Journal of Visualized Experiments

Visualization of High Speed Liquid Jet Impaction on a Moving Surface

--Manuscript Draft--

Manuscript Number:	JoVE52603R3
Full Title:	Visualization of High Speed Liquid Jet Impaction on a Moving Surface
Article Type:	Invited Methods Article - JoVE Produced Video
Keywords:	Liquid jet impingement; high-speed moving surface; spray nozzle; liquid friction modifier (LFM); air cannon; spinning disk; rail track lubrication; Fluid Mechanics
Manuscript Classifications:	93.34.17: flow measurement; 93.34.18: flow visualization (general applications); 93.34.22: fluid flow; 93.34.3: atomizers; 93.34.48: laminar flow (general); 93.34.54: multiphase flow; 93.34.6: boundary layer flow (general); 93.34.75: viscous flow
Corresponding Author:	Sheldon Green University of British Columbia Vancouver, British Columbia CANADA
Corresponding Author Secondary Information:	
Corresponding Author E-Mail:	Sheldon.Green@ubc.ca
Corresponding Author's Institution:	University of British Columbia
Corresponding Author's Secondary Institution:	
First Author:	Yuchen Guo
First Author Secondary Information:	
Other Authors:	Yuchen Guo
Order of Authors Secondary Information:	
Abstract:	Two apparatuses for examining liquid jet impingement on a high-speed moving surface are described: an air cannon device (for examining surface speeds between 0 and 25 m/sec) and a spinning disk device (for examining surface speeds between 15 and 100 m/sec). The air cannon linear traverse is a pneumatic energy-powered system that is designed to accelerate a metal rail surface mounted on top of a wooden projectile. A pressurized cylinder fitted with a solenoid valve rapidly releases pressurized air into the barrel, forcing the projectile down the cannon barrel. The projectile travels beneath a spray nozzle, which impinges a liquid jet onto its metal upper surface, and the projectile then hits a stopping mechanism. A camera records the jet impingement, and a pressure transducer records the spray nozzle backpressure. The spinning disk set-up consists of a steel disk that reaches speeds of 500 to 3000 rpm via a variable frequency drive (VFD) motor. A spray system similar to that of the air cannon generates a liquid jet that impinges onto the spinning disc, and cameras placed at several optical access points record the jet impingement. Video recordings of jet impingement processes are recorded and examined to determine whether the outcome of impingement is splash, splatter, or deposition. The apparatuses are the first that involve the high speed impingement of low-Reynolds-number liquid jets on high speed moving surfaces. In addition to its rail industry applications, the described technique may be used for technical and industrial purposes such as steelmaking and may be relevant to high-speed 3D printing.
Author Comments:	
Additional Information:	
Question	**Response**
If this article needs to be "in-press" by a certain date to satisfy grant requirements, please indicate the date below and explain in your cover letter.	

If this article needs to be filmed by a certain date to due to author/equipment/lab availability, please indicate the date below and explain in your cover letter.	

THE UNIVERSITY OF BRITISH COLUMBIA

a place of mind

Department of Mechanical Engineering
6250 Applied Science Lane
Vancouver, BC Canada V6T 1Z4

Tel: 604-822-0497
Fax: 604-822-2403
E-mail: green@mech.ubc.ca
http://mech.ubc.ca/

August 8, 2014

Journal of Visualized Experiments
1 Alewife Center, Suite 200
Cambridge, MA, USA 02140

Dear Editor,

We submit the following manuscript entitled "Experimental Methods for Examining High Speed Liquid Jet Impaction on a Moving Surface" for publication in JoVE as a multimedia piece.

The article provides operational specifications on two apparatuses built for examining liquid jet impingement on a high-speed moving surface. As the results of the two experimental approaches include videotaped recordings of liquid jet impingement behaviors, the experimental method would be effectively communicated through a multimedia format.

Yuchen Guo and I have worked on this project as part of a research and development project that involves engineering and refining liquid friction modifier products for reducing rail track friction. Mr. Guo has conducted experiments on the described apparatuses over the past several years as part of his Master's program in Mechanical Engineering at UBC and has built several components of the experimental set-up described. As the lead researcher on this project, I supervise Mr. Guo's experiments. JoVE Applied Physics Editor Mathew Solomon has provided editorial assistance throughout the submission process.

Sincerely,

Professor Sheldon Green
Head, Department of Mechanical Engineering

TITLE:

Visualization of High Speed Liquid Jet Impaction on a Moving Surface

AUTHORS:

Yuchen Guo
Department of Mechanical Engineering
University of British Columbia
Vancouver, BC, Canada
guoyuchen88@gmail.com

Dr. Sheldon Green
Department of Mechanical Engineering
University of British Columbia
Vancouver, BC, Canada
sheldon.green@ubc.ca

CORRESPONDING AUTHOR:

Dr. Sheldon Green
(604) 822-0497

KEYWORDS:

Liquid jet impingement; high-speed moving surface; spray nozzle; liquid friction modifier (LFM); air cannon; spinning disk; rail track lubrication; fluid mechanics.

SHORT ABSTRACT:

Two experimental devices for examining liquid jet impingement on a high-speed moving surface are described: an air cannon device and a spinning disk device. The apparatuses are used to determine optimal approaches to the application of liquid friction modifier (LFM) onto rail tracks for top-of-rail friction control.

LONG ABSTRACT:

Two apparatuses for examining liquid jet impingement on a high-speed moving surface are described: an air cannon device (for examining surface speeds between 0 and 25 m/sec) and a spinning disk device (for examining surface speeds between 15 and 100 m/sec). The air cannon linear traverse is a pneumatic energy-powered system that is designed to accelerate a metal rail surface mounted on top of a wooden projectile. A pressurized cylinder fitted with a solenoid

valve rapidly releases pressurized air into the barrel, forcing the projectile down the cannon barrel. The projectile travels beneath a spray nozzle, which impinges a liquid jet onto its metal upper surface, and the projectile then hits a stopping mechanism. A camera records the jet impingement, and a pressure transducer records the spray nozzle backpressure. The spinning disk set-up consists of a steel disk that reaches speeds of 500 to 3000 rpm via a variable frequency drive (VFD) motor. A spray system similar to that of the air cannon generates a liquid jet that impinges onto the spinning disc, and cameras placed at several optical access points record the jet impingement. Video recordings of jet impingement processes are recorded and examined to determine whether the outcome of impingement is splash, splatter, or deposition. The apparatuses are the first that involve the high speed impingement of low-Reynolds-number liquid jets on high speed moving surfaces. In addition to its rail industry applications, the described technique may be used for technical and industrial purposes such as steelmaking and may be relevant to high-speed 3D printing.

INTRODUCTION:

This research aims to determine strategies for applying LFM (Liquid Friction Modifier) in liquid jet form onto a moving surface while attaining high degrees of transfer efficiency and uniform deposition results. Achieving this objective involves developing a comprehensive understanding of factors that affect liquid jet impingement on moving surfaces.

The project is motivated by a need to improve the efficiency of lubrication application techniques used in the rail sector. As a means of reducing fuel consumption and locomotive maintenance costs, a thin film of friction modifying agent is now being applied to the upper rail surface of conventional railroad tracks. Recent studies have shown that applying one type of water-based LFM for top of rail (TOR) friction control reduced energy consumption levels by 6% and rail and wheel flange wear by in excess of 50%[1,2]. Other studies have shown that applying LFM to rail tracks reduces lateral force and noise levels as well as, more importantly, track corrugation and damage from rolling contact fatigue, which is a major cause of derailments[3,4]. These results were further confirmed in field tests on the Tokyo subway system[5].

LFMs are currently dispensed from air blast atomizers attached to dozens of locomotives throughout Canada and the United States. In this form of application, LFM is applied to the top of railroad tracks by atomizers mounted beneath moving rail cars. This mode of LFM application is difficult to implement on many railroad locomotives because the required high-volume and high-pressure air supply levels may not be attainable. Air-blast spray nozzles are also believed to produce highly irregular rail coverage when operated in a crosswind, as crosswinds cause fine spray droplets to deviate from their original trajectory. Crosswinds are also known to be implicated in nozzle fouling, likely for the same reason. Due to problems associated with air blast atomizers, the rail sector is currently seeking alternative approaches to LFM application onto rail tracks. One viable solution involves dispensing LFM by means of a continuous (not-atomized) liquid jet, as liquid jets are less susceptible to crosswind effects due to their lower drag-to-inertia ratio. Additionally, because the high air pressure and volume levels needed for atomizing nozzles are not required in liquid jet spray technologies, the latter act as more streamlined and robust spraying mechanisms that maintain effective control over the rate of LFM application.

An area of similar physics, droplet impingement, has been studied intensively. It was found by several researchers that for droplet impingement on a moving dry smooth surface, splashing behavior is dependent on many parameters including viscosity, density, surface tension and the normal component of the impact velocity[14,15]. Bird et al. demonstrated that both the normal and tangential velocities were of critical importance[16]. Range et al. and Crooks et al. have shown that for droplet impingement on a stationary dry surface, surface roughness decreases the splash threshold significantly (i.e., it makes the droplet more prone to splash)[17,18].

Despite its practical importance, jet impingement on moving surfaces has received little attention in the academic literature. Chiu-Webster and Lister performed an extensive series of experiments that examined steady and unsteady viscous jet impingement on a moving surface, and the authors developed a model for the steady flow case[6]. Hlod et al. modeled the flow by means of a third-order ODE on a domain of unknown length under an additional integral condition and compared predicted configurations with experimental results[7]. However, the Reynolds numbers examined in both of these studies are much lower than those associated with typical railroad LFM applications. Gradeck *et al.* numerically and experimentally investigated the flow field of water jet impingement onto a moving substrate under various jet velocity, surface velocity, and nozzle diameter conditions[8]. Fujimoto et al. additionally investigated flow characteristics of a circular water jet impinging onto a moving substrate covered by a thin film of water[9]. However, these two projects used relatively large nozzle diameters and lower surface and jet velocities compared to those employed in the present work. Furthermore, though previous experimental, numerical, and analytical studies provide a large body of data, the majority have focused on heat transfer parameters rather than on liquid flow processes such as jet splashing behavior. The experimental method provided in the present research thus contributes to liquid jet application technologies by refining such techniques under conditions involving smaller jet nozzle diameters and high-speed jet and surface velocities. The present method also refines knowledge on fundamental fluid mechanics problems associated with moving contact lines.

