IMPLEMENTATION OF LARGE SCALE SHADOWGRAPHY IN HYDROGEN SAFETY PHENOMENA

Dennis, K.[1,a] Maley, L.[1,b] Liang, Z.[2] Radulescu, M.I.[1,c]
[1]Department of Mechanical Engineering, University of Ottawa,
161 Louis Pasteur, Ottawa, K1N6N5, Canada
[a]kdenn034@uottawa.ca, [b] lmaley@uottawa.ca, [c] matei@uottawa.ca
[2]Atomic Energy Canada Limited, Ontario 17, Chalk River, Canada, liangz@aecl.ca

ABSTRACT

We have implemented a portable large-scale shadowgraph system for use in flow visualization relating to hydrogen safety. Previous large-scale shadowgraph and schlieren implementations have often been limited to background-oriented techniques which are subject to noise. The system built is based on a large-scale shadowgraph technique, developed by Settles, which allows for high-quality visualization. We have applied the shadowgraph system to complex phenomena and current issues in hydrogen safety including DDT in long channels, jet releases, and unconfined deflagrations. Shadowgrams taken are compared to a Z-schlieren system. This shadowgraph system allows analysis of these phenomena at longer length scales.

1.0 INTRODUCTION

Shadowgraph and schlieren visualization techniques are common and easy to implement in small scale [1]. For viewable areas exceeding approximately one meter, these methods become difficult to realize. Some of the primary issues with large scale visualization are the cost and availability of large optical components. Recently, Settles developed an affordable large-scale shadowgraphy system for visualization of explosions and gunshots [2]. We seek to determine the performance of this system as it pertains to issues in hydrogen safety, specifically hydrogen releases, flames, and detonations.

In order to construct a large-scale shadowgraphy system there are two prerequisites. The first is a powerful light source to illuminate a large area. The sun was the first light source used for shadowgraphy due to its availability and simplicity. Most notably, Weinstein's background schlieren produced an 80 m field of view surrounding a T-34 military aircraft using the sun as a light source [3]. The sun is the most powerful light source, however it cannot be used indoors or on days with poor weather conditions. NASA's Orion space vehicle was studied in a large-scale background-oriented schlieren (BOS) technique using a large array of LEDs [4]. A 2.74 m square flow field was generated surrounding the vehicle [4]. The light from an LED array is difficult to focus to single beam due to the size of the array. In flames, detonations, and explosions the light produced can overpower the light source making it impossible to resolve the phenomena. High intensity light sources such as the argon bomb have been developed to overcome this issue [5]. The argon bomb has been used in ballistics and shaped-charge explosive research [5, 6]. The light produced by an argon bomb has a duration of approximately 100 μs, ideal for capturing single images [5]. While an argon bomb produces intense light, its short duration makes it impractical for longer duration events where the evolution of the flow field is monitored by multi-frame video cameras. An arc lamp produces high intensity light continuously. Light can be easily collimated from a small opening for use with optical equipment. The arc lamp's potency in large-scale shadowgraphy has been previously demonstrated making it a strong light source candidate [2].

The second criteria for large-scale shadowgraphy is the background. Historically, outdoor backgrounds were used first, however their non-uniformity made it difficult to obtain high-quality images [7]. Grid-based backgrounds, such as those seen in BOS, remove the non-uniformity. Both BOS and outdoor background techniques produce noisy shadowgrams [4]. Large mirrors remove noise by providing a plain uniform surface and have high reflective ability. Settles demonstrated their functionality in large-scale schlieren [1]. Despite their advantages, large mirrors are very expensive and fragile, making them impractical. Edgerton developed a cheap and simple technique that removes most of the noise in large-scale shadowgraphy by using a retro-reflective screen [8, 9]. The screen reflects light back towards its origin, giving it a higher reflective ability compared to outdoor backgrounds, diffuse surfaces, and grid backgrounds. Edgerton's technique was used to make shadowgrams of vortices around helicopter rotor tips up to 1.5 m in radius [10]. Settles modernized and improved Edgerton's technique using an arc lamp and video camera. He produced shadowgrams of explosions and gunshots in a viewable region 2.4 m long [2]. The retro-reflective screen is flexible enough to be rolled into a tube, cheaper than mirrors and, minimizes background noise while reflecting most incident light making it ideal for use in shadowgraphy.

The large-scale shadowgraph system implemented in this paper uses an arc lamp for a light source, and retro-reflective screen as a background surface. The capabilities of this setup in general high-speed imaging have previously been demonstrated and optical theory in shadowgraphy is well understood [2, 1]. Large-scale shadowgraphy in hydrogen safety issues relating to jet releases, flames, and detonations is the focus of this paper. Hydrogen releases focus on jet release experiments modeling the sudden failure of a pressure vessel. Unconfined hydrogen-air flames model the dynamics of a flame in region of combustible gas. Deflagration-to-detonation transition (DDT) is studied in hydrogen mixtures in its relationship to detonation arrestors.

This paper is presented in two sections. The first section reviews the modernized Edgerton technique and documents the implementation of our large-scale shadowgraphy system. The second section evaluates the performance of the large scale visualization method for problems of hydrogen leak detection, jet release, unconfined deflagration, and DDT tests. Results are compared to a previously constructed schlieren setup.

2.0 SHADOWGRAPHY SYSTEM DESIGN

In 1958, Edgerton constructed a simple shadowgraphy system for visualization of explosions performed outdoors [8]. The Edgerton shadowgraphy technique is a simple direct shadowgraphy design using a retro-reflective screen. A schematic of the technique is shown in Fig. 1. Unlike walls which diffuse light, a retro-reflective screen reflects light back to its source. A key advantage of the screen is light entering at any angle and from any distance will be reflected back to its origin. By placing a light source and camera very close together, noise-free shadowgrams could be taken. The limitation of Edgerton's method is that the camera and light source were not on the same axis. Parallax caused by the misalignment creates a double image. When light returns from the screen, a significant amount is lost, decreasing luminosity.

