Digital In-line Holography of blood atomization

Reetam Das

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Digital In-line Holography of blood atomization

by

Reetam Das

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Mechanical Engineering

Program of Study Committee:
James B. Michael, Major Professor
    Jaime J. Juarez
    Sarah A. Bentil

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2019

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ABSTRACT

Bloodstain Pattern analysis (BPA) has been widely used as a forensic tool for crime scene reconstruction by law enforcement agencies worldwide. The ultimate pattern left behind by a blood-letting event has been well described in the literature but the connection between the pattern and the fluid dynamic origin of the droplets that caused the stain remain uncertain. A variety of bloodstain patterns could be traced to the flight of the droplets, the resulting size and velocity distributions of cast droplets, and wetting and drying on a surface. In this dissertation, a study of the atomization mechanisms in the immediate moments after impact on a film of blood is presented. Both blunt and projectile impacts have been examined using high-speed imaging, which show distinct drop breakup characteristics due to ligament formation and high velocity impact. Digital in-line holography (DIH), in conjunction with high-speed imaging at kHz-rates, was used to quantify drop diameters and velocities milliseconds after impact. The Sandia HOLOSAND code was utilized to process holograms and identify droplet trajectories over multiple frames, thus improving overall out-of-plane accuracy of position and velocity estimation. The merits of DIH over traditional backlit imaging in terms of three dimensional measurement is significant. The temporal evolution of blood droplets in blunt impact (flat-to-flat surface) at up to 4 m/s is reported and comparisons are made with water as a reference fluid. The characteristic velocities and diameters of blood droplets from a bullet impact are also reported. This quantitative data-set would be helpful in verification of theoretical models of droplet trajectories, which is a positive step towards connecting BPA and fluid dynamics communities.
CHAPTER 1. OVERVIEW

1.1 Introduction

Bloodstain pattern analysis (BPA) is being scrutinized as a valuable forensic tool to evaluate blood spatter at a crime scenes and to recreate the events that culminated into the specific pattern. The validity and scientific rigor of this tool has been examined in multiple cases over the years (Colloff (2019)). Though BPA had been used in testimonies of criminal cases since 1950s, the California Supreme Court became the first court in American history to accept testimony that examined bloodstains in 1957 (Smith (2018)). Acceptance of BPA as a scientific tool could be traced back to a Department of Justice funded research conducted by Herbert MacDonell, the findings of which were published in a report titled “Flight Characteristics and Stain Patterns of Human Blood” (MacDonell and Bialousz (1971)). At a crime scene, BPA experts primarily want to know the origin of blood drops, number of people or objects involved, the kind of weapon used, and the mechanism that caused the spatter pattern. Traditional methods like stringing and tangent method have been used for a long time to estimate the point of impact from which droplets were generated that resulted in the spatter. The ends of the multiple strings are attached to the drop spatters and are extended backwards. The point where the strings intersect is considered as the general region where the blood droplets originated from. The major drawback of this method is the fact that straight-line trajectories are assumed; gravity and drag forces experienced by the droplets are neglected. For a very short distance, neglecting a projectile trajectory and drag on blood droplets might not introduce significant errors but over slightly longer distances gravity and viscous drag from the surrounding air may alter the trajectory of slow-moving drops (Attinger et al. (2013)). In such cases, a straight-line trajectory assumption results in consistent overestimation of the height of impact (see Fig. 1.1).
Figure 1.1 Trajectory reconstruction of blood drops (Attinger et al. (2013)).

Such uncertainties associated with BPA motivates stronger scientific rigor in the community. The need for additional rigor in the use of forensic tools, including BPA, was identified in a report by the US National Research Council (NRC) titled “Strengthening Forensic Science in United States: A path forward” that identifies the said uncertainties and recommends further research to facilitate integration of Fluid Dynamics (FD) with BPA (Council et al. (2009)).

Blood is a complex fluid that consists of suspended particles (blood cells) in a fluid (plasma). The blood is a non-Newtonian fluid whose viscosity changes with changing shear rate. Among non-Newtonian fluids, blood is further classified as a shear thinning or pseudoplastic fluid whose viscosity decreases with increased shear rate. Due to this nature of blood, it appears to be less viscous when smeared as compared to while dripping when it behaves like a thick viscous fluid. Viscosity of blood is also dependent on temperature and hematocrit, which is the volumetric percentage of red blood cells in the blood. The fluid properties of blood mentioned in literature (Attinger et al. (2013)) are listed in Table 1.1. The complex fluid dynamic nature of liquid blood can lead to unpredictable behavior. High-speed video sequences have shown droplet formation a few inches away from the impact location. However, the connections between the drop formation and resulting spatter are limited. Recently, several studies have begun to address the knowledge
gap dealing directly with bloodstain pattern formation mechanisms (Laber et al. (2008)). Data on patterns formed as a result of blood spatter at crime scenes is available but there is a dearth of data on blood drop formation in the immediate moments after impact. This research attempts to make a connection between Fluid Dynamics (FD) and Bloodstain Pattern Analysis (BPA) community. BPA has been widely used by law enforcement agencies all over the world to investigate crime scenes and ascertain the nature of the blood-letting event that resulted in the subsequent pattern. Fluid dynamics on the other hand describes the motion of the fluid (both liquid and gasses) quantitatively and tries to answer what causes the typical phenomenon with the help of equations that have been derived from experimentation and laws of physics. Fluid dynamics governs the drop formation, flight and impact that results in the final spatter. Recently Comiskey et al. (2016) introduced fluid dynamics models that can predict initial droplet size and velocities, but available experimental data sets are limited. Specifically, information about the three-dimensional velocities and diameters of the droplets would facilitate validation of fluid dynamics models that could be implemented in software for crime scene reconstruction. Available commercial software packages like HemoSpat and BackTrack use the same straight-line trajectory assumption; neglecting gravity and air resistance similar to stringing method which results in the same inconsistencies getting carried over to software measurements (de Bruin et al. (2011)).

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<td>37 °C: 4.4 37 °C: 5.5 37 °C: 0.7</td>
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<td>37 °C: 5.2 37 °C: 5.1 37 °C: 7.0</td>
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<td>1060 1062 993</td>
<td></td>
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<tr>
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<td>0.40 - 0.45 0.39 - 0.46</td>
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With the help of high-speed visualization and laser diagnostics using Digital In-line Holography (DIH) technique, qualitative and quantitative data of droplet breakup mechanisms for blunt
impact and projectile impact are presented. Statistical data of the three-dimensional (3D) breakup is valuable to develop theoretical models of droplet trajectories. Perhaps a more detailed understanding of the droplet formation mechanisms and fluid dynamics, along with robust quantitative tools, would go a long way to help the members in the BPA community to reduce the uncertainty of predicting the origin of bloodstain. The NRC report, Council et al. (2009) recommends improvement of scientific basis of forensic examinations and also address issues of accuracy, reliability and validity in the forensic science discipline. Continued research in liquid atomization and breakup would significantly benefit both FD and BPA communities.
CHAPTER 2. REVIEW OF LITERATURE

2.1 Droplet formation

Droplet formation, atomization, and splashing of liquids have been actively studied in the last hundred years. Worthington (1908) was one of the first to closely study drop impact and subsequent breakup mechanisms. He identified outcomes varying from deposition, rebound, splashing and subsequent breakup into smaller droplets. The splashing of droplets were examined by Yarin and Weiss (1995) and they have studied capillary waves when a droplet impacts a dry surface and have theoretically shown a threshold where splashing occurs that results in formation of a mist of smaller droplets. Apart from blood spatter, the mechanisms of drop impacts are of fundamental interest to various other fields like spray, cooling, fuel injection and medicine. Theoretical models of drop impingement available in literature compared by Cossali et al. (2005) predict outcomes of spray impact on a surface (Bai and Gosman (1995); Park and Watkins (1996); Stanton and Rutland (1996); Samenfink (1997); Mundo et al. (1998); Marengo and Tropea (1999)). Roisman et al. (2006) points out that such models are based on experimental results and primarily require data like droplet diameter distribution and velocity upstream of the impact plane. Through this research, diameter distribution and characteristic three-dimensional velocity of droplets generated by impact on a pool of blood is reported. High-speed visualization has shown formation of droplets from breakup of sheets and jets. Sheet breakup has been studied in relation to drop impact on a thin film by Roisman et al. (2006). When a drop impacts on thin film, a sheet formation is observed, transverse instabilities on the rim then cause cusps and finger-like jets. These jets further experience longitudinal instabilities that result in breaking up into individual droplets. The surface tension of the liquid acts in a manner to reduce the surface area of the liquid volume to attain a state of minimum surface energy. This physical phenomenon causes necking in a thin liquid column or “ligament”, like in a jet, which results in the instabilities that finally result in formation of in-
Figure 2.1 Water drop impact on a dry wall showing formation of liquid ligament and subsequent breakup into individual droplets. Here 't' represents time after impact, as determined from high-speed image sequence.

