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RPPR Final Report
as of 12-Aug-2022

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STEM Degrees: 2 **STEM Participants:** 3

Major Goals: The University of California, Irvine (UCI) and Colorado School of Mines (CSM) recently completed a proof of concept ARO project to demonstrate the suitability of using Ultra-Short Pulse Off-Axis digital holography (USPODH) to image high pressure fuel sprays. The project showed that USPODH can produce 3D images of a realistic fuel spray from a hologram created by a single 100 fs pulse. The current project extends the results from the recently concluded proof-of-concept to investigate the full potential of the ultra-short pulse holographic technique and demonstrates its effectiveness for realistic sprays. The comparison of the technique in direct contrast to alternatives (in particular, the quality of the images and the details of the spray structure were to be quantified) were to take place at the Colorado School of Mines, but changes to the scope of work (i.e., the curtailment of the content to the initial 19-month phase) focused the effort on design improvements. The ultra-short pulse holography approach faces important questions regarding practical limitations when implemented in realistic spray systems. Examples include quantifying the trade-off between resolution and working distance, evaluating the potential for high framing rates, assessing the optical density limits, and the potential obscuration in situations where the scatterer size and number density prevent phase field reconstruction, and ultimately if the image content proves to contain valuable quantifiable information on spray formation dynamics. Hence, to evaluate the ultra-short holography method, we explore these aspects of the potential of Ultra-Short Pulse Off-Axis digital holography in imaging through optically dense media.

Accomplishments: The shutdown of university research during the COVID-19 pandemic has impacted the accomplishments in the first year of the project, particularly regarding the approved sub-award at CSM, which took 4 months to finally establish. Despite all of the major pandemic interruptions, important progress has been made. Details of the accomplishments are contained in the full final report document uploaded as part of this documentation.

RPPR Final Report
as of 12-Aug-2022

Accomplishments in USPODH:
1. UCI – Modifications and documentation of the experiment
1a. Videos of alignment procedure and improved SOP documentation were created.
1b. Optical train height was lowered from an excessive 24” to 6” in order to improve stability and safety.
1c. Vibration isolation was implemented to remove pump vibrations from affecting holograms.
1d. Spray pulse jitter was reduced so that images at known time following spray initiation can be obtained.
2. UCI – Optical modeling for holography optimization
2a. Holotool – holographic analysis software modifications
2aa. Transition and training with Holotool for additional users was completed.
2ab. Evaluated focus condition algorithms for automated depth of reconstruction determination.
2ac. Improved batch processing, zero padding, and reduced aliasing from undersampling.
2b. Zemax modeling for optical train design
2ba. Initial implementation of Zemax to evaluate singlet and doublet lens performance.
2bb. Initial tutorials completed of Zemax hologram modeling – sequential and non-sequential modes.
2c. Simulation of lensed configuration and effects of scatterer particle size
2ca. Combination of Zemax and SimuHolo creates simulated hologram and inversion
2cb. Evaluation of performance with optical density alone versus optical density plus particle scatterer
3. UCI – Lensed configuration evaluation completed
3a. Added a lens to the system for improved resolution and direct comparison with focused shadowgraphy.
3b. Collected images of sprays with the lensed system
3c. Completed optical simulations of lensed system

The details of the above accomplishments are contained in the conference papers and peer reviewed journal paper so only a bulleted list is included here.

Given the reduction in scope and budget, the CSM team leveraged a synergistic industry project to investigate atomization of high viscosity bio oils.

Accomplishments in spray imaging environment:
4. CSM – Ballistic imaging system
4a. Project initiated with experiment setup for ballistic imaging.
4b. Laser and optical train re-established.
5. CSM – Spray system
5a. Preparing for spray transition from UCI.
5b. Implementing bio-oil atomizer spray.
6. CSM – Optical modeling
6a. Zemax obtained for laying out ballistic imaging optical train.
6b. Monte Carlo simulation to be acquired.

Training Opportunities: The training accomplished for this project included two graduate students, both who graduated and used the research as part of their pre and post graduation training, along with an undergraduate student who also received important holography training.

Results Dissemination: The work was presented at conferences and was also published in a peer-review journal article as documented. These were the main dissemination channels. In addition, the general concept of the work was included in optical diagnostics presentations to interested students, and the work was shared with small business interests as they pursued potential SBIR funding.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Ongoing informal collaboration with Metrolaser, Inc., as a small business interested in holographic technology and its implementation. The collaboration is primarily discussions of potential SBIR targets that could use the technique being developed. No formal technology transfer has been effected as of yet.

PARTICIPANTS:

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Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

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Article Title: LONG-RANGE MICROSCOPY OF OPTICALLY DENSE SPRAY STRUCTURES USING ULTRA-SHORT PULSE OFF-AXIS DIGITAL HOLOGRAPHY
Authors: Marco Minniti, Derek Dunn-Rankin, Y.-C. Chien
Keywords: holography, imaging, optically dense sprays, primary breakup visualization
Abstract: The early stage of spray atomization has been the subject of extensive research efforts, and while early breakup often focuses on engineering sprays, the very same dynamics are important in medical sprays and natural spray generation. The current work expands the technical aspects from the previous study, particularly enhancing the field of view by adopting a lensed long-range microscopy setup. The achieved magnification is between 1.1 and 1.5, at a working distance of 35 cm, and resolves primary atomization lobes, ligaments, and droplets as small as 14 ?m in the near-nozzle region. USPODH successfully rejects light scattered by the shroud of primary atomization droplets surrounding the spray core and can image fluid structures at the gas-to-liquid interface, which are consistent with the structures predicted by primary atomization models.
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Paper Title: Long-range microscopy of atomization fluid structures in diesel sprays using Ultra-Short Pulse Off-Axis Digital Holography
Authors: Marco Minniti, Yu-Chien Chien, Ali Ziaee, Derek Dunn-Rankin
Acknowledged Federal Support: **Y**

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Authors: Jose Ulises Torres, Derek Dunn-Rankin, Yu-Chien Chien
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Partners

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I certify that the information in the report is complete and accurate:
Signature: Derek Dunn-Rankin
Signature Date: 8/12/22   2:19PM

Final Project Report - Grant # W911NF-20-1-0102

(Reporting Period: May 2020 – April 2022)

Single-shot Ultra-short Pulse Holographic Imaging of Dense Fuel Sprays

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Introduction

This report describes a project completed by UC-Irvine and Colorado School of Mines to develop and optimize Ultra-Short Pulse Off-Axis digital holography for imaging the core structure behind dense sprays. The proof-of-concept for the technique had been successfully demonstrated in prior work, and showed that it can produce 3D images of a realistic fuel spray from a hologram created by a single 100 fs pulse. The current project was originally expected to provide a side-by-side comparison between femtosecond holography imaging of sprays and other more standard approaches in the realistic environment of a diesel engine simulator. The project was shortened, however, and the modified project focused instead on demonstrating the optical resolution limits of the novel femtosecond holographic technique, and particularly how optical design methods can be used to enhance the performance of the technique depending on the conditions being examined.