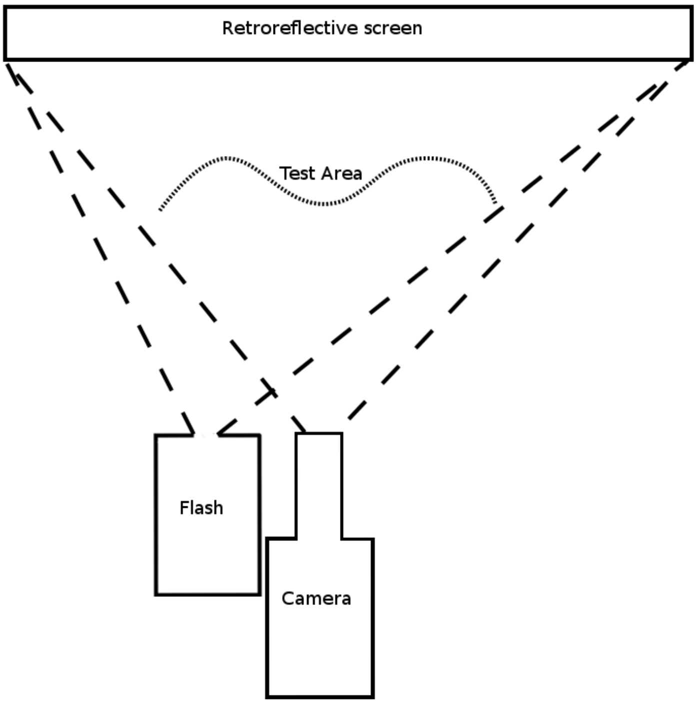

Figure 1: Top-view sketch of the retro-reflective shadowgraph technique by Edgerton [8].

Settles developed a solution to this problem by using two optical components. A condenser lens is used to focus light from the source to a point, as shown in Fig. 2. A small mirror mounted on the end of the camera lens reflects the focused light onto the retro-reflective screen [2]. In addition to optics changes, Settles introduced an arc lamp and high-speed camera. The 1000 W arc lamp used produced continuous illumination of the screen and allowed for video recording at up to 250,000 fr/s [2].

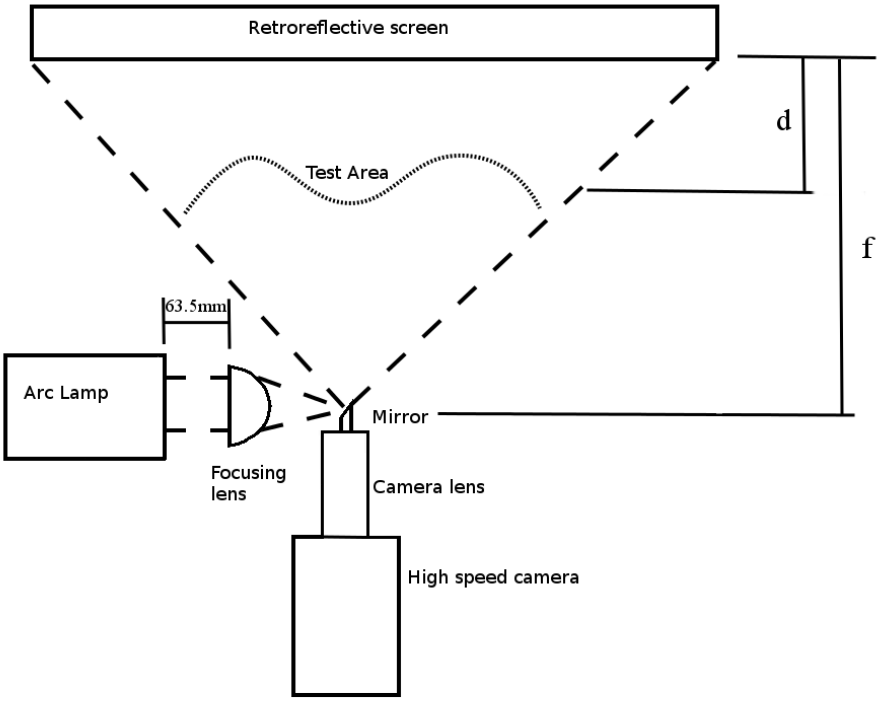

Figure 2: Top-view illustration of our retro-reflective shadowgraphy system

The shadowgraphy technique implemented in this paper uses the same layout as Settles design shown in Fig. 2. The light source is a 1600 W xenon arc lamp from Newport. The arc lamp bulb is held within a housing containing all ignition and cooling components. Using a 50 mm focal length lens the light is focused to a circle approximately 4 mm in diameter. A 10 mm diameter rod mirror is placed at the focal point of the lens which reflects light onto the screen. To ensure returning light enters the camera, the rod mirror is mounted on the end of the camera lens. A front view photograph of the setup is shown in Fig. 3.

Positioning of the camera and screen varied between 3.65 m, for jet release and deflagration tests, to 5.53 m for shock tube experiments. Fig. 2 defines the distance between the screen and test section d, and distance between the screen and camera f. Settles found the ratio d/f should be between 0.3 to 0.7 for highest image quality [2]. For all tests using our configuration d/f ranged between 0.4 to 0.5.

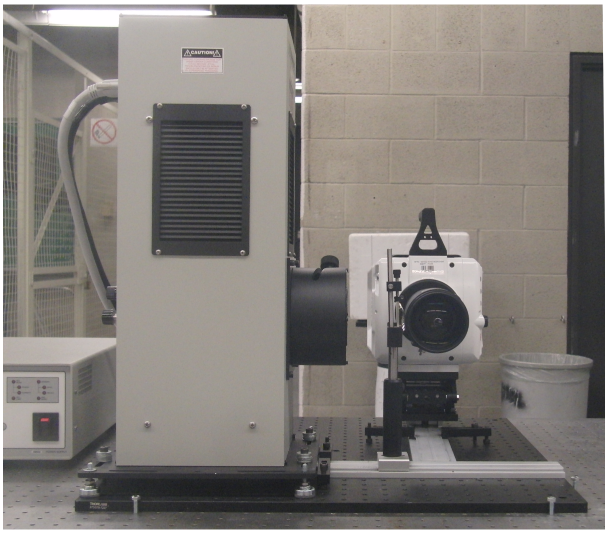

Figure 3: Front view picture of the arc lamp, high-speed camera, and optical components.

