# Exploring Cold Spray through Schlieren Imaging

Mechanical & Industrial Engineering
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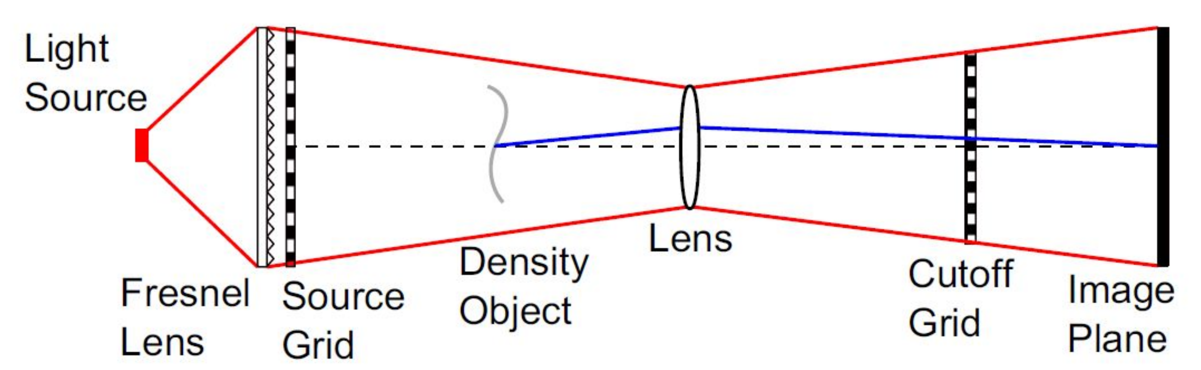
## Our Purpose

Our purpose was to design a **Schlieren Imaging set-up** to be used in a **cold spray** manufacturing lab. The Schlieren system captures images of spray patterns. The design helps improve efficiency of the cold spray process as the images provide an idea of the inefficiencies. This is possible as:

- Schlieren Imaging makes invisible flow elements visible, showing more than what can be seen with the naked eye
- Imaging works on compressible flow, with variable density, and is a non-intrusive process
- Mirror refraction against light beams are used to capture images of particle flow




Schematic depicting a basic Schlieren Imaging setup [1]

## Our Solution Path

The design team chose a **Fresnel Lens Focused Schlieren System** for this project. The benefits that come with this set-up are outlined below:

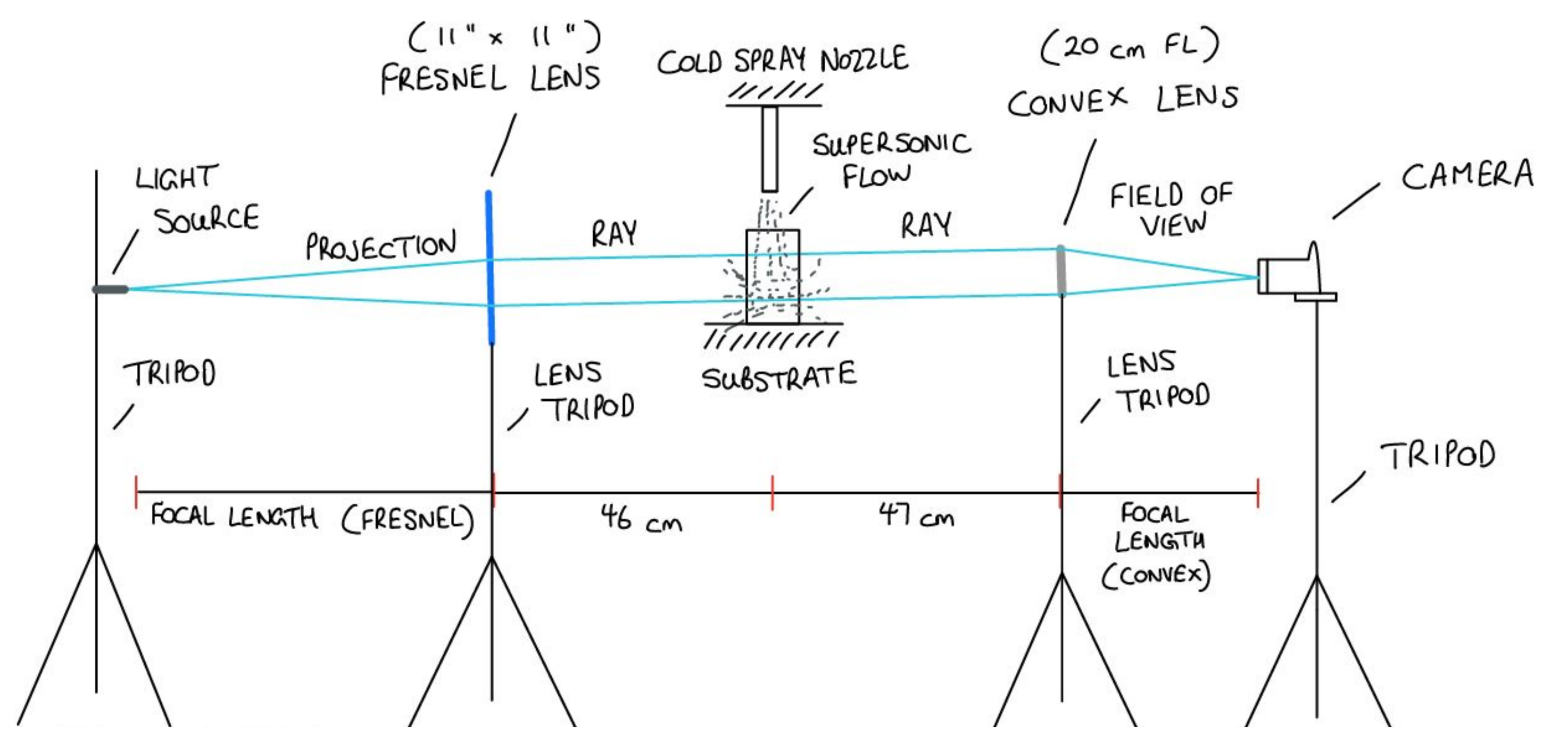
- Allows for optimal **clarity with little space**
- The implementation of a single fresnel lens and a single convex lens means the it is **relatively inexpensive** and more effective than other optical techniques (such as using two concave mirrors)
- Due to its **dimensional flexibility**, it is ideal for use in cold spray chambers as it can be adjusted for different sizes as needed
- The sensitivity of both the fresnel and convex lenses produces high-resolution images, allowing for **effective visualization of the refractive index variations in the air**

## Acknowledgments

Client and Supervisor: Prof. Ali Dolatabadi, Team Adviser: Mehdi Jadidi, TCI: Boran Kumral

## Our Final Design

- Image quality of **12 megapixels, 2~3 megapixels after post-processing** (the original objective was for a pixel count of 1~10 megapixels, therefore the design exceeded expectations)
- Camera with adjustable field of view (within the objective of **1 cm$^2$**)
- **Flexible set-up** to accommodate for different imaging applications
- Exceeded the original budget of $500 due to complexity (final costs were agreed upon between the design team, the client, and the supervisor)




Initial image captured using a high intensity NOMA halogen light source, blow-torch as the test-specimen, 13.8" focal length fresnel lens, and 150 mm focal length double convex lens. It was determined that the **light source was too intensive** for this application.

