SAND2016-2601C

High-Speed (20 kHz) Digital In-line Holography (DIH) to Quantify the Impact of a Viscous Drop on a Thin Film

Daniel R. Guildenbecher[*,1] and Paul E. Sojka[2]

[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*
[2]*Purdue University School of Mechanical Engineering, West Lafayette, Indiana 47907, USA*
[*]*Corresponding author: drguild@sandia.gov*

Abstract: Digital in-line holography (DIH) quantifies the fragments formed when a drop impacts a thin film. High-speed recording allows for quantification of transient dynamics. For the viscous liquids investigated here, a multimodal size distribution is observed.
OCIS codes: (090.1995) Digital holography; (100.6890) Three-dimensional image processing; (120.0120) Instrumentation, measurement, and metrology.

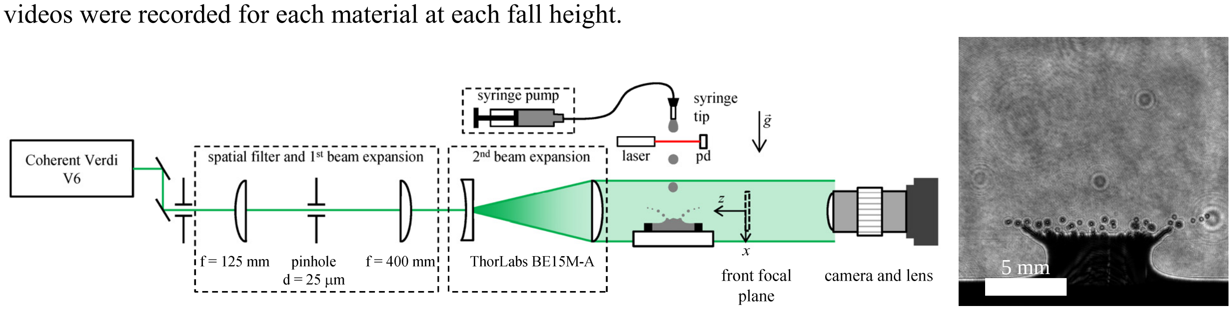
1. Introduction

The impact of drops on liquid surfaces has been widely studied with recent reviews provided by [1-3]. Despite the large body of work, limited measurements of secondary fragment properties (size, velocity, mass fraction) have been performed [4-7]. This is likely due to the inherent challenges in the measurement of micron sizes particles in transient, multiphase environments. For these applications, we have recently proposed a high-speed (20 kHz) digital in-line holography (DIH) methodology [7]. Particular advantages of this technique includes (1) measurement of all particles within a three-dimensional (3D) measurement volume enabling rapid quantification of flow statistics, (2) ability to accurately track particles over time enabling quantification of fragment temporal properties (trajectory, velocity, and formation time), and (3) accurate measurement of size-velocity correlations enabling quantification of mass flow rates. In [7] these techniques were applied to investigate the impact of single water drops on thin films of water. As discussed in [8, 9], it is well known that increased liquid viscosity can dramatically alter the observed breakup phenomena, and in this work the high-speed DIH methodology is applied to quantify viscous effects.

2. Experimental configuration

The experimental configuration is similar to our previous work [7] and is shown in Fig. 1(a). The output of a CW laser at 532 nm is spatially filtered and telescopically expanded before propagating through the splash created by the impact a liquid drop on a thin film of liquid. The resulting diffraction patterns are imaged through a long-distance microscope (Infinity K2/Distamax with CF1 objective) onto a high-speed CMOS sensor (Photron SA-Z monochrome camera, 1024 × 1024 pixels, 20 µm pixel pitch, 12-bit ADC depth). Fig. 1(b) shows one example image from a 20 kHz DIH video recording.