The camera used is a Phantom v1210 from Vision Research pictured in Fig. 3 next to the arc lamp. It is a high-speed video camera capable of 1280 by 800 resolution at 12,000 fr/s and 1,000,000 fr/s at reduced resolution. A 1.82 m square retro-reflective screen was made by Virtual Backgrounds containing 3M 7610 retro-reflective material and was fitted over an aluminum frame.

3.0 APPLICATION TO HYDROGEN SAFETY

The results presented in this section will compare images produced from the shadowgraphy setup documented above to a previously built schlieren system. The schlieren system is a Z-type design using the same camera and light source described above. The mirrors used were 31.75 cm diameter parabolic f/8 mirrors.

3.1 Hydrogen Leak Detection

To model a hydrogen leak, a bottle of pure hydrogen was connected to a flow meter calibrated to provide a constant flow rate of 0.537 normal cubic meters per hour (NCMH). The gas exited to the atmosphere through the flow meter where shadowgrams were taken.

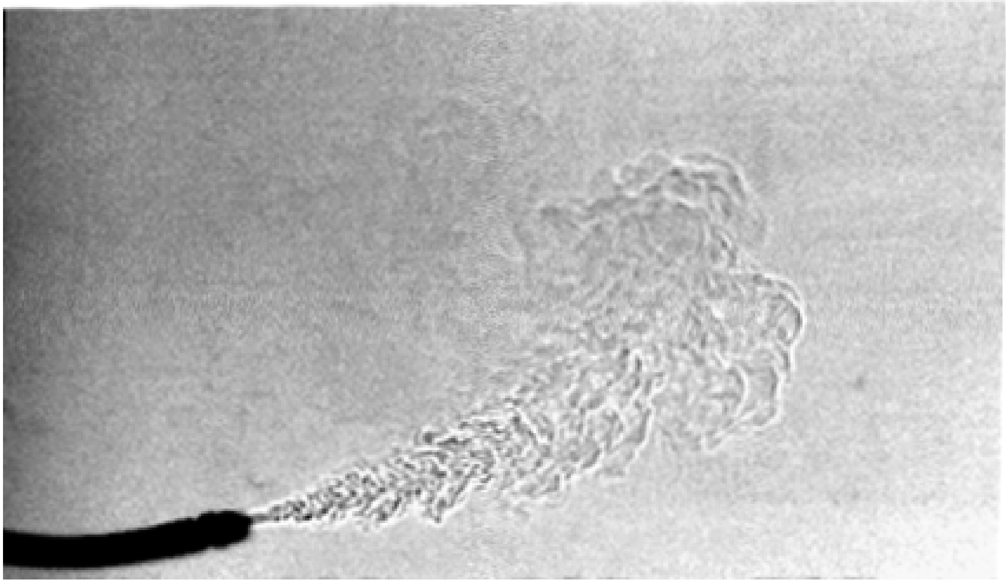

Figure 4: Shadowgram of a hydrogen leak at 0.537 NCMH from a 6.35 mm diameter tube. The height of the frame is 24.82 cm and its resolution is 429 x 248. The brightness and contrast of this image have been enhanced.

Fig. 4 shows a modeled hydrogen leak where gas flows out of a 6.35 mm diameter tube at 0.537 NCMH into the atmosphere. As hydrogen flows out, it turbulently mixes with the surrounding air making the shadowgram of the leak stand out. Images of hydrogen leaks demonstrate the diagnostic potential of large-scale shadowgrams in checking for leaks developed in hydrogen piping and storage systems.

3.2 Jet Releases

Jet releases occur when a small hole suddenly forms in a pressure vessel. A shock wave leads a high velocity stream of gas out of the pressure vessel. Under certain conditions in hydrogen releases the gas may spontaneously ignite. Several numerical and experimental studies have been completed on ignition conditions [11, 12]. Frequently, experimental studies of this phenomena focus on the events near the release point since it is where the gas is most likely to ignite [11, 13]. The shadowgraph system developed in the present study allows us to visualize the release on much larger scales.

Jet release tests were performed using a cylindrical vessel and the jet flowed into atmospheric conditions. Test pressures were selected from operational hydrogen pipelines in the United States [22]. Details on the procedure of this experiment have been documented by Dennis [23]. Schlieren and shadowgraph pictures of hydrogen jet releases are shown in Fig. 5 and Fig. 6.