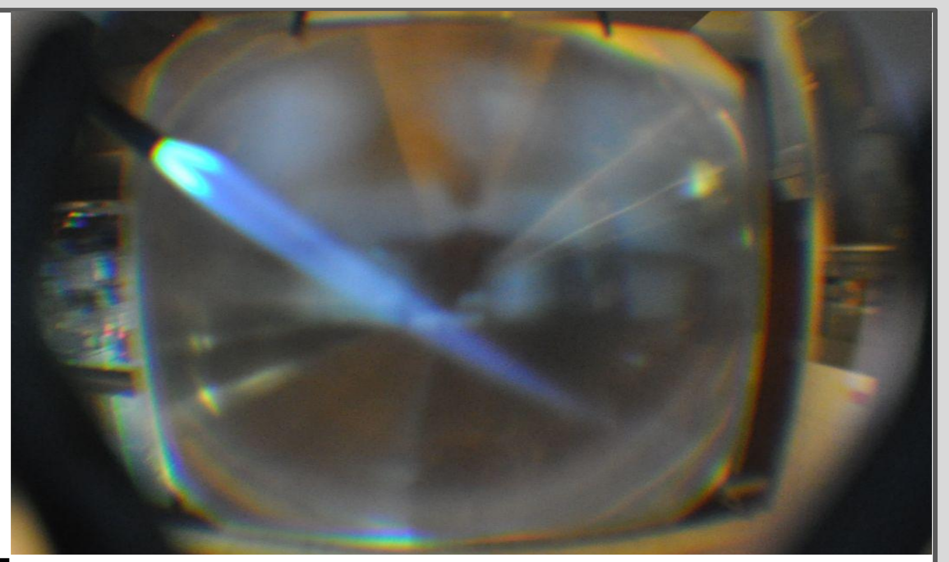
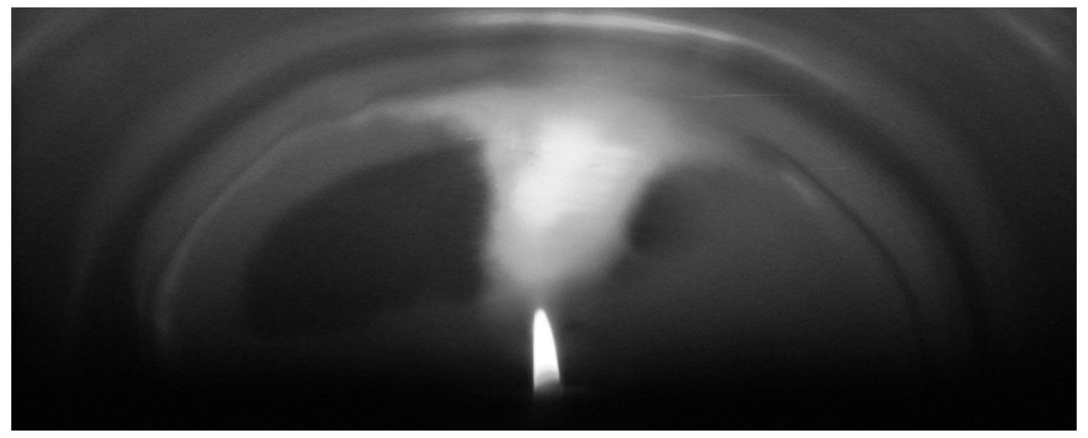


Image taken with revised design including a **point LED source** (low intensity), 12" focal length fresnel lens, and 150 mm focal length double convex lens. This resulted in a clear image of the flame, however, the air flow in the ambient environment was still not captured as a Schlieren image.

Image taken with the modified revised design using a **13.8" focal length** fresnel lens instead of the 12". This resulted in a very light Schlieren image, remotely showing the **heat signature of the flame in its ambient environment.**

## Analysis of Results

This is a raw image, as seen and captured by the camera. As can be seen, there is plenty of glare and unwanted light which needs to be filtered to better visualize the airflow above the candle.



This is the post-processed image, and the variations in the airflow can be seen. It has been converted into a black-and-white image for better visualization of the airflow.

## Future Work

Future developments that can be made to the design include:

- Developing a Schlieren imaging system based on a single fresnel lens [2]. Fresnel lenses have a larger, clearer aperture, therefore, relatively large objects can be tested.
- Due to presence of external light in the chamber, the light source must have a balance between its physical size and intensity, therefore, light sources with different intensities should be tested.
- More effective image processing methods can be helpful in deeper analysis and visualization of the spray patterns arising from the cold-spray process.

## References

[1] : E. Traldi, M. Boselli, E. Simoncelli, A. Stancampiano, M. Gherardi, V. Colombo, and G. S. Settles, "Schlieren Imaging: A powerful tool for atmospheric plasma diagnostic - EPJ techniques and instrumentation," SpringerOpen, 10-May-2018. [Online]. Available: https://epjtechniquesandinstrumentation.springeropen.com/articles/10.1140/epjti/s40485-018-0045-1. [Accessed: 30-Sep-2022].

[2] T. Kinsman, "A simple and inexpensive Schlieren optical system using a Fresnel lens," PetaPixel, 18-Jan-2020. [Online]. Available: https://petapixel.com/2020/01/18/a-simple-and-inexpensive-schlieren-optical-system-using-a-fresnel-lens/. [Accessed: 24-Mar-2023].

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# PROJECT: Exploring Cold Spray through Schlieren Imaging

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**Executive Summary**

The Final Design Specifications (FDS) document discusses the finalized design stage requirements for the Schlieren Imaging System that will be used to understand patterns of shockwaves created when particles hit a substrate during cold spray manufacturing processes. The goal of this report is to define and set both the theoretical and the practical requirements of the design, and to outline the final design solution.

The FDS document starts by defining the overall problem, and through discussing applicable details about cold-spray processes. It compares cold spray processes to other thermal processes and additive manufacturing methods. It then further goes on to introduce the Schlieren Imaging system, which helps give directionality to the report and to the design project as a whole. This section helps the reader gain an understanding of the project, and the final proposed design, as well as what can be expected of the design team by the end of the project.

In the State-of-the-Art Review section, the reader shall find information related to existing Schlieren Imaging systems and their usage in today's day and age. The Functions, Objectives, and Constraints (FOCs) section discusses essential tasks that the imaging system should perform, a list of goals that the design team would like to achieve, and various constraints to which the design must adhere. It is followed by a section dedicated to the design's Service Environment, which defines the physical space within which the design will be operated, as well as a section that discusses all important stakeholders to the project.

In the later sections, the finalized design specification is explained. Three proposed designs are introduced and the *Fresnel Lens Focused Schlieren System* is chosen as the final design, which is then justified through comparison to the original and updated FOCs. The testing stage and analysis of results are explained through the images produced, and through the summary of equipment used. Measures of design performance taken from testing the prototype, sourcing for the final design, and the iterations done in regards to the lens holders, is explained in detail. The final proposed design that will be tested in the future within the cold spray chamber is then referenced and visually explained.

Finally, a project timeline is included towards the end of the document, which includes important milestones that the design team has set and followed throughout this and last semester. It is a more detailed account than timelines outlined in previous documents for this specific project.

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### 1.0 Introduction and Problem Statement

Within the manufacturing industry, thermal spraying is a commonly used process. With the purpose of coating surfaces in order to improve component performance, thermal spraying is used to apply coatings to a wide range of materials. This results in providing materials with resistance to significant negative factors such as material wear, corrosion, erosion, cavitation, abrasion, or heat. This process also allows for certain surface properties to be modified such as; electrical conductivity, electrical insulation, lubricity, friction, and chemical resistance [1]. Cold spray, one type of thermal spraying, has a specialty of spraying fine, microscopic particles. Cold spraying is commonly used to provide thermal barriers which are used on various applications (such as aircraft wings and windows).

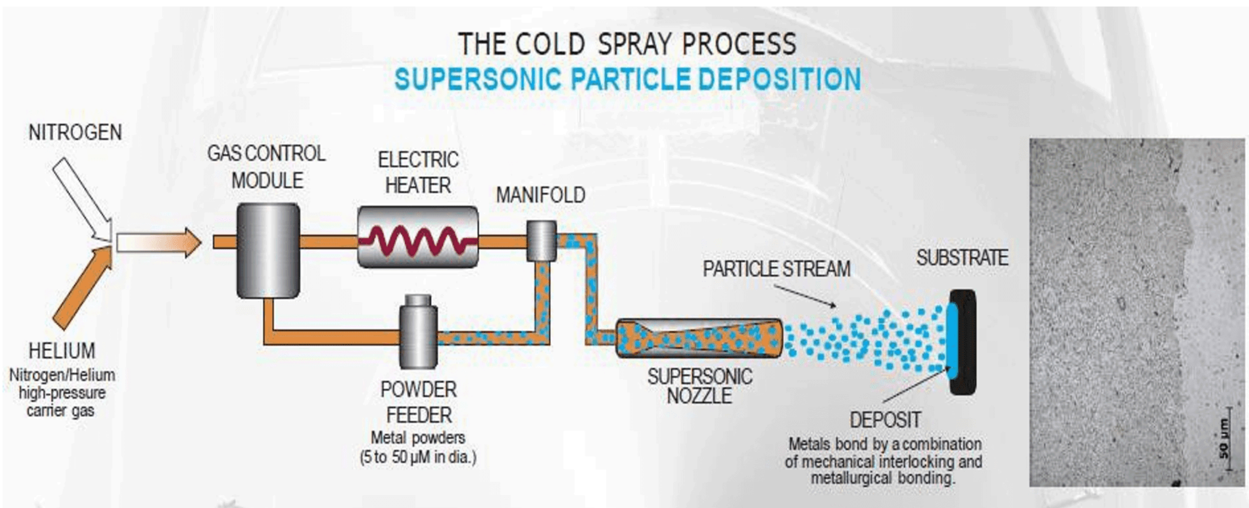



***Figure 1:*** *Schematic explaining the Cold Spray manufacturing process [2]*

Cold spray technology obtains several advantages over other thermal spraying processes. These advantages are outlined in the list below [3]:

- Low heat input, meaning no heat affected zones during the manufacturing process
- Improved structural properties
- No limit on the thickness of the particle deposition
- No oxide formation or alloy decomposition

Disadvantages with cold spray come from understanding the particle flow at the surface of the substrate. Particles tend to hit the substrate at specific angles, coating the surface with the entire particle. The flow of these particles when hitting the substrate causes plastic deformation which changes and optimizes surface properties of the original material. However, not all particles effectively coat the substrate surface – leading to inefficiencies in the cold spray process. With a focus on overcoming these inefficiencies, **Schlieren Imaging** will be used to analyze the flow of fluid at the surface of the substrate in order to optimize efficiency of cold spray manufacturing.