This phenomenon was first studied by Plateau (1873) and Rayleigh (1892) hence it is named after them as Plateau-Rayleigh instability. For a thin film of liquid on a fiber the predominant wavelength of oscillation scales as the seventh power of the radius of the fiber; this oscillation causes the film of liquid to break up into multiple droplets (Mead-Hunter et al. (2012)). The instabilities that result in sheet breakup has been explained really well by Villermaux and Bossa (2011). Corrugations are identified on the rim of liquid film, which increases as the sheet expands. The liquid from the inner bulk of the drop expands but the liquid composing the rim decelerates. Being fed by liquid from the expanding sheet, the rim thickens and stretches with the onset of instabilities similar to Plateau-Rayleigh instability. The destabilization and the corrugations on the edge results in formation of jets. Other ways of ligament formation have been comprehensively discussed by Eggers and Villermaux (2008) and Lin and Reitz (1998).
2.2 Blood Spatter

The method of strings is manually intensive but with the availability of computers, software programs were developed to help analysts to reconstruct crime scenes. The required precision for determining the approximate area of origin varies from case to case; the volume of a grapefruit or a basketball may be acceptable for many cases (Attinger et al. (2013)). Determining the angle of impact of a drop from the surface stain pattern can be challenging to determine in three dimensions using a protractor; Rowe (2006) has graphically shown the error in $x$ and $y$ measurements in point of origin of bloodstains and makes recommendations for the best spots to be selected for greater accuracy. As mentioned earlier, a straight-line trajectory assumption is inaccurate for longer drop flight trajectories. Kabaliuk et al. (2014) have developed a numerical code for modeling blood droplet flight that incorporated aerodynamic drag, gravity, drop deformation and possible breakup into consideration. The model was validated with experimental results, showing good agreement. For a typical crime scenario, they found that deformation effects could be neglected for cast off drops that fall a distance less than 1.5 m. Comiskey et al. (2016) developed a theoretical model to predict blood back-spatter from bullet impact on a wetted sponge. Drop deposition on the floor was numerically simulated and results were compared with experiments. A Rayleigh-Taylor instability mechanism was used to model the breakup of blood drops when a source is impacted with a conical shaped bullet. The experimental data of the splash pattern on the floor (i.e. the number of stains and total stain) area agreed with the order of magnitude of the numerical simulation. A significant difference in two experimental trials has also been noted. A similar study for forward spatter of blood from a bullet impact has been done by Comiskey et al. (2018), and the predicted number of stains show good agreement with experiments. However, the average stain area as a function of distance showed a wide variation across multiple experiments, making comparisons difficult.

Some researchers have made significant efforts towards 3D reconstruction of drop trajectories using software and modern measurement techniques. An example of ballistic reconstruction of drop trajectories could be found in Buck et al. (2011). A ballistics software that calculated the trajectory
based on drag coefficients of spherical droplets was used to get a more accurate reconstruction of
the crime scene and determine the point of origin of blood spatter (see Fig. 2.2). The efficacy
of using the ballistic software was demonstrated in two real crime scenes. Each crime scene was
documented by photogrammetry and 3D laser scanning, and demonstrated how using the ballistic
software could reduce time and effort in bloodstain pattern analysis.

![Figure 2.2 Groups of centre of origins determined by ballistic analysis of blood spatter
(Buck et al. (2011)).](image)

Ascertaining if blood spatters were formed by blunt impact or high energy projectile impact
poses a significant challenge to BPA experts. Quantitative differentiation of the nature of both
spatters is well described by Siu et al. (2017). Front spatter of impact on a blood-soaked sponge
was recorded by a high resolution camera. The results show that the absolute number of droplets
were higher for bullet impact than blunt impact, and a strong correlation between bullet speed and
number of droplets was observed. However, it was interesting to note that even a blunt impact
with significant force could generate more droplets than a bullet impact. Mean drop stain size
was observed to be smaller for bullet impacts than blunt impacts. The approximate height of
the assumed point of origin of droplet and the velocities are used to calculate the trajectories of
blood drops by the previously mentioned ballistics software. For a group of nearby drop spatters to
have originated from the same point, they should have had similar velocities that are less than the
maximum velocity that could be calculated for given drop size. Kneubuehl (2012) has determined
the maximum velocity possible for a given drop diameter taking drag into consideration. The
velocities range from 10 m/s – 25 m/s for drop sizes ranging from 6 mm to 1 mm in diameter,
respectively. Any velocity higher than this limit would result in liquid oscillation and breakup.
CHAPTER 3. DIGITAL IN-LINE HOLOGRAPHY

3.1 Introduction

A variety of engineering applications like sprays, atmospheric particulate matter, microscopic organisms etc. have the evolution of sparse particle and droplet fields. Quantification of characteristic size, velocity and shape are required to evaluate transport and track the evolution at the droplet field. The particles of interest may be quite small - the order of microns in diameter. Conventional imaging and microscopy techniques are capable of resolving such particle dimensions, but they do not provide an avenue to study the dynamic particle characteristics in a three-dimensional volume. Holography provides a way to resolve the particle field in three dimensions, based on the scattering and diffraction of coherent light. A hologram is created by recording the interference pattern created by coherent light (reference beam) and light diffracted by particles present in the field. Prior to invention of laser, traditional holography used photographic film coated with silver halide to record holograms. The traditional method theoretically offered superior, sub-100 nm resolution. With the advent of lasers in 1960s and improvement in digital cameras, digital holography has replaced traditional holographic techniques. The chemical processing of the holography screen was eliminated and digital holography also provides added advantage of numerical reconstruction using software programs. Some methods of holography could be characterized by the angle between objects and reference beam as off-axis and in-line holography. The reference beam and particle field are oriented in parallel for in-line holography (Katz and Sheng (2010)). The optical system required for in-line holography is fairly simple compared to off-axis method. Digital in-line holography has been used in flow measurement studies where two-dimensional (2D) wall stress distribution and three-dimensional (3D) flow structures of a turbulent boundary layer close to the wall were obtained by holography measurements of tracer particles (Sheng et al. (2008)). Buchmann et al. (2012) have demonstrated tomographical digital holographic Particle Image Velocimetry (PIV) by
measuring three-dimensional particle velocities and trajectories in a supersonic jet flow. PIV is an Eulerian method that measures velocity field in a rectangular grid by measuring velocities of individual tracer particles in the flow field that are assumed to be tiny enough to follow the flow dynamics of the fluid. Digital in-line holography has also been used to measure air bubbles in a cavitation tunnel (Lebrun et al. (2011)) and measuring ice crystals in clouds (Fugal et al. (2004)). Three-dimensional trajectories of free-swimming microorganisms have been measured using holographic Particle Tracking Velocimetry (PTV) technique (Lee et al. (2011)). PTV is a Lagrangian approach in which individual particles are tracked.

3.2 Depth Uncertainty

One of the major drawbacks of digital holography is the higher uncertainty of depth resolution compared to in-plane resolution. The resolution of the reconstructed image and the depth over which the particle identified remains in focus are limited by finite aperture of the hologram as the angle between the particle field and plane wave illumination is limited by the size of the sensor (Vikram (1992); Singh and Panigrahi (2010)). The reconstructed hologram remains focused over a certain depth which is proportional to $d^2/\lambda$, where $d$ is the diameter of object and $\lambda$ is the wavelength of the illuminating laser light (Katz and Sheng (2010)). Accuracy of the out-of-plane depth detection is critical to accuracy of velocity measurement. Multiple algorithms have been developed to process holograms and determine particle depth using information derived from amplitude and edge sharpness in reconstructed holograms. Two examples of such algorithms are:

1. Reconstructed intensity (amplitude): In a numerically regenerated hologram, a particle appears as a dark region in a lighter background. That identified particle can be considered in focus in the reconstructed hologram if its edges are sharp in contrast to the light background. So, the depth at which the particle has the sharpest edge in the reconstructed hologram is most likely the actual position of the said particle in depth. For this reason, a particle detection algorithm might use minimum amplitude as a criterion for focus (Sheng et al. (2003)).
2. Maximizing sharpness index: Depth of the particle could also be found by gradient based methods as shown by Ilchenko et al. (2005). This method aims at identifying the true depth of the particle by calculating the sharpness of the object which was defined as the normalized sum of absolute numerical gradient values calculated at the particle border. The depth at which the gradient was maximized could be identified as actual depth of the particle.