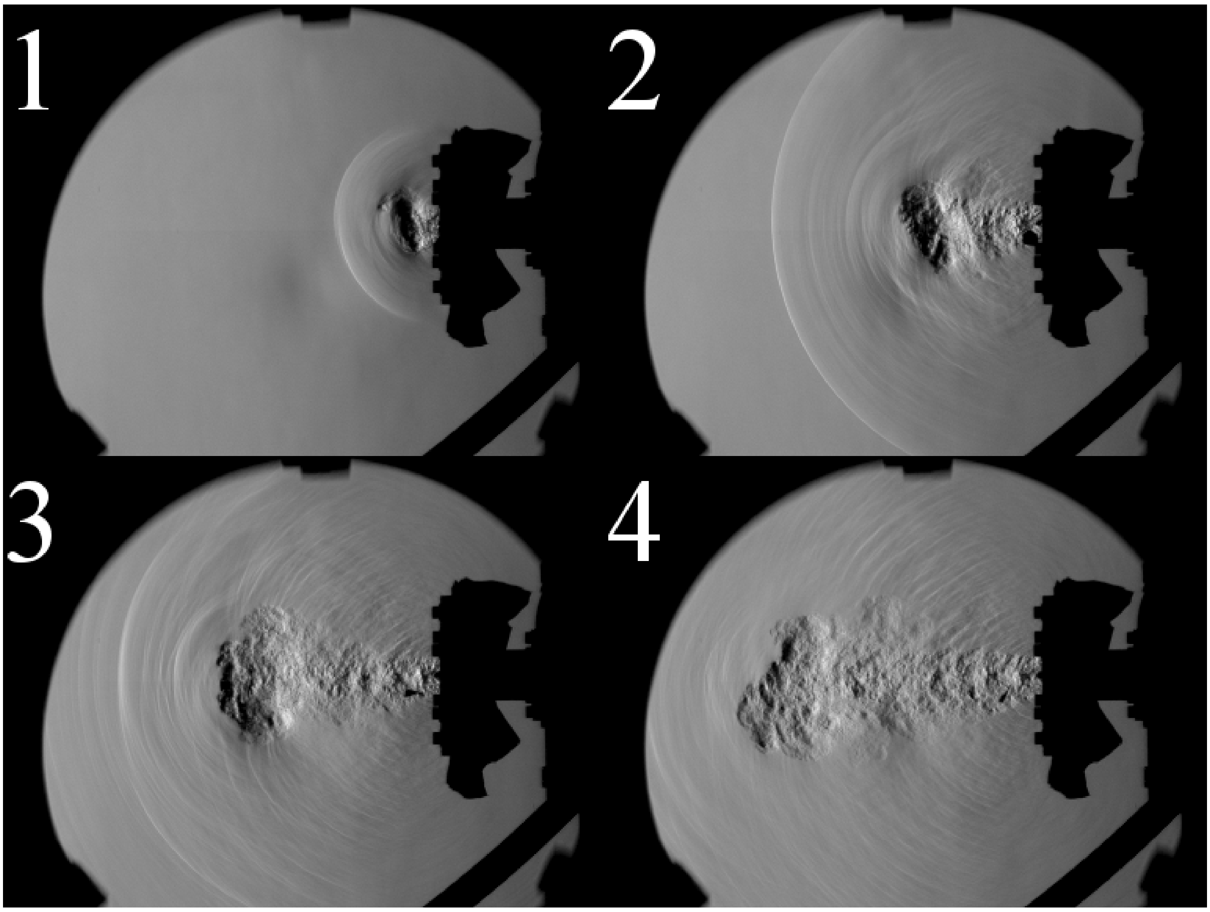

Figure 5: Schlieren images of hydrogen jet flowing into atmospheric air through 12.7 mm diameter hole. The initial pressure was 413.7 kPa. Time between frames is 259 μs and the field of view is 31.75 cm in diameter. The resolution of each frame is 384 x 288.

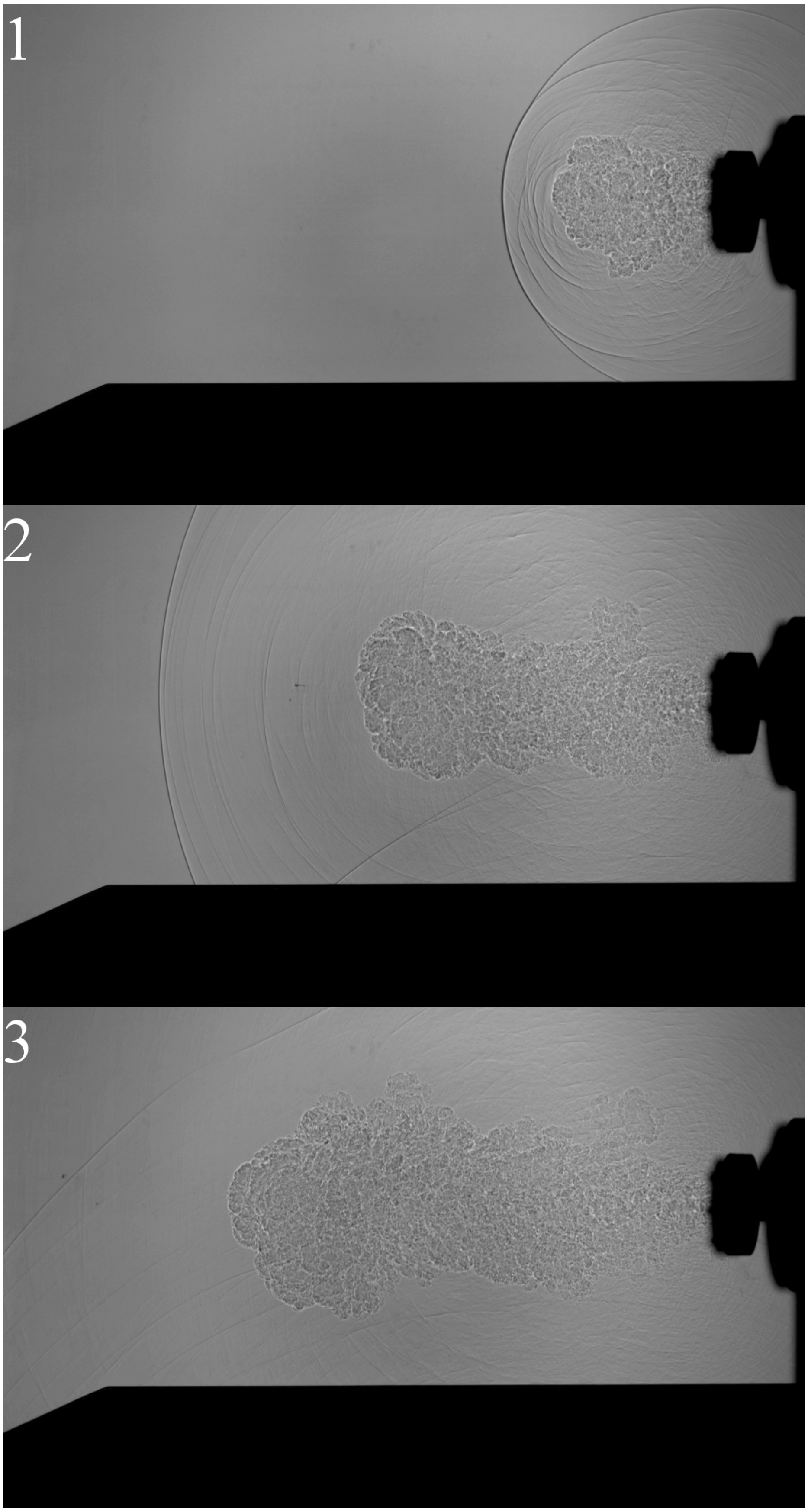

Figure 6: Shadowgraph images of a hydrogen jet flowing into atmospheric air through a 12.7 mm diameter hole. The initial pressure was 1378.9 kPa. Time between frames is 800 μs and the width of the frame is 73.15 cm. The resolution of each frame is 1280 x 800.