The studies mentioned above have generally involved the interaction of a low speed jet with a low speed moving surface. There have been comparatively few studies of laminar high speed jet impingement onto high-speed moving surfaces. During high speed liquid jet impaction the jet liquid spreads radially in the vicinity of the impingement location, forming a thin lamella. This lamella is then convected downstream by the viscous forcing imposed by the moving surface, producing a characteristic U-shaped lamella. Keshavarz et al. have reported on experiments employing Newtonian and elastic liquid jets impinging onto high-speed surfaces. They classified impingement processes into two distinct types: “deposition” and “splash”[10]. For impingement to be classified as deposition, the jet liquid must adhere to the surface, whereas splash is characterized by a liquid lamella that separates from the surface, and subsequently breaks up into droplets. A third impingement regime has also been described – “splatter”. In this, comparatively rare, regime the lamella remains attached to the surface, as for “deposition”, but fine droplets are ejected from near the leading edge of the lamella. In a subsequent study of non-Newtonian fluid effects, Keshavarz et al. concluded that the splash/deposition threshold is mainly determined by the Reynolds and Deborah numbers, whereas the jet impingement angle and jet velocity to surface velocity ratios only have a minor effect[11]. In experiments conducted under variable ambient air pressures, Moulson et al. discovered that the splash/deposition threshold Reynolds number dramatically increases with decreasing ambient air pressure (i.e., higher ambient pressures make jets more prone to splash), while decreasing ambient air pressure below a certain threshold suppresses splash completely[12]. This finding strongly suggests that aerodynamic forces acting on the lamella play a crucial role in causing lamella lift-off and subsequent splash. In recent work on high-speed impingement on a high-speed substrate, Sterling showed that for substrate speed and jet conditions close to the splash threshold, splash may be triggered by very small localized surface roughness and minor jet unsteadiness. He also showed that under these conditions lamella lift-off and reattachment is a stochastic process[13].

The experimental protocol described here may be used to study other physical situations involving the interaction of a fluid with a moving high speed surface. For example, the same approach could be used to study helicopter blade-vortex interaction (provided that the vortex fluid was colored with tracer particles) and robotic spraying of surfaces.

PROTOCOL:

1. Spinning Disk Device

1.1. Identify desired test conditions and record test conditions in a table (e.g. ambient temperature, fluid properties, jet and surface speed, etc.)

1.2. Preparation of Materials

1.2.1. Prepare glycerin-water or PEO-glycerin-water solutions for the impingement tests.

1.2.1.1. In the case of PEO-glycerin-water tests, gradually dissolve 4.5 grams of PEO powder (viscosity-average molecular weights of one million and four million) into 1495.5 grams of distilled water under gentle magnetic stirring over a 24 hr period. Avoid excessively agitating the PEO sample to prevent mechanical degradation.

1.2.1.2. Gradually add 1.5 kilograms of USP-grade glycerin to the aqueous PEO solution over a 24-hr period to reach an aqueous solution of 0.15% PEO concentration and 50% glycerine concentration.

1.2.2. Store the test liquids separately in airtight containers under room temperature before and after each test to minimize evaporation, water absorption from ambient air and contamination. Characterize and spray liquids within five days of preparation.

1.3. Performance of Experiments

1.3.1. Make sure the spinning disk air bearing's air supply valve is open and the pressure gauge reading is in the correct working range (60-80 psig). Clear anything that might impede the disk movement and turn the disk by hand in both directions 5 rotations to check for any problems with the disk and bearings.

1.3.2. Clean and secure the compressed gas closed accumulator for test fluid pressurization. Pour 3 kilograms of test liquid into the fluid port of the 1-gallon accumulator.

1.2.3. Connect the gas port of the accumulator to the nitrogen tank via a pressure regulator. Connect the fluid port of the accumulator to the jet spray nozzle.

1.4. Set up control system and high-speed imaging system.

1.4.1. Start the spinning disk control software and VFD control software. Position two high-speed cine cameras 35 cm away from the impingement point and adjust the high magnification lenses to capture the impingement point from two angles.

1.4.2. Adjust the 150 watts fiber-optic light source to achieve an evenly lit background for best image quality (Figure 1). Power on the control system at this point to facilitate camera adjustment.

1.4.3. Perform the self-check routine by clicking 'Self-check' button in the control software to make sure the system is functioning as expected.

1.5. Perform a jet impingement test

1.5.1. Set the disk speed to the desired value with the VFD control software (500 rpm - 3000 rpm).

1.5.2. To perform a test, launch the automated experimental sequence from the control software by clicking the 'Test sequence' button. The software will determine the optimal parameters automatically and coordinate each component of the system to perform the test accordingly.

1.5.3. Save the resultant impingement test video (see, for example, the screen shot in Figure 2). Read and record surface speed, nozzle back pressure and temperature from the control software.

Note: After each test, a disk cleaning sequence runs automatically to rinse and dry the disk surface. Repeat the cleaning cycle as necessary until all test fluid residue has been removed.

CAUTION: While water and glycerin solution test fluids may be cleaned with the cleaning sequence, other LFMs need to be cleaned with organic solvents such as acetone. In such cases, apply the cleaning material to a cloth rather than spraying the disk directly.

1.6. Data Analysis

1.6.1. Prepare a spreadsheet containing information on each test condition (e.g., fluid properties, ambient temperature, surface roughness, etc.).

1.6.2. Open the recorded jet impingement images with cine viewing software, play full video recordings at normal speed and observe jet impingement behaviors.

1.6.3. Record impingement behavior characteristics (splash/spattering/deposition; see Figure 3) in the prepared spreadsheet, logging any unusual trends that may indicate complications with the experimental set-up.

1.6.4. Save test results and conditions in a spreadsheet. Record notable findings and unusual occurrences in test log (e.g. splash/deposition threshold point, splash/deposition transitions, etc.). Save screenshots when necessary.

1.6.5. Conduct image analysis measurements and record data.

1.6.5.1. Launch the on-screen pixel measuring tool. Open impingement images, and calibrate the image scale by measuring a micro-ruler in the images with the on-screen pixel measuring tool (Figure 4).

1.6.5.2. Measure dimensions of interest (e.g., lamella spread width, W, and lamella stagnation point radius, R; see Figure 5) with the pixel measuring tool at a point where the jet appears to be most stable in the video and record data in the prepared spreadsheet. Then take another group of measurements 100 frames after the first group of measurements to confirm that both the jet and the lamella are stable. Plot data points on a graph and complete the curve fitting.

2. Air Cannon Device

2.1. Identify desired test conditions and prepare materials as in step 1.1 and step 1.2.

2.2. Performance of Experiments

2.2.1. Power up the system-control software.

2.2.2. Insert the projectile into the cannon barrel. Move the stop mechanism close to the barrel exit to properly capture the projectile after a test (Figure 6).

2.2.3. Open the pressurized building air line leading to the air tank. Pressurize the tank to between 30 psi and 70 psi, depending on the desired projectile velocity. 30 psi tank pressure gives a projectile speed of around 5 m/s, and 70 psi gives a speed of around 25 m/s.

2.2.4. Prepare the compressed gas closed accumulator for test fluid pressurization.

2.2.4.1. Pour 3 kilograms of test liquid into the fluid port of the accumulator. Connect tubing from the accumulator gas valve to the liquid jet spray nozzle, and set the accumulator pressure to up to 300 psig.

2.2.5. Attach and position the high-intensity light source and high-speed cine camera. Attach the camera to the scissor jack. Secure the scissor jack to the platform positioned next to the jet spray nozzle.

2.2.6. Secure the fiber-optic light to the platform positioned across from the camera and behind the diffusion sheet. Check lighting and camera positioning using the video camera viewing function of the software control interface, and adjust positioning as necessary (Figure 7).

2.2.7. Put on earmuffs for protection from the air cannon sound blast.

2.2.8. Unlock the cannon control panel, and press the warning button on the control panel multiple times to signal the start of an experiment.

2.2.9. Hit the control panel button that opens the solenoid valve connecting the air tank with the air cannon barrel.

2.2.10. After the device has been fired and the projectile captured, clean the device by wiping it with cleaning fluid and a sponge to remove residual test fluid. Finally, dry the impingement surface of the projectile.

2.3. Measure speed of the projectile in the recorded high-speed video by measuring the amount of time required for the projectile to travel a fixed (10 cm) distance. Analyze data as in step 1.5.

REPRESENTATIVE RESULTS:

As discussed in the introductory section, the three main behaviors associated with liquid jet impingement are deposition, splatter and splash. These jet impingement behaviors are observed using video data recorded by high-speed cine cameras positioned at various optical points. Examples of still images, obtained from the video recordings, which depict the three liquid jet outcomes are shown in Figure 3. Figure 3a depicts liquid jet deposition, in which the jet flows in a completely straight and steady stream towards the impingement surface. The jet adheres to the surface and remains on the surface for the remainder of the experiment. Figures 3b and 3c show less optimal results in which the liquid jet only partially adheres to the impingement surface, with the remainder of the jet either splattering (Figure 3b) or splashing (Figure 3c) upon impact.

Given the fairly straightforward nature of the given video data, ambiguous results are uncommon and repeatable results have been obtained from both experimental devices. However, in very rare cases that typically involve very smooth surface roughness conditions, the lamella of a liquid jet stream may interact with droplets or roughness on the surface in such a way that causes it to lift off from the impingement surface (Figure 8). In equally unusual circumstances, a small disturbance in the flow can produce irregularities in the jet, which upon surface impaction become amplified, causing the jet to separate from the surface for a long period of time (Figure 9). These rare phenomena typically occur only for high surface speeds and for intermediate jet fluid viscosities (Re=100~2500). The consistency of results is largely credited to the use of a pressure accumulator for driving the test liquid, which, unlike a pump, propels liquid at a constant rate, producing a very smooth action and thus a highly consistent, uniform and steady liquid flow.

With respect to splash/deposition characteristics, the results show that for metal surfaces of average roughness heights ranging between 0.01 µm and 1 µm, decreasing the surface roughness makes the impinging jet more susceptible to splash. For example, Figure 3(a) and

Figure 3(c) show impingement under similar jet and surface speed conditions. In Figure 3(a) jet deposition occurs on the surface, which has an average roughness height of 0.51 µm, but jet splash occurs when the average roughness height is 0.016 µm (Figure 3(c)). This dependence on roughness is opposite to that observed by Keshavarz et al.[10,11], who studied impingement on much rougher surfaces, where the surface roughness is significantly larger than the lamella thickness.

The threshold of splash is a complex function of the liquid jet velocity; liquid jet diameter; liquid viscosity, density and surface tension; the surface speed and roughness; and the surrounding air characteristics. Although some simple theories of splash have been proposed[10-12], there is currently no comprehensive explanation of the phenomenon. Lamella liftoff, which is usually a precursor to splash[12], is believed to be a function of lamella geometry. As seen in Figure 10, the lamella geometry is itself a complex function of many variables, including the jet and surface speeds and liquid physical properties.

Figure 1: Schematic of optical configuration of spinning disk device.

Figure 2: Screenshot of typical video recording.

Figure 3: Three typical flow regimes. (a) deposition, (b) splatter, (c) splash. In all instances the substrate moves from right to left and the jet diameter is 564 µm. The relevant jet and substrate conditions are: (a) V_{jet}= 18.3 m/s, $V_{substrate}$=7.50 m/s, μ_{jet}= 0.0194 Ns/m^2, ρ_{jet}=1180 kg/m^3, σ_{jet}=0.0656 N/m, Re_{jet}=629, We_{jet}=3400; (b) V_{jet}= 9.5 m/s, $V_{substrate}$= 7.63 m/s, μ_{jet}= 0.0097 Ns/m^2, ρ_{jet}= 998 kg/m^3, σ_{jet}=0.0717 N/m, Re_{jet}=552, We_{jet}=709; (c) V_{jet}=17.3 m/s, $V_{substrate}$= 7.71 m/s, μ_{jet}= 0.0194 Ns/m^2, ρ_{jet}=1180 kg/m^3, σ_{jet}=0.0656 N/m, Re_{jet}=594, We_{jet}=3040.