This work is relevant to the understanding of spray dynamics and fundamentals including, liquid jet breakup at orifices and subsequent ligament formation. This project is part of the continuing efforts to provide a tool for understanding the early breakup of sprays, as it is this early breakup that controls the later droplet formation and combustion in power systems. The holographic data can supply information for concept development and model validation, and it can help drive injector designs in engines that promote improved efficiency, reduced emissions signature, and fuel tolerance.

Optical spray diagnostic techniques have shown some limited success in imaging the core of dense sprays but they continue to be plagued by noise from multiple scattering from the particles surrounding the spray core (Linne, 2013). Some techniques, such as x-ray diagnostics, often require averaging but advances continue for short exposures, and phase contrast imaging is being used increasingly as a spray diagnostic (Sforzo et al., 2019, Mayhew et al., 2021). Unfortunately, x-ray imaging currently requires a sophisticated light source that is not yet local laboratory scale (Kastengren et al., 2012). Other techniques, such as ballistic imaging, use time-gated filtering strategies to eliminate scattering noise (Linne et al., 2006, Paciaroni and Linne, 2004, Paciaroni et al., 2006). The goal of the current research project was to continue demonstrating that coherence-based filtering using holography, where scattered light is excluded by its lack of coherence with a reference beam, is an effective addition to the dense spray imaging diagnostic toolbox. In addition, it shows that holography also adds the potential for high spatial and temporal resolution across a large depth of field, which can be valuable even in low density spray environments.

The project originally had two main aspects: (A) enhancement of the femtosecond digital holography system and (B) creating a comparator spray imaging environment. With the reduced project scope we focused on the first aspect, further developing and demonstrating the femtosecond holographic technique but some accomplishments were also achieved in (B).

Objective

As described above, The University of California, Irvine (UCI) and Colorado School of Mines (CSM) recently completed a proof of concept ARO project to demonstrate the suitability of using Ultra-Short Pulse Off-Axis digital holography (USPODH) to image high pressure fuel sprays. The project showed that USPODH can produce 3D images of a realistic fuel spray from a hologram created by a single 100 fs pulse. The current project extended the results from the recently concluded proof-of-concept to investigate the full potential of the ultra-short pulse holographic technique and demonstrates its effectiveness for realistic sprays. The comparison of the technique in direct contrast to alternatives (in particular, the quality of the images and the details of the spray structure were to be quantified) were to take place at the Colorado School of Mines, but changes to the scope of work (i.e., the curtailment of the content to the initial 19-month phase) focused the effort on design improvements. The ultra-short pulse holography approach faces important questions regarding practical limitations when implemented in realistic spray systems. Examples include quantifying the trade-off between resolution and working distance, evaluating the potential for high framing rates, assessing the optical density limits, and the potential obscuration in situations where the scatterer size and number density prevent phase field reconstruction, and ultimately if the image content proves to contain valuable quantifiable information on spray formation dynamics. Hence, to evaluate the ultra-short holography method, we explored these aspects of the potential of Ultra-Short Pulse Off-Axis digital holography in imaging through optically dense media.

Ultra-Short Pulse Off-Axis Digital Holography (USPODH) is a variety of off-axis holography that relies on the use of short coherence length femtosecond laser pulses to select only ballistic and quasi-ballistic photons when imaging a target hidden in a turbid environment. This is achieved, similarly to what other techniques have achieved in the past, by rejecting photons that have encountered multiple light/matter interactions. Differently from other techniques that adopt ultra-fast shutters to gate-out the delayed photons, however, USPODH relies on "coherence filtering," where a reference pulse is routed around the target and is interfered with the object pulse that traveled through the scattering media. Only the unperturbed photons of the object pulse will still be sufficiently coherent with the reference to create an interference pattern on the camera sensor. This interference pattern is a hologram, and it can be numerically reconstructed into an image of the target field at a chosen distance from the pattern plane. This image will contain information pertaining primarily to ballistic and quasi-ballistic photons. Since these photons did not scatter off particles while traversing the target field, they create a shadowgraph-like image of the target.

The USPODH technique has been described and detailed in our prior work (Minniti et al., 2018, Trolinger et al., 2011, Ziaee et al., 2017) but briefly the method is off-axis holography using a femtosecond laser light source. Our previous efforts showed how ultrashort pulse off-axis holography can be used to image targets through optically dense media. We have demonstrated the efficacy of coherence filtering offered by ultra-short pulse off-axis digital holography (USPODH) in incrementally more realistic conditions. First by imaging USAF resolution charts hidden behind mono and polydisperse scattering suspensions (Ziaee, 2016, Ziaee et al., 2017), then by imaging plain jet water sprays placed at the center of a vessel filled with a high OD polydisperse water mist (Minniti et al., 2018), by imaging a commercial single orifice diesel fuel injector at ambient pressure and temperature (Minniti et al., 2019), and lastly by showing that USPODH can successfully image transient sprays in confined environments at pressures up to 17.2 atmospheres, both at ambient temperature and in evaporating conditions (Minniti, 2019). This earlier work concentrated on images from idealized spray configurations to show how the combination of digital holography and coherence filtering using an ultrashort-pulse can provide the scattering noise filtering performance of ballistic imaging while also allowing for 3D numerical focusing and optical sectioning typical of holographic techniques.

Approach

The research approach that was to be adopted is best described in reference to the project flowchart shown in Figure 1. There were to be CFD modeling efforts to support the enhancement of the diesel engine simulator environment and optical modeling to improve the performance of the optical configurations (all imaging); the experiments were to be done first separately at the two

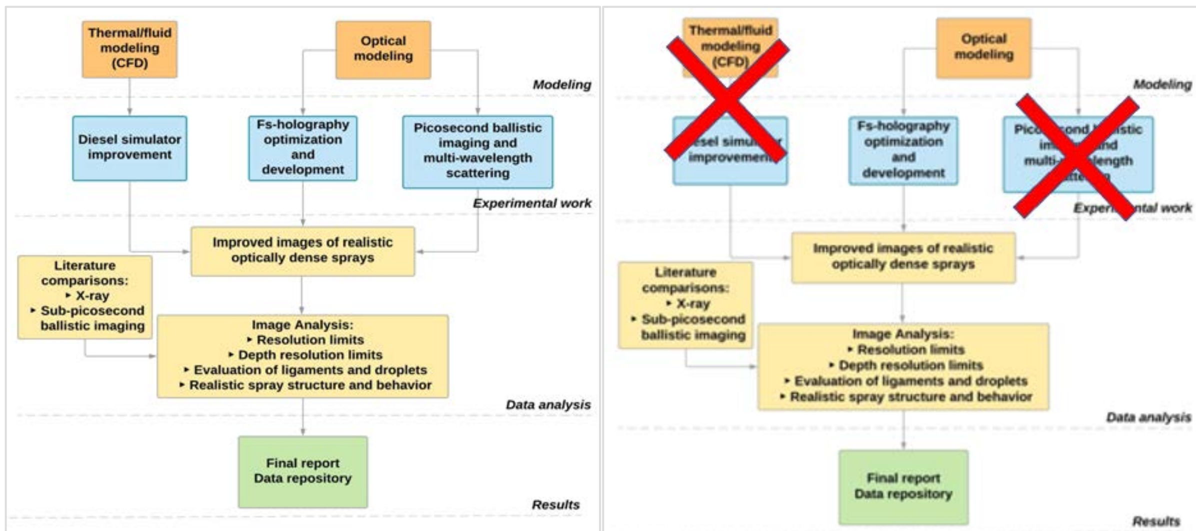

Figure 1. Flow diagram of original research plan (left) compared to the revised research plan adopted.