Fig. 5 depicts a hydrogen jet initially at 413.7 kPa propagating from right to left viewed with schlieren imaging. Similarly, in Fig. 6 a hydrogen jet starting from 1378.9 kPa propagates in the same direction and is visualized in shadowgraphy. In both figures, a weak shock wave leads the stream of hydrogen into the air. The frames presented were selected such that the lead shock exits the picture by the last frame.

In frames 3 and 4 in Fig. 5, the gas at the front of the jet was pushed off to the side. Without support from behind, it slowed down and stagnated. The longer length scale provided by the shadowgraphy system shows the same in frame 2 and 3 of Fig. 6. The shock diamonds in Fig. 5 were in sharp contrast to the background. In comparison to the shadowgrams, the shock diamonds were not visible. The lead shock wave and compression waves of frame 1 in Fig. 6 were made clearer by using shadowgraphy. The sharp gradient in frames 2 and 3 of Fig. 5 at the front of the hydrogen stream is under-exposed in schlieren, but becomes visible in frame 1 using shadowgraphy.

The viewable area between schlieren and shadowgraph tests increased by approximately a factor of 4. The detail visible in schlieren is lost in order to gain a larger viewable area. The shadowgraphy system did permit bulk analysis of the flow field produced by the jet.

3.3 Unconfined Deflagrations

Unconfined deflagrations in hydrogen-air mixtures model the dynamics of large-scale accidents. Required safety distances to limit damage in hydrogen explosions have been previously studied [14]. Nonhomogeneous hydrogen-oxygen cloud ignition limits and flame speeds have also been investigated [15]. Leblanc developed a large soap bubble technique to study buoyant effects in lean hydrogen-air mixtures [16]. In cases where clouds of combustible gas are nearby, ignition of one cloud may spontaneously ignite the other. We model these phenomena using the soap bubble method and large-scale shadowgraphy will allow for visualization of large radii bubbles at various separation distances.

Hemispherical soap bubbles were formed on a flat plastic surface. The surface was outfitted with a spark plug to ignite the combustible mixture. Details on the procedure of this experiment have been documented by Leblanc [16].

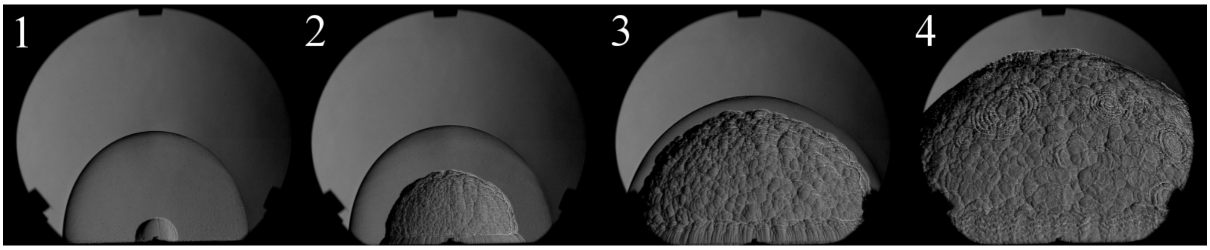

Figure 7: Schlieren images of a stoichiometric hydrogen-air deflagration. Time between frames is 3.56 ms, and the field of view is 31.75 cm in diameter. The resolution of each frame is 512 x 512.

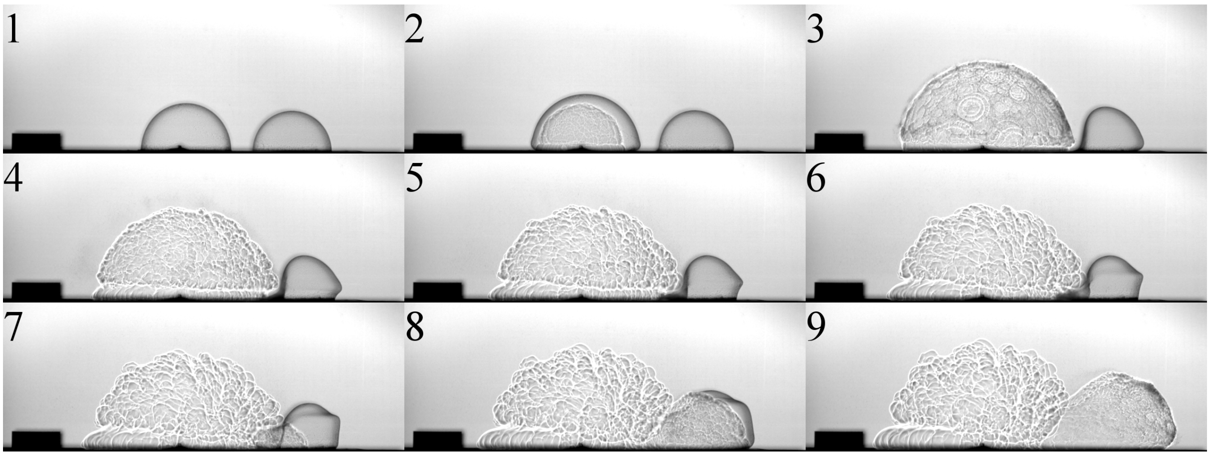

Figure 8: Shadowgraph images of stoichiometric hydrogen-air deflagrations. Time between frames is 4.73 ms, and the field of view is 22.37 cm tall. The resolution of each frame is 850 x 315.