Schlieren Imaging is a method used to make invisible flow elements visible. This type of imagining works on compressible flow, where there is change in density. Mirror refraction against light beams is used to capture images of particle flow. This is done without adding dye to the flow, which could ultimately alter the flow and render data from the images useless once added. Therefore, Schlieren Imaging provides a non-intrusive approach to particle flow image capture, as no alterations to the fluid itself are needed. All equipment used within image processing is set up outside the spray chamber. This is an important feature as the imaging process occurs within the vacuum chamber in order to capture microscopic details. For this reason, Schlieren Imaging is the most optimal method to use for imaging the fluid when cold spray is used on a substrate.

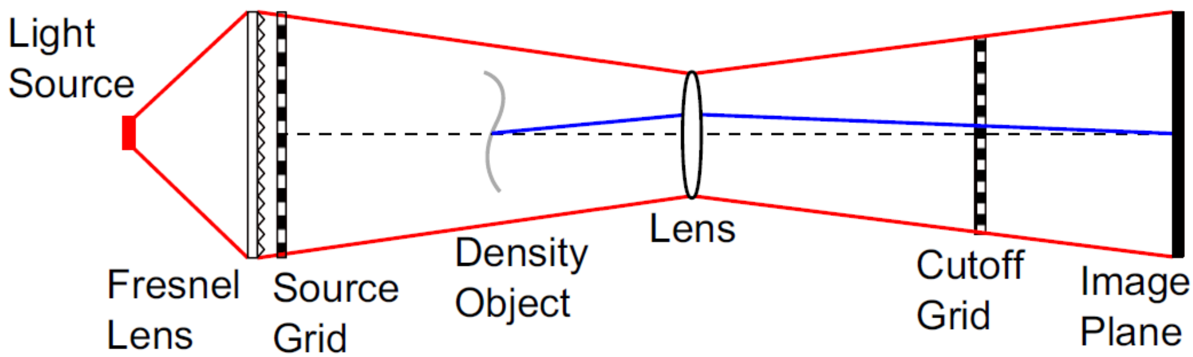



***Figure 2:*** *Schematic depicting a basic Schlieren Imaging setup (diagram) [4]*

For the purpose of this project, the cold spray process will be photographed using a camera, lens, and light source setup which outputs Schlieren Images. These images will be used to map out the flow of particles hitting the substrate. More specifically, the interaction of the substrate with cold spray produces different types of waves that can be analyzed such as: shock waves, expansion waves and compressional waves. Cold spray is easily used on flat surfaces and generally decreases in efficiency on complex geometries such as uneven surfaces, abnormal angles and crevices. The mapping determined by the images taken by the camera will ultimately help guide the user towards choosing the most optimal approach when cold spraying the desired substrate.

## 2.0 State-of-the-Art Review

### 2.1 Schlieren Imaging: a powerful tool for atmospheric plasma diagnostics

The process of Schlieren Imaging is a highly effective way in providing qualitative information on the fluid-dynamic characteristics of supersonic flow of plasmas generated by several different types of sources. However, when working with complex surface geometries and applications of atmospheric pressure plasma sources, obtaining accurate and reliable results from Schlieren Imaging can be tedious. Therefore, it is crucial that carefully thought out setups and physical image capturing principles are applied in order to investigate plasma flow physics and their complex wave behavior when applied on surfaces of different materials [5].

### 2.2 Single Source/Cutoff Grid, Self-Aligned Focusing Schlieren System

Schlieren Imaging, a popular particle flow visualization tool, is often applied to wind tunnel experiments in order to provide qualitative information about gradient fields of density present in a specific test section. The potential setups of the Schlieren system in this experiment consisted of either using dual-field-lens or a dual-parabolic-mirror-z-type arrangement. In both cases, the first lens/mirror is used to align light parallel from a point illumination source, where the resulting rays pass through a measurement volume field where variations in refractive indexes cause angular deflections to a portion of the total rays. The second lens/mirror is then applied to focus the rays of light to a specific point, through a spatial filter, which is used to block deflected incident rays. A camera embedded within this Schlieren system is used in this light projection to accurately image a spatially-filtered intensity pattern consisting of light and dark regions, which represent the position of various density structures present in the measurement volume [6].

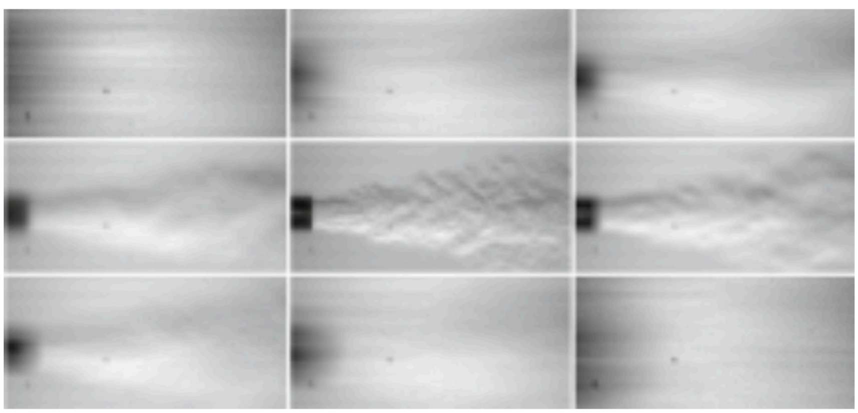


***Figure 3:*** *Supersonic Flow Image captured by Compact Focusing Schlieren system [7]*

## 3.0 Functions, Objectives and Constraints (FOCs)

### 3.1 Functions

Functions were chosen based on a functional decomposition chart [Appendix A]. The primary and secondary functions are outlined in Table 3.1.1 below.

***Table 3.1.1:*** *Primary and Secondary Functions of the design*

| Primary Function | Secondary Function |
|---|---|
| Provide Schlieren images to analyze particle flow. | Capture images of shockwaves. |
| | Capture images at a microscopic level. |

| | |
|---|---|
| | Transfer final captured images onto a computer. |
| | Capture images of particle flow on various surface geometries |

### 3.2 Objectives

This project focuses on creating a Schlieren system for understanding the particle flow from a cold spray additive manufacturing system. Table 3.2.1 below has objectives outlined for this design.

***Table 3.2.1:*** *Objectives with metrics and goals*

| **Objectives** | **Metric** | **Objective Goal** | **Reasoning** |
|---|---|---|---|
| Camera system should operate within a small field of view | Area in sq. mm or sq. cm | = 0.5-5 sq. cm | The cold spray mechanism operates within 2 $mm^2$ and the camera should capture the direct spray and any deflected particles |
| Should take high quality Schlieren Images | Pixel count of the image captured | = 1 - 10 megapixels [8] | To obtain highly qualitative images that visualize cold spray supersonic flow |
| Schlieren camera position should be adjustable for a custom field of view | Length in cm from centre point of surface | = ±5 cm | To observe shockwave behavior across the surface area of the substrate from supersonic particle flow |

| | | | |
|---|---|---|---|
| Schlieren camera lens should be able to zoom in/out for a custom field of view | Zooming capability in x | =0.5x - 10x | To observe intricacies in the shockwaves and understand wave patterns |

### 3.3 Constraints

As an imaging system, the design would need to satisfy conditions due to environmental factors, and the client's needs. The main constraints in this project would be related to system operation and cost. At a minimum, the design must be able to capture sound and shock waves near the substrate that result when particles from the cold spray hit the surface. The maximum area that can be sprayed by the cold spray system is 2 $mm^2$, which would be needed to account for during the Schlieren Imaging process. There is a limitation with respect to the camera placement too, it cannot be placed less than 30 cm from the nozzle of the cold spray. Additionally, the entire design must be placed within a 1m radius of the cold spray chamber. Furthermore, the available budget for this project is $500, which will have a significant impact on determining the quality of our results. Table 3.3.1 lists these conditions below.

