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Holographic Flow Visualization as a Tool for Studying Three-dimensional Coherent Structures and Instabilities

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***Abstract*:** Holography is capable of three-dimensional (3D) representation of spatial objects such as fluid interfaces and particle ensembles. Based on this, we adapt it into a 3D flow visualization tool called Holographic Flow Visualization (HFV). This technique provides a novel means of studying spatially and temporally evolving complex fluid flow structures marked by a disperse phase or interfaces of different fluids. This paper demonstrates that HFV is a straightforward technique, especially when the In-line Recording Off-axis Viewing (IROV) configuration is used. The technique can be applied either as a stand-alone experimental tool for studying scalar-based coherent structures, flow instabilities, interactions of different fluids driven by fluid dynamics, interfacial phenomena, or as a precursor to volumetric 3D velocity vector field measurement of complex transient flow dynamics. Experimental results in several complex fluid flows and flames demonstrate the effectiveness of HFV. Different methods are used to mark flow structures undergoing different instabilities: 1) a vortex ring grown out of a drop of polymer suspension falling in water, 2) cascade of a bag-shaped drop of milk in water, and 3) internal flow structures of a jet diffusion flame.

***Keywords*:** holographic flow visualization, holographic PIV, particle-laden flows, jet diffusion flame, flame-vortex interaction, vortex cascade, vortex ring instability, drop instability.

1. Introduction

Flow visualization has been employed as an experimental tool in fluid mechanics for decades (Merzkirch, 1980; Lauterborn and Vogel, 1984). Based on light scattering of smoke, fluorescence of dye, visualization of fluid density variation, image of hydrogen bubbles or other types of flow markers, flow visualization has been widely applied to observe flow patterns and fluid fields. Numerous examples can be given in which flow visualization has been extremely insightful (a good source book is provided by Van Dyke, 1982). It reveals important flow physics, guides intuition into complex phenomena, inspires formulation of theories, and provides valuable feedback for engineering designs. For example, the notion of coherent structures – organized structures underlying transitional and turbulent flows – was born as a result of flow visualization of the plane mixing layer (Brown and Roshko, 1971). The coherent structure approach is key to understanding flow mechanisms and offers an effective means of flow control (Hussain, 1986). Much of the early development in the coherent structure approach can be attributed to flow visualization (Fiedler, 1988), which was later complemented by quantitative flow-field descriptions such as phased-locked measurements using hot-wire anemometry (Zaman and Hussain, 1981; Tung and Kleis, 1996), Direct Numerical Simulation (DNS) (Metcalfe et al., 1987) and Particle Image Velocimetry (PIV) (Adrian 1986). Also noteworthy are the 3D reconstructions of coherent structures such as those of Lasheras ét al. (1988), Jiménez et al. (1985), and Agüí and Hesselink (1988).

Despite its enormous contributions in the past, flow visualization has been primarily limited to two-dimensional (2D) representations of three-dimensional phenomena. It normally functions in one of the following scenarios:

(¡) Flow structures seen within the depth of field of an imaging lens (or eyes), where the imaging process is 2D.
(™) A 2D slice of a flow structure illuminated by a light sheet.
(£) Integration of a 3D density field along the path of a laser beam.

In this sense, common visualization techniques based on photography, shadowgraphy, Schlieren, laser-induced fluorescence, laser-induced scattering (Rayleigh, Raman, Mie), interferometry and holographic interferometry (integration of a density field) are all 2D in nature. These techniques do not provide full 3D instantaneous visualization. Since most complex fluid flows are essentially 3D, many critical details of these flows require 3D visualization tools to capture. Although a flow field can be scanned using a light sheet, it is rather difficult to record details of the 3D structures when the flow is highly transient.

Holographic imaging is capable of instantaneous 3D representation of spatial objects including fluid interfaces and particle ensembles. It holds great promise as a 3D diagnostic tool – both qualitative and quantitative – for spatially and temporally evolving complex flow structures. Holography has been used for diagnosis of particles or aerosols in different types of flows and in combustion (Lee and Kim, 1986; Vikram, 1990). It has also been recently used in Holographic Particle Image Velocimetry (Holographic PIV or HPIV) to measure instantaneous full-field 3D velocity fields (Meng and Hussain, 1991; Barnhart et al., 1994; Meng and Hussain, 1995a, b; Pu et al., 1998). On the other hand, however, the power of holography as a scalar-based 3D flow-visualization tool has not yet been fully investigated.

This paper introduces a 3D flow-visualization method based on holographic imaging. Referred to as Holographic Flow Visualization (HFV), this method can instantaneously and three-dimensionally capture transient flow structures that are properly marked by a dense disperse phase. Since it allows time-resolved experimental study of detailed 3D topology of structures, HFV has great potential for providing insight into vortex dynamics, 3D instabilities, particulate flows and interfacial phenomena. In what follows we will discuss methods of recording the 3D holograms using relatively simple optical arrangements and methods of taking advantage of the three-dimensionality of holographic imaging to study the reconstructed flow structures.

2. Marking the Flow Structures

To be recorded by a hologram, the subject flow structure must scatter laser light elastically so that it produces an object wave that is coherent with a reference wave from the same laser. Fluids having different refractive indices can produce the desired elastic scattering on their interfaces. So can the disperse phase in a multiphase flow and tracer particles seeded in a single-phase flow. Ideally, the most faithful tracer for a continuous-phase flow is the fluid molecules, but elastic scattering from molecules (Rayleigh scattering) is generally too weak to be recorded on a hologram. On the other hand, particles of sizes comparable to or larger than the laser wavelength (which is usually a fraction of a micrometer) produce much more intense scattering called Mie scattering. A flow structure marked by a disperse phase (at high concentrations) is therefore suitable for holographic visualization.