Fig. 7 shows schlieren images of a stoichiometric hydrogen-air deflagration. Fig. 8 comprises shadowgrams of two soap bubbles with the same hydrogen-air mixture where one bubble ignites the other. In Fig. 7, a 14.14 cm radius soap bubble is ignited and the expanding products fill the schlieren mirror. In frame 3, the soap bubble increases its radius as the burning gas expands inside it. The details of the turbulent flame structure and soap film as it breaks are made clear in frames 3 and 4. The shadowgrams in Fig. 8 show the flame structure in bright white curves that stand out on the background. The location and details of the bubbles and flames are very clear and no blurring is visible. The ignited bubble in Fig. 8 frame 2 has a radius of 7.23 cm and the other bubble is 6.12 cm. The expansion of the burning gas in the first bubble tends to shift the second bubble away, as illustrated in frames 3 through 6 of Fig. 8. During this time, the second soap bubble demonstrates some resiliency to disturbances. After some time, the gas in the second bubble ignites and the expansion breaks any remaining soap film.

3.4 DDT in Long Channels

Deflagration-to-detonation transition is the process that transforms a subsonic combustion wave (deflagration) into a supersonic combustion wave (detonation). The process may occur in vapor cloud explosions and greatly amplify damage severity in a large accident. There are a number of mechanisms postulated to cause the transition: shock reflection, expansion of burnt products, and turbulence [17]. Several studies in hydrogen-air and hydrogen-oxygen mixtures have been completed to study the process, however understanding of the mechanism remains incomplete [18, 19, 20]. We use a 3.5 m long, 203 mm high and 19 mm wide rectangular shock tube, shown in Fig. 9, to analyze DDT in long channels using hydrogen mixtures [21]. Details of the experimental procedure and other shock tube experiments are documented by Maley [21]. Large-scale shadowgraphy can be used to visualize a large section of the channel providing for an analysis of the process over a long length scale. The walls of the third section are made of optical-quality glass permitting shadowgraph visualization of the whole section.

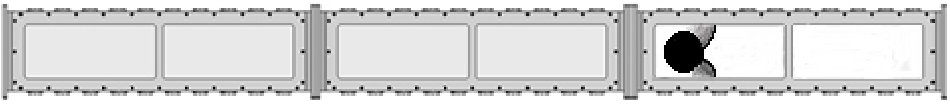

Figure 9: Side-view illustration of shock tube with detonation traveling around the full circle obstacle

Both a 15.24 cm diameter circle and a 30.5 cm diameter semi-circle were used as an obstacle to simulate a detonation interacting with a detonation arrestor. Both obstacles can separate a detonation into a strong shock followed by a flame, a shock-flame complex, on the downstream side of the obstacle. Sometimes, the shock-flame reformed a detonation and under certain conditions the detonation would not separate into a shock-flame.

Fig. 10 shows schlieren pictures of a $2H_2 + O_2 + N_2$ detonation after interacting with a semi-circle obstacle. The semi-circle was on the left of the field of view and is not pictured. A full field of view is shown in Fig. 11 using shadowgraphy and the full circle obstacle.

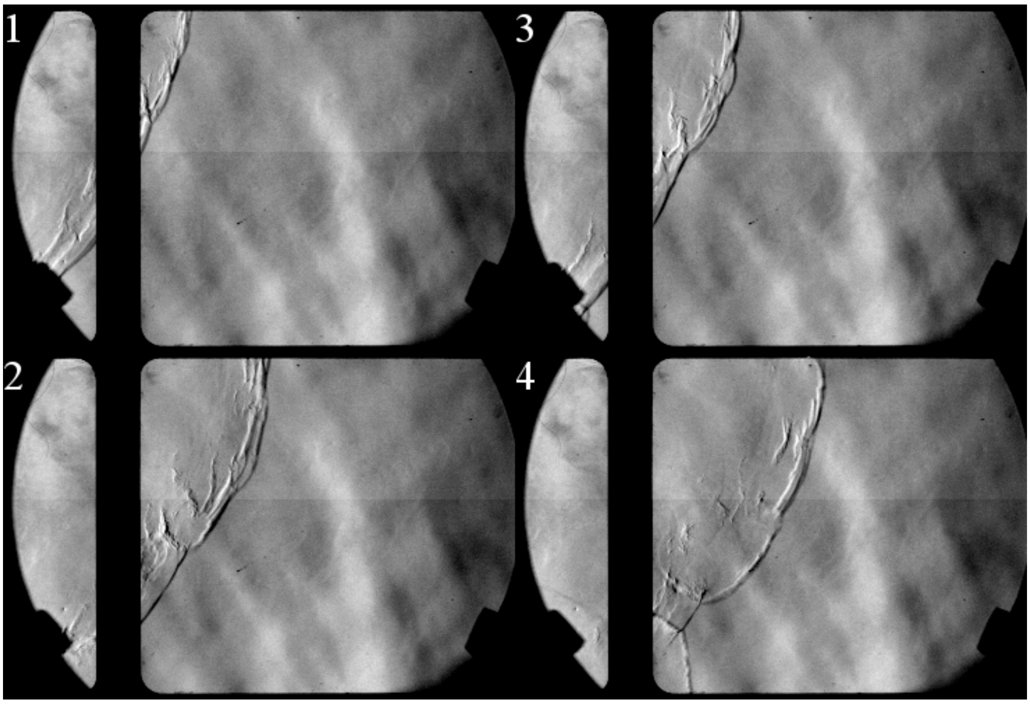

Figure 10: Schlieren images of a $2H_2 + O_2 + N_2$ detonation initially at 12.41 kPa moving around a semi-circle. Time between frames is 12.95 μs. The height of the windowed section is 20.32 cm. The resolution of each frame is 368 x 250. The brightness and contrast of the frames in this image have been enhanced.