Figure 4: Measurement of jet diameter and lamella geometry with image processing software.

Figure 5: Planform view schematic of jet impingement showing characteristic lamella dimensions.

Figure 6: Air cannon mechanical configuration.

Figure 7: Air cannon optical configuration.

Figure 8: Time sequence showing the transition from jet deposition to jet splash. In this

sequence the transition is caused by very fine droplets adhering to the otherwise dry substrate. The substrate is moving from right to left at a speed $V_{substrate}$=7.52 m/s. The jet conditions are: D_{jet}= 564 μm; V_{jet}= 17.5 m/s, μ_{jet}= 0.0194 Ns/m^2, ρ_{jet}=1180 kg/m^3, σ_{jet}=0.0656 N/m, Re_{jet}=600, We_{jet}=3110.

Figure 9: Time sequence showing the transition from jet deposition to jet splash. In this sequence the transition is caused by a small air bubble in the jet that perturbs the flow. The substrate is moving from right to left at a speed $V_{substrate}$=7.43 m/s. The jet conditions are: D_{jet}= 564 μm; V_{jet}=15.8 m/s, μ_{jet}= 0.0194 Ns/m^2, ρ_{jet}=1180 kg/m^3, σ_{jet}=0.0656 N/m, Re_{jet}=542, We_{jet}=2530.

Figure 10: Lamella spread width to jet diameter ratio, as a function of Reynolds number of substrate. Substrate speed $V_{substrate}$ is varied from 15 m/s to 60 m/s, giving a Reynolds number Re_S of 75 to 300. The jet conditions are: D_{jet}= 281 μm; V_{jet}=14.6 m/s, μ_{jet}= 0.0701 Ns/m^2, ρ_{jet}=1220 kg/m^3, σ_{jet}=0.0640 N/m, Re_{jet}=71.4, We_{jet}=1140.

DISCUSSION:

The projectile used for the air cannon set-up is composed of a lightweight, wooden base. Though the wooden material chips slightly after numerous tests, it has been found to absorb kinetic energy more effectively than projectiles composed of materials such as plastic or metal, which tend to shatter upon impacting the stop mechanism. The dimensions of the wooden projectile are designed to closely match the steel barrel interior, thus restricting air leakage. A 1/8” thick rubber sheet secured between two layers of plywood is attached to the back of the projectile to further tighten the seal around the inside of the barrel. The metal impingement surfaces mounted on top of the projectile are fastened as three separate metal plates of different roughness heights, positioned 2.5 cm apart, so that the liquid jet can impinge on all three surfaces in one test with minimal interference. The front of the projectile is shaped into an aerodynamic nose with a barb on the bottom of the nose so that the stop mechanism, which has a heavy aluminum body with a latch mechanism inside, connects securely to the projectile upon impact. Rather than being fixed in place, the stop mechanism slides backwards by roughly 60 cm upon catching the projectile. This function dissipates kinetic energy from the projectile and prevents material damage.

The high-speed cine camera attached to the air cannon device visualizes jet impaction on the projectile surface. The camera’s wide-screen CMOS sensor allows one to capture images at extremely high frame rates and resolutions. A 1 kW, high-intensity incandescent light source is used to illuminate the field of view, and a light diffusor sheet is placed between the light source and the impingement point to achieve an evenly lit background. Two cameras and light sources are installed on the spinning disk device to capture video recordings from more than one angle. One camera positioned above the impingement point records the front view of the jet impingement, while the second camera records a side view. The camera lenses are covered with a sheet of acetate film to prevent contact with test fluids and to provide a clear viewing window after each test. The side-view camera is illuminated by a high-intensity, fiber-optic light source that locally illuminates the impingement site without blocking the axle. The front-view camera is illuminated by a high-intensity, 100-watt, 6700 Lumen white LED array fitted with a collimating lens.

The two experimental set-ups are controlled electrically by two custom-built control boxes. The custom-built control software allows the user to generate and collect digital and analog signals through a USB DAQ system inside the control box. A controllerthen utilizes these signals to control each component of the experimental set-up (high-speed camera, light, nozzle, etc.).

The described experimental set-up is limited in that two separate machines were built to test a broad range of surface speeds. The air cannon device can only be operated at slower speeds because it is very difficult to stop non-destructively a projectile moving at velocities higher than 25 m/sec, within the limited space of a laboratory. With the spinning disk there was concern that the rotary motion of the disk would cause associated centripetal forces on the fluid, which would in turn affect the fluid mechanics. This concern proved to be unwarranted as testing with the same jet conditions and same surface speeds on the air cannon (linear surface velocity) and the spinning disk yielded almost identical impaction characteristics. The maximum allowed Reynolds number is limited by liquid jet breakup. In the experiments conducted on these set-ups, a Reynolds number of 1,500 was easily reached. Substrate speed on the high-speed set-up is limited by the capacity of the VFD motor (i.e. maximum rotational speed and maximum power output to overcome drag, inertia, etc.), provided the disk and shaft are well balanced.

The described apparatuses differ from existing techniques that examine liquid jet impingement in that they accommodate the study of high-speed liquid jet impingement over high surface speed conditions (25-100 m/sec) using small liquid jet nozzle diameters. Because liquid jet impingement processes that occur on stationary and low-speed moving surfaces differ considerably from those associated with high-speed moving surfaces with respect to liquid build-up and spread patterns, the described technique can further existing knowledge on liquid jet impingement behaviors under a broader range of conditions. The technique’s focus on splash, splatter and deposition processes associated with liquid jet impingement also addresses a knowledge gap in this field, which has previously been preoccupied with heat transfer patterns. As liquid jet impingement onto a substrate is a highly complex multiphase fluid mechanics problem that poses many possible avenues for future research, the described technique may be used for a number of technical and industrial applications such as steelmaking and ink-jet printing, cooling, heating and surface coating.

DISCLOSURES:

The authors have nothing to disclose.

ACKNOWLEDGMENTS:

The Natural Sciences and Engineering Research Council of Canada (NSERC) and L.B. Foster Rail Technologies, Corp. jointly supported this research through the NSERC Collaborative Research and Development Grant program.

REFERENCES:

1. Cotter, J. *et al.* Top of Rail Friction Control: Reductions in Fuel and Greenhouse Gas Emissions. In: *Proc. Of the 2005 Conference of the International Heavy Haul Association (Rio de Janeiro),* 327-334 (2005).

2. Eadie, D.T., Bovey, E., and Kalousek, J. The role of friction control in effective management of the wheel/rail interface. *Railway Technical Conference* (2002).

3. Stock, R., Eadie, D.T., Elvidge, D., & Oldknow, K. Influencing rolling contact fatigue through top of rail friction modifier application–A full scale wheel–rail test rig study. *Wear*. **271** (1), 134-142, doi: 10.1016/j.wear.2010.10.006 (2011).

4. Eadie, D.T., Santoro, M., Top-of-rail friction control for curve noise mitigation and corrugation rate reduction. *Journal of Sound and Vibration.* **293** (3), 747-757, doi: 10.1016/j.jsv.2005.12.007 (2006).

5. Tomeoka, M., Kabe, N., Tanimoto, M., Miyauchi, E., Nakata, M. Friction control between wheel and rail by means of on-board lubrication. *Wear*. **253** (1), 124–129, doi: 10.1016/S0043-1648(02)00091-1 (2002).

6. Chiu-Webster, S., Lister, J. R. The fall of a viscous thread onto a moving surface: a 'fluid-mechanical sewing machine'. *Journal of Fluid Mechanics.* **569** (1), 89-111, doi: 10.1017/S0022112006002503 (2006).

7. Hlod, A., Aarts, A. C. T., Van De Ven, A. A. F., & Peletier, M. A. Mathematical model of falling of a viscous jet onto a moving surface. *European Journal of Applied Mathematics.* **18** (06), 659-677, doi: 10.1017/S0956792507007206 (2007).

8. Gradeck, M., Kouachi, A., Dani, A., Arnoult, D., & Borean, J. L. Experimental and numerical study of the hydraulic jump of an impinging jet on a moving surface. *Experimental Thermal and Fluid Science.* **30** (3), 193-201, doi: 10.1016/j.expthermflusci.2005.05.006 (2006).
9. Fujimoto, H., Suzuki, Y., Hama, T., & Takuda, H. Flow Characteristics of Circular Liquid Jet Impinging on a Moving Surface Covered with a Water Film. *ISIJ international.* **51** (9), 1497-1505, doi: 10.2355/isijinternational.51.1497 (2011).
10. Keshavarz, B., Green, S. I., Davy, M. H., & Eadie, D. T. Newtonian liquid jet impaction on a high-speed moving surface. *International Journal of Heat and Fluid Flow.* **32** (6), 1216-1225, doi: 10.1016/j.ijheatfluidflow.2011.08.001 (2011).
11. Keshavarz, B., Green, S. I., & Eadie, D.T., Elastic liquid jet impaction on a high speed moving surface. *AIChE Journal*, **58** (11), 3568–3577, doi: 10.1002/aic.13737 (2012).
12. Moulson, J. B. T., & Green, S. I. Effect of ambient air on liquid jet impingement on a moving substrate. *Physics of Fluids.* **25** (10), 102106-1-11, doi: 10.1063/1.4823726 (2013).
13. Sterling, G. E. G. An experimental study on jet impingement on a very high speed moving surface. *UBC M.A.Sc. Thesis* (2012).
14. Povarov, O. A., Nazarov, O. I., Ignat'evskaya, L. A., & Nikol'skii, A. I. Interaction of drops with boundary layer on rotating surfaces. *Journal of Engineering Physics and Thermophysics*. **31** (6), 1453-1456, doi: 10.1007/BF00860580 (1976).
15. Fathi, S., Dickens, P., & Fouchal, F. Regimes of droplet train impact on a moving surface in an additive manufacturing process. *Journal of Materials Processing Technology*. **210** (3), 550-559, doi: 10.1016/j.jmatprotec.2009.10.018 (2010).
16. Bird, J. C., Tsai, S. S., & Stone, H. A. Inclined to splash: triggering and inhibiting a splash with tangential velocity. *New Journal of Physics*. **11** (6), 063017, doi: 10.1088/1367-2630/11/6/063017 (2009).
17. Range, K., & Feuillebois, F. Influence of surface roughness on liquid drop impact. *Journal of Colloid and Interface science*. **203** (1), 16-30, doi: 10.1006/jcis.1998.5518 (1998).
18. Crooks, R., & Boger, D. V. Influence of fluid elasticity on drops impacting on dry surfaces. *Journal of Rheology*. **44** (4), 973-996, doi: 10.1122/1.551123 (2000).