***Table 3.3.1:*** *Constraints with metrics*

| **Constraints** | **Metric** |
|---|---|
| Must be able to capture images within a 1 $cm^2$ surface spray area | Surface area in $cm^2$ |
| Schlieren imaging camera must be placed at least 30 cm from the cold spray nozzle | Distance in cm |
| Imaging setup must be placed within a 1 m radius of the cold spray chamber | Radius in m |
| The project cost must not go over $500 | Amount in CAD ($) |

## 4.0 Service Environment

As the design will operate in Toronto, more specifically within a lab on the 8th floor of Bahen Centre. Specifications include; room temperature, camera location, lighting. The design will be operated in a demanding environment, with continuous exposure to dust and various other particles, along with a certain degree of variation in the ambient temperature. These points would need to be considered during the design phase.

## 5.0 Stakeholders

The below listed parties are indirectly impacted through the design of the schlieren system. Listed in Table 5.1 are the stakeholders classified on the basis of their involvement and the impact the design could have on them.

***Table 5.1:*** *Description of External, Primary and Secondary Stakeholders*

| Stakeholder | Type | Impact of Design |
|---|---|---|
| Professors/Teaching Staff | Primary | A successful, operating design would aid professors and teaching staff in their research or teaching/demonstration work. |
| Manufacturing Companies (specifically, Additive Manufacturing companies) | External | Manufacturing companies would be interested in the data output and how it can make manufacturing processes more efficient. |
| Materials Trading Companies | External | Upon analysis of cold spray techniques on various materials, surfaces and geometries, material traders would be interested in working together with manufacturing companies. |
| Students | Secondary | Graduate and undergraduate students who are interested in using the system for their education and experiments. |
| UofT/Myhal Entrepreneurship Hatchery | Secondary | Upon successful development of the design in-house (at UofT), the Entrepreneurship Hatchery may have an interest in commercializing the design. |
| Cold Spray Equipment Manufacturing Companies | External | Companies in the business of manufacturing the equipment used in cold spray techniques would be interested in learning new breakthroughs in the capability of these techniques for the purpose of developing their manufacturing processes, and would be appealed by the Schlieren Imaging System. |
| Companies in the Aerospace sector | External | The usage of cold-spray technologies has seen a rise over the years particularly in the Aerospace/Aviation domain, where one of |

| | | |
|---|---|---|
| | | their major applications is repair and maintenance work of aircrafts [9]. Companies in this domain would have an interest in the design as it would uncover new details about the capabilities of cold-spray technologies. |

## 6.0 DfX Principles

This section outlines certain basic principles that the design is intended to satisfy or serve:

### 6.1 Design for Durability and Longevity

Choices regarding the types of materials and equipment used in the Schlieren system need to be made carefully, in order to minimize the risk of failure. Appropriate codes and regulations, if applicable, need to be consulted with too so as to ensure the design satisfies all requirements. Furthermore, the design will be operated in an environment with constant exposure to dust and several other particles. Careful consideration needs to be given in the design process to ensure it can withstand these conditions.

### 6.2 Design for Safety

Due to the design working with supersonic cold spray particle flow, safety standards must be reinforced to be of top priority. Durable barriers must be fitted around the cold spray chamber, with the chamber itself being situated in a sound-proof insulated room. Due to high sound levels, it may be necessary that the user interacting with the design may need to wear appropriate hearing protection equipment. The barriers would also provide shielding against harmful airborne particles.

### 6.3 Design for Robustness

The design needs to be able to accommodate certain arrangements to the camera setup to allow for better view angles. Users must have some flexibility with arranging certain parameters such as camera position and the zoom settings to help understand the shockwave patterns better.

## 7.0 Human Factors

The design team interacts directly with the system through the camera. The system shall be set up for ease of accessibility, such that the design team member capturing the photo can click the shutter-release button. The design team must also retrieve data from the camera to be used in analysis. Therefore, ease of data extraction must be considered in the design of the Schlieren system. The data must be easily transferred to a computer where it can be interpreted by the design team. As the camera may need to be taken away for various reasons, such as data extraction, ease of set-up must be considered. The design should be able to accommodate iterative processes during the experiment, i.e. users should have the ability to make any adjustments to parameters such as flow pressure, speed, etc. in order to view the effects these changes cause to the pattern of shockwaves formed on the substrate, which would be captured by the imaging system. The camera should be easy to place in the correct location to ensure consistency across images captured at any point. The aim is to be able to see the shockwaves and vortices formed after hitting the surface of the substrate clearly, hence making the placement an important human factor.

## 8.0 Final Design Specifications

### 8.1 Conceptual Design Brainstorming

The team brainstormed 3 conceptual designs for a Schlieren imaging setup with the aim to be used in the cold-spray chamber. These designs are briefly mentioned below:

*Design 1: Simple Dual Lens Schlieren System*

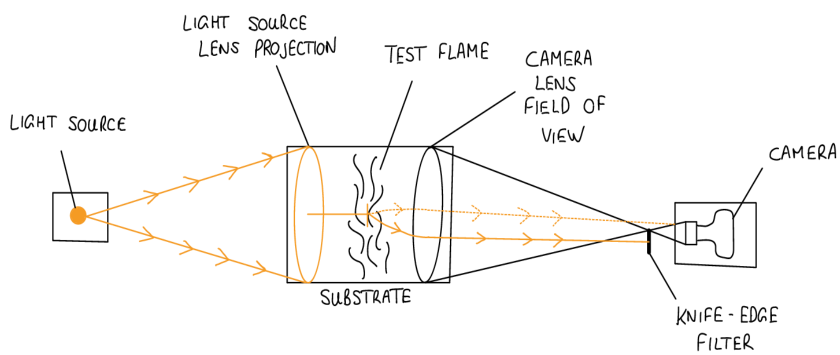



***Figure 4:*** *Schematic of a Simple Dual Lens Schlieren System*

This setup utilizes two convex lenses, between which, the specimen to be analyzed will be placed (in this case, a test flame). The light source needs to be placed at the focal point of the primary lens, so that it can result in a parallelized ray output [10]. These parallel rays are then captured by the secondary lens, which then converges them onto the image plane (which is where the camera is placed), resulting in a schlieren image of the heat signature of the flame.

Some additional features such as source/cutoff grids and a knife-edge filter may also be included in order to filter the light and develop clearer images.

This design was not chosen because convex lenses typically have low converging power meaning that the entire setup would need to be very closely spaced. This would not be ideal, as the cold-spray system has a relatively larger workspace, and would need an imaging system that can operate in it.

*Design 2: Dual Mirror Schlieren System*

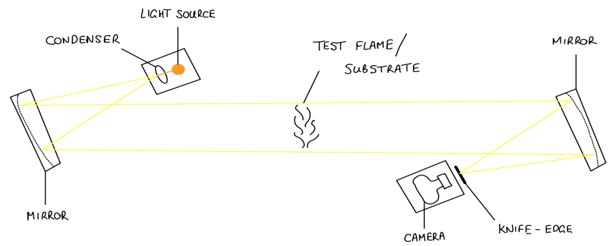



***Figure 5:*** *Schematic of a Dual Mirror Schlieren System*

This setup utilizes two concave mirrors, which converge a well-defined beam of light onto the field of view of the camera lens. A knife-edge is placed partially in front of the camera lens to filter out any remaining scattered light. To create a Schlieren effect, the test flame/substrate is placed in the path of the light beam between the two mirrors. The camera is used to image the changes in the refractive index of the air through the visible gradient of the light beam.

This design was not finalized as our proposed design since image quality is significantly compromised by the light beam reflection off the concave mirrors. Additionally, the scale of this system is not feasible given the service environment (cold spray chamber) it will be installed in.