institutions and then in a combined fashion, with analysis and evaluation of the images for internal value and then comparative value. The final step would be to quantify the information gain regarding the physical processes dominating spray breakup in diesel engine conditions. The experimental components were all fully functioning and included the holography system, the ballistic imaging and multi-wavelength imaging systems, and the diesel spray simulator chamber. The project was to include substantial improvement in these components but the baseline performance of each of these components had already been demonstrated. Reiterating, the current project was to enhance the existing imaging and spray simulator performance capabilities and then to thoroughly evaluate USPODH in realistic sprays. Again, because of the limitation in the project scope from the curtailed timeline, the project focused on the optical aspects of the system design.

Relevance to the Army

The relevance of this work to the army remains in its efforts to improve a range of direct injection engines for mobility in domestic operations and in the field. This interest is growing to include advanced power generation for advancing units. While batteries continue to improve, there will always remain a critical need for the use of energy-dense liquid fuels. As such, efficiency, fuel tolerance, reliability, and low emission signature are desirable performance improvements for any power system. It is well-known that engine performance for liquid-fueled engines (particularly diesel engines) is strongly coupled to spray injection performance and dynamics. The diesel engine relies on the interaction of a transient, high-pressure spray event with a high pressure and high temperature gas charge produced by compression in the engine cylinder. The energy release that accompanies combustion interacts strongly with the spray and both mixing and fuel/oxidizer chemistry have significant roles in the process. The direct observation of this process has been an important contributor to improvements, and they will continue to be if the observation tools can improve sufficiently to give insight into domains currently inaccessible. This work is relevant to the army systems as it will have impacts both in the field of non-intrusive measurements of optically thick media (i.e., diesel sprays) and, more importantly, on the acquisition of data that can be used to validate the modeling of such sprays. For non-intrusive measurements, the research program is exploring and optimizing a novel optical diagnostic capable of visualizing moderately sized spray structures through strong optical scattering from surrounding mist during spray atomization. A critical challenge for current spray models is that they do not yet incorporate all the relevant physics; rather, many primary atomization models have to use empirical correlations specific to a particular atomizer or nozzle configuration to produce droplet size and momentum distributions. These distributions are then allowed to evolve within the overall flow field. Directly applicable experiments providing data in the direct vicinity of the atomizer/nozzle are a first step on the path to an accurate break up model. This research program produced tools that can be used to provide detailed quantitative and semi-quantitative results in the dense region of sprays of spray shedding structure, shedding frequencies, and velocities. Such measurements can then be used for well-specified injector and spray background conditions and thereby form a validation set to accurately benchmark existing spray models by the spray-modeling community. Although diesel sprays are the main target, the technique can be used on any dense spray breakup process.

Accomplishments of the Project

The shutdown of university research during the COVID-19 pandemic impacted the accomplishments in the first year of the project, particularly regarding the approved sub-award at CSM, which took 4 months to finally establish. Despite all of the major pandemic interruptions, important accomplishments were achieved. These accomplishments can be divided into 5 major elements: (1) Improvements to the experimental apparatus; (2) Experimental demonstration of performance improvement using a lensed holographic system; (3) Improvements in holographic reconstruction software and methods; (4) Optical system modeling for optimization of holographic design parameters, including scattering noise; and (5) standard imaging insights of bio-fuels. The first four elements pertain to Aspect (A) and the last to Aspect (B).

(1) UCI – Modifications and documentation of the experiment

While relatively minor, these modifications to the experiment and its comprehensive documentation provided important improvements to both the current experiment and any future implementation. In particular, videos of the alignment procedure and improved SOP documentation were created, the optical train height was lowered from 24” to 6” in order to improve stability and safety, vibration isolation was implemented to remove pump vibrations from affecting holograms, and spray pulse jitter was reduced so that images at known time following spray initiation could be obtained.

(2) UCI – Lensed configuration evaluation completed

This was the major accomplishment of the project. It involved adding a lens to the system for improved resolution and direct comparison with focused shadowgraphy. Images of a spray were then collected with the lensed system, and optical design was implemented to determine trade-offs. The bulk of this effort was documented in a presentation (Minniti et al., 2020 - ILASS) and publication (“Long-range microscopy of optically dense spray structures using Ultra-Short Pulse Off-Axis Digital Holography,” M. Minniti, D. Dunn-Rankin, Y.-C. Chien, Atomization and Sprays, v??.Minniti et al., 2021 - AAS). The highlights of this project element are described in the following.

Prior work demonstrated the feasibility of USPODH imaging in ambient and realistic conditions with OD up to 12. The current work expanded the technical aspects from the previous demonstration, particularly enhancing the field-of-view by adopting a lensed long-range microscopy setup. The achieved magnification was between 1.1 and 1.5, at a working distance of 35cm, which resolved primary atomization lobes, ligaments, and droplets as small as 14 μm in the near-nozzle region. The results showed that USPODH successfully rejects light scattered by the shroud of primary atomization droplets surrounding the spray core and can image fluid structures at the gas-to-liquid interface which are consistent with the structures predicted by primary atomization models. Hence, in addition to the direct insights into spray breakup that imaging can provide, near nozzle primary atomization data is valuable to the simulation community because it provides tuning and validation material for computational methods that include primary breakup (Gorokhovski and Herrmann, 2008, Manin, 2018, Manin et al., 2014).

The modified optical setup is shown in Figure 2. As with all our USPODH systems, the optical layout is similar to a Mach-Zender interferometer with an adjustable delay stage along the test path (referred to as the object beam), and a reference path that goes around the test region. The two path lengths are matched to achieve interference at the camera sensor plane. A doubling crystal converts the initial 800 nm pulse wavelength from the Coherent Evolution fs laser to 400 nm. Then a Galilean telescope expands the beam and collimates it. The expanded beam diameter is 9 mm. After the expansion, a beam splitter (BS1) divides the object and reference beam. The object beam is delayed using a motorized translation stage that allows adjustment precision for the pathlength match and beam interference on the camera sensor. The two beams meet at a beam splitter that is placed in front of the camera; this beam splitter is angled so that the two beams interfere at a small angle of $\vartheta = 0.03$ radian. This angle is important in off-axis holography because it must be optimized to trade off between field of view, resolution, and noise rejection. The pathlength matched reference and object pulse interference pattern is recorded on a TSI Powerview 1.4MP camera (cooled, monochromatic, CCD sensor; 6.45 µm pixel size).