3.3 Image processing routine and HOLOSAND code

For all experiments in this dissertation, a collimated Helium-Neon (He-Ne) laser beam was used to illuminate the background of the particle field. A diffraction pattern is created by the particles passing through the light field that is well described by scalar diffraction theory. The diffracted light and the co-linear reference beam interfere to create a hologram \( h(m, n) \) (\( m \) and \( n \) represent the horizontal and vertical axes respectively), which is discretized by the digital image sensor of a high-speed camera and was saved in multi-tiff image format. The HOLOSAND code from Sandia National Lab was used to numerically reconstruct the hologram in \( z \)-direction by evaluating the Rayleigh-Sommerfeld diffraction integral equation at the desired \( z \) slice in three dimensional space (Guildenbecher (2015)). The amplitude of the reconstructed hologram is represented by:

\[
A(x, y; z) = |F^{-1}\{F\{h(m, n)\}G(m', n', z)\}|
\]

(3.1)

described by an inverse Fourier transform of the analytical Rayleigh-Sommerfeld diffraction kernel, \( G(m', n', z) \) (Katz and Sheng (2010)). The Rayleigh-Sommerfeld kernel is given by

\[
G(m', n', z) = e^{jkz\sqrt{1-(\lambda m/M\Delta\xi)^2-(\lambda n/N\Delta\eta)^2}}
\]

(3.2)

where \( k \) is the wavenumber, \( F \) and \( F^{-1} \) denote the fast-Fourier and inverse fast-Fourier transforms, and \( M \) and \( N \) are the number of pixels in the horizontal and vertical directions of sizes \( \Delta\xi \) and \( \Delta\eta \), respectively. Reconstruction of the hologram in the optical depth \( z \) as well as the object finding
and particle linking routines are performed in MATLAB using the Sandia HoloSand code. Gao et al. (2013a) have proposed a ‘Hybrid method’ for particle detection which has been implemented in HoloSand. This method selects the pixels with minimum intensity and maximum edge sharpness to identify the boundary of particle or droplet objects. Slice-by-slice volume reconstruction of the hologram generates a map of minimum intensity on which segmentation thresholds are automatically selected to identify all the particle edges. The Tenengrad operator quantifies the sharpness of particle edges in the reconstructed hologram, defined as

\[
T(x, y; z) = [A(x, y; z) * S_x]^2 + [A(x, y; z) * S_y]^2
\]  

Here, \( S_x \) and \( S_y \) are the horizontal and vertical Sobel kernels and * denotes the 2D convolution. Pixels with maximum Tenengrad values are considered in focus. A preliminary \( z \)-depth is estimated by averaging the depth of each of the edge pixels. A final estimate of the object depth \( z \) is estimated by two refinement steps in which a local window twice the size of the particle is identified and new optimal thresholds are calculated for the local intensity (Gao et al. (2014)). A reconstructed hologram at a focused plane appears dark in contrast to the background with sharp edges, hence minimum intensity and maximum Tenengrad are implemented in the hybrid method and have also been validated by Guildenbecher et al. (2013). Gao et al. (2013b) have used the hybrid method and demonstrated the utility of DIH to extract 3D location and size of secondary droplets in multiphase fragmentation. DIH is also capable of extracting complex 3D morphologies as was demonstrated in the case of protruding jets (Guildenbecher et al. (2014)). The following subsections give a detailed description of the processing routine followed to acquire 3D velocity and diameter data of droplets.

### 3.3.1 Hologram reconstruction

The intensity of the generated hologram is recorded by the CMOS sensor. The pixel-wise intensity average of the first twenty five frames of the high speed recording is assumed as the background image. To obtain a normalized image of each subsequent frame of the hologram that contains the
particles of interest, the intensity of the background image is divided from the intensity of the single hologram frame in consideration. The HOLOSAND code uses the analytical solution of the propagation equation of the complex amplitude to calculate the simulated hologram at given \( z \)-depths. The Fresnel integral equation using the same non-dimensional parameters as the analytical solution was used for the reconstruction step in the code. A hybrid method as proposed by Guildenbecher et al. (2013) was incorporated in the code to detect the particle shape and position in the reconstructed hologram. Minimizing the intensity and maximizing the edge sharpness in the depth direction were used to accurately represent particle shape and in-plane position. Multiple thresholds were initially applied to the minimum intensity map to identify the most probable particle edges and then the edge sharpness was estimated by averaging the values of the Tenengrad map on each pixel of the identified particle edges. The edge with maximum Tenengrad operator is chosen as the in-focus edge and the average of all the \( z \)-locations along the Tenengrad depth-map is selected as the depth of the particle. A major advantage of the hybrid method is that the optimum thresholds are automatically calculated and hence requires minimum human intervention. A second depth refinement step was performed to improve the depth calculation and detection of small or non-spherical particles. In this step the intensity is reconstructed at the best estimate of particle depth to find best possible family of particle edges.

Fig. 3.1 shows the sequence of steps in which drops in the spray field are identified. These images show water drops of sizes ranging from 50 – 300 \( \mu \)m that were recorded at a distance of 12 cm away from the blunt impact location (see Fig. 3.1 (a)). The hologram was numerically reconstructed at a depth of 200 mm (Fig. 3.1 (b)) and the Tenengrad shows the edge sharpness of the drops (Fig. 3.1 (c)). The colour of the circles represent the predicted depth in the field (Fig. 3.1 (d)).
3.3.2 Particle linking and quantification

The hybrid method was used to process each hologram as described in the previous subsection. The three-dimensional coordinates of each drop identified were extracted along with the two-dimensional morphology. An equivalent circle having the same area as that of the 2D morphology defined the drop diameter $d$. The minimum drop size was set to 50 µm to minimize erroneous detection of particles. The identified drops were matched across multiple frames using a Hungarian linker algorithm implemented by Tinevez and Cao (2012) on MATLAB and incorporated in the HOLOSAND code. To improve the number of acceptable matches, the diameter variation between linked particles were limited to 20%. The maximum allowable distance between linked particles was adjusted between 2 mm to 4 mm on case-by-case basis. A minimum of 4 linked particle tracks was set as default and the trajectories were fit to linear models to address the uncertainty caused by depth of focus problem as mentioned earlier (Katz and Sheng (2010)).
Fig. 3.2 shows the steps followed after linking the identified drops. Around 8 – 10 consecutive frames were linked which accounted for 330 $\mu$s. A single track is isolated in Fig. 3.2 (b), and the position coordinates as well as diameter is shown in Fig. 3.2 (c)–(f). A linear fit modeled the predicted $x$, $y$ and $z$ coordinates from a spread of measured coordinates which are shown by black dots. These linear fits were the velocity vectors in each individual axes, the resultant of which was reported as the calculated three dimensional velocity. The diameter reported for the detected drop was averaged across all frames.
CHAPTER 4. EXPERIMENT SETUP

4.1 Blunt impact apparatus

To study jetting breakup in a lab configuration, a flat-flat surface blunt impact apparatus was used. The apparatus consisted of two aluminum cylinders mounted on a central aluminum guide rod. The diameters of the top and bottom cylinders were 38 mm and 77 mm respectively. To generate a spatter, the top cylinder was allowed to fall freely from a height of 600 mm that resulted in an impact velocity of 4 m/s. 0.3 ml of blood was placed on top of the bottom cylinder and the impact between both the cylinders resulted in the spatter that was studied by both back-lit imaging and holography. The thin film of blood was placed in such a way that the liquid film extended till the edge of the top cylinder of blunt impact apparatus. This ensured the repeatability of the experiments for holography recording. An O-ring was used to seal the annular region between the lower cylinder and the center guide rod so that the fluid was not lost through the gap. Impact velocity of 2.4 m/s was achieved from a free fall height of 300 mm. A 500-W band heater was used to heat the lower cylinder to test heated blood. A PID controller circuit was set up to maintain the surface temperature of the blood film at 38±1 °C. A thermocouple securely mounted on the top face of the lower cylinder close to the blood film monitored and provided feedback to the PID circuit to maintain consistent temperature throughout the heated blood impact experiments. An acoustic trigger, manufactured by Kapture group, placed in close proximity to the blunt impact apparatus was used as a reference for time in all experiments. Being limited by the speed of sound in air, a trigger delay of up to 66 µs was observed between the impact and the signal activating the camera. Photron high speed cameras have the functionality to save frames before the triggering event which was utilized in data collection.
4.1.0.1 Holography

A 15-mW He-Ne laser that emitted a coherent beam of 632.8 nm was used to generate the collimated background light field. The beam was expanded in two stages by using lenses of 50 mm and 200 mm focal lengths for the first stage and a pair of 30 mm and 150 mm lenses for the second stage (see Fig. 4.1) to achieve a resultant beam diameter of 50 mm. In a preliminary phase of experiments, holography was performed in a side-view configuration. Multiple challenges were faced in this configuration. In the preliminary backlit videos, it was observed that the blood spatter fanned out in the plane of the flat surface of the cylinder. Different sized droplets were observed at different heights and due to the limited size of the sensor, only a ~20 mm region could be observed. Additionally, due to the spreading liquid film that fans out in the $y$-direction (along the holography beam), a large number of overlapping droplets are observed in the holography field that resulted in poor holograms from which very few particle tracks could be extracted every trial. To resolve these issues, the setup was modified to have the holography beam running along $z$-direction so that a top-down view could be achieved (see Fig. 4.2). For the top-down view, the camera was mounted on a tripod and the ball-head was oriented to point downwards such that the tripod legs did not obstruct the spray field.