To investigate viscous effects, 6 different liquid mixtures were investigated, with the measured material properties given in Table 1. Surface tension, σ, was quantified with the Du Noüy ring method. Viscosity, ν, was measured with u-tube viscometers. Mass fraction and density, ρ, were determined from the measured mixture volumes along with the known single component densities. To vary the impact velocity, the syringe tip shown in Fig. 1(a) was positioned at three separate fall heights (720, 1000, and 1500 mm). In all cases, the liquid film thickness, h, was equal to 2.35 mm. Initial drop diameters, d_0, were between 1.8 to 2.6 mm giving a non-dimensional film thickness, $\delta = h/d_0$ between 0.9 to 1.3. Finally, to quantify experimental variability, forty high-speed DIH videos were recorded for each material at each fall height.



(a) (b)

Fig. 1 (a) Experimental configuration for kHz rate DIH measurement of drop impact, and (b) an example hologram.

3. Data processing

Each high-speed DIH video was processed in the manner briefly described here and described in detailed in [7]. First, each video frame was processed to measure the 3D position and in-plane size of all fragments within the field of view.

Table 1. Liquid material properties

mass fraction (%)			surface tension,	viscosity, ν	density, ρ
H_2O	methanol	glycerin	σ [mN/m]	[cSt]	[kg/m3]
88	--	12	67.5 ± 0.7	1.34 ± 0.01	1020
72	--	28	62.4 ± 0.7	2.18 ± 0.01	1070
--	85	15	26.6 ± 0.4	1.54 ± 0.26	840
--	67	33	29.0 ± 0.2	2.94 ± 0.02	930
26	18	56	44.4 ± 0.1	2.74± 0.25	990
100	--	--	75.8 ± 0.1	1.0 (assumed)	998

Next, frame-to-frame matching was used to find an initial approximation of the 3D particle trajectories. Finally, a regression-based multiframe tracking algorithm (RMT) was used to link together similar trajectories in an attempt to track each particle along the entirety of its trajectory. To address the uncertainty caused by the depth of focus problem [10], trajectories were fit to smooth models (quadratic in *x* and *y* and linear in *z*).

4. Results and discussion

Fig. 2 shows an example DIH video after processing in the manner described. Here τ is the non-dimensional time given by $\tau = (t-t_0)v_0/d_0$ where t is the dimensional time, t_0 is the impact time, v_0 is the impact velocity, and d_0 is diameter of the initial drop. These images reveal that the kHz DIH method is able to accurately quantify a vast majority of the fragments observed in this example.

The measured fragments from all forty videos recorded at the condition shown in Fig. 2 were used to construct the size probability density shown in Fig. 3(a). Interestingly, the size distribution appears to be multimodal as highlighted by the two best-fit log-normal components shown in red and blue in Fig. 3(a). This is likely caused by separate particle formation mechanisms in the ejecta sheet and crown as discussed in [8, 9]. We believe this may be the first time that such multimodal behavior has been quantified.