In holography, reducing the recording and numerical propagation distance increases image resolution and reduces aliasing errors. Figure 2 shows the lensed USPODH setup where a 250 mm focal length achromatic doublet lens (L3) is placed between the beamsplitter BS2 and the camera sensor. In this setup, the lens is close to BS2 at a distance from the object of about 35 cm, the distance between the lens and the camera can be adjusted to achieve the desired magnification and allows experimentation with the focus. The results show how this setup successfully reduces the propagation distance between the hologram and object plane while increasing the reconstructed image resolution.

To demonstrate the performance of the lensed USPODH quantitatively, a USAF resolution test chart was placed in the middle of the test section at the spray nozzle location to evaluate the resolution achieved by the system. All the images in this work are contrast stretched to maximize the dynamic range. Figure 3 compares a focused shadowgraph image (left) and an off-axis hologram (right). The focused shadowgraph do not exclude multiple scattering noise but they do represent the best case images attainable. As shown in the figure, the reconstructed hologram has equivalent quality to the shadowgraph image. The holographic reconstruction is obtained from the off-axis system by adopting a 400-pixel reconstruction mask surrounding the cross-correlation term and then zero-padding the image matrix to bring it to the original image resolution. What is new in the current work is the addition of a relay lens. The lens is placed 35 cm from the chart, and the camera is then approximately 96 cm from the lens to focus the spray plane ($1/Do + 1/Di = 1/f$). The magnification factor M follows the standard geometric optics formula ($M = Di/Do$), and is approximately equal to 2.74. Because the system is arranged to focus on the target plane, to numerically focus the USAF chart, the hologram diffracted field must be propagated only by $z=12$ mm, which is a fraction of the actual physical distance of 35 cm between the target and the lens. According to holographic theory, this then increases the resolution by virtually moving the detector closer to the target. In addition, it introduces no aliasing error when back-propagating the diffracted field via the angular spectrum method (ASM). The reconstructed image shows an improvement in resolution with respect to previous results without a lens. The vertical resolution is approximately 17 µm (element 4, group 6), and the horizontal resolution is 11 µm (group 5, element 4).

To confirm that the hologram image quality is due to magnification and not simply to the fact that the relay lens is being focused on the spray plane, Figure 4 shows a configuration where the lens has been deliberately focused away from the target plane. This causes the shadowgraph image to be out of focus (left) whereas the holographic reconstruction on the right can be numerically refocused to deliver the same horizontal resolution of approximately 11 μm and vertical resolution of 17 μm. Hence, the new lensed configuration delivers a resolution and sharpness improvement by a factor of 2 with respect to early results achieved in the lensless configuration, with the additional benefit that the longer working distance allows the camera to be placed further away from the target, or in this case further from the pressure vessel windows. In addition, the holographic approach permits numerical refocusing on any plane in the system.

The introduction of a lens to the setup allows for a direct comparison of lensed focused shadowgraph, inline holography, and off-axis holography when imaging a realistic spray. The average spray properties are reported in Table 1, with injection taking place into atmospheric pressure.

Fuel	n-dodecane ($C_{12}H_{26}$)
Temperature (K)	295
Dynamic viscosity (Pa*s)	0.00134
Surface tension (mN/m)	25.35
Density (Kg/m^3)	750
Calculated fuel velocity at nozzle exit (m/s)	643
Re	57555
We	$1.95*10^6$
Oh	0.024
Orifice diameter (μm)	160
P_{inj} (MPa)	150

Table 1. Average spray properties.

From an initial overview of the images with various imaging techniques, the lensed shadowgraph image (Figure 5; upper left) shows many small droplets surrounding the major spray cone (red circle). These small droplets are present also in the inline hologram image (upper right), but not in the off-axis reconstruction image (bottom). This suggests that this is a shroud of primary atomization droplets surrounding the core spray and that the off-axis reconstruction is rejecting this source of multiple scattering noise. This shroud has been highlighted by comparing the spray cone angle measured in shadowgraph images against the one measured in off-axis hologram reconstructions.

Figure 6 shows an off-axis hologram and a shadowgraph image shot at the same time from spray injection inception. The off-axis hologram cone angle is overlaid on the shadowgraph images. A smaller cone angle suggests that the off-axis configuration is effectively rejecting the droplet cloud signature surrounding the liquid core. The lensed shadowgraph image also shows many droplets surrounding the spray; these structures seem to be clouds of droplets undergoing "rollup." These images suggest that there is a shroud of primary atomization droplets surrounding the core spray and the off-axis reconstruction is rejecting this source of multiple scattering noise. The current work focuses on the imaging technology that can expose the behavior during primary breakup, and future work will make explicit comparisons between simulation and experiments.

The background speckled features of reconstructed holograms highlight one of the biggest challenges to the USPODH coherence filtering images of sprays. Fortunately, however, separating random speckle from fluid objects is less problematic than it seems because fluid ligaments and speckle noise can be distinguished when looking at several reconstructions over a depth range. That is, when scanning the focus through the image depth plane (z-direction) fluid ligaments appear, come into focus as they branch off the spray core, and then disappear (or become defocused) as we move past the spray plane. Speckle noise on the other hand conveys a constant granular appearance throughout the whole depth field. Nevertheless, speckle noise creates an undesirable granular appearance, and speckle noise suppression strategies should be investigated to further improve USPODH's image quality.

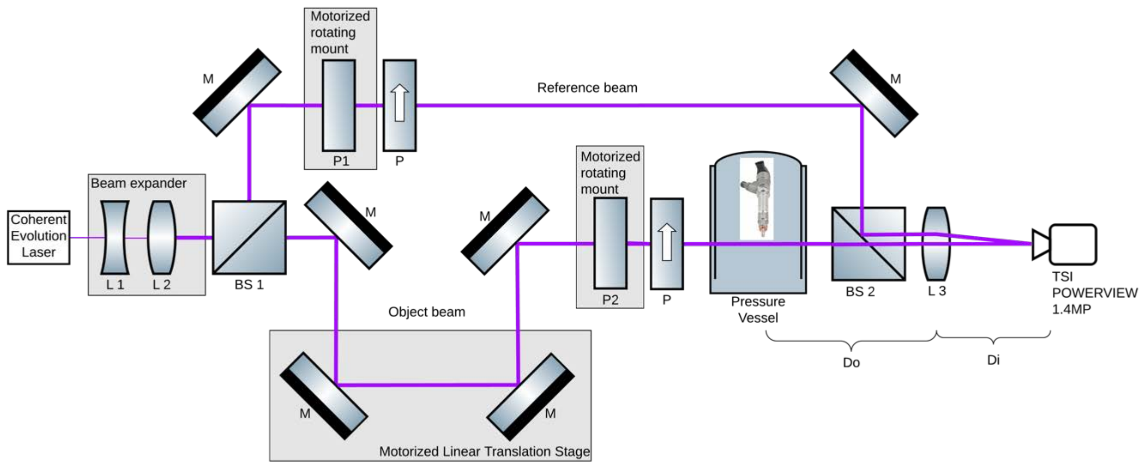

Figure 2. Lensed Ultra-Short Pulse Off-Axis Digital Holography (USPODH) setup. Do is object distance; Di is image distance.