In the schlieren images in Fig. 10, the semi-circle obstacle was upstream and outside the field of the view. The semi-circle was placed flat-side down on bottom wall of the shock tube. The shadowgrams in Fig. 11 show the third section of the shock tube in a test using the full circle. Both figures show a detonation traveling from left to right and all frames are from a single test.

The test in Fig. 10 is an example of a detonation that did not form a shock flame complex. At the top of the first frame the shock wave and reaction zone are still closely coupled. In frames 2 and 3 some separation occurs on the lower half of the wave. The wave reflects off the bottom wall creating a detonation front visible in frame 4. At the top wall in all the frames, the shock wave and flame never fully separated.

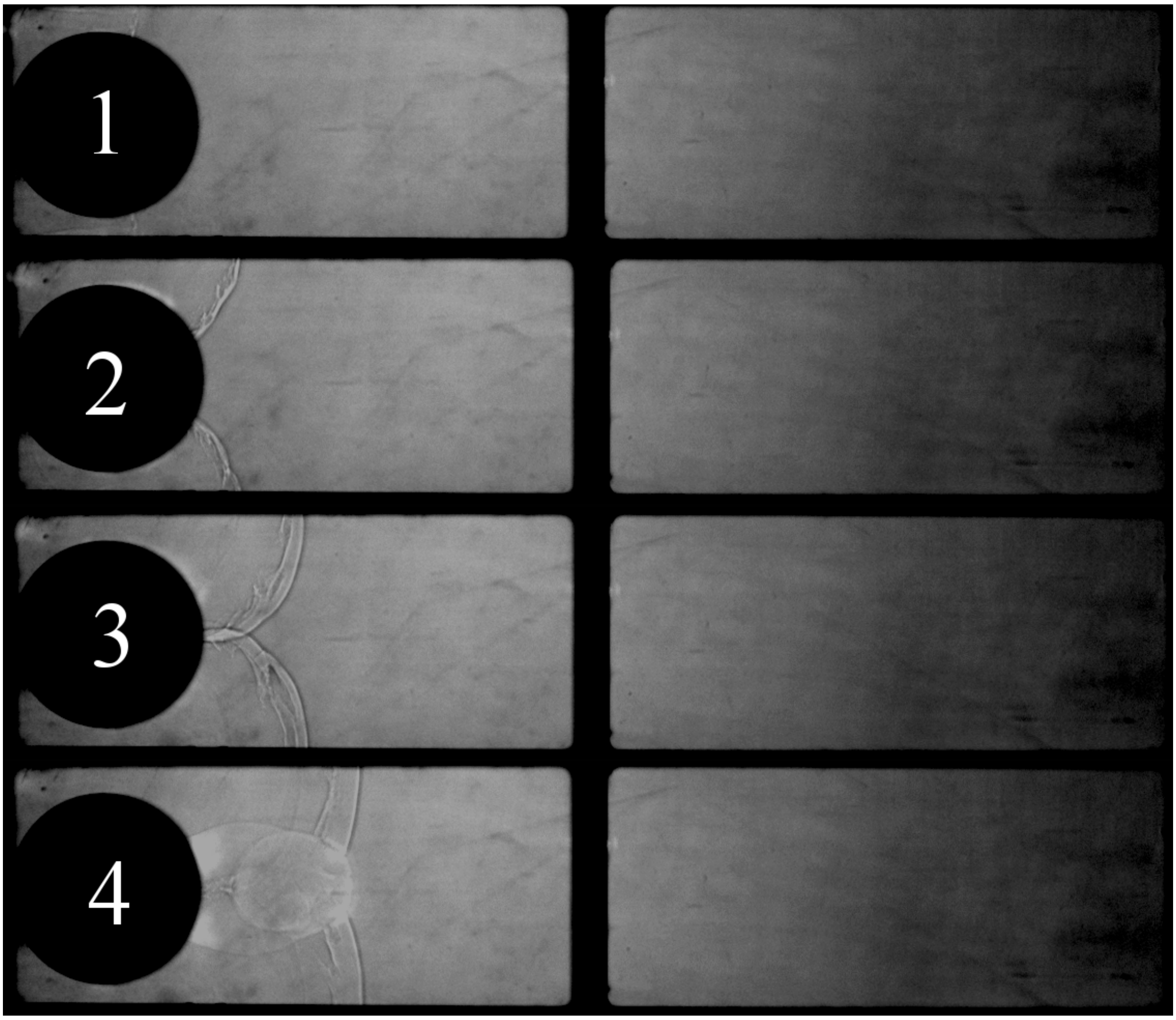

Figure 11: Shadowgraph images of stoichiometric hydrogen-oxygen shock-flame transitioning to detonation initially at 14.13 kPa. Time between frames is 34.9 μs. The viewable section is 20.32 cm tall and 99.06 cm long. The resolution of each frame is 1130 x 246. The brightness and contrast of the frames in this image have been enhanced.

The shadowgrams in Fig. 11 showed significantly less detail than the schlieren images and did not permit analysis of small events. In frame 1, the very faint decoupling detonation travels around the full circle. Only the shock wave and flame can be clearly identified in frames 2 through 4. The reforming detonation front is clear in frame 4 though its structure is invisible. Large-scale shadowgraphy permitted accurate velocimetry measurement and general flow-field analysis.

In Fig. 11 the shock-flame complex re-initiated into a detonation. The location of the transition varies in the shock tube, however with the shadowgraph system the entire section following the obstacle is viewable ensuring that if transition happens we can see it. This phenomena in hydrogen mixtures has been compared to other gases by Maley [21]. The mechanism involving re-initiation is discussed in detail by Bhattacharjee [24].

4.0 CONCLUSION

The purpose of this paper is to apply large-scale shadowgraphy to hydrogen safety issues relating to jet releases, flames, and detonations. A retro-reflective screen and arc lamp have shown potential in high-speed flow visualization from Settles' design. The same design was used to measure its applicability to visualization of high-speed phenomena in hydrogen.