![Figure 4.1 Laser beam expansion and layout on portable optical breadboard](image-url)
A Photron Fastcam SA-5 camera with a 50-mm f/1.4 objective lens was used, resulting in a field of view of about 200 mm by 200 mm. The larger aperture enabled operation at faster shutter speeds but the depth of field was limited to about a few mm. The camera was operated at 7.5 kHz to get a full frame image and a shutter exposure of 3.7 µs. The camera was positioned approximately 1200 mm away at the same height as that of the lower cylinder. A white card stock illuminated by an LED lamp was used as a background.

4.2 Bullets impact

To test bullet-impact, a polyurethane foam board with a 2-in cavity was used as a blood source. The top surface was covered with tape to retain the blood. This polyurethane board was mounted on cardboard stock in a vertical orientation. The bullet impact studies were performed at a local indoor shooting range (Izaac Walton League, Ames, IA) under the supervision of Iowa State
University (ISU) Officer Darin Van Ryswyk. The firearms were mounted on a ransom-rest with the muzzle approximately 600 mm from the ground. The ransom-rest enabled repeatable impacts at the same position. Particulars for the firearm and rounds used are shown in table 4.1:

<table>
<thead>
<tr>
<th>Weapon</th>
<th>Bullet</th>
<th>Caliber</th>
<th>Weight</th>
<th>Muzzle velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith and Wesson 9 mm handgun</td>
<td>AE9AP</td>
<td>9 mm Luger</td>
<td>124 grains</td>
<td>350 m/s</td>
</tr>
<tr>
<td>Rock river arms LAR-15 rifle</td>
<td>AE223</td>
<td>223 Rem</td>
<td>55 grains</td>
<td>987 m/s</td>
</tr>
</tbody>
</table>

4.2.0.1 Backlit imaging

To capture the impact sequence of a high velocity bullet, the camera needs to record at much higher frame rate and shorter exposure as compared to blunt impact. A Photron Fastcam SA-X2 was used to record the backlit video sequence at 12.5 kHz and shutter exposure of 1 µs. To achieve a brightly lit background, an LED lamp was used with a diffuser placed about a meter away from the blood source. The camera was placed 2-3 meters away to protect it from shrapnel if any. A 105 mm f/2.8 objective lens was used.

4.2.0.2 Holography

Similar to the initial blunt impact experiment set up, the holography setup was mounted horizontally. Proper resolution of the primary and the secondary rings on the hologram are detrimental to numerical refocusing. Positioning the camera sensor close enough to the particle field to capture holograms with clearly visible diffraction patterns while maintaining a safe distance from the bullet path was challenging. A relay imaging setup was constructed which allowed the camera to be placed further away from the bullet path, while preserving the phase information at the input to the telescope. The relay imaging system consists of two convex lenses with long focal lengths placed at a distance of twice their focal lengths apart (see Fig. 4.3). The resulting image has a magnification of 1. This allowed the camera to be moved away from the bullet path while preserving the quality.
of the hologram.

Figure 4.3 Experimental arrangement for holography experiments at indoor shooting range.
CHAPTER 5. RESULTS

5.1 Blunt impact

The blunt impact apparatus was set up to collect both holography data and record high speed backlit images of the spatter. In the following sections the droplet formation mechanism as observed is presented. Drops reconstructed by digital in-line holography are quantified and the observed trends are presented.

5.1.1 Backlit imaging

A lateral view in Fig. 5.1 shows the formation of droplets due to blunt impact on a thin film of blood at an impact velocity of approximately 2.4 m/s (30 cm drop height). 0.3 ml of blood was used to achieve an estimated film thickness of approximately 2.4 mm. The blood sample was positioned in such a way that the outer edge did not extend beyond the envelop of the outer diameter of the top impacting cylinder. The image sequence was recorded at 7 kHz using a Nikkor 50 mm f/1.4G objective lens at maximum aperture with a shutter exposure of 0.36 µs. The shallow depth of field due to the wide open aperture resulted in a narrow depth of field in which the drops are in focus. The snapshots show two distinctly different drop breakups happening at different timescales. The cylinder impact pushes out the bulk of the liquid in the film and generates considerable shear in the $x$-direction. The shear-thinning nature of blood accentuates the long ligament formation. A large number of droplets are formed as a result of the impact and they seem to have different characteristics than the ones formed from ligament breakup. Region (i) in Fig. 5.1 (b) indicates a liquid sheet that subsequently collapses into a ligament in (c) that continues to break up into individual drops in (d). These drops are considerably larger in size as compared to the ones in (e) that formed form ligaments in region (ii). There doesn’t seem to be any significant difference in the drops formed immediately after impact and the ones formed from ligament breakup from region
(ii) in these image sequences. However it is interesting to note the timescales of drop formation in region (i) and (ii). Drops are formed more slowly from region (i) but are larger in size and fewer in number than the ones formed from the other region.

Figure 5.1 Backlit images of blunt impact on a thin film of blood (0.35 ml). The impact velocity was 4 m/s.

To better understand the mechanism of ligament formation, the blunt impacts were repeated for a larger quantity of fluid (1 ml of blood). Though the film thickness was comparable, due to the larger volume, the liquid extended further beyond the outer diameter envelop of the top impacting cylinder. Fig. 5.2 shows pronounced liquid bag formation and breakup. An initial splash and corona formation is observed when the top cylinder first comes in contact with the liquid film. As
the cylinder progresses to impact the lower cylinder, the bulk of the fluid in the liquid film pushes out and breaks through the outer liquid layer to form a liquid bag. This liquid bag expands rapidly and is fuelled by the out-flux of the liquid. After the impact, when all the liquid gets expelled from between the two cylinders and there’s no more liquid available to support the expanding liquid bag, it begins to break up into thin ligaments. These ligaments further proceed to form individual drops, as mentioned previously. The stability of the liquid film has been studied extensively in literature and the initial breakup mechanism has been attributed to film oscillations by Squire (1953). It is believed that Rayleigh-Taylor instability is responsible for the rupture of the film (Comiskey et al. (2016); Guildenbecher et al. (2009)).

![Figure 5.2 Blunt impact on a thin film of blood (1 ml).](image)

Fig. 5.3 shows the backlit sequence of blunt impact with water. The experiments were conducted to match the experimental conditions in blunt impact on thin film of blood as closely as
possible. Due to the difference in surface tension of both fluids, the contact angle of water on the aluminum cylinder is larger which resulted in slightly larger film thickness of 3.2 mm compared to around 2.4 mm of blood for the same area covered on the flat surface. To ensure repeatability of experiments where the liquid film extended till the envelop of outer diameter of the top cylinder, 0.5 ml of water was used in contrast to 0.3 ml of blood. Fig. 5.3 (a) and (b) show the splash properties of 0.5 ml of water. Bag breakup can be observed but extensive ligament formation similar to blood is not observed. Majority of the droplets formed seem to be produced from the initial aftermath of the impact and a very minor proportion of the drops seems to form from ligament breakup. Due to the transparent nature of water, the liquid bag can be seen with greater clarity in Fig. 5.3 (c) and (d).

Figure 5.3 Blunt impact on a thin film of water - (a) and (b): 0.5 ml, (c) and (d): 1 ml.
5.1.2 Holography

5.1.2.1 Depth Test

As mention earlier, uncertainty of depth detection is the biggest challenge in digital holography. The holograms from the experiment were processed using HOLOSAND code that incorporated the hybrid method of particle detection as proposed by Guildenbecher et al. (2013). The robustness of this method in depth measurement is described at great length by Gao et al. (2013a). The calibration of the experimental setup was validated by quantifying the precision of $z$-depth measurement. A quartz glass window with opaque dots of arbitrary sizes was placed on a translation stage in the collimated light field. The stage was translated in steps of 2 mm along the holography beam. The holograms were recorded and reconstructed in a manner similar to that of the experiments. The error in measured displacement is shown in Fig. 5.4.