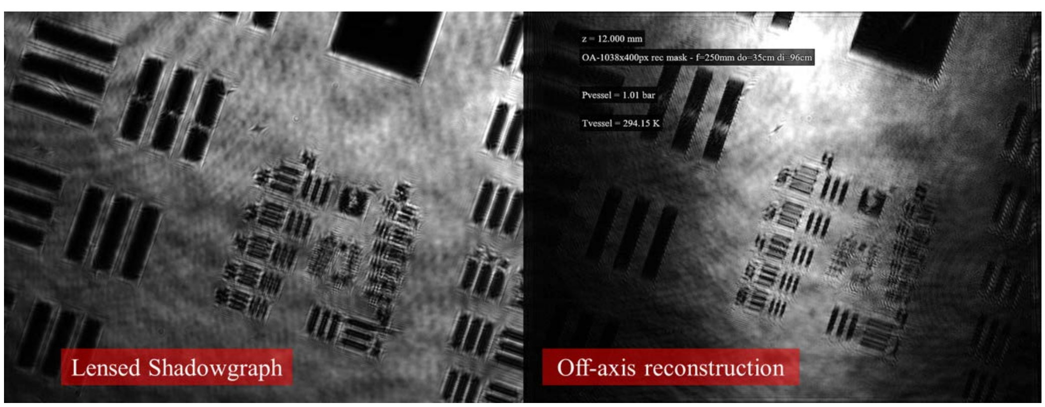

Figure 3. Comparison between lensed shadowgraph image and reconstructed hologram with reconstruction depth z=12 mm; object distance Do=350 mm; image distance Di=960 mm; lens focal length f=250 mm; magnification M=2.74.

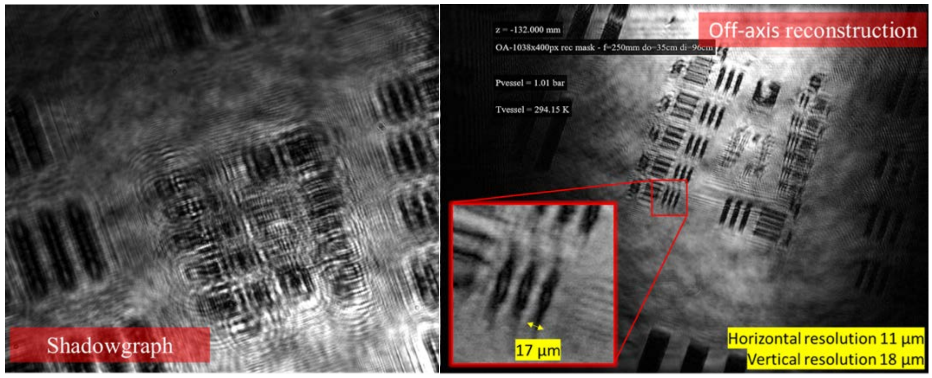

Figure 4. Comparison between out of focus shadowgraph image and reconstructed hologram with reconstruction depth z=-132 mm, object distance Do=350 mm; image distance Di =1000 mm; lens focal length f=250 mm; magnification M=2.85. The object resolution highlighted in the enlarged box is at an angle and shows therefore a combination of horizontal and vertical resolution.

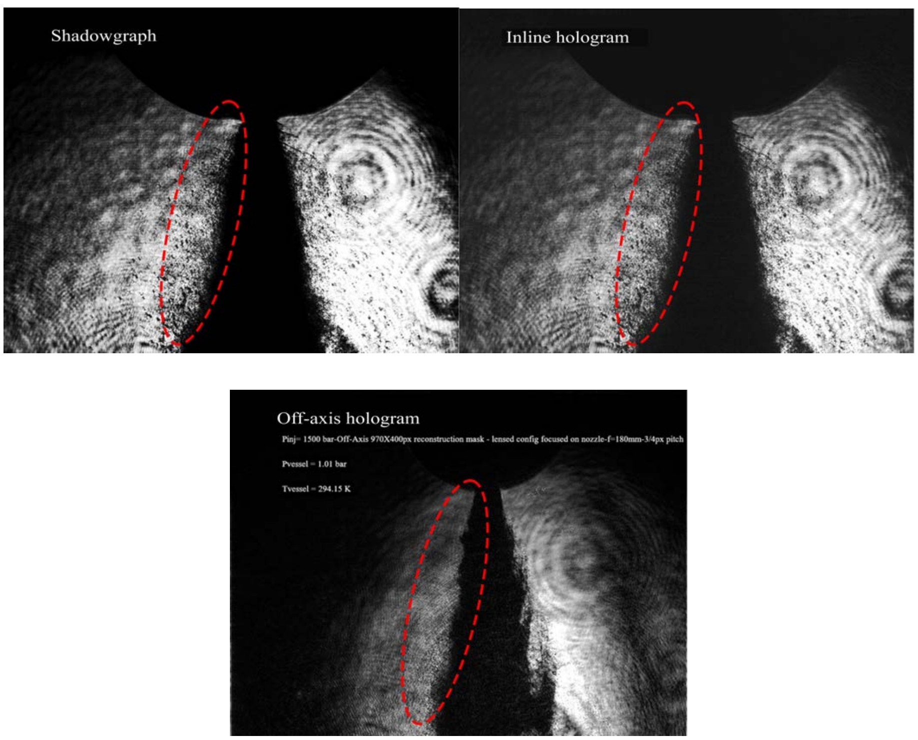

Figure 5. Focused shadowgraph (upper left) with object beam only; brightness +80%, contrast +10%. Reconstructed inline hologram (right) - 1000px reconstruction mask - z=0mm - brightness +80%. Reconstructed off-axis hologram (bottom), z=0mm, 970x400px reconstruction.