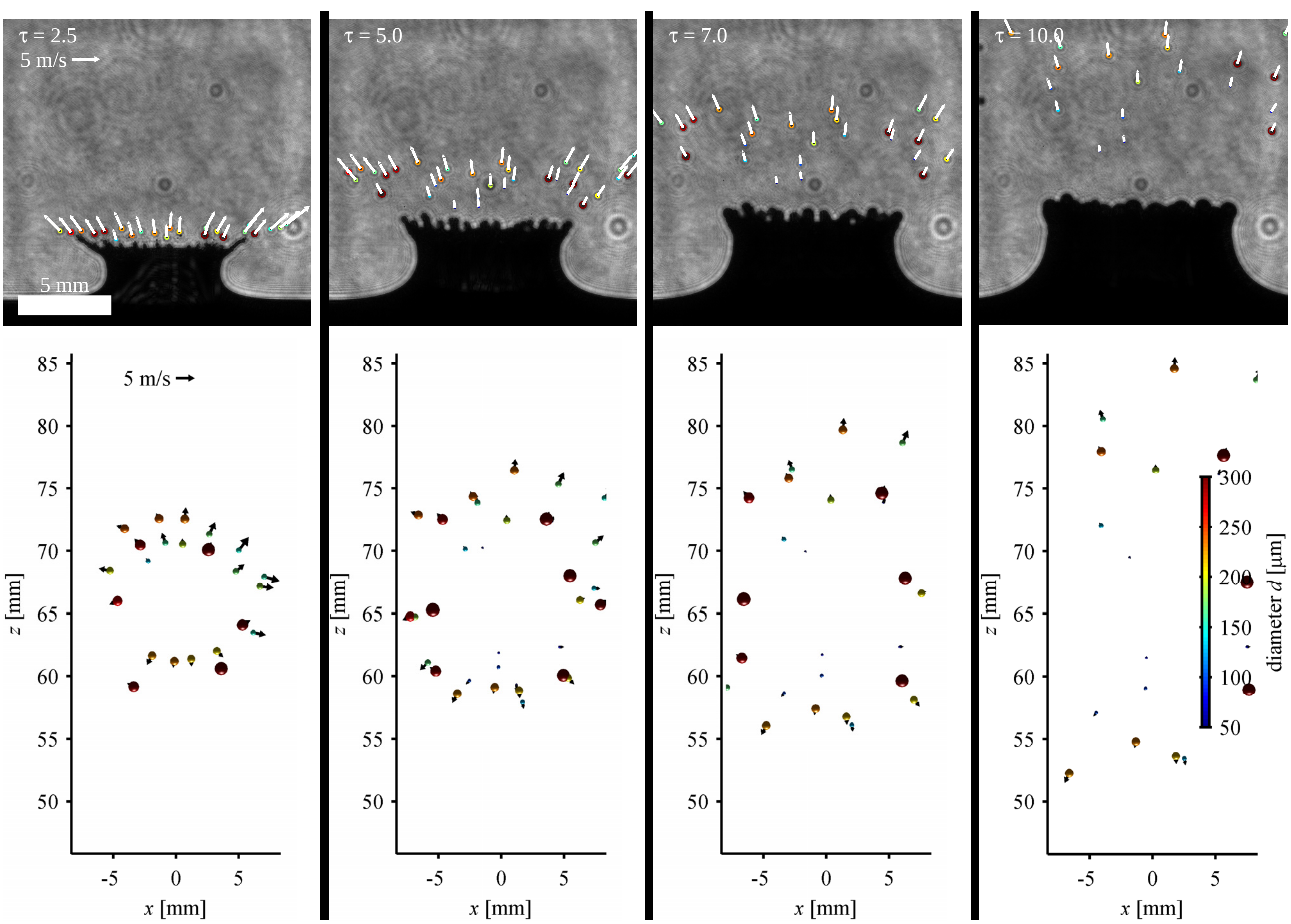


Fig. 2 Example DIH results for the 72% H20-28% glycerin solution at a fall height of 1500 mm, (top) numerically refocused holograms overlaid with the measured fragment in-plane positions, sizes, and velocities, (bottom) the corresponding out-of-plane positions and velocities.

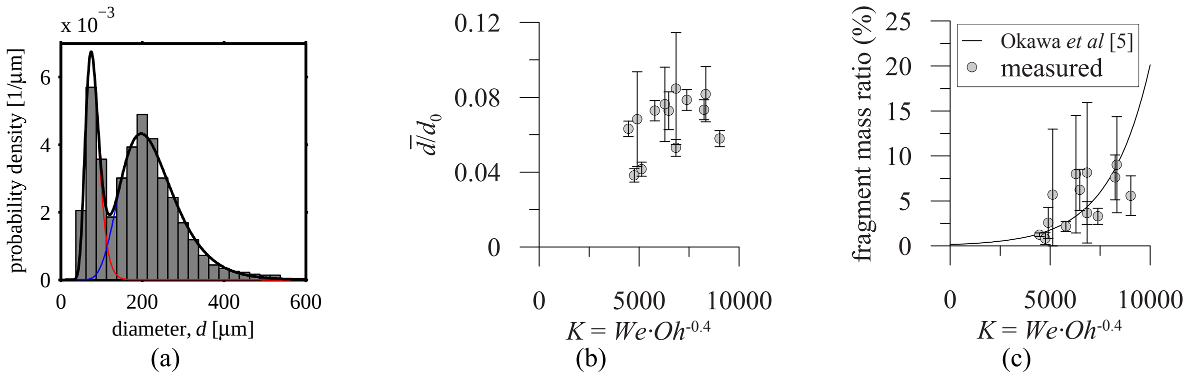


Fig. 3 Summary of measured fragment properties, (a) fragment size probability density for the 72% H_2O-28% glycerin solution at a fall height of 1500 mm, (b) mean diameter for all conditions investigated, and (c) the mass ratio of the fragments to the initial drop mass. Uncertainty bars in (b) and (c) show the standard deviation of the quantities measured from each high-speed DIH video.