We have investigated two scenarios where the flow structures are marked for light scattering in HFV: 1) flow structures formed and marked by milk or a dense polymer-sphere suspension, evolving in water and 2) flow structures of a jet traced by small solid particles, evolving in air, with or without the presence of a flame. In the first case, the visualized physical phenomena are results of hydrodynamic interaction of a particle-laden fluid (emulsion or dense polymer-sphere suspension) with water. Here the flow "marker" is the subject of study. In the second case, light-scattering particles are introduced artificially as tracers of the air flow. Here it is desirable to use small particles to minimize their inertia and gravity effects; yet the preferential dispersion dominated by coherent structures (Squires and Eaton, 1991) is actually helpful to mark the structure boundaries. In any case, HFV visualizes structures through markers, and care must always be exercised when interpreting the hydrodynamic significance of the visualization results. Depending on its properties, the flow marker itself may strongly influence the structure through density-sensitive instabilities and particle-flow interactions.

In the area of turbulence and vortex dynamics, although the use of scalars as a basis for *defining* coherent structures is debatable, *visualization* of scalar structures has provided and will continue to provide valuable insight into coherent structures. It should be noted however, that the dynamics of coherent structures based on a scalar field differs from that based on the flow vorticity field. Not only do the rates of diffusion of scalar and vorticity differ from one another when Schmidt number is non-unity, but scalar dynamics does not include vortex stretching, which is an important mechanism of vortex dynamics (Meng and Hussain, 1991). In the context of this paper, HFV implies visualization of scalar-based structures. Visualization of the vorticity-based structures is much more challenging and is possible only through high-spatial-resolution 3D velocimetry techniques such as Holographic PIV(HPIV), where particle displacements and hence velocities are measured (Meng and Hussain, 1995a, b; Pu et al., 1998). In fact, it is conceivable to build a holographic instrument that performs both HFV and HPIV, which was the motivation of this research (Estevadeordal et al., 1997a). This paper will only focus on HFV — the relatively simple method — and not on HPIV.

3. Holographic Flow Visualization Principle

Holography consists of two phases: 1) Recording, where the object wave (the laser light scattered off an object) is mixed with a coherent reference wave to produce interference fringes, which are recorded on the holographic plate, and 2) Reconstruction, where the object wave is reconstructed from the developed hologram, forming a real image and a virtual image on separate sides of the hologram. This process is illustrated in Fig.1(a), which (without loss of generality) shows an in-line configuration using the same collimated beam to serve as the reference wave and to illuminate the object. The two phases can share the same laser source. For fluid flows, however, the recording laser generally should be pulsed to freeze transient flow motions, while a continuous-wave (cw) laser may be more convenient for reconstruction and observation. The recording laser shown in Fig. 1(a) is a Nd:YAG laser with pulse duration of a few nanoseconds. The reconstructed-image size l' compared with the actual-object size l scales with $\lambda_2 / n\lambda_1$:

$$l'/ l = \lambda_2 / n \lambda_1$$

where λ_1 and λ_2 are the wavelengths of recording and reconstruction lasers, respectively, and n is the refractive index of the ambient fluid of the flow structure to be imaged. For structures in water, for example, n=1.33. A holographic movie is produced by a series of laser pulses, each producing a single hologram on a film. The movie allows studying the dynamics of the flow structures.

Holographic imaging of flow structures is made possible through dense particle seeding of the structures. A three-dimensional image of a continuous 3D surface of structures, marked by a collection of particles, is sought rather than individual particle images. HFV therefore operates at much higher particle seeding densities than Holographic PIV. A major obstacle in the HPIV technique, namely speckle noise resulting from superposition of scattered light waves from different particles, is not a problem in HFV. Instead such speckle is used constructively to visualize the flow structure. Typically, particles will not be uniformly distributed in the flow (e.g., less particles are present in vortex cores), and thus speckle will not be uniform over the entire flow region. This actually helps the visualization by providing different tones.

For imaging non-transparent spatial objects, off-axis holography configuration has been widely used. Since HFV is used to image extended flow structures marked by densely seeded particles, off-axis holography is appropriate. It employs a separate reference beam to interfere with the object beam. However, another much simpler, novel configuration, namely the In-line Recording Off-axis Viewing (IROV) method, can be used for HFV. This method was originally developed as a configuration for Holographic PIV (Meng and Hussain, 1995a, b). It has the distinction of using only one laser beam for hologram recording. Since no separate reference beam is needed, a laser with a short coherence length (~ centimeters) and low pulse energy (~ 10 mJ) is sufficient. Any laser that is adequate for regular planar PIV can be used for 3D HFV, whereby only a single laser rather than dual lasers is needed since double exposure is not required. A copper-vapor laser could even be used for HFV with the advantage of high pulse repetition rate (tens of kHz) for high-speed holographic movie (Meng and Hussain, 1991). The optical arrangement of IROV is rather simple as illustrated in Fig. 1(a). A detailed analysis of the IROV technique is given by Meng and Hussain (1995a). To image flow fields with temperature gradients such as those in flames or combustion chambers, IROV holography is not suitable and one must resort to off-axis holography. There, a laser with a much longer coherence length (tens of centimeters) and higher pulse energy (>100 mJ) is required for off-axis hologram recording. Often, the coherence length of a pulsed Nd:YAG laser is achieved by providing the laser with injection seeding.