Figure 1
Click here to download high resolution image

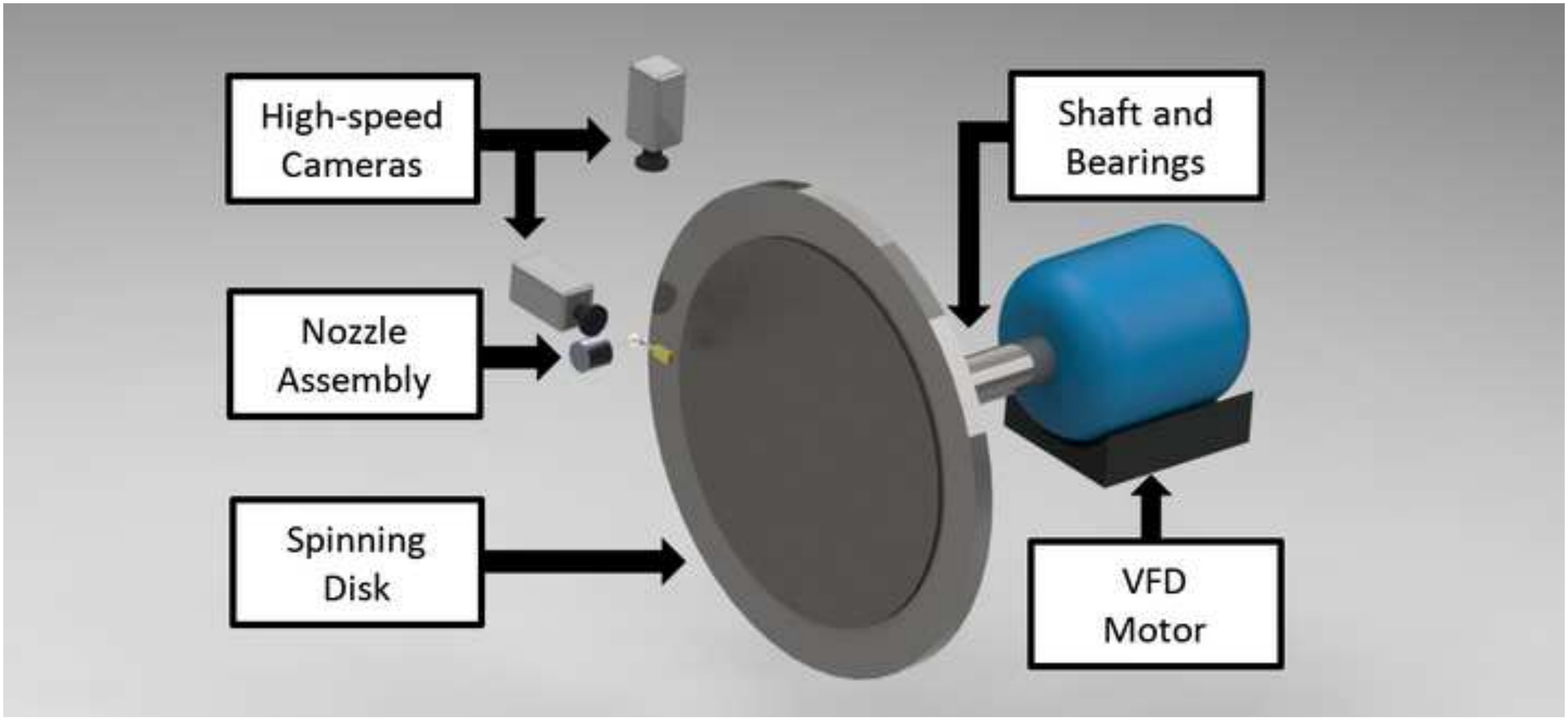


Figure 2
Click here to download high resolution image

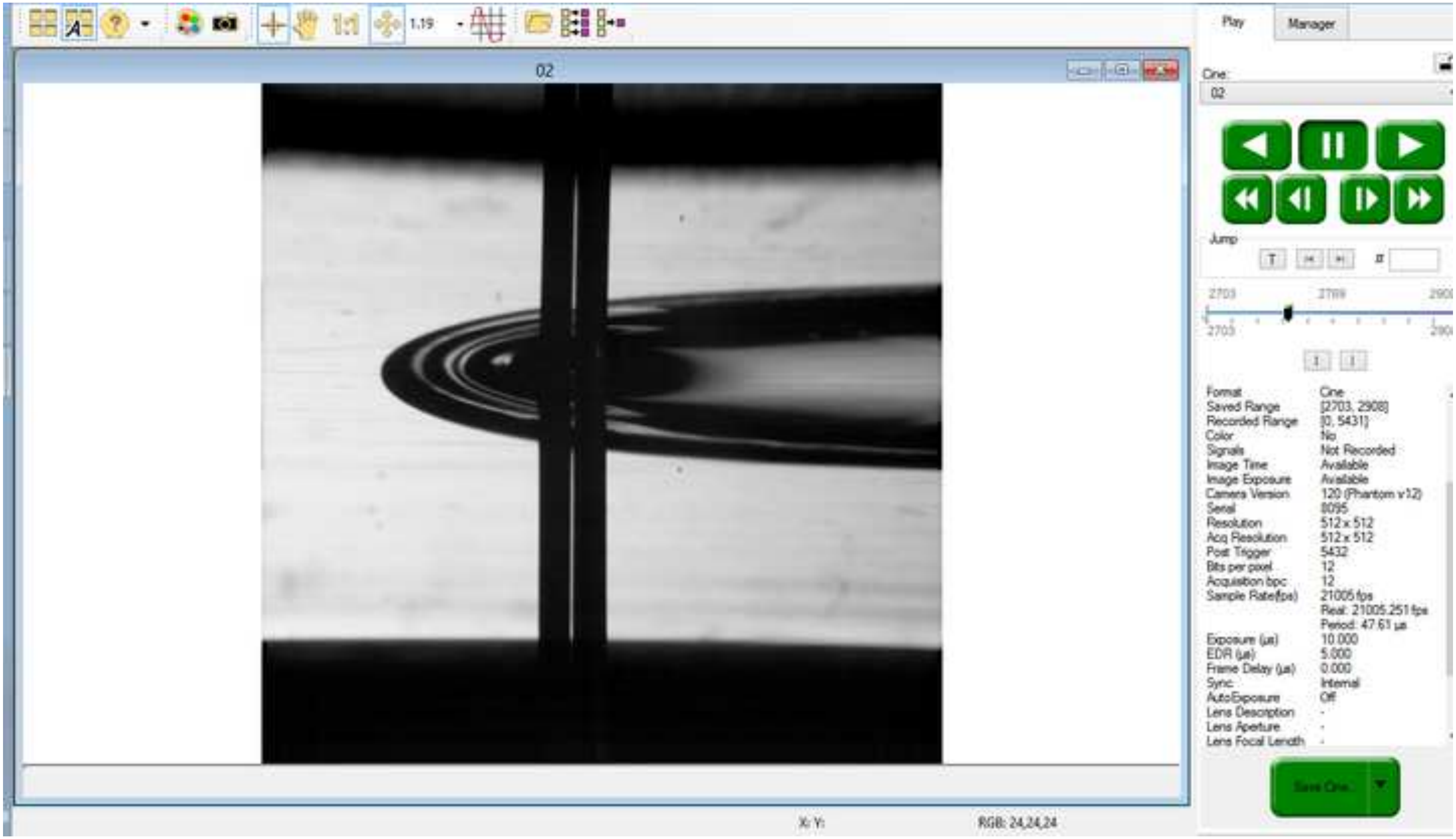


Figure 3
Click here to download high resolution image

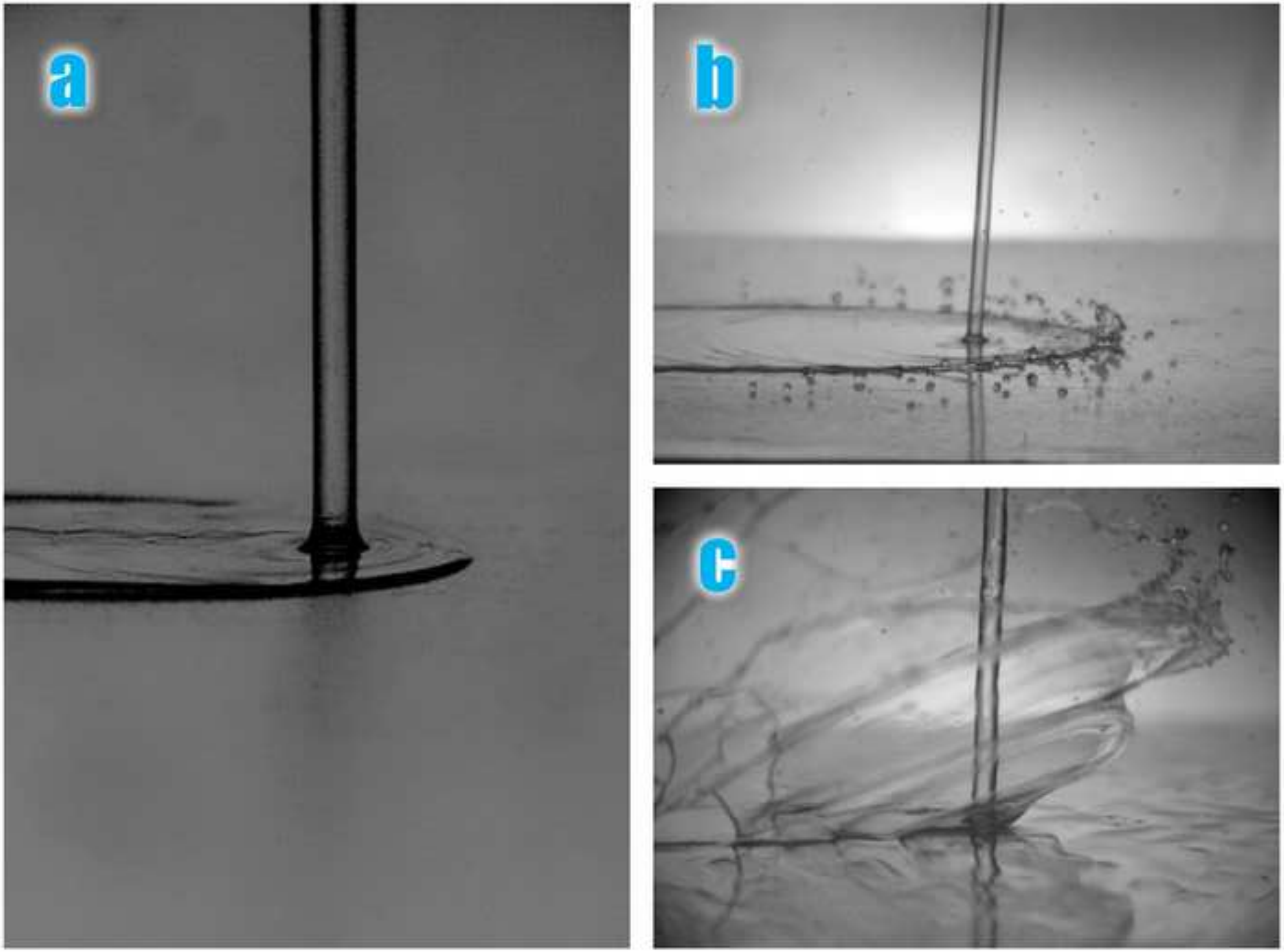


Figure 4
Click here to download high resolution image

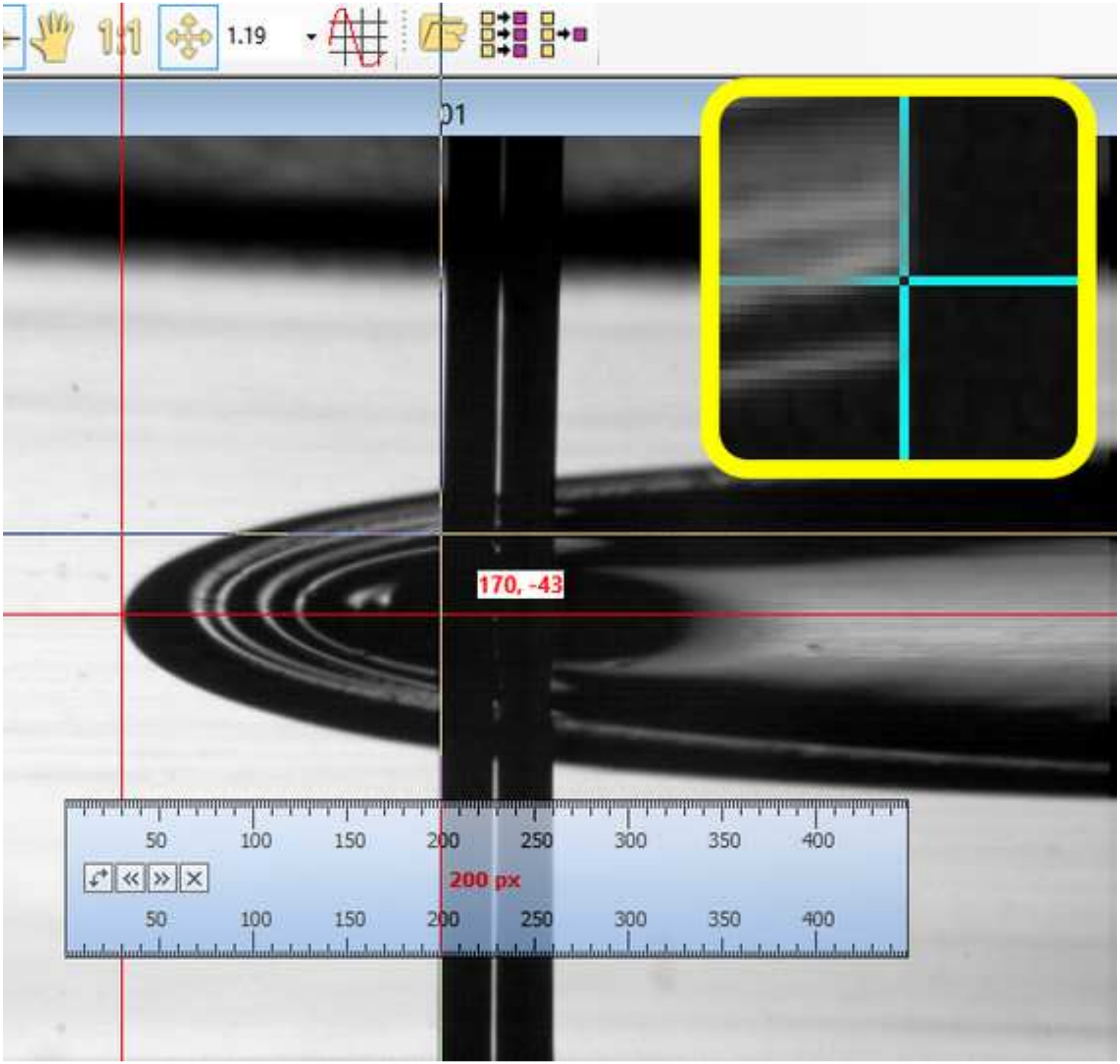


Figure 5
Click here to download high resolution image

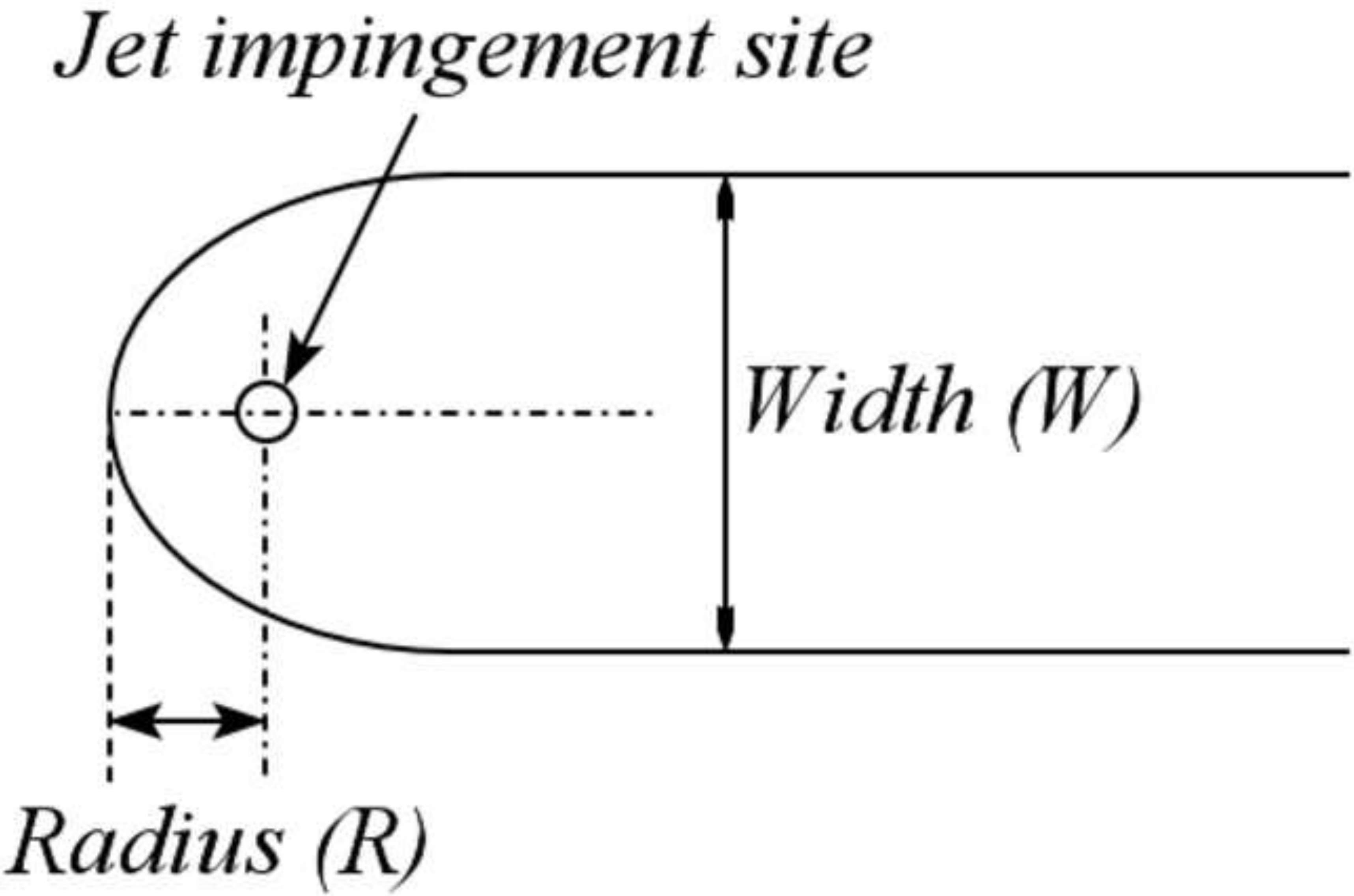


Figure 6
Click here to download high resolution image

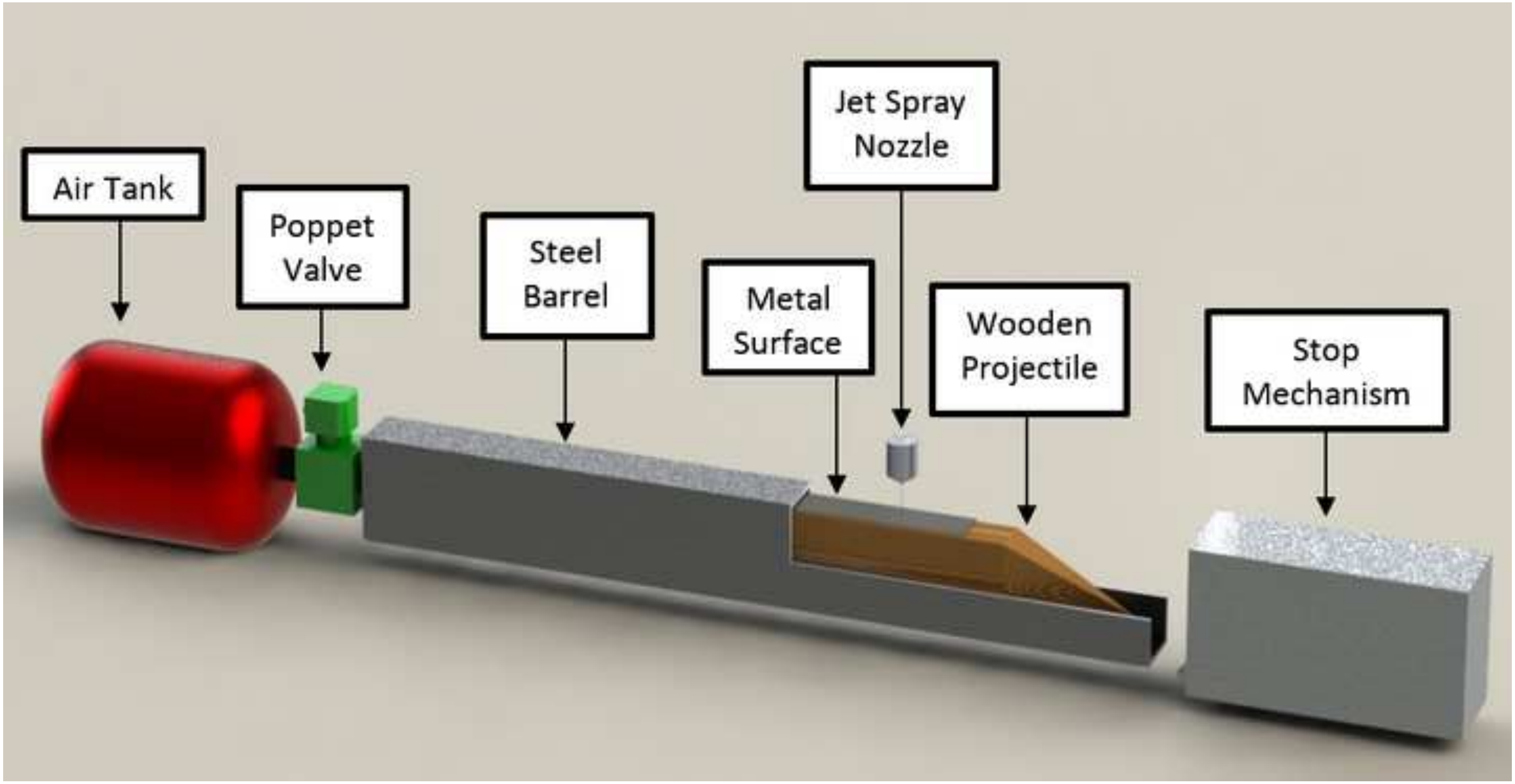


Figure 7
Click here to download high resolution image

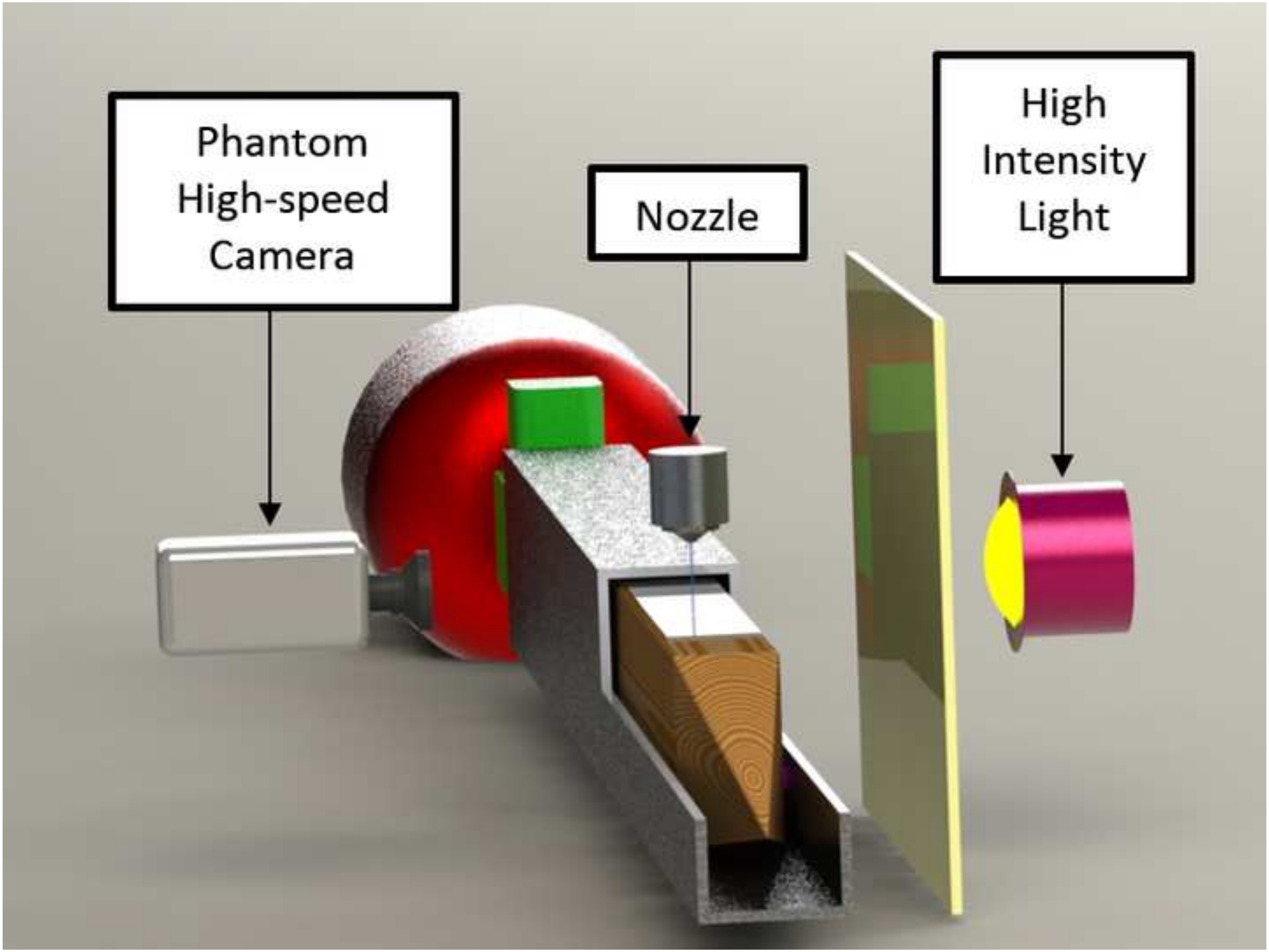


Figure 8
Click here to download high resolution image

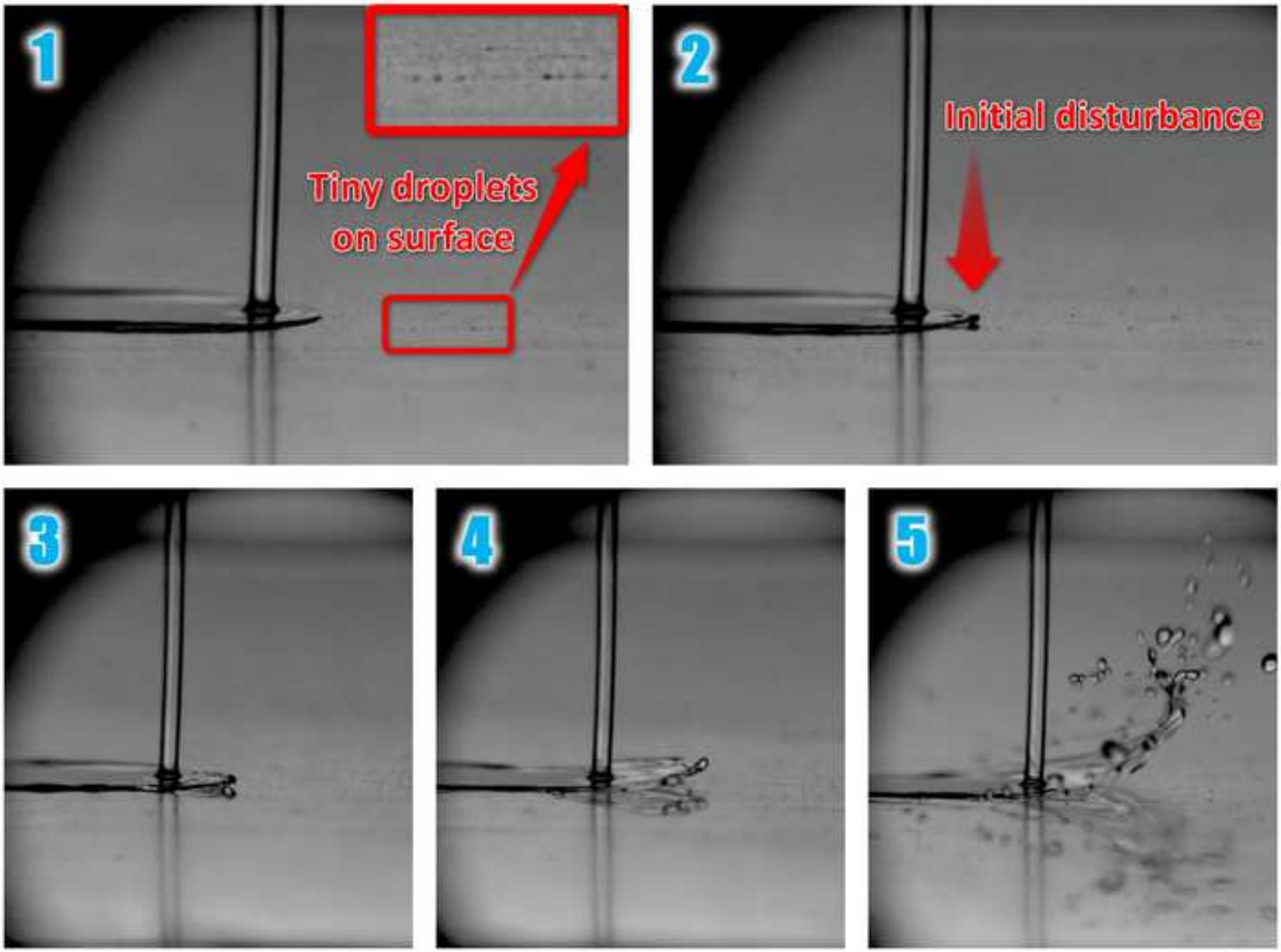


Figure 9
Click here to download high resolution image

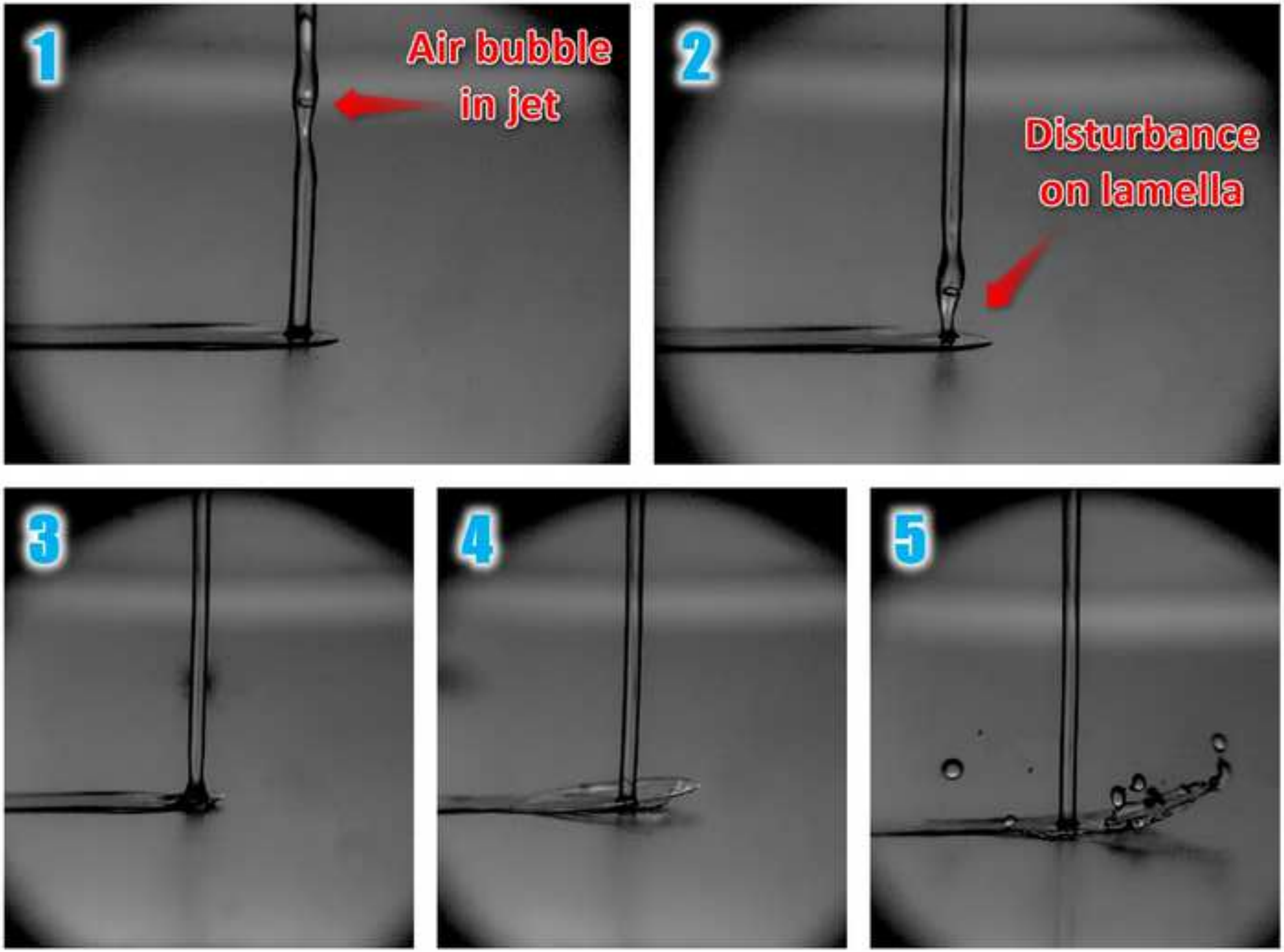
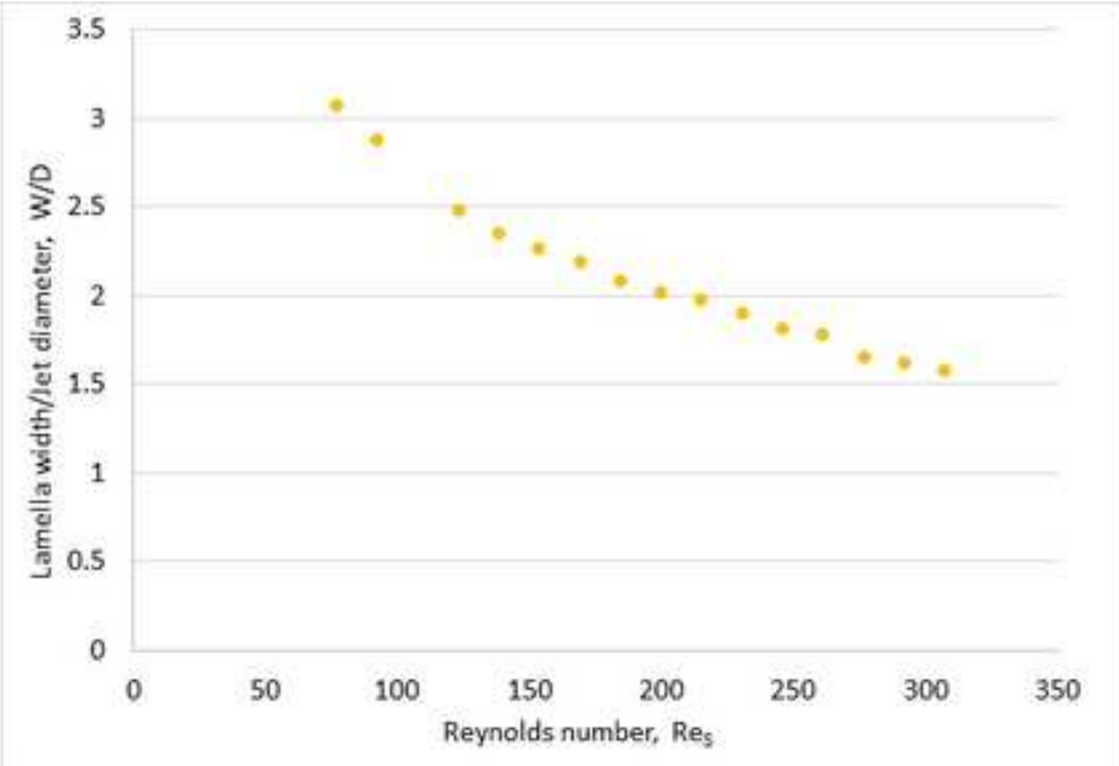


Figure 10 (Lamella width to Jet Diameter)
Click here to download high resolution image



Excel Spreadsheet- Table of Materials/Equipment
Click here to download Excel Spreadsheet- Table of Materials/Equipment: Materials Table.xls

Name of Material/ Equipment	Company	Catalog Number
Equipment for Air Cannon Set-Up		
30-gallon air tank	Steel Fab	A10028
Solenoid actuated poppet valve	Parker Hannifin Corp.	#16F24C2164A3F4C80
1.5"NPT rubber hose		
Rectangular steel tubing		
Stop mechanism	Customized	N/A
Stainless steel plates	Customized	N/A
Wooden projectile	Customized	N/A
1kw high-intensity incandescent light	Photographic Analysis Ltd.	T986851
Light diffuser sheet		
Optic sensor	BANNER	SM312LV
Equipment for Spinning Disc Set-Up		
Motor	WEG	TEFC-W22
Bearings		
Disk	Customized	N/A
Fiber optic light source	Fiberoptics Technology Incorporated	MO150AC
High intensity LED array	Torshare Ltd.	TF10CA
Vacuum	Ridge Tool Company	WD09450
Interrupter	Customized	N/A
Shared Equipment for Both Devices		
Phantom v611 high-speed cine camera	Vision Research Inc.	V611
Phantom v12 high-speed cine camera	Vision Research Inc.	V12
Zoom 7000 lens	Navitar Inc.	Zoom 7000
Zoom 6000 lens	Navitar Inc.	Zoom 6000
Compressed nitrogen tank	Praxair Technology, Inc.	
Pressure regulator	Praxair Technology, Inc.	PRS20124351CGA
Hose for compressed nitrogen	Swagelok Company	SS-CT8SL8SL8-12
Hose for liquid	Swagelok Company	SS-7R8TA8TA8
Accumulator	Accumulators, Inc.	A131003XS
Solenoid Valve	Solenoid Solutions Inc.	2223X-A440-00

Pressure transducer	WIKA Instruments Ltd	#50398083
Nozzle assembly	Customized	N/A
Glycerin		