![Figure 5.4 Error in z measurement on a translating stage.](image)

A more detailed examination of the precision of $z$ and diameter measurement was done by inspecting the residual of predicted $z$ and diameter as shown in Fig. 5.5. A residual value is the difference between the recorded value and the predicted value of a regression fit. The value of $z$ from the regression fit over multiple frames was used to calculate the velocity vector in $z$ direction.
5.1.2.2 Drop velocities

The velocity distributions of a number of test cases are compared in Fig. 5.6. In this data set the leading droplets of the advancing droplet cloud were tracked. Each plot represents data collected from 20 trials of each test condition. The number of tracks identified in those trials range from 91 in the case of blood drops at room temperature 120 mm away from impact at velocity 4 m/s to 256 tracks identified for blood drops observed 200 mm away from impact at velocity 2.4 m/s. The distribution is represented as a box plot where the box represents data between first and third quartile and the horizontal line represents the median value. The whiskers represent the maximum and minimum values of velocities observed in the data set. For an impact velocity of 4 m/s, the estimated drop velocities at different distances from the point of impact are shown in Fig. 5.6(a). The median drop velocities decreases intuitively with increasing distance. However it is interesting to note that drops identified at 120 mm have lower variation in velocity as compared to the ones identified further away which have a few drops travelling at a higher velocity.

The velocity distribution of blood at room temperature (21 °C) is compared with water at room temperature and blood heated to body temperature (38 ± 1 °C) in Fig. 5.6(b). The impact
cylinder height was set to 300 mm for the experiments which resulted in an impact velocity of 2.4 m/s. Water drops exhibited very little variation in velocities as compared to blood. Drop velocities of heated blood was observed to be slightly lower than that of blood at room temperature but apart from that the velocity distribution is comparable.

Figure 5.6 (a) Blood drop velocities at increasing distance away from impact location (impact velocity - 4 m/s). (b) Drop velocities of different fluids (distance - 200 mm, impact velocity - 2.4 m/s). (c) and (d) Blood drop velocities at room temperature but different impact velocities 200 mm away from impact.

The velocity distribution of blood drops at room temperature and 200 mm away from impact is compared in Fig. 5.6(c) and (d) for different impact velocities. The median velocities are similar
in both cases at around 32 m/s and there’s only a marginal difference in maximum and minimum velocities observed which indicates that the impact velocity is not the significant factor that dictates drop velocities after impact. A distinct contrast in the median velocities of water and blood drops could be observed when compared at longer time scales as shown in Fig. 5.7. The plot represents data collected from 10 trials at a distance of 200 mm from impact location with impact velocity of 4 m/s. The time axis represents the time after trigger when the camera starts recording. The median velocity of water drops show a steady declining trend but blood drops show fluctuation in median velocity and have a declining trend but absolute values higher than water.

![Figure 5.7 Median drop velocities 200 mm away at 4 m/s impact velocity.](image)

### 5.1.2.3 Drop diameters

Fig. 5.8 shows the comparison of drop diameters of blood formed from blunt impact at 4 m/s. Not much difference was observed in the drop diameters as distance from impact is increased. Water drops have slightly larger size than blood drops. Fig. 5.9 shows the temporal evolution of drop diameters identified at a distance of 200 mm from impact location with impact velocity of 4 m/s.
Figure 5.8  (a) Drop diameters at increasing distance away from impact location (impact velocity - 4 m/s).  (b) Drop diameters of different fluids (distance - 200 mm, impact velocity -2.4 m/s).

Water and blood drops show a contrast in temporal evolution of their diameters. For instance Fig. 5.9 shows an increasing trend in median diameters of blood drops identified at 200 mm away for impact velocity of 4 m/s whereas water drops show a decreasing trend.

Figure 5.9  Median drop diameters 200 mm away at 4 m/s impact velocity.
5.1.2.4 Velocity - diameter correlation

In Fig. 5.10(a) the temporal evolution of blood drop velocities at 200 mm from impact for impact velocity of 4 m/s are shown at three different points in time - 12 ms, 22 ms and 32 ms after trigger. The velocity distribution is represented as a box plot where the boxes represent all values between the first and third quartile, while the horizontal blue line represents the median value. The whiskers represent values that are within 1.5 times the inter-quartile range. The outliers are indicated by additional ‘+’ symbols in red. As expected, the median velocities of drops passing through the field of view of the holography beam drops with progressing time. It is however interesting to see few drops traveling at significantly higher velocities than the rest later in the sequence. A closer inspection of the velocity-diameter correlation of the identified drops 32 ms after trigger reveals that the faster drops are among the smallest in diameter (see highlighted region).

The difference in the characteristics of drops of water and blood can be seen in Fig. 5.11 which shows the velocity - diameter correlation of water and blood drops identified at 200 mm away for an impact velocity of 2.4 m/s. The variation of water drop velocities remain flat throughout the spectrum of drop diameters. In contrast blood drops display a wide variation in observed velocities,
for example compare drop velocities of size 200 µm - The velocities are tightly grouped between 20 and 30 m/s for water drops whereas for blood they range from 20 to about 85 m/s.

![Velocity - diameter correlation of (a) Water and (b) Blood drops (distance - 200 mm, impact velocity - 2.4 m/s).](image)

Figure 5.11  Velocity - diameter correlation of (a) Water and (b) Blood drops (distance - 200 mm, impact velocity - 2.4 m/s).

The contrast in droplet forming mechanisms of water and blood is indicated in the spread of drop velocities and diameters. Lower velocity variation of water drops indicates that majority of the drops identified in the field were generated within similar time-frames, such is not the case with blood drops. This theory is further reinforced by the observation in Fig. 5.10 where the fastest drops late in the sequence were identified to be among the smallest. These drops were presumably formed very late by ligament breakup and did not experience drag for as long as similar sized particles might have experienced.

### 5.1.2.5 Kinetic Energy

Temporal evolution of kinetic energy of individual drops identified is shown in Fig. 5.12. Holography data was recorded for experiments conducted at distance of 200 mm away for an impact velocity of 4 m/s. Density of water and blood were assumed to be 1000 kg/m^3 and 1060 kg/m^3 respectively. The data is presented as box plots that represents distribution of kinetic energy of observed drops across 10 trials each for water and blood. The boxes encompass all data between
first and third quartile of calculated kinetic energies of all drops identified. The horizontal blue line represents the median velocity. Water drops have high kinetic energy in the initial moments after impact; the energies however drop as time progresses in the next 2 ms. In contrast blood drops show lower kinetic energies at beginning but in the next 2 ms drop energies rise.

![Figure 5.12 Temporal evolution of kinetic energy of identified drop of (a) water and (b) blood (distance - 200 mm, impact velocity - 4 m/s).](image)

The trend in kinetic energy of droplets generated from blunt impact is predominantly influenced by the drop diameters in the beginning and by drop velocities later in the sequence. Median diameters of water droplets were observed to be larger and showed a decreasing trend whereas the median velocities of blood drops were higher overall. Since kinetic energy scales by cubes of diameter and squares of velocity, it reflects in decreasing kinetic energy trend of water and increasing trend for blood drops.

### 5.2 Projectile impact

To study the blood spatter mechanism of a projectile impact, a blood source was placed in the path of a bullet at an indoor shooting range. The blood source was fabricated out of a polyurethane foam with a 2” cutout in the centre to hold 10 ml of blood. The cutout was covered with tape to
prevent the blood from leaking out. The gun was positioned on a ransom-rest to ensure repeatability of test every time. The acoustic trigger was positioned close to the muzzle of the gun.

5.2.1 Backlit imaging

The temporal evolution of the initial spatter of blood when impacted with handgun and rifle bullets are shown in Fig. 5.13 and 5.14. Considerably long ligament formation could be observed. The initial impact results in a dense spray of blood drops and later in the sequence, ligament breakup results in formation of drops as far as 10 cm away from the impact location (in the current field of view). The significant difference in the speed of impact of the bullet does not translate into any significant difference in the initial splash mechanism as observed in the backlit images though it might seem that the higher impact velocity of the rifle bullet might have resulted in a denser spray at 2 ms mark.

Figure 5.13 AE9AP handgun bullet impacting blood source.