The methods for observing the reconstructed 3D flow structure are very versatile. A hologram reconstructs, in 3D space, a real image field and a virtual image field located on either side of the hologram. Either image field

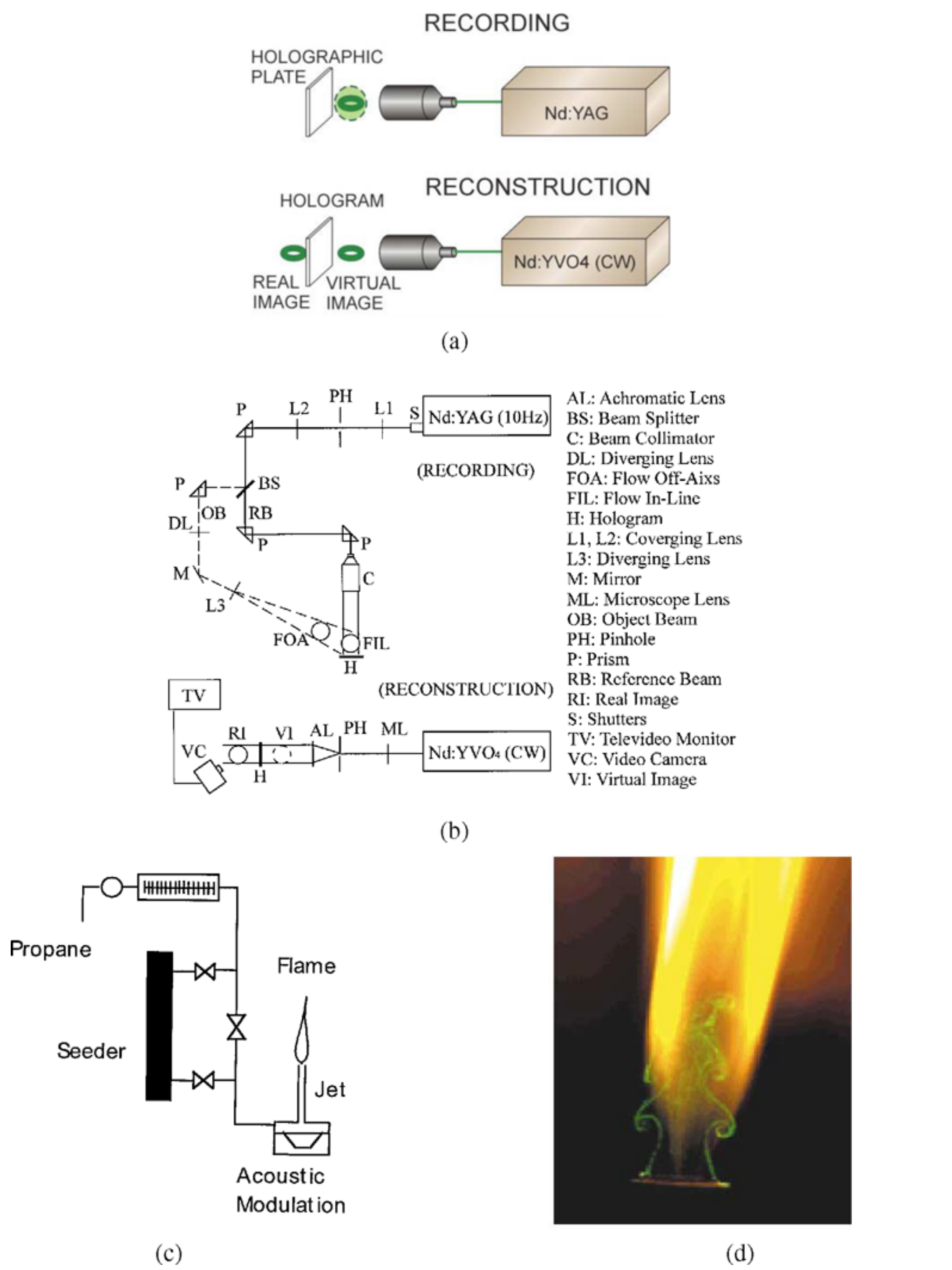

Fig. 1. Experimental setups:

(a) Holographic recording and reconstruction principle, illustrated using the IROV scheme implemented in this work.

(b) HFV experiment layout. The recording setup can be switched between IROV mode and off-axis mode. In IROV mode, flow test section is placed at FIL (Flow In-line), RB serves as both reference beam and object illumination beam, and OB is blocked. In off-axis mode, flow test section is placed at FOA (Flow Off-Axis), OB is used to illuminated the object field, and RB remains as reference beam. The reconstruction setup is the same for both modes.

(c) Schematic of vortex-flame system used for HFV experiments of flames.

(d) A typical vortex-flame picture (both flame and vortex structures) generated from the forced jet, illustrated two-dimensionally using a laser sheet.

can be used for visualization. With the IROV method, the direction of observation must be at an angle to the hologram axis to avoid the directly transmitted illumination beam and the twin image. The three dimensionality of the reconstructed flow structure can be explored by changing the viewing angle and focusing at different distances on the 3D image. Different flow scales and details can be analyzed by changing the magnification.