Poly(ethylene oxide)		

Comments/Description

1 Alewife Center #200
Cambridge, MA 02140
tel. 617.945.9051
www.jove.com

ARTICLE AND VIDEO LICENSE AGREEMENT

Title of Article: Visualization of High Speed Liquid Jet Impaction

Author(s): Yuchen Guo, Sheldon Green

Item 1 (check one box): The Author elects to have the Materials be made available (as described at http://www.jove.com/publish) via: ☐ Standard Access ☒ Open Access

Item 2 (check one box):

☒ The Author is NOT a United States government employee.

☐ The Author is a United States government employee and the Materials were prepared in the course of his or her duties as a United States government employee.

☐ The Author is a United States government employee but the Materials were NOT prepared in the course of his or her duties as a United States government employee.

ARTICLE AND VIDEO LICENSE AGREEMENT

1. Defined Terms. As used in this Article and Video License Agreement, the following terms shall have the following meanings: "**Agreement**" means this Article and Video License Agreement; "**Article**" means the article specified on the last page of this Agreement, including any associated materials such as texts, figures, tables, artwork, abstracts, or summaries contained therein; "**Author**" means the author who is a signatory to this Agreement; "**Collective Work**" means a work, such as a periodical issue, anthology or encyclopedia, in which the Materials in their entirety in unmodified form, along with a number of other contributions, constituting separate and independent works in themselves, are assembled into a collective whole; "**CRC License**" means the Creative Commons Attribution-Non Commercial-No Derivs 3.0 Unported Agreement, the terms and conditions of which can be found at: http://creativecommons.org/licenses/by-nc-nd/3.0/legalcode; "**Derivative Work**" means a work based upon the Materials or upon the Materials and other pre-existing works, such as a translation, musical arrangement, dramatization, fictionalization, motion picture version, sound recording, art reproduction, abridgment, condensation, or any other form in which the Materials may be recast, transformed, or adapted; "**Institution**" means the institution, listed on the last page of this Agreement, by which the Author was employed at the time of the creation of the Materials; "**JoVE**" means MyJove Corporation, a Massachusetts corporation and the publisher of *The Journal of Visualized Experiments;* "**Materials**" means the Article and / or the Video; "**Parties**" means the Author and JoVE; "**Video**" means any video(s) made by the Author, alone or in conjunction with any other parties, or by JoVE or its affiliates or agents, individually or in collaboration with the Author or any other parties, incorporating all or any portion of the Article, and in which the Author may or may not appear.

