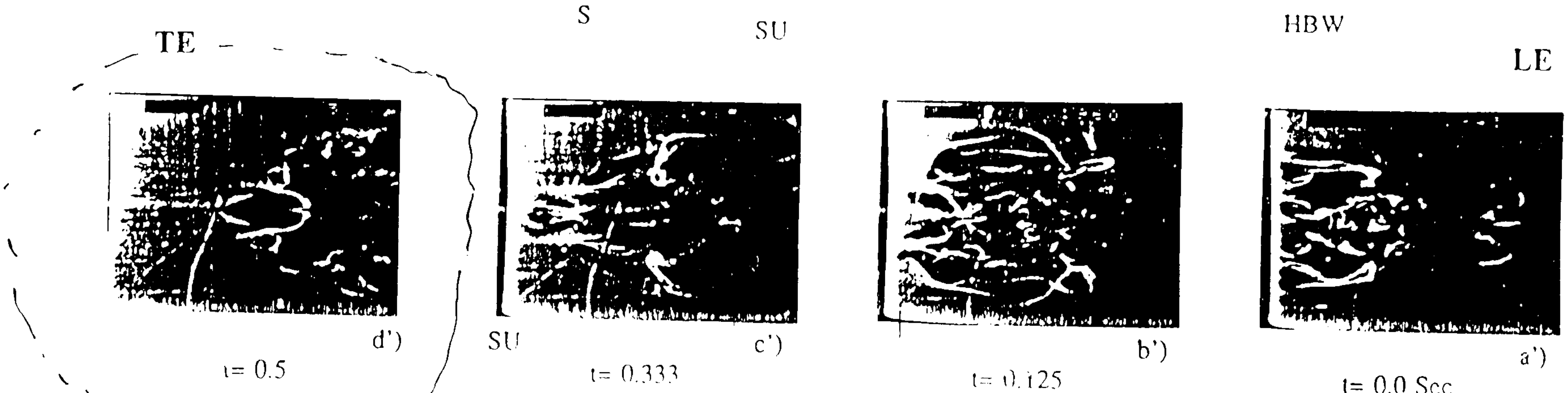


b') x=7.0 cm
y=0.25 cm

Turb. Spot (T.E.)