4. Visualization Experiments

In the present study, the IROV and off-axis techniques are used for single-exposure holographic flow visualization for a drop of fluid falling into water and a jet-diffusion flame in air. The results are used to demonstrate the effectiveness of HFV in flows with three types of seeding undergoing different instabilities: 1) a vortex ring generated by a falling drop of polymer suspension in water, 2) cascade of a bag-shaped drop of milk in water, and 3) internal flow structures of a jet diffusion flame seeded with $TiCl_4$ particles premixed with water (which produce particles TiO_2 particles).

A holographic imaging system was set up using a 10Hz pulsed Quanta-Ray Nd:YAG laser (Spectra-Physics) at a wavelength of 532 nm and pulse duration of 10 ns, as shown schematically in Fig. 1(b). To make the recording of off-axis holograms easier, the laser was injection-seeded to provide a coherence length greater than 1 m. This laser was joined with a second laser to produce double exposures needed for Holographic PIV. But for the purpose of HFV the second laser was not used and hence not shown in the figure. The laser beam was split into two by a beamsplitter BS: the reference beam (RB) and the object beam (OB), where RB was collimated and projected to the hologram perpendicularly. When IROV holograms were recorded, only RB was used, both as reference beam and object illumination beam. When off-axis holograms were recorded, OB was used to illuminate the object field, while RB remains as reference beam. Hence the recording setup can be switched between the IROV mode (with the flow test section being placed at FIL) and the off-axis mode (with the flow test section being placed at FOA). For reconstruction, we used a cw laser – Millennia Nd:YVO_4 laser (Spectra-Physics) to produce a collimated beam like RB with the same wavelength, 532 nm. The setup for reconstruction is the same for both IROV and off-axis modes.

Initial tests of the technique were conducted in water. Holographic visualization was tested with drops of milk and aqueous suspensions of polymer microspheres (with specific gravity of 1.05 and diameter of 14.5 μm) injected into a water tank ($7.62\times10.16\times27.94$ cm^3). The drops, with a typical size of 3.5 mm, were manually injected into the water with a drop counter and were allowed to fall freely (gravitational momentum) from a distance of 1 cm above the water surface.

The feasibility of holography for flame studies was explored in a combusting cylindrical jet forced with acoustic modulation (through a chamber with a speaker to perturb the propane line at a known frequency), as shown schematically in Fig. 1(c). The purpose of the acoustic excitation was to provide a reproducible vortex-flame system (Chen and Roquemore, 1986). The driving frequency was chosen to be a multiple of the Nd:YAG laser frequency, 10 Hz, to provide a strobe effect. A typical vortex-flame system (both flame and vortex structures) generated from the forced jet is shown in Fig. 1(d) using standard 2D laser-sheet visualization. The dense pre-formed seeds are submicron-size TiO_2 particles produced by premixing $TiCl_4$ particles with water. This seeding method produces a dense scalar field appropriate for the visualization of the inner coherent structures in the jet diffusion flame. Preliminary tests of HFV in flames revealed the effects of distortion of the reference beam by temperature and density gradients, and of the need to increase particle seeding density.

The flow structure images from HFV can be observed with the naked eye in most cases. The images are the 3D replicas of the real flow at the time of exposure and can be viewed from different sides and angles (top and bottom, inside and outside, etc.). To demonstrate this feature, photographs were taken with a video camera from different angles, using different magnifications, and focused at different parts of the 3D images.

5. Results and Discussion

It is our common experience that the best way to observe a 3D image is to view it with naked eye with the freedom of changing perspective. Since it is not convenient to allow such direct observation in this communication, we show two to three photographs for each 3D image reconstructed from our holograms so that the reader can get a glimpse of the three-dimensionality of the holographic images. It must be clarified that a holographic image is three-dimensional; its depth of focus is the depth of the entire 3D object. A photograph (2D) taken from a reconstructed 3D holographic image, however, does have a finite depth of focus determined by the camera lens setting. The photographs shown in this paper will appear like regular photographs of some 3D objects—only that these are not real objects but the holographic reconstruction of them. Like frozen sculptures, they no longer move or change with time. We sometimes deliberately choose a small depth of focus on the camera lens to illustrate the freedom offered by the hologram for us (and for our cameras) to focus on different details of the reconstructed 3D flow structures.

5.1 HFV of Drops of Two-phase Fluid into Water

The HFV instabilities of a drop of two-phase fluid falling into water will be discussed first. Figures 2-4 show photographs of reconstructed images from IROV holograms. Figure 2 shows different stages of a drop of polymer-sphere suspension falling in water, while the drops falling in water shown in Figs. 3 and 4 are made of milk. Evidently, the drop of polymer-sphere suspension (Fig. 2) initially assumes a donut shape, while the drop of milk (Fig. 3) takes on a bag shape. Both leave behind a wake and a surface wave. In each figure, different stages of the flow evolution are demonstrated including the initial drop-water interaction, instability and subsequent cascading. Each group of photographs demonstrates different aspects of the same 3D holographic image viewed from different angles or focused on different regions.