2. Background. The Author, who is the author of the Article, in order to ensure the dissemination and protection of the Article, desires to have the JoVE publish the Article and create and transmit videos based on the Article. In furtherance of such goals, the Parties desire to memorialize in this Agreement the respective rights of each Party in and to the Article and the Video.

3. Grant of Rights in Article. In consideration of JoVE agreeing to publish the Article, the Author hereby grants to JoVE, subject to **Sections 4** and **7** below, the exclusive, royalty-free, perpetual (for the full term of copyright in the Article, including any extensions thereto) license (a) to publish, reproduce, distribute, display and store the Article in all forms, formats and media whether now known or hereafter developed (including without limitation in print, digital and electronic form) throughout the world, (b) to translate the Article into other languages, create adaptations, summaries or extracts of the Article or other Derivative Works (including, without limitation, the Video) or Collective Works based on all or any portion of the Article and exercise all of the rights set forth in (a) above in such translations, adaptations, summaries, extracts, Derivative Works or Collective Works and (c) to license others to do any or all of the above. The foregoing rights may be exercised in all media and formats, whether now known or hereafter devised, and include the right to make such modifications as are technically necessary to exercise the rights in other media and formats. If the "Open Access" box has been checked in **Item 1** above, JoVE and the Author hereby grant to the public all such rights in the Article as provided in, but subject to all limitations and requirements set forth in, the CRC License.

4. Retention of Rights in Article. Notwithstanding the exclusive license granted to JoVE in **Section 3** above, the Author shall, with respect to the Article, retain the non-exclusive right to use all or part of the Article for the non-commercial purpose of giving lectures, presentations or teaching classes, and to post a copy of the Article on the Institution's website or the Author's personal website, in each case provided that a link to the Article on the JoVE website is provided and notice of JoVE's copyright in the Article is included. All non-copyright intellectual property rights in and to the Article, such as patent rights, shall remain with the Author.