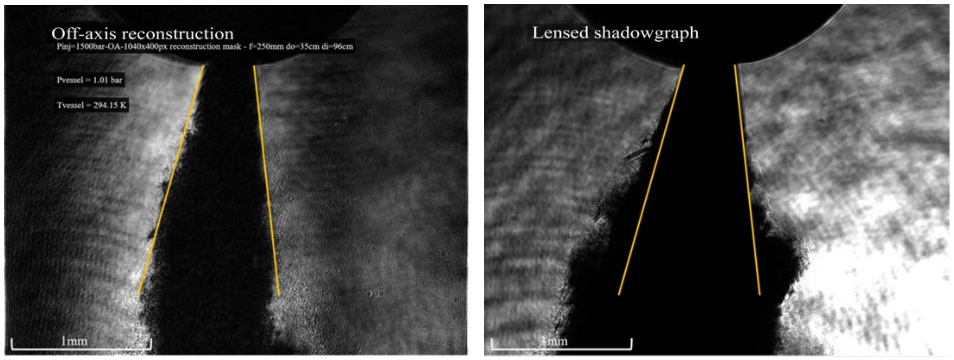

Figure 6. Left: Reconstructed Off-axis Hologram, reconstruction distance z=0 mm, 400 px reconstruction mask, object distance Do=350 mm; image distance Di=960 mm; lens focal length f=250mm; magnification M=2.7. Right: Focused, lensed shadowgraph with the superimposed spray cone angle from the off-axis hologram reconstruction. Object distance Do=350 mm imaged distance Di=960 mm; lens focal length f=250mm; magnification M=2.7.

(3) UCI - Improvements in holographic reconstruction software and methods

The improvements in holographic reconstruction were all of a technical nature and were incorporated into the software. These modifications included an automatic evaluation of the focus condition (for identifying the reconstruction plane by image edge sharpness) to permit automated depth of reconstruction determination. The results of this automated approach were variable and ultimately all such methods needed confirmation by visual observation of the user. This automated methodology remains a potential area for further improvement. In addition, the software was modified for improved batch processing and stepping through reconstruction depths to help separate objects from speckle noise and an improved zero padding approach for better resolution. The algorithm was also adjusted to reduce aliasing from undersampling.

In addition to the specific improvements in the software, a transition process with demonstration examples and operating procedural steps was created so that future users can quickly master the software.

(4) UCI - Optical system modeling for optimization of holographic design parameters, including scattering noise

This optical system modeling was the other major progress component of the project. The details are contained in a presented paper at the International Conference on Liquid Atomization and Spray Systems (Torres, et al., 2021). The steps leading to the results included initial implementation of Zemax to evaluate singlet and doublet lens performance, completion of tutorials in Zemax hologram modeling for both sequential and non-sequential modes, simulation of the lensed USPODH configuration and the effects of scatterer particle size, developing a combination of Zemax and SimuHolo (an open source software tool) to create simulated holograms and their inversion, and then evaluation of performance with optical density alone versus optical density plus particle scatterer as the measure of optical image obscuration challenge.

The overall goal was to examine the potential of simulating the digital hologram of a diesel spray and then reconstructing the spray from the hologram using the commercial optical software, Zemax™ in order to permit design optimization of the holographic system. The approach is to take a recorded hologram and place it in an optical path with any desired optical aberrations. As the test case, we take an idealized USAF resolution chart hologram through an optical train in Zemax™ and digitally reconstruct the object to demonstrate the feasibility of this technique. The results correspond well with past experimental findings.

Another component of the study is the concept that the OD alone is not sufficient to fully characterize the level of scattering noise in a spray imaging system because the size of the scattering particle impacts how the photon paths are disrupted. For example, a scattering environment with larger particles at lower number density can have the same OD as an environment with smaller particles at higher number density but the smaller particles will scatter light to a much larger solid. This work examines this concept by simplifying the distribution to be a single size of scatterer and varying the radius and number density to achieve desired optical depth values. We then introduce optical components to magnify the hologram in order to determine the effects of additional potential aberration elements on resolution. The approach will help design the optical layout of a holographic system when an optically scattering media disrupts the collected light signals.

The hologram recording and reconstruction process is accomplished with two pieces of software: SimuHolo (Poon and Liu, 2014) which is a MATLAB script, and Zemax OpticStudio. OpticStudio was primarily used to run ray traces in order to simulate the noise from scattering conditions as well as aberrations from lenses. The SimuHolo code was based on an off-axis holography simulation code from (Hariharan, 2002) that was modified for noise reduction by introducing a Fourier domain cropping technique. The experimental setup that is the basis for the simulations is as shown in Figure 2. Using SimuHolo the mirrors, beam splitters, and polarizers for the reference beam can be ignored, because SimuHolo does not propagate that beam, but rather sums its complex amplitude to the object beam numerically while keeping track of the phase and thus creating the interference pattern. The working distance, off-axis angle, laser wavelength, and the object are user inputs in SimuHolo. The laser coherence length, the optical components, and the scattering conditions are considered within the OpticStudio environment. The simulation process is to first use SimuHolo to record an aberration-free hologram, then to insert the hologram into the Zemax environment to simulate noise and aberrations, and finally to use SimuHolo again to perform a numerical reconstruction. The details of the algorithm behind SimuHolo appear in the references; the flowchart is shown in Figure 7. SimuHolo consists of three distinct steps:

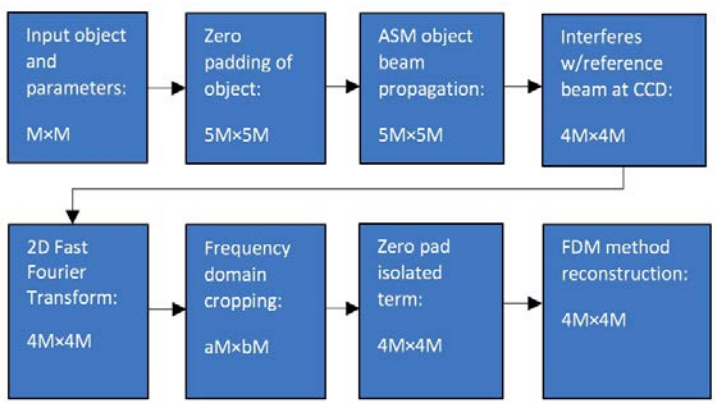

Figure 7. Flowchart of SimuHolo algorithm. M is the number of pixels. The constants a and b represent values less than 1.

propagation simulation, beam interference at detector, and reconstruction. After the first two steps, the recorded hologram is brought into the Zemax workspace where scattering noise is simulated.

The hologram is then brought back to SimuHolo to be reconstructed. The break in using SimuHolo where Zemax is used occurs between the 4^{th} and 5^{th} box in the flowchart in Figure 7.

Zemax OpticStudio is used entirely in the Non-Sequential mode to include the scattering feature, coherence length modeling, and detector customization. The "Rectangular Volume" object within OpticStudio is used to simulate the scattering cell. We varied the particle radius from a lower limit of 1μm to an upper limit of 15μm.

The first task is to create a "perfect" hologram using SimuHolo, and to use this ideal hologram as a basis for all subsequent performance evaluations. A USAF Resolution chart was selected as the object. Having an ideal test hologram to work with, the next step was to create a more realistic hologram that contains the noise generated after having passed through an optically scattering environment. The scattering comes from a collection of equally-sized spherical water droplets, with a refraction index n of 1.33, and a number density of 10^6 cm^{-3}. The "Rectangular Volume" mode was used to simulate a scattering cell as shown in Figure 8, and an increase in OD was achieved by increasing the length of the scattering cell (while keeping scatterer size and number density fixed.