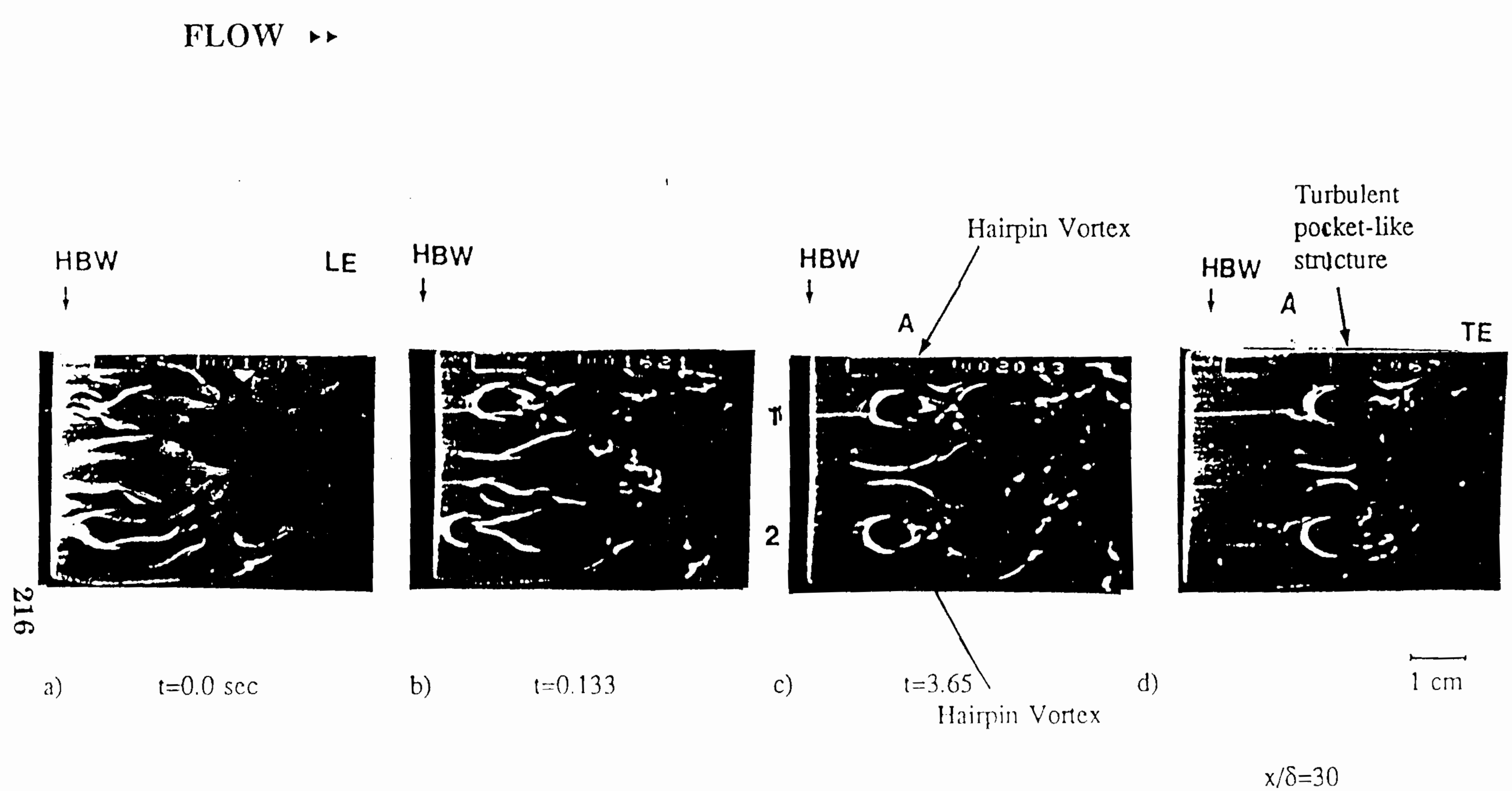
b) x=1.0 cm
y=0.39 cm

Single Hairpin Vortex

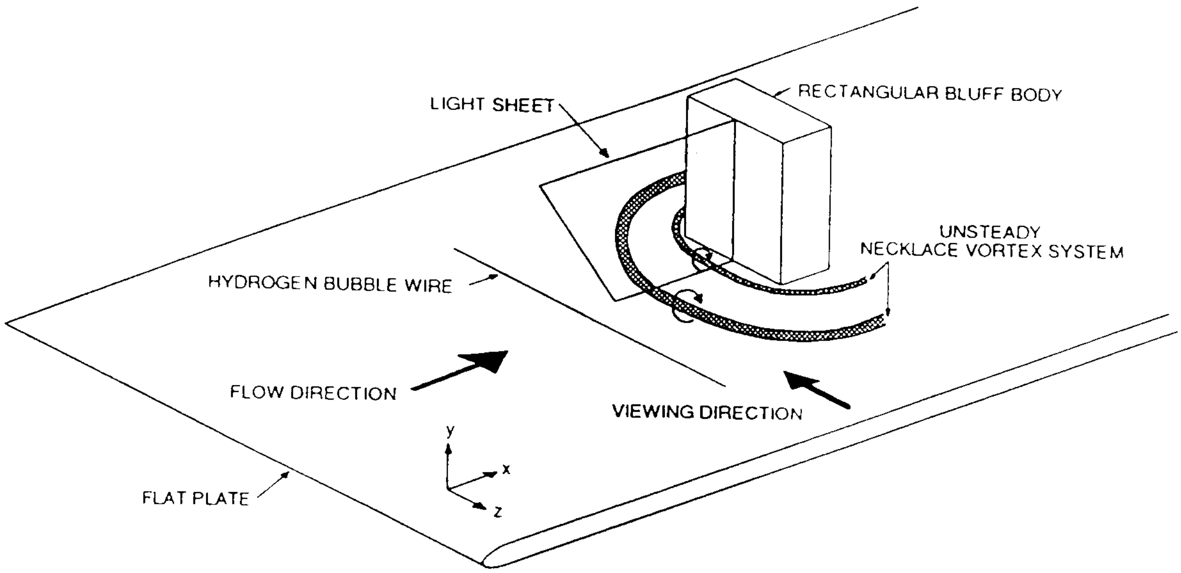


t= 0.5 t= 0.333 t= 0.125 t= 0.0 Sec.

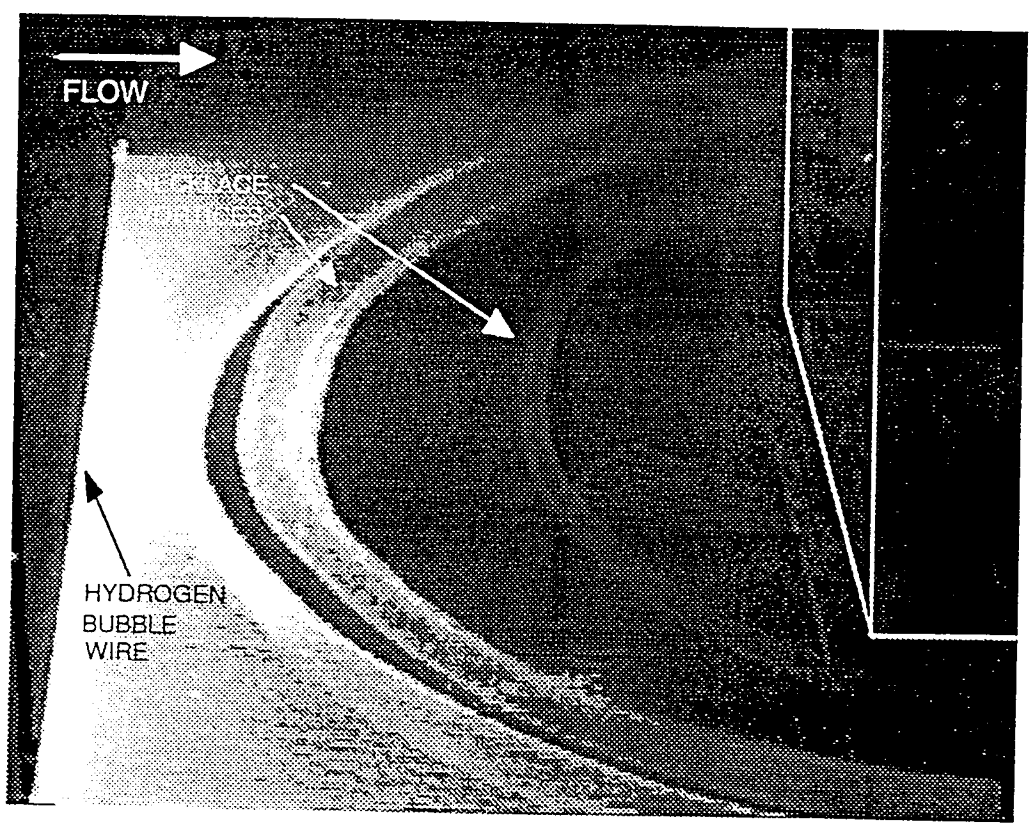
Effect of Reynolds number on the growth to a turbulent spot, as visualized by hydrogen bubbles. a) through d) $Re_{\delta 1}^{*}=440$, a') through d') $Re_{\delta 2}^{*}=530$.