5.2.2 Holography - with slit

The high density of droplets in the background laser light field was detrimental to detection of particle tracks as there were too many overlapping particles. To mitigate this challenge, a card
stock with a slit 5 mm in width oriented perpendicular to the holography beam was used to let only a small fraction of droplets pass. Fig. 5.15 shows the velocity and diameter distributions of identified drops at different points in time. A maximum velocity of up to 200 m/s was observed at a distance of 200 mm from impact with the AE9AP round.

![Figure 5.14 AE223 rifle bullet impacting blood source.](image)

The viability of the slit being used for holography measurements was further examined in the lab. Despite the fact that the slit was able to reduce spray density by restricting a large number of
droplets, it was found that the edges of the slit caused fragmentation of larger drops (see Fig. 5.16) which seems to have changed the trajectories of multiple drops. Further improvements need to be made on the slit design or alternate methods to manage the spray density at a close range needs to be developed to get a more accurate representation of the velocity and diameter distribution.

Figure 5.16  Backlit top-view of slit showing droplet breakup at slit edges.
Distinct atomization regimes were identified in blood drop production from a flat-to-flat surface blunt impact setup. Comparisons were made between blood at room temperature (21 °C), blood at body temperature (38 °C), and water at room temperature. The majority of droplets were observed forming immediately after blunt impact, however, a significant number of droplets formed from ligament breakup away from the liquid film impact. This mechanism of droplet formation was also observed in the case of projectile impact where ligament breakup occurred as far as 100 mm from the impact location. The droplet fields of water and blood were characterized using digital in-line holography to track the three-dimensional drop locations evolving in time. The HOLOSAND code was used to extract this three-dimensional position and velocity data using high-speed holography data with particle-linking algorithms. To enable quantitative estimates of the measurement accuracy, the precision of the holography experimental setup was also established.

Comparisons between the breakup and resultant drop velocities were made between blunt impact and bullet impact in a backspatter configuration. Individual drop velocities of up to 85 m/s for single drops were observed for blunt impact, whereas for backspattered droplets resulting from a gunshot, velocities of up to 200 m/s were observed for single drops of blood. However, for both configurations the median velocities were comparable at similar distances away from the impact location. Increasing the kinetic energy of impact results in a greater magnitude of drop fragmentation in the immediate aftermath of the impact. This result is consistent with the findings of Siu et al. (2017), where the spray pattern formed due to gunshot impacts are much smaller than those formed by blunt impact. In the experiments presented, median blood drop diameters of 120 µm was observed for gunshot backspatter in contrast to 200 µm for blunt impact at 2.4 m/s. Increasing the kinetic energy of blunt impact reduced drop diameters to about 150 µm for an impact velocity of 4
m/s, which indicates that even blunt impact with sufficient impact energy could generate droplets with similar characteristics as gunshot impact.

Quantitative evaluation of droplets presented in this dissertation is a positive step towards filling the void of experimental data in literature, which could be useful in verification of drag-based fluid dynamics models or other validated predictive models. Digital inline holography (DIH) enabled three dimensional measurement of velocity, which was estimated to be 20 – 30% higher than the two dimensional projection which would be represented by shadowgraphy. In addition to the current study, exploring the interaction of blood droplets with muzzle gas and aerodynamic wake of the bullet could provide valuable insights into droplet trajectories which would be enhanced by three dimensional measurements. Further research along these lines would set the stage for detailed analysis of measurement errors of validated fluid dynamic models, which will greatly enhance their predictive capabilities. Detailed prediction of blood atomization mechanisms and improved accuracy of point of origin estimation would greatly benefit the forensic community and allow for improved quantitative uncertainty metrics essential to forensic analysis tools and techniques.
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APPENDIX A. SCHLIEREN IMAGING

A.1 Experiment setup

If shot at close range, the spray of blood droplets from the back-spatter might be influenced by the muzzle gasses from the gun. To study the muzzle gas expansion, a schlieren imaging/ shadowgraph setup was fabricated. Schlieren and shadowgraph are both well-accepted flow visualization techniques that use the property of light bending in different refractive indices to visualize flow fields and shock wave in transparent air. Shadowgraph is less complicated than Schlieren which perform a similar function but the latter requires placing a knife's edge at the focal point of the light beam. A mercury lamp was used as a point source of light and the shadowgraph image was projected on a white foam board. The SA-X2 high speed camera was used to record the image formed on the whiteboard screen as shown in Fig. A.1.

Figure A.1 Schlieren imaging setup.
The experiment setup in the indoor shooting range is shown in Fig. A.2. Due to operational safety concerns at the indoor range, the rifle was silenced. Shadowgraph and schlieren images were recorded at muzzle and 70 cm away. Shadowgraph images show the expanding shock wave from the initial muzzle gas expansion from the handgun (see Fig. A.3). Schlieren images of the bullet passing through 70 cm away from the muzzle gas (Fig. A.3 (right)) shows a shock cone on the bullet, which is travelling at a speed slightly higher than the speed of sound. Partial schlieren images of the rifle show prominent shock cones on the supersonic bullet and muzzle gasses. Mach diamonds are visible on the muzzle tip later in the sequence indicating supersonic plume (see Fig. A.4).

Figure A.2 Schlieren imaging setup at shooting range.
Figure A.3 Handgun muzzle gas expansion.

A.2 Muzzle gas expansion measurement

The following steps were followed to quantify the muzzle gas expansion (See Fig. A.5):

1. A grid was overlaid on the video. Distance between red and blue lines are 10 mm and 2.5 mm, respectively.

2. The distance travelled by the muzzle gas front within the yellow box was tracked over time in multiple frames (bullet path is represented in green). The position of the furthest point in the muzzle gas cloud was rounded up to the next line.

3. Results show distance vs time plot of muzzle gasses at muzzle as well as 70 cm away from the muzzle (Fig. A.6).

In the silenced rifle the muzzle gasses took longer to expand inside the silencer so they were observed slightly later than the muzzle gas from the handgun. But since rifle muzzle gas had higher velocity, the muzzle gas cloud appeared earlier for rifle than handgun at 700 mm away.
Figure A.4 Rifle muzzle gas expansion.

Figure A.5 Tracking muzzle gas.
Figure A.6  Distance travelled by muzzle gas in time.
APPENDIX B. DIGITAL IN-LINE HOLOGRAPHY FOR DROP SIZING FROM HIGH VELOCITY WALL IMPACT

This work has been presented at the Central States Section of The Combustion Institute’s spring technical meeting at University of Minnesota- Twin cities in May 2018.

B.1 Introduction

The interaction of liquid droplets with solid walls is a topic of great interest for several practical applications in spray cooling, aerosol processes, combustion sprays, and forensic sciences. In developing physics-based engineering models for the interaction of droplets during wall impact requires knowledge of the controlling set of parameters. The outcome of a single droplet impacting a wall can vary widely based on impact velocity, droplet diameter, surface tension, fluid viscosity, angle of impact, surface roughness and wettability of the substrate (Yarin (2006)). Extensive characterization of droplet-wall impact outcomes has resulted in identification in a range of critical parameters. A range of possible outcomes have been identified by Rioboo et al. (2001) for impact with dry surfaces including deposition, prompt splash, corona splash, receding break-up, partial rebound and compete rebound using water and ethanol. Rioboo et al. (2002) also report the temporal evolution of droplet spread. The roles of wall substrate surface characteristics have been examined by Moita and Moreira (2007) using water, ethanol, diesel and biodiesel on varying substrate materials and surface roughnesses intended to replicate physical characteristics of an internal combustion (IC) engine piston. They characterized the disintegration of droplets on impact with cold and hot walls, as well as the effect of surface roughness and wettability on droplet disintegration. An extensive review by Josserand and Thoroddsen (2016) highlights recent understanding in droplet impacts on solid surfaces, where multiple physical properties govern the outcome of the droplet-wall impact. To summarize some of these trends, surface roughness promotes the formation of prompt splashing
at lower relative momentum, larger droplets and lower surface tension facilitate the appearance of corona splashing, and higher liquid viscosity acts to resist liquid breakup processes (Rioboo et al. (2001)). These general trends in outcomes have been well-described through a common set of non-dimensional parameters including the Weber and Reynolds numbers in the literature (Mundo et al. (1995); Marmanis and Thoroddsen (1996); Moreira et al. (2010)). Weber number is a relative measure of the fluids inertia to its surface tension and Reynolds number is the ratio of inertial forces to the viscous forces. They are denoted by We and Re respectively and defined as follows:

\[ We = \frac{\rho v^2 d}{\sigma} \]  
\[ Re = \frac{\rho v l}{\mu} \]  

where \( \rho \) is the fluid density (kg/m\(^3\)), \( v \) is the impact velocity (m/s), \( l \) is the characteristic length of the droplet (m), \( \sigma \) is the surface tension (N/m), and \( \mu \) is the dynamic viscosity of the fluid (N.s/m\(^2\)). In a combustor, the high injection pressures can result high momentum fuel jets and resulting atomized fuel droplets at extremely high velocity (up to 150 m/s) (Koo and Martin (1990)). Impact sequences at high velocities may differ from sequences at low velocity. At low velocity, a droplet may deposit on the wall, but at higher impact velocities splashing and subsequent droplet breakup is prevalent. In describing this interaction, the timescales of droplet spreading, the onset of splashing due instabilities in the crown during spreading have been found to govern the breakup process (Yarin and Weiss (1995)).