It is evident from Fig. 2 that the polymer-suspension drop behaves like an impulsive jet flow that is unstable and evolves into a vortex ring. The holographic reconstruction allows different views of the initial ring as shown in Figs. 2(a)-(c). Holograms recorded after the ring formation show that the flow undergoes more complex evolution characterized by a cascade process. The ring is susceptible to 3D instabilities and breaks down into smaller droplets, which now behave as mini-jets and generate smaller rings or "ringlets". This breakdown is shown from three different angles in Figs. 2(d)-(f). The cascade develops on smaller and smaller scales, producing many generations until diffusion processes dominate the fine-scale mixing of the suspension and water. Details of cascade on a smaller scale are shown in the three photographs of Figs. 2(g)-(i), which are produced from one hologram.

Figure 3, showing a milk drop in water, reveals that a drop falling into a fluid can be susceptible to other instabilities such as the "bag" instability (Craig, 1984; Pilch and Erdman, 1987), whereby a nearly spherical drop changes its shape into a surface resembling a bag. The bag develops a concave or convex shape depending on its Weber number. Two views of the bag are shown in Figs. 3(a), (b). This bag subsequently breaks up into droplets on the rim because of secondary instabilities. The resulting flow is shown in Figs. 3(c)-(e) from different perspectives. The bag-shaped instability occurs more often for milk drops than for the polymer-sphere suspension drops (Estevadeordal et al., 1997b).

It is observed that characteristics of the drop instability and cascade depend on factors such as the initial momentum of the falling drop, the viscosity and density of the fluid of the drop, the surface tension and capillary effects. These factors determine not only the initial shape of the drop, but also differences between generations. For example, as the droplets become smaller, surface tension becomes more important, and hence newer breakdowns assume different characteristics.

It can be seen from Figs. 2 and 3 that, among other common features both drops develop a localized defect that appears to be a preferred site for initiation of the cascade. A symmetrical breakdown (such as a perfect "crown" around the rim) is expected to occur only in ideal situations; in practice, some asymmetries will develop as a result of upstream perturbations (e.g., defect in the injector nozzle). It is noteworthy that each droplet has a trailing "wakelet" shared by the neighboring droplets. These "wakelets" remain connected to each other, giving the cascade a 3D arcade structure that is readily observed in the holographic visualizations. Some viewing angles of the reconstructed image (not shown here) allow observation of the reflection of the drop on the water surface.

Figure 4 shows holographic images of a milk drop injected with high momentum into water at an initial stage (Fig. 4(a)) and its downstream breakdown (Figs. 4(b), (c)). Although the initial stage (Fig. 4(a)) has footprint of a ring or bag shape, the drop quickly evolves into turbulent-like states (Figs. 4(b), (c)). This particular rapid flow shows different labyrinthic structures and chaotic connections not seen in the slower cascades in Fig. 3. This demonstrates the power of the HFV technique's ability to freeze the instantaneous 3D flow features and allow detailed analysis of them.