*Design 3 (Final Design): Fresnel Lens Focused Schlieren System*

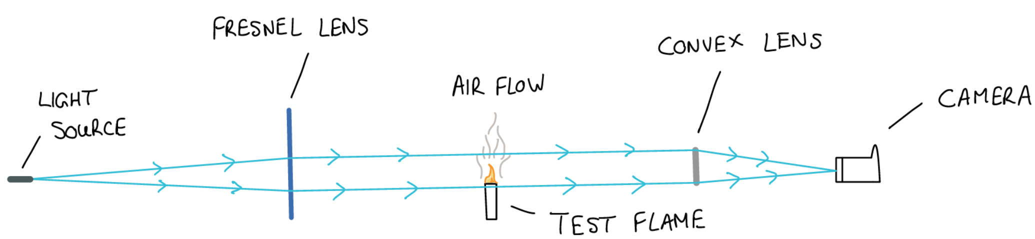



***Figure 6:*** *Schematic of a Fresnel Lens Schlieren System*

This setup is a dual lens system similar to Design 1, with the implementation of a Fresnel lens instead. The Fresnel lens is made up of a series of concentric rings that is ideally used to collimate the projection of light from the light source and focus it into a parallel beam of light [11]. This leads to an effective transmission of light to enhance Schlieren imaging. The convex lens is curved in shape and is ideally used to create a magnification effect of the test flame to be captured by the camera.

This design was chosen as the final design as in comparison to Design 1, a clearer image is produced and in comparison to Design 2, and less space is required. Figure 3 above serves as a visual depiction of this setup. This decision was made during the Design Review phase of the project, whereby the above designs were thoroughly discussed and critiqued to select the most suitable setup for implementation in the spray chamber.

### 8.2 Alignment of the Chosen Design with the Project Requirements

The following section outlines and justifies how the final proposed design meets the design team's FOCs. Functions, objectives, and constraints are analyzed against test results in order to properly understand how each parameter has been met.

1. ***Functions***

   The primary function, "Provide Schlieren images to analyze particle flow," has been met during testing of the project. The design team has not yet captured Schlieren Images in the cold spray chamber, which is their ultimate goal, however the design team has taken images of a candle flame for testing. These tests demonstrate the validity of the Schlieren set-up, specifically through providing raw images that can be effectively post-processed. Image subtraction can be used on the images captured, resulting in observable particle flow.

2. ***Objectives***

   The system has filled all objectives outlined previously. In testing, the camera operates in a small field of view, effectively capturing the candle flame as well as surrounding smoke and particle flow. The pixel count in the resulting images is approximately 12 megapixels, which is slightly over our objective. In this way, the design team has performed more favourably than originally planned, as higher pixel count ultimately leads to higher clarity in images produced. After image subtraction (post-processing) the image quality reduces to 2~3 megapixels. This is a significant reduction, however the image quality still meets the original objective of the design team. The camera within the Schlieren system is adjustable and has been tested for different fields of view. The camera can be moved physically to varying distances from the observed point (the cold spray nozzle), and can also be adjusted through zooming in or out depending on the desired field of view.

3. ***Constraints***

   The final design satisfies all constraints set out in the original plan. The camera sufficiently captures images within, and beyond the surface spray area. In testing, the design team (the system user) was able to adjust the field of view to photograph within 1 $cm^2$ as well as outside of that dimension, as desired. This was done through the camera's zoom feature, or through physically moving the camera itself (as outlined above in the "Objectives" section). The imaging setup can fit properly in the cold spray chamber, and is still flexible if needed. The design team has simulated the proper setup, however has not yet captured images within the chamber, therefore the distances between lenses, the camera, and the light source are not finalized. Additionally, the project has exceeded the original budget of $500 due to complexity of equipment required for the setup. All additional costs, however, were discussed and agreed upon between the design team, the client, and the supervisor. Therefore, the constraint changed with time to accommodate for accurate material costs (as opposed to considering the capstone-allocated budget as our maximum limit).

The design team successfully met all their functions, objectives, and constraints. Some parameters, such as the image quality objective, exceeded the original expectation or goal, whilst others, such as the cost constraint, had to be reassessed in order to better reflect the project requirements. Any changes to FOCs throughout the project have been effectively communicated with the project client and supervisor, to ensure transparency across the entire project team.

### 8.3 Initial Testing Prototype Using a Candle-Flame as Test Specimen

The final proposed prototype design, the *Fresnel Lens Focused Tabletop Schlieren System*, was chosen due to its cost-effectiveness, flexibility, and adaption of high-resolution images. The design team prototyped a simple initial setup inspired from this design on a tabletop to analyze and capture Schlieren images of a candle-flame. The sole utilization of a single fresnel lens and single convex lens is relatively inexpensive and more effective when compared to other optical techniques such as concave mirrors. The sensitivity of both the fresnel and convex lenses allows high-resolution images to be captured in order to effectively visualize refractive index variations in air. An overview of the equipment used in this prototype is shown in Table 8.3.1.

***Table 8.3.1:*** *Summary of Equipment Used during testing of Schlieren Imaging System Prototype (using a candle-flame as a test specimen)*

| Sr. No. | Component | Manufacturer | Model / Specification | Quantity | Cost [CAD] |
|---|---|---|---|---|---|
| 1 | DSLR Camera | Nikon | 7000 Series | 1 | $800.00 - $1000.00 |
| 2 | Telephoto Lens | Nikon | 18 - 140 mm ED VR | 1 | N/A |
| 3 | Light Source | Panasonic | White LED | 1 | $10.00 |
| 4 | Convex Lens | Edmund Optics | 20 cm Focal Length | 1 | $148.40 |
| 5 | Fresnel Lens | Edmund Optics | 6.7” x 6.7” (12” Focal Length) | 1 | $65.10 |

| | | | | | |
|---|---|---|---|---|---|
| 6 | Camera Tripod | Manfrotto | 209 Kit | 1 | $249.99 |
| 7 | Tripod for light source | N/A - Assembled Manually | N/A | 1 | $50.00 |
| 8 | Lens Tabletop Holders (used only for testing) | N/A - Sourced from CACT Lab | N/A | 2 | N/A |

The team initially sourced a high intensity light source manufactured by *NOMA*, a popular manufacturer of lighting products. However, it was soon realized that the light source was too intense for this application, and would heat up anything placed in front of it (light filtering paper, etc.) posing a fire hazard. The team hence decided to phase out the idea of using this product, and chose a more suitable point light source, with lesser intensity for the purpose of prototyping.

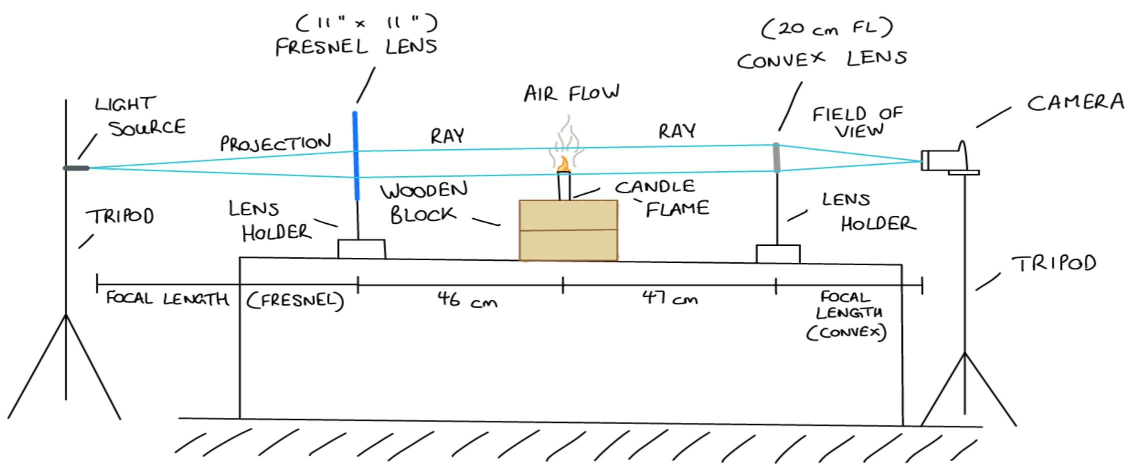



***Figure 7:*** *Schematic of the tabletop Schlieren Imaging System Prototype used for testing*

In order to determine the accurate distances between the setup elements and their positions, the design team referred to the refraction laws of fresnel and convex lenses. The light source was placed at the focal length of the fresnel lens, with the smoothe face of the fresnel lens facing the light source, and the side with concentric circular layers facing the testing specimen (candle-flame, in this case). The camera to capture the schlieren images was placed at the focal length of the convex lens, as parallel rays are converged at the focal point by a convex lens. As for the positioning of the test specimen, it should be placed approximately at the midpoint, between the two lenses; however, this parameter can be slightly variable.

The team experimented with this setup in two environments; a large room having a moderate amount of external light, and the other one being a smaller, pitch dark room, and determined that the presence of external light was inversely proportional to image quality, and to the potential of capturing Schlieren images. The images captured in the pitch dark room were of greater quality as compared to those captured in the brighter room. It must be considered that this setup is a prototype, with which specific modifications of the lens holders will be required for successful installation in the cold spray chamber.