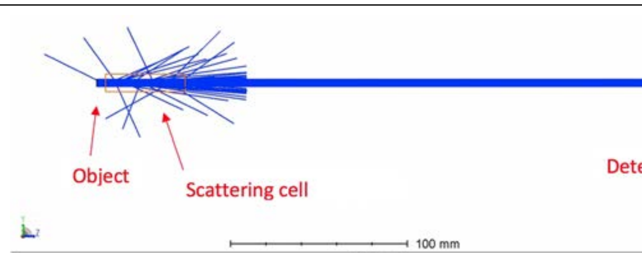

Figure 8. OpticStudio optical layout. The object and detector are in the x-y plane.

The holograms created by the described approach, and their corresponding reconstructions are shown in Figure 9. The smallest resolvable element for OD of 1 is Group 5 element 3, which has a size of 12.40µm. For OD 3 it is Group 5 element 2, which corresponds to 13.92µm. The harshest scattering environment produced here has an OD value of 7, and in this case it is possible to resolve up to Group 4 element 4, which corresponds to 22.10µm. Note that the OD 7 reconstruction lost significant sampling data in order to reduce noise levels, and in the process produced distorted

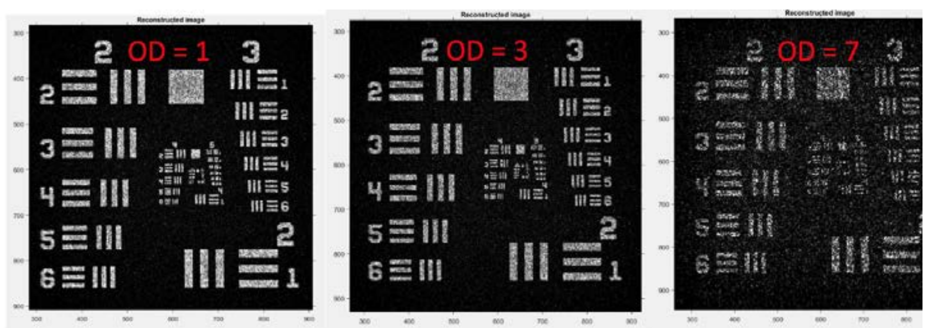

Figure 9. All reconstructions are calculated at z = 100cm. The x and y axis values in the reconstructions are in units of pixels.

elements in Groups 4 and 5 which were previously resolvable. To determine if the optical depth parameter on its own is sufficient to describe a scattering environment, the scattering cell length is then fixed at 45mm and the OD =7, but with varying scatterer number density and radius: 1µm, 5µm, and 15µm. The results are shown in Figure 10. The harshest scattering environment has the largest particle radius of 15µm, and allows only the elements from Group 2 to be resolved, corresponding to a resolution of 70.15µm. In the radius = 1µm reconstruction the smallest

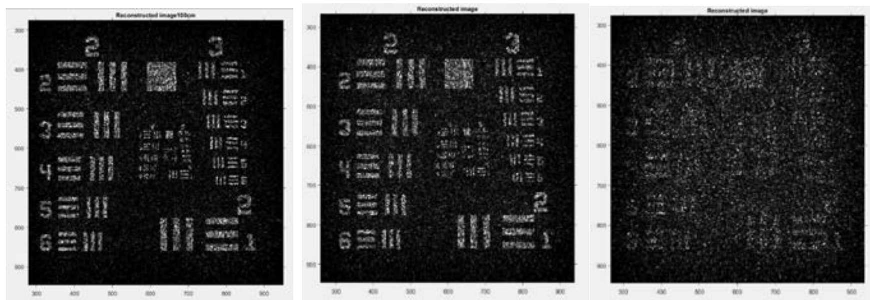

Figure 10. Study 2 reconstructions at z = 100cm and a constant OD of 7. The x and y axis are in units of pixels. The pixel cut out widths in the frequency domain are a constant 200.

resolvable element is 3 in group 4, corresponding to 24.80μm, and the same goes for the 5μm radius case although the higher noise levels produce a weak contrast with the black background.

Conclusions from primary accomplishments in USPODH – Aspect (A); Elements (2) & (4)

This project demonstrated the most recent imaging results from an ultra-short pulse off-axis digital holography (USPODH) system, where an improved lensed configuration reduced the recording and propagation distance necessary to focus on the object. The reduced propagation distance increased the reconstructed image resolution by a factor of 2 when compared to previous iterations of the technique (measured object-side resolution between 17 and 11 μm). These results indicate that USPODH is successfully rejecting the scattering produced by the shroud of primary atomization droplets surrounding the spray core and that the fluid structures observed at the gas to liquid interface are consistent with structures predicted by primary atomization models but more example images and further comparison is needed to provide confirmation of the consistency. This coherence filtering method for observing the primary breakup region of practical sprays can eventually provide direct design information and data for validating numerical simulations.

This project also introduced a new method of simulating off-axis digital holography imaging systems. The results show a “perfectly” simulated USAF resolution chart hologram produced with a MATLAB script being taken through a Zemax environment and subjected to scattering noise and optical aberrations. The reconstructions agree with expected outcomes previously suggested in experimental measurements that a scatterer should be parametrized by more than one variable, and that a lensed configuration improves image quality. The size of the scatterer plays a central role in the lower limits of resolution as it was shown that for a given value of optical depth, the particles themselves become recorded in the hologram, and are part of the reconstructed image. In future work, a hyper-realistic scatterer could be simulated in the Zemax OpticStudio workspace that reflects a real-world distribution. The limitation of using a "perfect" hologram is identified as being due to the fact that the MATLAB script used, SimuHolo, or any code in fact, takes in a finite-pixeled image file as the object, and thus produces a hologram with less pixel data than a real holographic system would produce. An experimentally obtained hologram would not suffer from the limitations described here, but rather should yield a sound theoretical basis for which to compare with experimental results.

(5) CSM - Spray Imaging Environment

Given the reduction in scope and budget, the CSM team leveraged a synergistic industry project to investigate atomization of high viscosity bio-oils. A master's student, Derek Jacobsen,