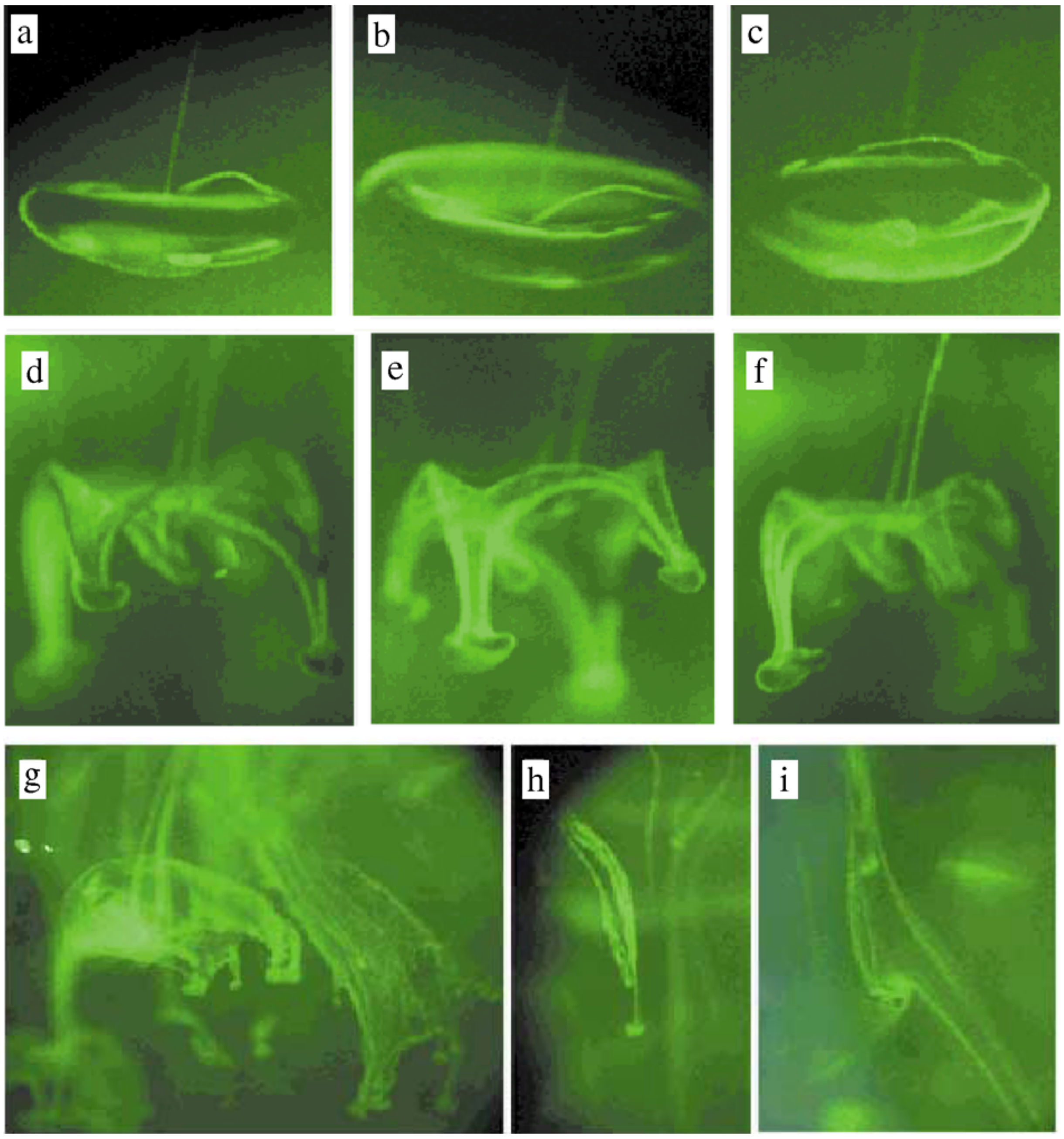

Fig. 2. Holographic images of polymer-suspension drop falling in water undergoing vortex-ring instability, photographed from 3D images reconstructed from IROV holograms:

(a)-(c) Initial vortex ring evolved from the falling drop, photographed from different angles with respect to the normal of hologram. All are 20° horizontally; a) 0° vertically; b) 20° vertically; c) –20° vertically.

(d)-(f) Breakdown of the ring into smaller droplets forming a crown, shown from three different angles with respect to the normal of hologram. All are 0° vertically; d) 20° horizontally; e) –20° horizontally; f) –10° horizontally.

(g-i)s Details of further cascade on a smaller scale, photographed from one hologram from different angles and focused at various distances.

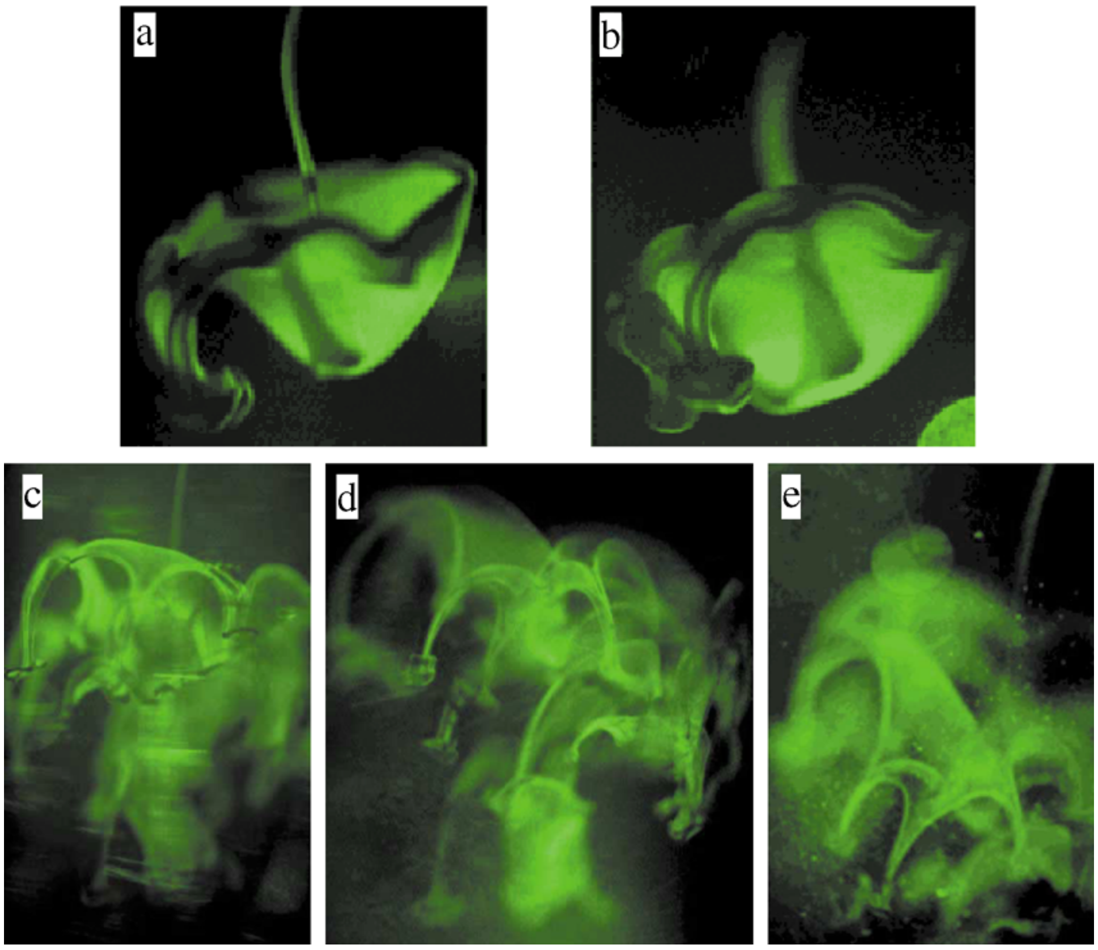

Fig. 3. Holographic images of a milk drop falling in water undergoing bag instability, photographed from 3D images reconstructed from IROV holograms:

(a),(b) Initial bag evolved from the drop, photographed from different angles with respect to the normal of hologram. Both are 20° horizontally; a) 20° vertically; b) 0° vertically.