### 8.4 Analysis of Test Results from Prototype

The preliminary setup used the previously mentioned high intensity *NOMA* halogen light source, a blow-torch as the test specimen, a 11” x 11”, 13.8” focal length fresnel lens and a 150 mm focal length double convex lens. However, it was immediately made clear that the light source was too intense for this application, and caused a dangerous level of heat buildup on its surface, which also posed a fire hazard (especially when paper filters were used to filter the light). An image captured from this setup is included below (Figure 8).

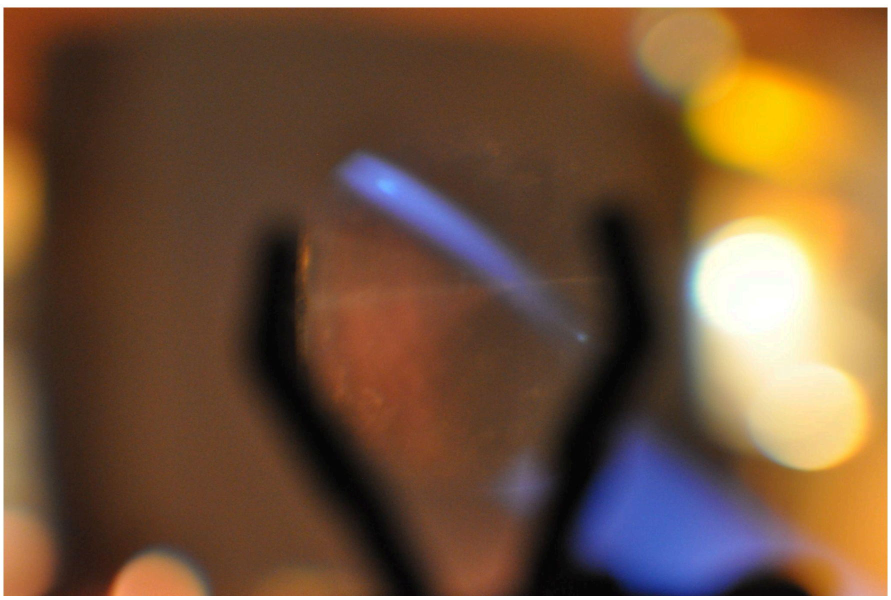
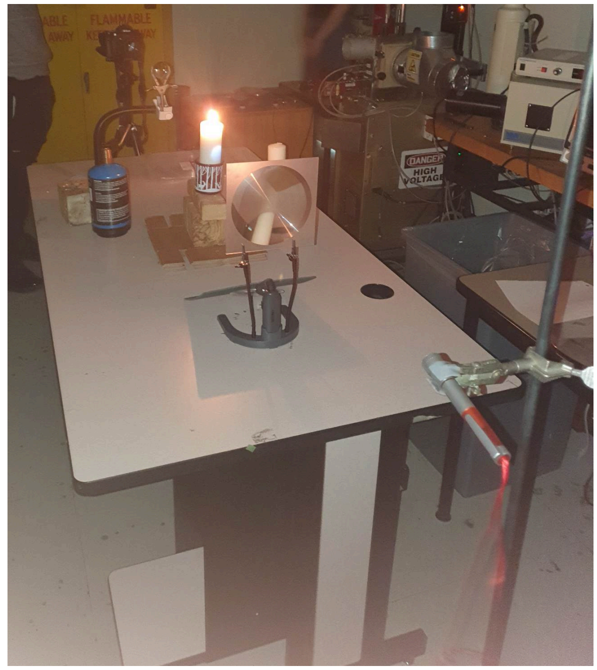
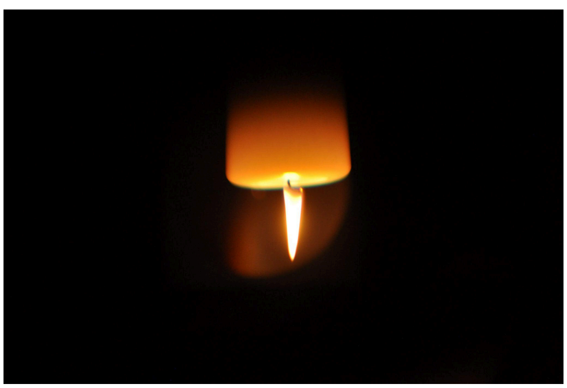


***Figure 8:*** *One of the first images taken in the preliminary testing phase (with the high intensity light source)*

As a next step, the team decided to replace the overpowering, high intensity *NOMA* halogen light source with a low intensity, point LED source, a 6.7” x 6.7”, 12” focal length fresnel lens, 150 mm focal length double convex lens, and a candle as the test specimen (image of the setup shown in Figures 9 and 10). This resulted in a better image of the flame itself (Figures 11 and 12), but still did not provide any visuals of the flame’s proximate environment.

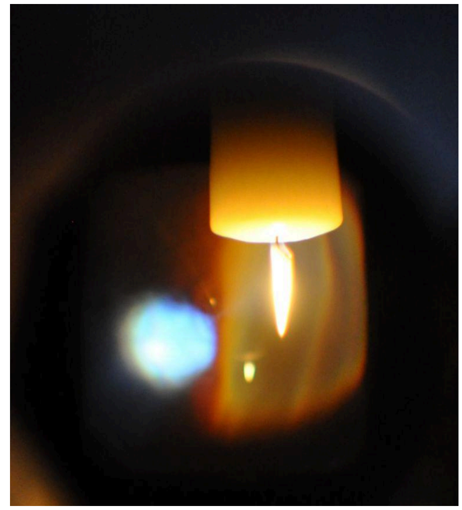
***Figures 9, 10:*** *Setup used for testing the Schlieren Imaging technique*

***Figures 11, 12:*** *Images of the flame captured with the new setup*

The team then chose to reuse the 11" x 11", 13.8" focal length fresnel lens, in combination with the 150 mm focal length double convex lens, the same low-intensity LED light source, and the candle flame test specimen. The team was able to produce a very light schlieren image, remotely showing the heat signature of the candle flame. The raw images of this experiment are included below (Figures 13, 14, 15).





***Figures 13, 14, 15:*** *Raw images captured of the candle flame, remotely showing the heat signature of the flame*

These images were chosen for post-processing, as they best captured the candle flame's heat signature. Software like *MATLAB* and *ImageJ* were applied for post-processing; however, the design team ultimately determined that *MATLAB* provided more flexibility and accuracy with image processing due to coding implementation [*Appendix*].

This post-processing was done by first capturing an image of the flame, and then, in the same orientation, capturing another image without the flame. A *MATLAB* script [*Appendix B*] was then used to perform image subtraction, wherein the image without the flame was subtracted from the image with the flame, and then converted to grayscale (refer to Figure 16 below).

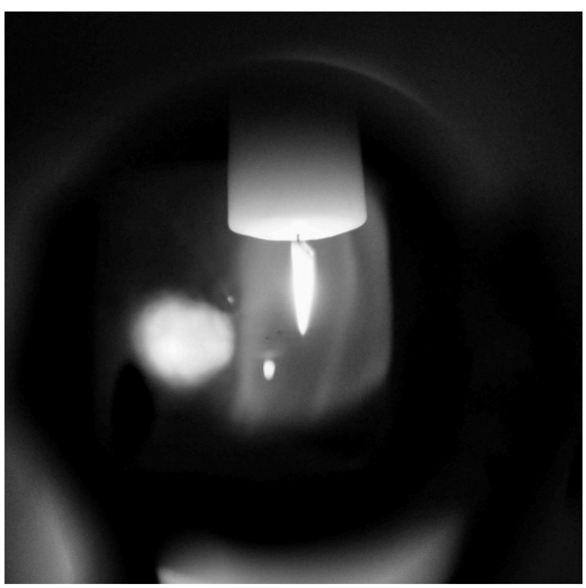


***Figure 16:*** *Processed schlieren image of the candle-flame*

The digitally processed image above, after subtraction implementation, allowed an enhancement in visibility of the Schlieren optical technique, an improved contrast, and an effective visualization of the refractive index variations. By subtracting the two images with and without the flame, this resulting image made small variations of air flow around the flame more visible, which would otherwise be difficult to discern in an non-subtracted, raw image. Additionally, the subtraction of the reference image of the background from the image of the flame itself, allowed the resulting image to have a darker background and a brighter flame, which made it easy to distinguish Schlieren behavior. Lastly, refractive index variations were more clearly observed as compared to past images taken, which confirmed that the design team had the correct setup and had solidified the ideal process of image subtraction.