Fig. 3(b) summarizes the mean diameter, $\bar{d}$, measured for all liquids and fall heights investigated here. Results are plotted as a function of the *K*-number, given by $K = We \cdot Oh^{-0.4}$, where $We = \rho v_0^2 d_0/\sigma$ is the Weber number and $\mathrm{Oh} = \nu\rho^{1/2}/(d_0\sigma)^{1/2}$ is the Ohnesorge number. In the literature, [1-3] the *K*-number is often suggested as the appropriate non-dimensional grouping for the investigation of drop impact. For example, Okawa *et al*. [5] measured the secondary fragments from the impact of a water drop on a thin film of water and for $\delta < 0.2$ found that $\bar{d}/d_0 \approx 0.07$ independent of *K*. The results in Fig. 3(b) generally agree with this finding, although there does appear to be a small increase in mean diameter with increased *K*. This suggests that viscous effects, not considered by Okawa *et al*. [5], may have some effect on the measured mean diameters and more work is warranted.

Finally, Fig. 3(c) summarizes fragment mass ratio calculated as the total volume of all measured secondary fragments divided by the volume of the initial drop. Once again the results generally agree with the correlation proposed by Okawa *et al*. [5] in their investigation of water drops. This appears to confirm that the *K*-number is an appropriate non-dimensional group which accounts for viscous effects. On the other hand, the significant scatter in the results does suggest that more investigation may reveal detailed trends which are not clearly revealed in these figures.

5. Aknowledgements

This work was supported by the Weapons Systems Engineering Assessment Technology program and the Laboratory Directed Research and Development program. The authors gratefully acknowledge these sources of support. Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy, under contract DE-AC04-94AL85000.

References

[1] A. L. Yarin, "Drop impact dynamics: Splashing, spreading, receding, bouncing…," *Annu. Rev. Fluid Mech*. **38**, 159-192 (2006).

[2] S. T. Thoroddsen, T. G. Etoh, and K. Takehara, "High-speed imging of drops and bubbles," *Annu. Rev. Fluid Mech*. **40**, 257-285 (2008).

[3] A. L. N. Moreira, A. S. Moita, and M. R. Panão, "Advances and challenges in explaining fuel spray impingement: How much of single droplet impact research is useful?," *Prog. Energy Combust. Sci*. **36**, 554-580 (2010).

[4] G. E. Cossali, M. Marengo, A. Coghe, and S. Zhdanov, "The role of time in single drop splash on thin film," *Exp. Fluids* **36**, 888-900 (2004).

[5] T. Okawa, T. Shiraishi, and T. Mori, "Production of secondary drops during the single water drop impact onto a plane water surface," *Exp. Fluids* **41**, 965-974 (2006).

[6] D. R. Guildenbecher, L. Engvall, J. Gao, T. W. Grasser, P. L. Reu, and J. Chen, "Digital in-line holography to quantify secondary droplets from the impact of a single drop on a thin film," *Exp. Fluids* **55**, 1670 (2014).

[7] D. R. Guildenbecher, M. A. Cooper, and P. E. Sojka, "High-speed (20 kHz) digital in-line holography for transient particle tracking and sizing in multiphase flows," *Appl. Opt*. In Press (2016).

[8] S. T. Thoroddsen, "The ejecta sheet generated by the impact of a drop," *J. Fluid Mech*. **451**, 373-381 (2002).

[9] R. D. Deegan, P. Brunet, and J. Eggers, "Complexities of splashing," *Nonlinearity* **21**, C1 (2008).

[10] J. Katz and J. Sheng, "Applications of holography in fluid mechanics and particle dynamics," *Annu. Rev. Fluid Mech*. **42**, 531-555 (2010).