5. Grant of Rights in Video – Standard Access. This **Section 5** applies if the "Standard Access" box has been checked in **Item 1** above or if no box has been checked in **Item 1** above. In consideration of JoVE agreeing to produce, display or otherwise assist with the Video, the Author hereby acknowledges and agrees that, Subject to **Section 7** below, JoVE is and shall be the sole and exclusive owner of all rights of any nature, including, without limitation, all copyrights, in and to the Video. To the extent that, by law, the Author is deemed, now or at any time in the future, to have any rights of any nature in or to the Video, the Author hereby disclaims all such rights and transfers all such rights to JoVE.

6. Grant of Rights in Video – Open Access. This **Section 6** applies only if the "Open Access" box has been checked in **Item 1** above. In consideration of JoVE agreeing to produce, display or otherwise assist with the Video, the Author hereby grants to JoVE, subject to **Section 7** below, the exclusive, royalty-free, perpetual (for the full term of copyright in the Article, including any extensions thereto) license (a) to publish, reproduce, distribute, display and store the Video in all forms, formats and media whether now known or hereafter developed (including without limitation in print, digital and electronic form) throughout the world, (b) to translate the Video into other languages, create adaptations, summaries or extracts of the Video or other Derivative Works or Collective Works based on all or any portion of the Video and exercise all of the rights set forth in (a) above in such translations, adaptations, summaries, extracts, Derivative Works or Collective Works and (c) to license others to do any or all of the above. The foregoing rights may be exercised in all media and formats, whether now known or hereafter devised, and include the right to make such modifications as are technically necessary to exercise the rights in other media and formats. For any Video to which this Section 6 is applicable, JoVE and the Author hereby grant to the public all such rights in the Video as provided in, but subject to all limitations and requirements set forth in, the CRC License.