### 8.5 Measures of Design Performance

The following points-based matrix was used to measure the prototype's performance against a list of design factors which is presented within Table 8.5.1 below.

***Table 8.5.1:*** *Design Performance Matrix*

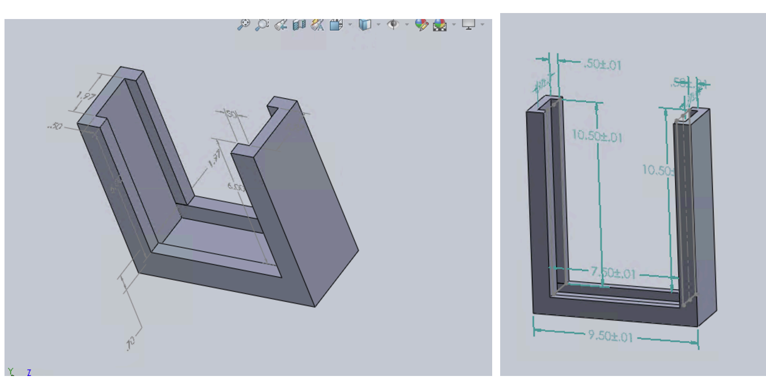
| **Design Factors** | **Scores** | | | | |
|---|---|---|---|---|---|
| | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** |
| Is the flame seen properly in the image? | | | | | ✔ |
| Is the air surrounding the flame visible? | | ✔ | | | |
| Is the flame's heat signature (heat contours) visible? | | | ✔ | | |
| How well can the system be implemented in the cold spray chamber (dimension-wise)? | | | | ✔ | |
| Is it possible to have minimal human input? | | | | | ✔ |
| Is the test flame illuminated uniformly by the light source filtering through the fresnel lens? | | | | | ✔ |
| How beneficial was the | | | ✔ | | |

| | | | | | |
|---|---|---|---|---|---|
| method of image processing? | | | | | |

Based on this chart, the design prototype scored an average of *3.8/5* points; this is primarily because of its inability to produce images showing the activity of the air surrounding the flame. The design however scored well in terms of its potential to have minimal human input. The camera can be adjusted to be in 'recording' mode, which will enable users to capture video clips of the spray flow patterns with minimal interference. As for the design's capability to withstand the conditions in the cold-spray chamber, the subsequent section will explain the thought process behind enabling it to do so.

### 8.6 Sourcing and Developing Additional Tools to Support the Final Design Setup

When determining the optimal combination of a convex and fresnel lens that produced the clearest image possible, it was recognized that lens holders were of importance. The lens holders had to securely hold the lens in place (while being durable and stable), withstand the environment within the chamber (high pressure environment) and minimize the surface area it covered on the faces of the lenses. Finding lens holders on the market for convex lenses was easily available whereas for fresnel lenses, the holders were harder to find. The initial thought process was that an order would be placed for the convex lens holder and the fresnel lens holders would be made using SolidWorks and 3D printed. An example of a fresnel lens holder is shown in Figure 17 and 18 below. With the initial notion that the lens holders would be placed on a table within the chamber, the design was created to resemble a sleeve for each square or rectangular fresnel lens. This design was created to hold the fresnel lens snugly while minimizing the amount of surface area that is covered by the lens holder on the front and back faces of the lens. The lens holder grips the lens by the side and bottom edges of the fresnel lens, leaving the top open to slide in and out the lens as required.




***Figures 17, 18:*** *Fresnel lens holder created using SolidWorks*

It was soon discovered that the initial design for the lens holder would not be ideal for use. This was due to multiple reasons, the first being that the table would not withstand the environment within the chamber for a long time and deteriorate quickly. The second being the height of the table not being high enough for the lens holders and the lenses to be at the same height as the cold spray. The third being that the 3D printers at the university could not print the design as the dimensions surpassed the printable area of all available 3D printers as shown in Figure 19 below. The fourth being the high shipping costs associated with the convex lens holders available in N. America, coupled with longer lead times.

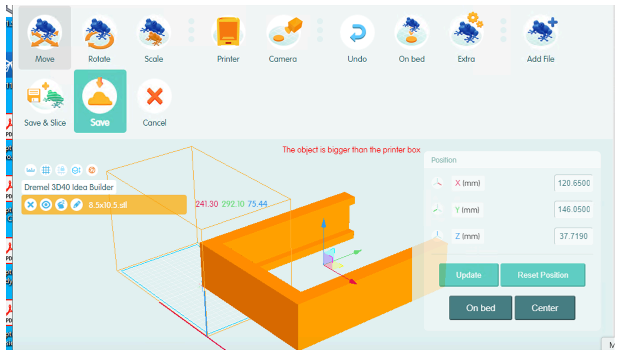



***Figure 19:*** *Visual representation of the 3D design being sliced for printing*

The second iteration of lens holder designs was the final lens holder design chosen. Instead of using a table, moveable lens holders were designed to have a plastic base (tripod with three legs), a steel rod standing upright (60 inches in height with a 0.5 diameter) and a clamp placed on the upper half of the rod which held either a convex or fresnel lens. All parts were sourced locally or within the lab. This design met the height criteria as the clamp holding the lens is adjustable along the rod, can withstand the environment within the chamber due to the steel material chosen (spray will possibly only affect the upper half of the rod so the plastic tripod base remains safe) and has the feature to move easily to any position within the chamber unlike the table which would have had to stay at one position at all times. The design is stable as the rod and base are secured by multiple layers of heat shrinks (reinforced by blow torching) making the diameter of the pole fit snugly into the tripod base therefore minimizing the effect of bending and shaking at the top of the rod. An example of the lens holders produced is shown within Figure 20 and 21 below.

***Figure 20, 21:*** *Lens Holders for both Fresnel and Convex Lenses to be Deployed in Chamber*

### 8.7 Final Proposed Design

The setup developed so far has been able to produce an image that can remotely produce a Schlieren image of a test flame. It utilizes a fresnel-double convex lens combination to produce Schlieren images, and requires the test specimen to be placed in between the 2 lenses. In the testing phase, lens holders sourced from the CACT laboratory were used to analyze and capture Schlieren images of the flame.

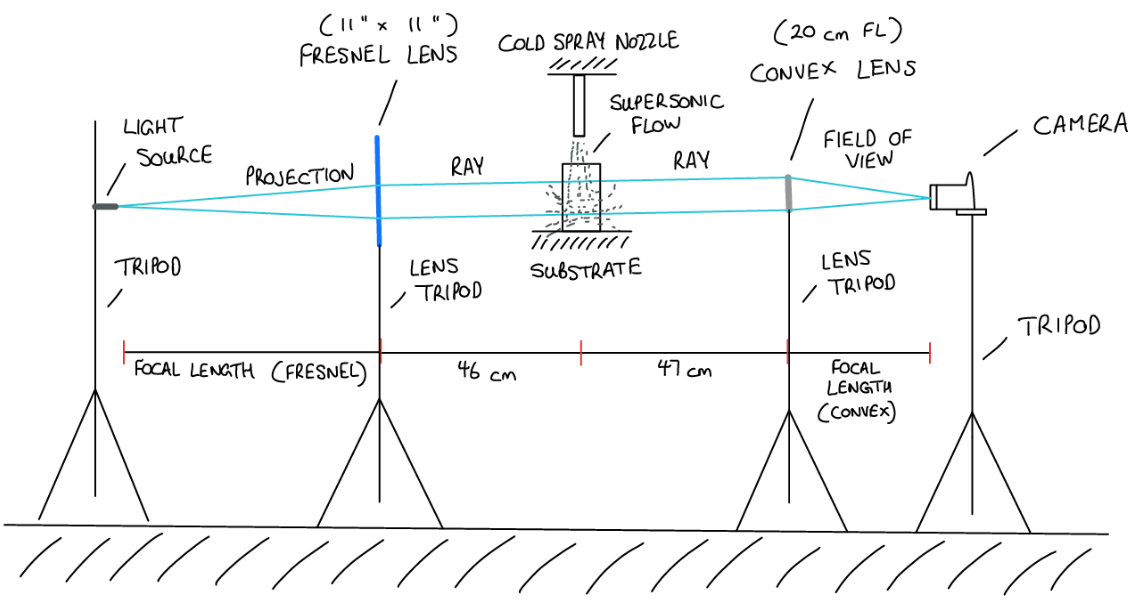



***Figure 22:*** *Design implementation schematic in the cold-spray chamber*

However, in order to successfully implement this design in the cold-spray chamber to capture cold spray flow patterns, the lenses and the light source would need to be mounted onto the tripods, as shown in Figure 22 above. These tripods are durable, and can withstand the environment in the cold-spray chamber. The distances determined between the tripods using optical scaling of the focal lengths of the lenses are still valid, given the space of the chamber and the area of the cold spraying of the substrate.