(c)-(e) Downstream cascade of the bag, photographed from different angles with respect to the normal of hologram and focused at various distances. c) –20° horizontally and 0° vertically, d) 20° horizontally and 0° vertically, e) 20 horizontally and 40° vertically.

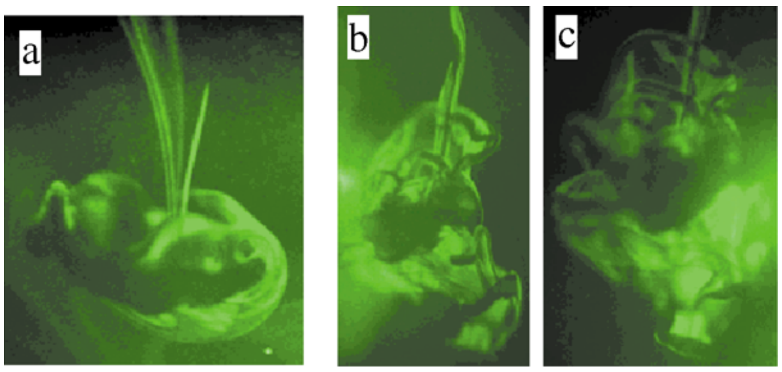

Fig. 4. Holographic images of a turbulent milk drop injected with high momentum into water, photographed from 3D images reconstructed from IROV holograms:

(a) Initial structure of the drop.

(b),(c) Downstream breakdown of the drop, photographed from different horizontal angles with respect to the normal of hologram. b) 20°; c) –20°.

5.2. HFV of Jet Diffusion Flames

3D holographic visualization of propane jet diffusion flames is discussed next. A typical vortex-flame system is shown in Fig. 1(d) using standard 2D laser-sheet visualization, which shows only one plane (sheet). The jet coherent structures are vortex rings generated through shear-layer instability at the nozzle exit. They undergo various hydrodynamic instabilities as they are convected downstream. The flow evolution is changed by the presence of the flame, whose behavior is also affected by the flow.

Holographic visualization relies on light scattering from markers, and thus the structures captured by the hologram are those marked by the collection of particles. The existence of temperature gradients in the presence of flame brings about the so called thermophoresis forces: forces that push particles away from the flame front (Song et al., 1993). Hence, the flame front itself often cannot be recorded by the hologram for lack of particles. However, flow structures can be traced by particles reasonably well even in the presence of flame, and flame-vortex interactions are readily observed. In high temperature regions, we found that we had to increase the particle seeding density.

The main challenge for HFV in presence of flames is the strong density/temperature gradients in the flow field. For in-line recording, the reference beam, which is also the illumination beam, passes through the temperature and density gradients of the flame. These gradients destroy the reference beam wavefront. As a result, flame holograms obtained with IROV contains a large amount of speckle noise resulting from the reference beam destruction by the flame. In this case the off-axis configuration should be used with the reference beam separate from the illumination beam.

Three different jet-diffusion flames were studied using off-axis holography based HFV. The 3D holographic reconstruction of the flow structures is shown in Figs. 5(a)-(c). Each pair of pictures was photographed by focusing at two different distances and from two slightly different angles. The first two cases correspond to forced jets (under different conditions) and the third one, an unforced turbulent jet. The maximum allowed viewing angle from the holographic image, based on this off-axis setup, was not as wide as that based on the IROV configuration. This is because the object was placed farther away from the hologram. However, characteristics of 3D structures are obvious from the pictures. Toroidal 3D structures are clearly visible in Fig. 5(a) and Fig. 5(b), where the vortex rings are evidently connected in contrast to planar flow visualization where each ring is only represented by a cross-section (Fig.1 (d)).

An interesting phenomenon was observed from holographic visualization of case (c). Notice from Fig. 5(c) that after the jet exit (visible from the pictures), not many structures are present, but after about one jet diameter down stream, a vortex ring with 'bulges' or 'protuberances' can be seen. About five bulges (known in the jet community as 'lobes') are counted, consistent with prediction by Widnall instability (Widnall et al., 1974). These bulges grow in amplitude, generate streamwise vortices, and eventually undergo transition to turbulence. On the other hand, as the experiment was conducted, we clearly observed that the flame was not located at the jet exit, but was lifted up by 1 jet diameter. Therefore, we postulate that the flame was attached to the vortex ring that was undergoing the first instability. This postulation was confirmed with repeated experiments. Most of the lifted flames in this experiment had the common feature of being attached to the first vortex instability, usually with five lobes, which further generated five flamelets.

6. Conclusions and Discussions

Holographic Flow Visualization (HFV) techniques have been investigated as a unique 3D visualization tool for flow structures that are marked by densely seeded, light scattering particles. Preliminary experiments were conducted to study the feasibility of using this technique in the diagnosis of coherent structures, flow instabilities, flames, and hydrodynamic interactions of different fluids. Three-dimensional visualization was accomplished using IROV and off-axis holographic configurations. In all cases HFV results yielded good agreement with the expected flow and flame characteristics. The IROV configuration has simpler optical geometry. However, when the flow field includes significant density and/or temperature gradients (such as in flames), the off-axis configuration is preferred. It has been demonstrated that holographic imaging, which has the capability of instantaneous 3D representation of spatial objects including fluid interfaces and particle ensembles, holds great promise as a 3D diagnostic tool – both qualitative and quantitative – for spatially and temporally evolving complex fluid flow structures.