7. Government Employees. If the Author is a United States government employee and the Article was prepared in the course of his or her duties as a United States government employee, as indicated in **Item 2** above, and any of the licenses or grants granted by the Author hereunder exceed the scope of the 17 U.S.C. 403, then the rights granted hereunder shall be limited to the maximum rights permitted under such statute. In such case, all provisions contained herein that are not in conflict with such statute shall remain in full force and effect, and all provisions contained herein that do so conflict shall be deemed to be amended so as to provide to JoVE the maximum rights permissible within such statute.

8. Likeness, Privacy, Personality. The Author hereby grants JoVE the right to use the Author's name, voice, likeness, picture, photograph, image, biography and performance in any way, commercial or otherwise, in connection with the Materials and the sale, promotion and distribution thereof. The Author hereby waives any and all rights he or she may have, relating to his or her appearance in the Video or otherwise relating to the Materials, under all applicable privacy, likeness, personality or similar laws.

9. Author Warranties. The Author represents and warrants that the Article is original, that it has not been published, that the copyright interest is owned by the Author (or, if more than one author is listed at the beginning of this Agreement, by such authors collectively) and has not been assigned, licensed, or otherwise transferred to any other party. The Author represents and warrants that the author(s) listed at the top of this Agreement are the only authors of the Materials. If more than one author is listed at the top of this Agreement and if any such author has not entered into a separate Article and Video License Agreement with JoVE relating to the Materials, the Author represents and warrants that the Author has been authorized by each of the other such authors to execute this Agreement on his or her behalf and to bind him or her with respect to the terms of this Agreement as if each of them had been a party hereto as an Author. The Author warrants that the use, reproduction, distribution, public or private performance or display, and/or modification of all or any portion of the Materials does not and will not violate, infringe and/or misappropriate the patent, trademark, intellectual property or other rights of any third party. The Author represents and warrants that it has and will continue to comply with all government, institutional and other regulations, including, without limitation all institutional, laboratory, hospital, ethical, human and animal treatment, privacy, and all other rules, regulations, laws, procedures or guidelines, applicable to the Materials, and that all research involving human and animal subjects has been approved by the Author's relevant institutional review board.

10. JoVE Discretion. If the Author requests the assistance of JoVE in producing the Video in the Author's facility, the Author shall ensure that the presence of JoVE employees, agents or independent contractors is in accordance with the relevant regulations of the Author's institution. If more than one author is listed at the beginning of this Agreement, JoVE may, in its sole discretion, elect not take any action with respect to the Article until such time as it has received complete, executed Article and Video License Agreements from each such author. JoVE reserves the right, in its absolute and sole discretion and without giving any reason therefore, to accept or decline any work submitted to JoVE. JoVE and its employees, agents and independent contractors shall have

ARTICLE AND VIDEO LICENSE AGREEMENT

full, unfettered access to the facilities of the Author or of the Author's institution as necessary to make the Video, whether actually published or not. JoVE has sole discretion as to the method of making and publishing the Materials, including, without limitation, to all decisions regarding editing, lighting, filming, timing of publication, if any, length, quality, content and the like.

11. Indemnification. The Author agrees to indemnify JoVE and/or its successors and assigns from and against any and all claims, costs, and expenses, including attorney's fees, arising out of any breach of any warranty or other representations contained herein. The Author further agrees to indemnify and hold harmless JoVE from and against any and all claims, costs, and expenses, including attorney's fees, resulting from the breach by the Author of any representation or warranty contained herein or from allegations or instances of violation of intellectual property rights, damage to the Author's or the Author's institution's facilities, fraud, libel, defamation, research, equipment, experiments, property damage, personal injury, violations of institutional, laboratory, hospital, ethical, human and animal treatment, privacy or other rules, regulations, laws, procedures or guidelines, liabilities and other losses or damages related in any way to the submission of work to JoVE, making of videos by JoVE, or publication in *JoVE* or elsewhere by JoVE. The Author shall be responsible for, and shall hold JoVE harmless from, damages caused by lack of sterilization, lack of cleanliness or by contamination due to the making of a video by JoVE its employees, agents or independent contractors. All sterilization, cleanliness or decontamination procedures shall be solely the responsibility of the Author and shall be undertaken at the Author's expense. All indemnifications provided herein shall include JoVE's attorney's fees and costs related to said losses or damages. Such indemnification and holding harmless shall include such losses or damages incurred by, or in connection with, acts or omissions of JoVE, its employees, agents or independent contractors.

12. Fees. To cover the cost incurred for publication, JoVE must receive payment before production and publication the Materials. Payment is due in 21 days of invoice. Should the Materials not be published due to an editorial or production decision, these funds will be returned to the Author. Withdrawal by the Author of any submitted Materials after final peer review approval will result in a US$1,200 fee to cover pre-production expenses incurred by JoVE. If payment is not received by the completion of filming, production and publication of the Materials will be suspended until payment is received.

13. Transfer, Governing Law. This Agreement may be assigned by JoVE and shall inure to the benefits of any of JoVE's successors and assignees. This Agreement shall be governed and construed by the internal laws of the Commonwealth of Massachusetts without giving effect to any conflict of law provision thereunder. This Agreement may be executed in counterparts, each of which shall be deemed an original, but all of which together shall be deemed to me one and the same agreement. A signed copy of this Agreement delivered by facsimile, e-mail or other means of electronic transmission shall be deemed to have the same legal effect as delivery of an original signed copy of this Agreement.

A signed copy of this document must be sent with all new submissions. Only one Agreement required per submission.

CORRESPONDING AUTHOR:

Name: Sheldon Green

Department: Mechanical Engineering

Institution: UBC

Article Title: Visualization of High Speed Liquid Jet Impaction . . .

Signature: Sheldon G Date: Aug. 8, 2014

Please submit a signed and dated copy of this license by one of the following three methods:

1) Upload a scanned copy of the document as a pfd on the JoVE submission site;
2) Fax the document to +1.866.381.2236;
3) Mail the document to JoVE / Attn: JoVE Editorial / 1 Alewife Center #200 / Cambridge, MA 02139

For questions, please email submissions@jove.com or call +1.617.945.9051

Editorial comments:

Changes to be made by the Author(s):

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues. The JoVE editor will not copy-edit your manuscript and any errors in the submitted revision may be present in the published version.

The manuscript has been proofread and no spelling or grammatical issues were found.

2. A number of areas need greater detail:
-Step 1.1.5 asks to enter information on the test condition. These conditions should be mentioned in the protocol prior to this point if this data should be collected. How is this information collected?

A new step is added in the protocol prior to the original Step 1.1. Information on how to record test conditions can be found in Step 1.5.3.

-Describe the possible conditions listed in step 1.5.3 in a table or other way so that the various characteristic options are known.

We think there is no need to list the conditions in a table because all possible outcomes can be well described in three terms, namely splash, deposition and spatter. Also, the three outcomes are already shown and described in Figure 3.

-Section 1.5.5 does not describe how many images this information should be taken from. For instance, should it come from the video at 5 second intervals?

More details on image measurements are included in the protocol (Step 1.6.5). Because the test conditions are well-controlled in the impingement experiments, both the jet and the resulting lamella are highly stable in the case of deposition. Therefore, only two to three measurements are needed to confirm the measurement results are constant and reliable.

-How is the projectile speed measured in section 2?

This information is added to Step 2.3

- Please describe the stop mechanism in greater detail.

More detail on the stop mechanism is added to the Discussion.

3. References are missing DOIs in some cases. Please provide DOIs if available.

All available DOIs are provided in the reference list.

Reviewer #1:

(1) In the Intro, the authors refer to "dozens" of locomotives. I would much prefer an indication of the uptake of this technology in terms of percent use, for example.

The total amount of locomotives railroad companies possess is considered confidential business information, and therefore not disclosed to us. The company that makes profit from this technology, L.B. Foster, is currently listed in NASDAQ with a market cap of half a billion. Their global customers include Union Pacific and Canadian Pacific Railroad.

(2) In the Intro, two paragraphs start with effectively the same sentence: "Despite its practical importance, ..." and then "There have been comparatively few studies of ...". I think the second could be eliminated.

The second paragraph is modified to make the logic flow more explicit.

(3) While jet impingement onto surfaces hasn't been much studied, drop impingement has, and there's been lots of work on splashing and deposition, and the effect of roughness, for example. I'm not asking that the authors comprehensively cite that work, but I think an acknowledgement of that work, and references to one or two reviews would be appropriate.

A new paragraph is added in the introduction.

(4) Finally, I know this article isn't about the physics of jet impingement onto moving surfaces, but I was surprised that the authors didn't present their experiments in non-dimensional terms (e.g. Re, We, Oh, ...). Just a thought.

The dimensionless numbers are added to the manuscript.

Reviewer #2:

Manuscript Summary:
The article describe the design and use of two different devices for characterizing low-reynolds-number liquid jets on moving surfaces for applications in the transportation industries.

Major Concerns:
No Major Concerns.

Minor Concerns:
No Minor Concerns.

Additional Comments to Authors:
Very well written article. Illustrations are clear and the devices used are well described.

Reviewer #3:

1. The references in the introduction are insufficient. Searching the citations of, for example, reference 7 brings up 18 other articles; and the references are biased towards the work of the corresponding author and do not fully communicate the state of the field. In addition, a discussion of applications beyond lubrication of rails (pages 2 and 3) would increase interest for a broader readership.

5 more references have been added. A brief discussion of some possible applications of the experimental method is included in the last paragraph of Introduction (page 4).

2. The protocol steps in 1.4 (especially those describing the automated software acquisition) are poorly described. Is the software here custom-built or commercial? If the former, what are the critical design/control parameters? This information would be required to design a similar apparatus.

More details on the control system are added to Discussion.

3. This protocol would be significantly more useful if the authors were to provide specifics about the relevant dimensionless number regimes that they are able to access. For example, what is a "high speed" surface? What is an "intermediate fluid viscosity" (page 10 of protocol)? Such descriptors are not meaningful without the relevant dimensionless parameters. What Reynolds and Deborah numbers (in the case of non-Newtonian fluids) does this protocol allow access to (for example, in their test case data)? It is critical to specify these dimensionless numbers if the protocol is to be used to probe flow regimes that are inaccessible by other techniques. This information should probably be included in/near the introduction (as part of a comparison to existing techniques) and also in the discussion.

The dimensionless numbers are added to the manuscript.

4. The data analysis section is insufficient — although the authors provide a picture of a measuring tool in Figure 4, representative data (not simply pictures) should also be included. Again, this would aid researchers who wanted to use this technique to make quantitative measurements across a wide parameter space.

Figure 10 is added to the manuscript showing some representative measurement data.