In jet release experiments, the large length scale provided allowed for visualization of the general jet behavior with some detail. The finer details were lost due to the increase in viewable area. DDT experiments showed a large portion of the shock tube visible, allowing for detection of re-initiation and velocimetry measurement. Similar to jet experiments, details of the detonation wave and shock-flame complex were lost and only the position of the wave could be resolved. In contrast, analysis of complex unconfined flame dynamics became possible with a large length scale. There was enough detail to clearly view the flame structure and dynamics.

The shadowgraphy system is very easy to set up and can be operated by two people. Its simplicity makes it potentially suitable for use in optical gas leak detection systems. Jet release and DDT experiment results exhibited potential for large-scale flow analysis. The positive results from unconfined flame dynamics tests suggest this system would be ideal for use in studying large-scale flame propagation.

REFERENCES

[1] Settles, G.S., *Schlieren and Shadowgraph Techniques*. Springer-Verlag, 2001.

[2] Settles, G.S, Grumstrup, T.P, Miller, J.D., Hargather, M.J., Dodson, L.J., and Gatto, J.A., “Full-Scale High-Speed Edgerton Retroreflective Shadowgraphy of Explosions and Gunshots,” *5th Pacific Symposium on Flow Visualisation and Image Processing*, 2005.

[3] Weinstein, L.M., Culliton, W., and Rivers, R., “Visualization of Transonic Flow over a T-38 Aircraft,” *Proceedings of the 8th International Symposium on Flow Visualization*, 1998.

[4] Reinholtz, Carrie K., Heltsley, Fred L., and Scott, Kenneth E., “Plume Visualization of Orion Launch Abort Vehicle Jettison Motors Using Background-Oriented Schlieren,” 2010.

[5] Fuller, Peter W. W., *High Speed Photography and Photonics*. The International Society for Optical Engineering, 1997.

[6] Held, Manfred, “Optical diagnostics of shaped-charge jets,” pp. 476–489, July 2003.

[7] Mach, E., *Popular Scientific Lectures*. Open Court, 1943.

[8] Edgerton, Harold E., “Shock Wave Photography of Large Subjects in Daylight,” *Review of Scientific Instruments*, vol. 29, pp. 171–172, Feb. 1958.

[9] Edgerton, Harold E., *Electronic Flash, Strobe - 3rd Edition*. The MIT Press, 3 ed., Apr. 1987.

[10] Norman, Thomas R. and Light, Jeffrey S., “Application of the Wide-Field Shadowgraph Technique to Rotor Wake Visualization,” 1989.

[11] F. L. Dryer, M. Chaos, Z. Zhao, J. N. Stein, J. Y. Alpert, and C. J. Homer, “Spontaneous Ignition Of Pressurized Releases Of Hydrogen and Natural Gas into Air,” *Combustion Science and Technology*, vol. 179, no. 4, pp. 663–694, 2007.

[12] Maxwell, B.M. and Radulescu, M.I, “A Lagrangian Reaction-Diffusion Model For Predicting The Ignitability of Pressurized Hydrogen Releases,” *3rd International Conference on Hydrogen Safety*, 2009.

[13] V. Golub, D. Baklanov, T. Bazhenova, S. Golovastov, M. Ivanov, I. Laskin, N. Semin, and V. Volodin, “Experimental and numerical investigation of hydrogen gas auto-ignition,” *International Journal of Hydrogen Energy*, vol. 34, pp. 5946–5953, July 2009.

[14] S. Dorofeev, “Evaluation of safety distances related to unconfined hydrogen explosions,” *International Journal of Hydrogen Energy*, vol. 32, pp. 2118–2124, Sept. 2007.

[15] Sochet, I. and Gillard, P. and Gulon, F., “Effect of the concentration distribution on the gaseous deflagration propagation in the case of H2/O2 mixture,” *Journal of Loss Prevention in the Process Industries*, vol. 19, pp. 250–262, Mar. 2006.

[16] Leblanc, L., Manoubi, M., Dennis, K., Liang, Z., and Radulescu, M.I., “Influence of Buoyancy in Unconfined Deflagrations: Experiments in Soap Bubbles,” *Proceedings of the Seventh International Seminar on Fire and Explosion Hazards*, 2013.

[17] Schultz, E., Wintenberger, E., and Shepherd, J., “Investigation of Deflagration to Detonation Transition for Application to Pulse Detonation Engine Ignition Systems,” *16th JANNAF Propulsion Meeting*, 1999.

[18] Teodorczyk, A., Drobniak, P., and Dabkowski, A., “Fast turbulent deflagration and DDT of hydrogenair mixtures in small obstructed channel,” *International Journal of Hydrogen Energy*, vol. 34, no. 14, pp. 5887–5893, 2009.

[19] Kuznetsov, M., Alekseev, V., Matsukov, I., and Dorofeev, S., “DDT in a smooth tube filled with a hydrogenoxygen mixture,” *Shock Waves*, vol. 14, 2005.

[20] Gamezo, V. N. and Oran, E. S., “Mechanisms for Deflagration-to-Detonation Transition in Type Ia Supernovae and Terrestrial Systems.”

[21] Maley, L., Bhattacharjee, R., and Radulescu, M.I., “A comparative study of detonability and propensity to sustain high-speed turbulent deflagrations in hydrogen and methane mixtures,” *International Conference on Hydrogen Safety*, 2013.

[22] Vinjamuri, G.K., “Development of US-DOT Regulations for Hydrogen Transportation Systems,” *Challenges of Hydrogen Pipeline Transmission, International Pipeline Conference and Exposition*, 2004.

[23] Dennis, K., “The Implementation of a High Power LED in Schlieren Photography and Construction of a Large-Scale Shadowgraphy System,” *B.A.Sc. Thesis University of Ottawa, Ottawa, Canada*, 2013.

[24] Bhattacharjee, R., “Experimental investigation of detonation re-initiation mechanisms following a Mach reflection of a quenched detonation,” *M.A.Sc. Thesis University of Ottawa, Ottawa, Canada*, 2013.