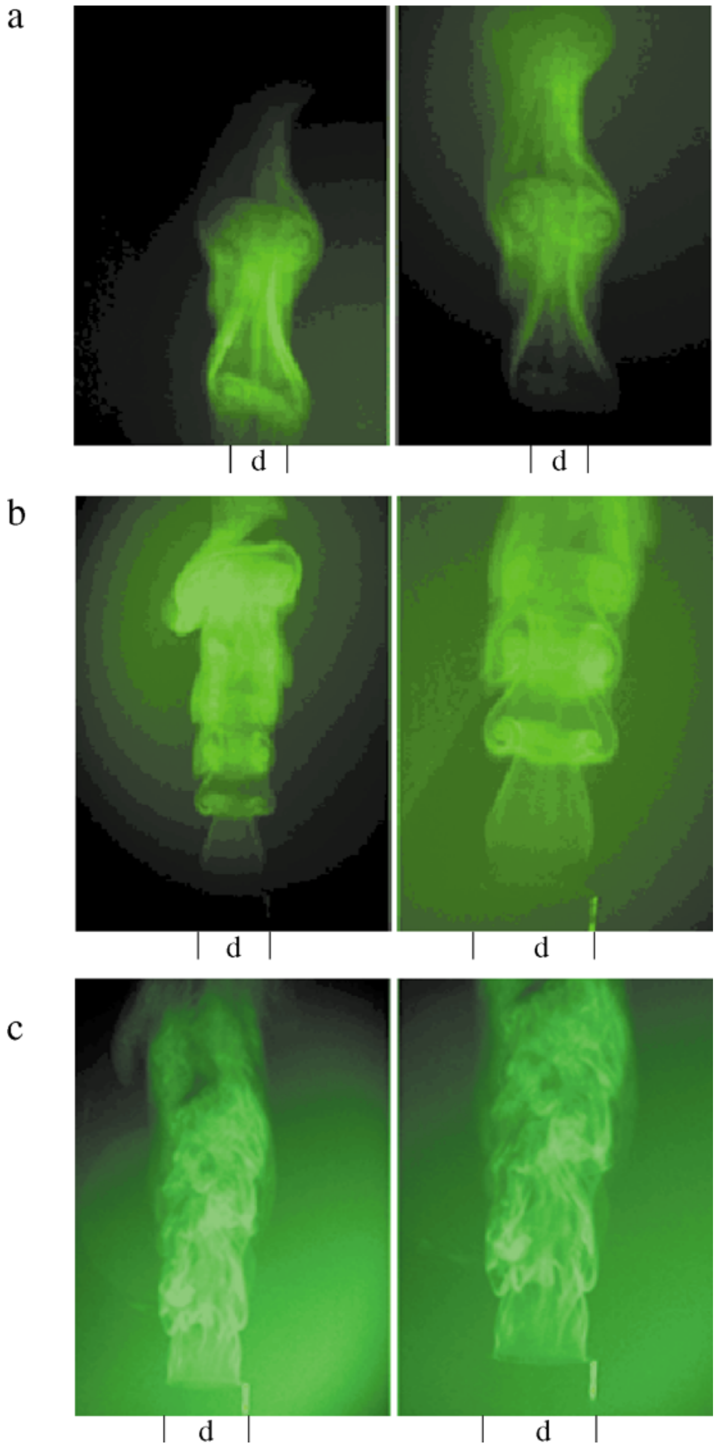

Fig. 5. Holographic images of three vortex-flame systems, photographed from 3D images reconstructed from off-axis holograms. The flame is not visible from these images. Nozzle location and diameter (*d* =1 cm) are marked as reference:

(a) A forced jet, photographed from two horizontal angles with respect to the normal of hologram (Left: –5°, Right: 5°).

(b) A forced jet, photographed using two different magnifications. Toroidal 3D structures are clearly visible.

(c) An unforced forced jet, photographed using two different magnifications. About 1 jet diameter down stream, a vortex ring with 'bulges' or 'protuberances' can be seen. It was found that the flame was lifted and attached to this unstable vortex ring.

The limitations of the HFV technique include the need for a disperse phase (particles) or interfaces of fluids with different refractive indices. The reason as already discussed, is that in order to produce a hologram of the flow structure, elastic light scattering on flow markers needs to be produced to interfere with the reference laser beam. Like in PIV and HPIV, the introduction of seeds into the flow may not always be desirable or possible, especially because the seeding density required for HFV is generally higher than those for PIV and HPIV. This could prevent the HFV technique from being applied to some flow problems. Two other issues we would like to address are related to the limitation of the current HFV experiments. First, we did not perform quantitative analysis of the 3D images. This can be done with a CCD camera, a traverse, and a computer data acquisition system. Since the 3D holographic images are "frozen" during reconstruction, they are ready to be scanned by a CCD camera and input into a computer. Second, we did not perform time-resolved study of the flow structures. Again, this can be done in a more sophisticated study. Based on a continuously pulsing laser (like the 10Hz pulsed YAG laser used in this study or a chopped cw laser), temporal HFV requires sequential recording of a series of holograms. They can be implemented by a roll of holographic film, multiple holographic plates, or multiplexed onto one hologram. The current investigation has shown the feasibility and application potential of the holographic flow visualization technique, and its capabilities should further expand to include quantitative and time-resolved analyses.

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