## 9.0 Conclusion and Future Work

The fresnel-double convex lens setup is theoretically capable of capturing Schlieren images in the cold spray chamber, however, as depicted in *Table 8.5.1*, there is still work to be done in order to produce higher quality Schlieren images. Due to logistical reasons, the design team was unable to test the proposed design in the cold-spray chamber; however, based on an inspection of the chamber and the working of the cold-spray technology, it can be concluded that the elements and materials proposed will hold well in the chamber.

From a performance standpoint, there are a few things that can be considered in order to further improve image quality. One iteration that can potentially be made is to eliminate the use of the convex lens, and develop a Schlieren imaging system solely based on a single fresnel lens [12]. The image sensitivity varies with the distance of the heat source, and would provide added flexibility in placing the fresnel lens and the camera. Since fresnel lenses have a larger, clearer aperture, relatively large objects can be tested.

Additionally, a different, slightly more intense light source may be needed as there could be a presence of external stray light in the chamber which may possibly interfere with the light source in use currently. The light source needs to have a balance between its physical size (point nature) and intensity meaning that multiple light sources with different intensities would need to be tested in the chamber to finalize the most suitable source.

Lastly, a powerful and more effective image processing method can further be helpful in deeper analysis and visualization of the spray patterns arising from the cold-spray process. Softwares such as *FORTRAN* and *Adobe Photoshop* can be employed to fulfill this purpose [13]. Overall, the final proposed design, with these enhancements, will aid in visualizing cold spray flow patterns to better understand the interaction of flow particles with the substrate, and can serve as a tool to assist further research into the field, especially to do with process efficiency and optimization.

## 10.0 References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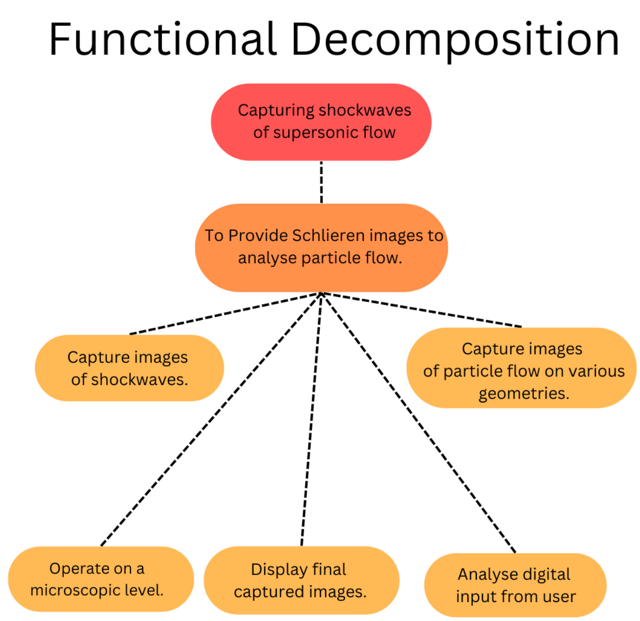
## 11.0 Appendices

***Appendix A:*** *Functional Decomposition, used to generate functions for the design.*



*__Appendix B:__ MATLAB code used for image subtraction*

```matlab
% Load the two images
image1 = imread("C:\Users\Shalin\Desktop\DSC_0227.JPG"); %image with flame
image2 = imread("C:\Users\Shalin\Desktop\DSC_0435.JPG"); %image without flame

% Convert the images to double precision for accuracy
image1 = im2double(image1);
image2 = im2double(image2);

% Perform subtraction
result = image1 - image2;
result = rgb2gray(image1) %converting to grayscale
% Display the result
figure
imshow(result);
```

*__Appendix C:__ Project Timeline*

Depicted below is the timeline followed for this design project, with the appropriate milestones and the corresponding due dates for each.

**Note:** The timelines mentioned in the "Dates" column are tentative, and are subject to change depending on internal and external circumstances.

| Week | Dates | Tasks to be completed | Formal Deadline |
|---|---|---|---|
| 1 | Sept 19-23 | -Project Requirement (PR) guidelines<br>-Assigning tasks<br>-Cost analysis<br>-FOC<br>-Stakeholder analysis<br>-DFX (design for x) principles<br>-Human factors<br>-Service environment<br>-Prepare any questions for the Client and Supervisor | |
| 2 | Sept 26-30 | Finish draft PR and Review | Draft PR - September 30 |

| | | | |
|---|---|---|---|
| 3 | Oct 3-7 | -Look into buying a camera<br>-Look into software for mapping (MATLAB, Image J) | |
| 4 | Oct 10-14 | -Investigate a new way to set up the schlieren system<br>-Assign tasks for PR and ask questions<br>-Meet with TCI | |
| 5 | Oct 17-21 | -Work and finalize PR | Final PR - October 21 |
| 6 | Oct 24-28 | -Work on conceptual design<br>-Map out how the system will work<br>-Reach out to sponsors (i.e. for camera) | |
| 7 | Oct 31- Nov 4 | -Lab visit<br>-Iterate on conceptual design<br>-Reach out to Client and Supervisor for lab time<br>-Plan lab visit with Eva | |
| 8 | Nov 7-11 | -Meet with Supervisor and Client to finalize design of the Schlieren system | |
| 9 | Nov 14-18 | -Begin the Design Review written summary | |
| 10 | Nov 21-25 | -Continue work on the Design Review summary (maximum 4 pages in length)<br>- Follow up with sponsors as necessary to ensure all equipment can be set up | |
| 11 | Nov 28-Dec 2 | -Continue work on the Design Review written summary | |
| 12 | Dec 5-9 | -Finalize Design Review written summary | |
| 13-16 | Dec 9-Jan 6 | Winter Break | |
| 17 | Jan 9-13 | -Finalize Client Presentation of Design Review | Design Review - January 19 |
| 18 | Jan 16-20 | -Design Review presentation on Jan 19 to confirm design parameters<br>-Final decisions regarding equipment purchases for the Schlieren system | Design Review materials submitted a week prior to the meeting - Jan 12 |

| | | | |
|---|---|---|---|
| 19 | Jan 23-27 | -Purchase all equipment for the system | |
| 20-22 | Jan 30 - Feb 17 | -Equipment delivery<br>-Work with Client to execute the project | |
| 23 | Feb 20-24 | Reading Week | |
| 24 | Feb 27 - March 3 | -Set up testing for the system<br>-Begin testing<br>-Analyze testing results and adjust system as needed | |
| 25-26 | March 6-24 | -Continue testing and analysis<br>-Work with Client to execute the project, making necessary changes based on testing<br>-Document the design process for use in the Final Design Specifications and the Final One-Pager Description | Final Design Specifications & Final One-Pager Description - March 24 |
| 27 | March 27-31 | -Test the Imaging set-up in the cold spray chamber<br>-Finalize the Final Poster and work on presentation notes | |
| 28 | April 3-7 | -Submit Final Poster to be printed | Final Poster - April 5 |
| 29 | April 14 | -Final presentation for TCI, faculty, students, and industry representatives | |

**Attribution Table:**

**Project Title: Exploring Cold Spray through Schlieren Imaging**
**Document Names: Final Design Specifications + Single-Page Description**
**Supervisor: Ali Dolatabadi**
**Date: March 24, 2023**

| Section | Student Names | | | |
|---|---|---|---|---|
| | Shalin | Harshi | Kate | Kirti |
| Executive Summary | | | ✔ | ✔ |
| Introduction | ✔ | ✔ | ✔ | ✔ |
| Problem Statement | ✔ | ✔ | ✔ | ✔ |
| State-of-the-Art Review | | ✔ | | |
| FOCs | ✔ | ✔ | ✔ | ✔ |
| Service Environment | | | | ✔ |
| Stakeholders | ✔ | | | |
| DfX Principles | ✔ | ✔ | | |
| Human Factors | | | ✔ | ✔ |
| Final Design Specifications | ✔ | ✔ | ✔ | ✔ |
| Conclusion & Future Work | ✔ | ✔ | | |
| Single-Page Description (separate document) | | | ✔ | |
| All | ✔ | ✔ | ✔ | ✔ |