Few studies have examined droplet impact at high relative velocities to investigate the parameters as mentioned above. Mehdizadeh et al. (2004) showed the formation of fingers around the circumference of the droplet upon impact and examined the effect of surface roughness on number of fingers. They achieved impact velocity of 40 m/s and Weber numbers of 44500 in their experimental setup with water droplets of sizes 0.55 and 1.3 mm. Allen (1975) approached the fingering observed theoretically based on Rayleigh-Taylor instability. Kim et al. (2000) developed a more sophisticated linear perturbation theory to predict the number of fingers on the spreading front.
Visser et al. (2012) could generate droplets as small as 20 microns and droplet velocities up to 100 m/s using a novel technique using laser-induced cavitation in a capillary tube. The laser-induced vapor generation drives a high-speed liquid jet that subsequently breaks up into droplets. They compared the maximum spreading radius to other models available in literature and confirmed the presence of air layer under impacting droplet. Pan et al. (2010) could achieve Weber number of up to 12000 using 0.5 mm diameter water droplets accelerated to a velocity of 42 m/s by creating an air flow surrounding the droplet. They demonstrated that prompt splash could also occur on a smooth surface at high Weber number contrary to general belief that it was limited to a rough surface. Although these studies have identified interesting phenomena, additional data capturing trends to allow prediction over a range of impact parameters and fluid parameters is required.

Further experimental investigation is required to identify the impact outcomes and study the effect of physical parameters such as surface tension, surface roughness, and droplet momentum on drop-wall interaction at high velocity. This paper investigates droplet impact outcomes at high impact velocity of 10 m/s on dry non-heated surfaces. The study further identifies the role of Weber number, surface tension, and surface roughness on drop-wall impact characteristics at Weber number of 10000. High magnification imaging and digital in-line holography are used to estimate distributions of the secondary droplet size and velocity in three dimensions.

B.2 Methods

B.2.1 Solenoid-actuated mechanism for high velocity impact

Fig. B.1 shows the schematic of the experimental setup. Impact velocities of up to 10 m/s were achieved using a class 3 lever mechanism. In this mechanism, actuation of the lever was controlled by a high-force linear push solenoid (AC-Laminate Model 18P-I120A, Guardian Electric Manufacturing). An interchangeable stainless-steel substrate was attached to the load arm. Both the load arm and solenoid were installed on separate cast iron bases to isolate unnecessary vibrations. A syringe pump (Harvard Apparatus, Model 1150) was used to generate liquid droplets of diameter 2.8 - 3.3 mm. The impact velocity and thus Weber number of the impacting droplets was varied by
changing the height of the syringe pump platform. At a height of 165 mm from the impact point of droplet with the substrate the droplet had a velocity up to 1.7 m/s and at a height of 965 mm droplet velocity up to 4.2 m/s was observed. The substrate achieved a velocity of 6.0 – 6.1 m/s at the position of impact with the arm oriented orthogonally (horizontally) with respect to the falling droplet.

![Figure B.1 Schematic of setup to study drop wall interaction at high velocity.](image)

To ensure repeatability of drop-wall impact at the center of the substrate and in a horizontal condition, a timing circuit was devised using a National Instruments data acquisition card (NI-DAQ USB-2009) and implemented in LabView. A low power laser diode (Thorlabs CPS450, 450 nm) and photodiode were positioned below the tip of the needle such that the falling droplets block the path of the beam and the negative pulse triggers the solenoid after a user-set delay time specified in the LabView program. A temporal repeatability of better than 1 ms was achieved from trial-to-trial. The delay was adjusted manually to ensure droplet impact on the substrate at a near horizontal position with the resulting impact velocity between 7.7±0.1 m/s and 10.3±0.1 m/s. A 500-W halogen lamp was used with a diffuser as a background light source. A 150 mm focal length
plano-convex lens was used to collimate the background light to achieve a uniform light field. The images were recorded using a high-speed camera (Photron Fastcam SA-X2) at 30000 kHz with an exposure of 0.25 s. A Nikon 50 mm variable aperture lens was used with a 20 mm extension tube and at f/16 aperture allowing a 20 mm depth of field. The images were normalized by the background light field. Two stainless-steel substrates were used with the surface roughness 0.20 µm and 3.20 µm respectively.

### B.2.2 Digital in-line holography

This technique uses a collimated laser beam to illuminate the background of the object field and is implemented by collecting the hologram created by casting this illuminating beam and the generated diffraction pattern on a digital imaging sensor. Particles or droplets present in the field result in a diffraction pattern that is digitally recorded. The standard digital in-line holography technique assumes a planar reference wave. Using this representation and a known diffraction integral, the light field can be reconstructed numerically by solving the diffraction integral equation. The present study uses a 10-mW He-Ne laser (632 nm wavelength) to provide the reference beam for the holograms. The beam is expanded to a final diameter of 50.8 mm in two steps as shown in the experimental configuration in Fig. B.2.

![Figure B.2 Dual view holography set up](image-url)
A Photron Fastcam SA-X2 camera with $1024 \times 1024$ - pixel sensor and a pixel size of 20 $\mu$m was used to capture the holograms. A Model KX InfiniMax long-distance microscope was used with an MX-5 objective lens that provided a magnification of 2.56. The camera was set up to record image sequence at 60 kHz and with an exposure of 0.25 $\mu$s. Each of the experiments were repeated 20 times to identify particle tracks. A secondary camera (Photron Fastcam SA-5) was used without any lens to capture an unmagnified view of the drop-wall interaction at 15 kHz and an exposure time of 10 $\mu$s. A 2” Pellicle beam-splitter was used to split the hologram to be recorded simultaneously by both cameras (Figure 4). The magnified images are recorded with an offset of 1.5 to 2 diameters away from the impact point of the primary droplet to capture secondary atomization droplets.

After recording the images, the hologram is reconstructed every 10 $\mu$m through the optical depth of 10 mm. The image processing routine implemented in Holosand extracts the 3D position of detected individual particles. A Hungarian linker algorithm is used to link those particles in subsequent frames as implemented by Guildenbecher et al. (2014). The tracks are then identified across multiple user-defined frames to extract secondary droplet diameter and 3D velocities. Fig. B.3 shows an example of recorded and reconstructed holograms and Fig. B.8 shows an example of particle tracking. The image processing was done on a Windows 10 PC running on Intel Core i5-3230M CPU (clock frequency 2.6GHz) with an installed DDR3 memory of 8GB and total available graphics memory of 5GB on Nvidia GeForce GT 740M GPU. With this configuration, the process of hologram reconstruction, particle detection and tracking across 8 frames at a time took 20 – 25 minutes for each event. The frames for reconstruction and particle tracking were manually selected to detect the maximum number of particles across the selected frames.

### B.3 Results and discussion

This section reports and discusses observations in the drop-wall impact experiments. Backlit images show the characteristics of splash at different conditions. The particle tracking algorithm is elaborated, and quantitative data of secondary droplet size and velocity is discussed. Further, in
Figure B.3 Example holograms recorded for n-heptane droplet impacting a rough substrate (3.20 µm RMS, We = 5400). (a) Reconstructed hologram of primary droplet at distance 306 mm from the image sensor. (b) Original recorded hologram 0.8 ms after impact, (c) reconstructed image of (b) The box shows spatial location of magnified image recorded 1.5 diameters away. (d) Reconstructed hologram from the magnified view at a z-depth of 64 mm. (e) Tenengrad for the reconstructed hologram. (f) Objects detected by the image processing algorithm where the scale bar represents 500 µm.

In the discussion, the stainless-steel substrate with roughness of 0.20 µm RMS is referred as smooth and the substrate with roughness value of 3.20 µm RMS is referred as rough.