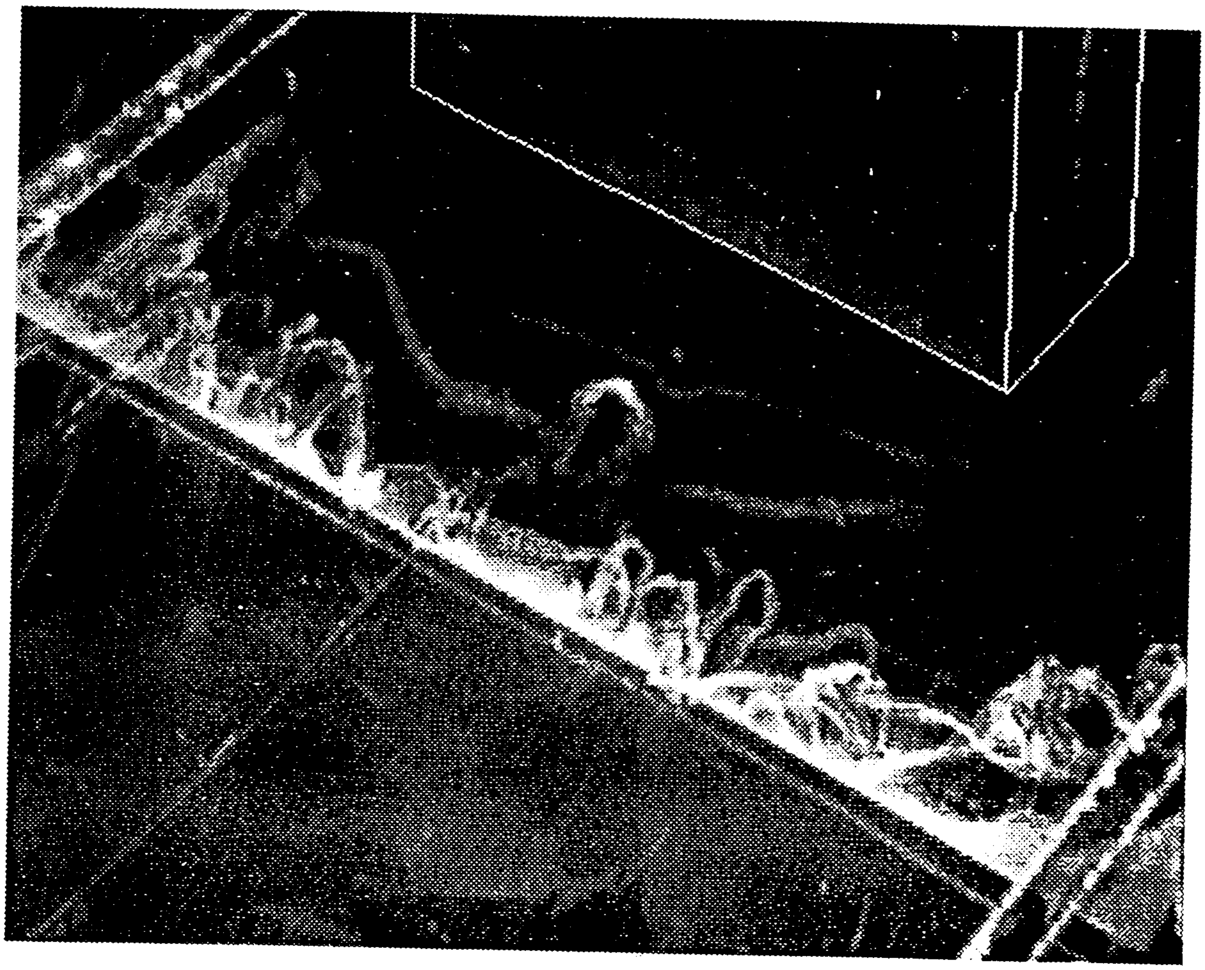
Plan-view sequence of hydrogen bubble visualization within a turbulent spot structure, illustrating the existence of hairpin vortices. $Re_{\delta}^{*}=440$, $Re_{Vw}=10.5$, $x_{wire}=30$ cm, $y_{wire}=0.635$ cm.



Schematic of experimental configuration



Hydrogen bubble visualization of the necklace vortex system formed at the junction of a rectangular bluff body and flat plate.



TRANSITIONAL