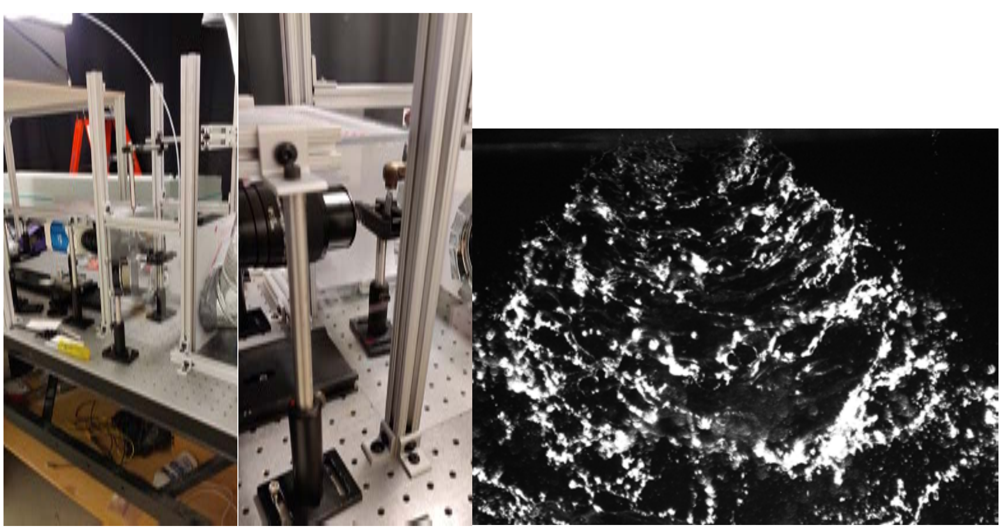

Figure 11. Spray imaging setup. Left: spray chamber (camera on left, exhaust on right). Middle: Camera, Air Force target, and fan atomizer. Right: laser (NdYag) sheet imaging of fan atomizer with water spray.

designed optical trains for laser sheet scattering and Schlieren imaging of sprays. Another team built a bio-oil injection system, composed of a pressurized oil reservoir, a high-pressure dual syringe pump, and a gas-assisted atomizer. A custom atmospheric spray chamber was also constructed with optical access for spray imaging (Figure 11). The predominant pathway for production of bio fuels from biomass is direct gasification of solid feedstocks. However, there are several groups pursuing an intermediate pyrolysis/hydrothermal liquefaction (HTL) step to product bio-oils from solids followed by gasification of the bio-oil. The pyrolysis/HTL step produces a more consistent feedstock with fewer impurities, potentially increasing operational efficiency. However, entrained-flow gasification of bio-oils requires atomization to small droplet sizes to ensure complete conversion in the finite residence times of these gasifiers. The high viscosity of bio oils precludes pressure atomization, and most groups use gas-assisted fluid

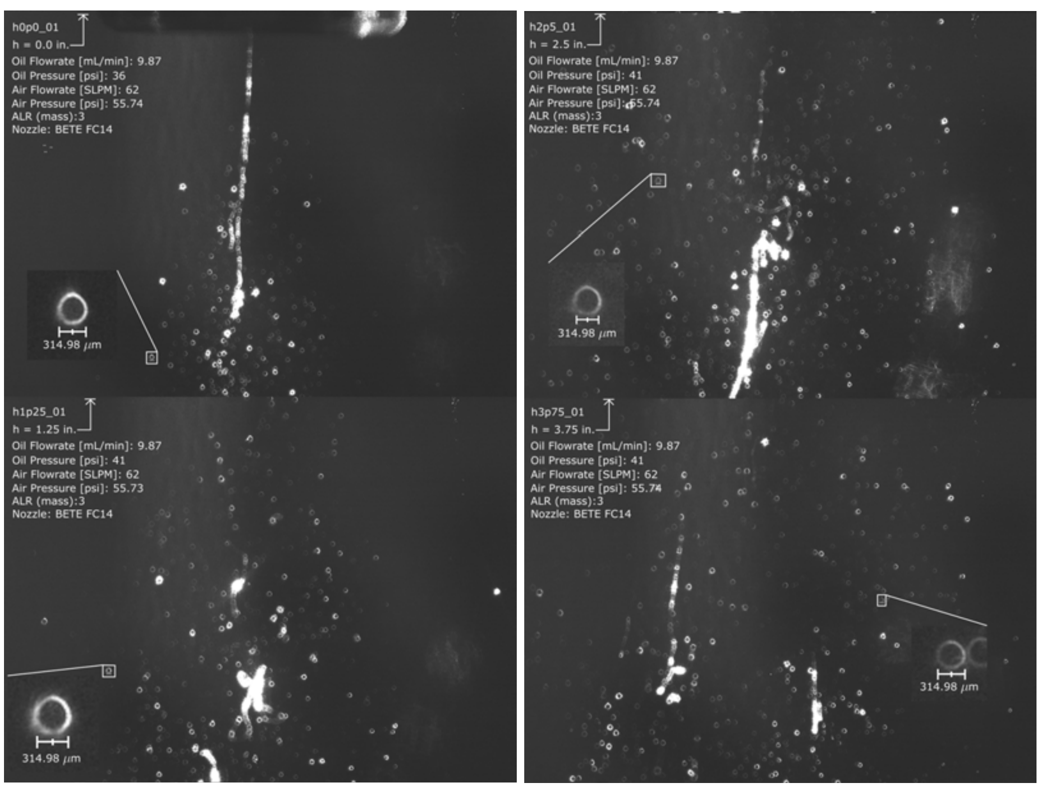

Figure 12. Pulsed-laser sheet imaging of oil injection with an ALR of 3.

breakup. Further, many of these bio oils require pre-heating to reduce viscosity to a point where atomization is feasible.

Pulsed-laser sheet scattering images were collected from bio oil surrogate (vegetable oil) over a range of air-to-liquid ratios (ALR). Initial results are shown in Figure 12. Images showed large uniform droplets and ligaments. This poor atomization is likely due to low liquid flow rates and low ALR. Future work (not in the current project plan) will include high-speed imaging of bio-oil sprays at more realistic flow rates and ALRs.

Collaborations and Technology Transfer

- Collaborations – ongoing informal collaboration with Metrolaser, Inc., as a small business interested in holographic technology and its implementation. The collaboration is primarily discussions of potential SBIR targets that could use the technique being developed.

Resulting Publications During Project

- Minniti, M., Chien, Y.-C., and Dunn-Rankin, D. (2021) "Long-range microscopy of primary atomization fluid structures in diesel sprays using Ultra-Short Pulse Off-Axis Digital Holography," ILASS-Americas 31st Annual Conference on Liquid Atomization and Spray Systems, Virtual Conference hosted by Argonne National Laboratories, May 16-19.
- Torres, J., Dunn-Rankin, D., and Chien, Y.-C. (2021) "Digital Hologram Construction and Reconstruction Optimization for Sprays Using Optical Software, ICLASS 2021, 15th Triennial International Conference on Liquid Atomization and Spray Systems, Edinburgh, UK (virtual), 29 Aug. - 2 Sept.
- Minniti, M., Dunn-Rankin, D., and Chien, Y.-C. (2021) "Long-Range Microscopy of Optically Dense Spray Structures using Ultra-Short Pulse Off-Axis Digital Holography," *Atomization and Sprays*, vol. 31, no. 11, 47–59. DOI:10.1615/AtomizSpr.2021039404
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Researchers Involved During Reporting Period

- Derek Dunn-Rankin (PI, UCI)
- Jason Porter (Collaborator, sub-award PI, CSM)
- Yu-Chien Chien (postdoctoral project scientist, UCI)
- Marco Minniti (Ph.D., graduated, UCI)
- Derek Jacobsen (M.S., graduated, CSM)
- Jose Ulises Torres (B.S., UCI)

Awards, Honors and Appointments

- None to date.

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