B.3.1 Influence of Weber number and surface roughness

Droplet impact outcomes of water at two different Weber number of 2680 and 4990 are shown in Fig. B.4. On a smooth surface, deposition of the water droplet is observed at a Weber number of 2680. As the relative impact velocity increases, the splashing becomes more prominent. A fine mist of secondary is observed at a higher Weber number of 4990. On a rough surface, the water droplet impacts to produce a corona splash at both Weber numbers. Several finger-like ligaments
characterize the corona and these fingers are connected by a thin liquid film, as previously observed by Rioboo et al. (2001). Increasing the Weber number from 2680 to 4990 increases the corona width and reduces the apex height as observed in the frame-wise comparison. This increasing impact velocity drives changes in the breakup morphology and is expected to modify the secondary droplet characteristics.

Figure B.4 Image sequence of water drop-wall impact. The primary droplet diameters are 3.3 – 3.4 mm. The smooth surface has a roughness of 0.20 µm RMS and the rough surface has a roughness of 3.20 µm RMS.

The second set of results shows an overview of characteristics for impact of n-heptane with the same smooth and rough substrates. Fig. B.5 shows the high density of secondary droplets after the impact of the heptane droplet on the rough surface at both low Weber number of 5400 and high Weber number of 10100. At 132 µs, a mist of heptane droplets is observed to form the corona. However, on smooth surface at Weber number of 5400, the mist is hardly visible, deposition is the primary outcome. At Weber number of 10100, the mist of secondary droplets forms a very
prominent crown on smooth surface. Further at 264 $\mu$s and 396 $\mu$s, the crown-like structure of the corona disappears. The mist of secondary droplets formed due to impact on the rough surface is denser than that formed on the smooth surface at higher Weber number, however the crown of the corona in the later is taller.

![Image sequence of heptane drop-wall impact. The primary droplet diameters are 2.7 – 2.8 mm.](image)

Vertical liquid ligaments form on the rough surface later in the impact sequence of a heptane droplet (396 $\mu$s). Such ligaments were not observed in the case of water. During the disintegration, filaments orient perpendicular to the substrate and detach from the wall as it travels radially outwards. As shown in Fig. B.6, after detaching from the larger body of fluid, these filaments disintegrate into secondary droplets. These droplets are significantly larger than the secondary droplets formed from the disintegration of the crown. Increasing surface roughness promotes the generation of these late-forming ligament structures.
Figure B.6  Enlarged image sequence of heptane impacting a rough stainless-steel substrate (3.20 µm RMS) at We = 10100 showing ligaments disintegrating into secondary droplets.

B.3.2 Influence of surface tension

The surface tension of water exceeds that of heptane by over three times and the effect is observed prominently in the impact sequences at comparable Weber numbers of 4990 and 5400, respectively. The crown of the corona splash is larger and lasts longer in case of water. On a rough surface, the higher surface tension of water enables the crown to sustain the liquid film but in the impact sequence of heptane the film quickly breaks up, resulting in the absence of any observable film but numerous small secondary droplets. The heptane crown breakup occurs on significantly shorter timescales, as evident from comparing between water and heptane for equal frame spacing, as shown in Fig. B.7.

B.3.3 Comparison of secondary droplet size and velocities

The magnified images from the SA-X2 camera were used to estimate the droplet size and positions in 3D space. The magnification of 2.56× allows particles to be detected that are smaller
Figure B.7 Enlarged image depicting the difference between the crown breakup of water (left) at \( \text{We} = 4990 \) and heptane (right) at \( \text{We} = 5400 \). Primary droplet diameters: water - 3.3 to 3.4 mm, heptane - 2.7 to 2.8 mm.

than the pixel size of the camera. The minimum allowable diameter of the detected particle is set to 15 \( \mu \text{m} \). The previously mentioned hybrid method of particle detection is used to identify secondary droplets. The tracking algorithm uses the position data extracted from the reconstructed hologram and links the particles across multiple frames in two dimensions by minimizing the sum of the square of distance between them. The \( z \)-location used for velocity calculation is approximated to the \( y \)-intercept of a linear fit of the estimated depth \( z \) obtained from the hologram reconstruction (see Fig. B.8). The diameter of the particle tracked is reported as the average of the diameters detected across the selected frames. As showed by Guildenbecher et al. (2013), this procedure can improve \( z \)-location uncertainty to within two times the mean particle diameter. The high density of small particles in the image field causes difficulty in recognizing overlapping tracks, but the particle-matching algorithm results in improved confidence that spurious detection are filtered out.

Secondary droplets produced by drop-wall impact of heptane at a Weber number of 10100 on both surfaces were too small to be detected by the current experimental setup, so results are only
presented for We 5000 for both water and n-heptane. Probability distribution functions of secondary droplet size and 3D velocity of heptane and water on rough surface at a Weber number of 5400 and 4990 respectively are compared in Fig. B.9. The data represent diameter and velocities for detected droplets tracked in 6–8 frames between 716 ± 33 µs and 884 ± 33 µs after droplet impact using the particle-linking algorithm. A total of 106 individual heptane droplets were tracked in 6 impact events and 119 water droplets in 10 instances out of 20 trials for each.

Fig. B.9 indicates a wider range of detected particle sizes and velocities for water. Most heptane particles had velocities under 20 m/s and diameters below 50 µm. These values were lower than values for water, where most droplet velocities were equal and above 20 m/s and diameters were larger than 50 µm. The impact velocity of primary water droplet was 10.3 m/s and that of heptane was 7.7 m/s, the primary water droplet is also larger than heptane by 7.3 µL which implies that it has higher kinetic energy at impact. The higher kinetic energy of the primary water droplet manifests as higher momentum of individual secondary droplets. Therefore, a greater proportion

![Sample output of particle tracking across 8 frames. (a) Particle tracks of Heptane at We = 5400. (b) Individual track with information of the particle position and diameter in 3D space.](image-url)
of secondary droplets of water travel at higher velocities compared to heptane. The diameter of the droplets ejected are also bigger in case of water. The higher surface tension of water allows the secondary droplets to be stable at slightly larger diameters. The relation between diameter and velocity of the detected secondary droplets 1.5 to 2 diameters away from point of impact is shown in Fig. B.10 which complements the results presented above. No correlation between droplet velocity and size was observed for water but for heptane, the data suggests lower velocities than water at the same spatial location relative to the droplet impact. Secondary droplets of heptane form earlier than water (see Fig. B.7) and thus experience air resistance (drag) for a longer time which might explain the lower velocities.

![Comparison of distributions of droplet diameter and velocity of heptane and water at Weber numbers 5400 and 4990 respectively.](image)

**Figure B.9** Comparison of distributions of droplet diameter and velocity of heptane and water at Weber numbers 5400 and 4990 respectively.

### B.4 Conclusion

An experimental apparatus was built to study the outcomes of drop-wall impact at high velocity of 10 m/s. The Weber numbers for water were 2680 and 4990 and for heptane were 5400 and 10100. A corona splash was observed on a rough surface in all experimental cases. Increasing Weber number resulted in the increase of corona width in case of water and reduction in secondary droplet size in case of heptane. Deposition and splashing was the predominant outcome of drop-wall impact on smooth surface at Weber number 2680 for water and 5400 for heptane. Increasing surface
roughness facilitates the formation of corona splash. Vertical ligaments were observed in case of heptane splash on rough surface at Weber number of 10100. Surface tension was found to influence the crown morphology of the corona splash. Higher surface tension results in the formation of liquid film and a characteristic crown in case of water, whereas the crown after the impact of a heptane droplet constitutes mist of secondary droplets. Droplet sizing and velocities were quantified by digital in-line holography. Secondary droplets of heptane were smaller and travelled at lower velocities than water at comparable Weber numbers near 5000.
APPENDIX C. REGIME DIAGRAM OF HEATED DROP-WALL IMPACT

The characteristics of the surface in drop-wall impact influences the type of splash. In a heated drop-wall impact, the surface characteristics affect the heat transfer and the vapor layer formation affects the morphology of splash. An aluminum block heated by a band heater was used to heat the surface that was attached to the solenoid actuated lever mechanism used in the drop-wall impact holography setup. Temperatures of up to 275 °C was achieved. At room temperature, n-heptane droplets displayed deposition on a smooth surface at Weber number of 1900. At elevated temperatures, splashing was observed right at impact. The same stainless steel surfaces were used as the ones used for holography experiments.

The splash morphology identified were classified into three categories: prompt, corona and transition to corona splash. In a corona splash, a distinctive crown of liquid sheet could be seen which form ligaments and fragments into droplets. In contrast, prompt splash results in droplet formation without any visible liquid sheet being formed. A transition to corona splash regime was identified in which a clear corona was not visible. Fig. C.1 shows the three categories of splashing regimes that have been identified and represented on the regime diagram in Fig. C.2.

Figure C.1 Types of splash.
Figure C.2  Regime diagram showing the splashing threshold for impact of n-heptane on a heated wall.