# CALCULATING AND SETTING UP A SCHLIEREN SYSTEM

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**ABSTRACT:** This paper defines the parameters one must focus on while trying to set-up a schlieren system; its purpose is to follow and explain a mathematical path that can be used to pre-set a system, to offer alternatives in terms of optical path components, and point to the optimum equipment. The end result will be building and aligning an actual optical Schlieren system that will be used to visualize phenomena that are invisible to the naked eye.

**KEYWORDS:** Z-type, Schlieren, Shadowgraph, parabolic mirrors

**NOMENCLATURE**

A- slit area
Al - aluminium
B- brightness of the light source
CRI- colour rendering index
$D_0$ - diameter of the nozzle
E - general illumination of the background
$E_0$ - illumination upon the first mirror
C - contrast
S - sensitivity
$P_0$ - flow pressure
$P_1$ - atmospheric pressure
f - focal distance
$f_1$ - focal distance of the first parabolic mirror
$f_2$ - focal distance of the second parabolic mirror
f3 - focal distance of the camera's lens
fps- frames per second
$n_0$ - refractive index of atmosphere
x - distance from the nozzle to the first shock diamond
$\Delta E$- differential illumination
$\varepsilon$ - anlge of refraction
$\emptyset$ - efficacy of the light source
$\boldsymbol{\theta}$ - the offset angle.

## 1. INTRODUCTION

The schlieren system's conventional form is attributed to the german scientist Auguste Toepler, his predecessors being Jean Bernard Foucault (1849) and Robert Hooke (1665). [1] The "schliere" word is of german origin and means "streak". Hubert Schardin was another important figure, whose work represents the last important milestone of the technique. Schardin was the first to apply filters and to obtain quantitative information based on schlieren measurements. [6] The working principle is simple: the Schlieren technique relays on the deflection of light by a refractive index gradient.

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The latest development in the field implies using a Schlieren system and a PIV system together, in order to fully characterise the flow. This subject is debated in G.Settles' paper, "*Schlieren "PIV" for turbulent flows*"[7]. There are many adaptations of the schlieren technique .

A very important one is the "*coloured schlieren*", which allows one to visualize, for example, the shock waves over a 2D wedge-plate, where every type of shock wave has a different colour. This can be achieved by placing a prism in front of the light source. The notion of a coloured schlieren has been inspired by the idea of coloured interferometry. One paper that focuses on the optical path of a coloured schlieren system that includes a double-prism, and has variable sensitivity is "*A variable sensitivity and orientation colour schlieren system*", by D.R. Phillpot [8].

The third most important new use of the technique is the *quantitative schlieren*. This technique's purpose is to measure refractive-index distributions and other quantities related to the flow. A paper that characterises the use of schlieren as a quantitative tool is „*A quantitative schlieren method for the investigation of axisymmetrical shock waves*", by Andrzej Cwik and Helmut Ermert [9].

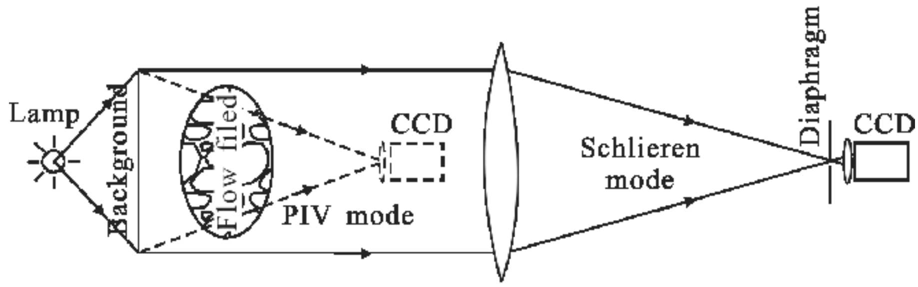



**Fig.1 PIV - background oriented schlieren system [4]**

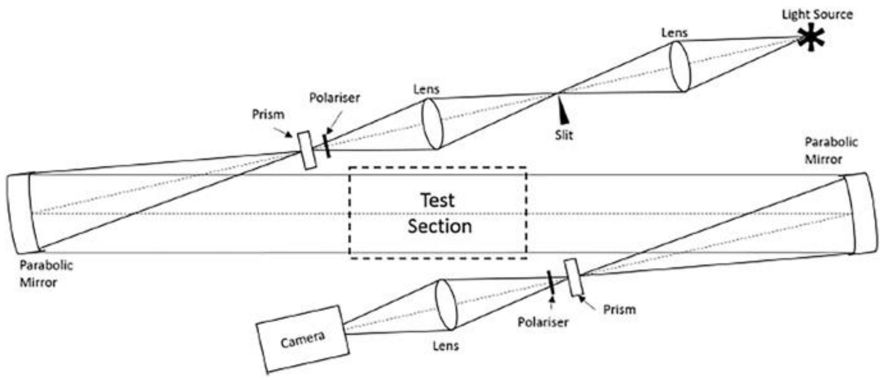



**Fig.2 Coloured Schlieren Configuration [5]**

The optical characterisation of density can be achieved through the schlieren method of visualization, which can take many forms. It can be easily changed by redefining the optical path: using lenses, 2 parabolic mirrors (Z-type), one single mirror (single mirror configuration), or not using any mirrors or lenses and observing the density changes on a speckled background (Background Oriented Schlieren or Synthetic Schlieren). Usually, the schlieren method, regardless of its configuration, uses one focusing lens, that helps focusing the rays from the light source.

It is important to know the scale of the experiment and how sensitive the system has to be in order to register the density variation. Since the point of the experiments conducted is to obtain quantitative results with the help of the schlieren system, it is safe to say the system will be used as a "*quantitative schlieren*", and therefore, its configuration needs to be the most sensitive; the highest sensitivity belonging to the Z-type schlieren system. Another reason for setting up a Z-type is it implies using mirrors instead of lenses, and mirrors have a larger field of view; off-axis mirrors also cancel each other's aberration in this configuration.

## 2. OPTICAL PATH CALCULATION AND ERRORS

The shock diamond formed by air exiting a supersonic nozzle is used to conduct a Shadowgraphy test. Shadowgraphy is defined as: a simple light source that helps the object cast a sharp shadow over a white board.

This shadow can only show large variations of density (for example if the flow is supersonic or if there's a variation of temperature (see Fig. 3 a) and b) ). Taking shadowgraph pictures of the phenomenon in this case, helps with future calibration. From the showgraph pictures, one can learn what errors might appear. For example, if the image is blurry, the CCD camera's parameters must be reset or the contrast sensitivity must be increased, in order to see all the elements of the shock diamond. In the figure below, some errors in performing the shadowgraph method can be spotted. The first error is the penumbra just above the air compressor's nozzle (Fig. 3 a). The penumbra appears when the light source is not a point source, but rather an extended one, causing the double-image of the compressor nozzle to form. This means that the jet itself will also have a double image. The second error can be spotted in image of the plume, where the image is too dark and the amout of zoom-in from the camera is affecting the quality of the image. Errors regarding the equipment, and not the technique can be spotted with the help of shadowgraphy.

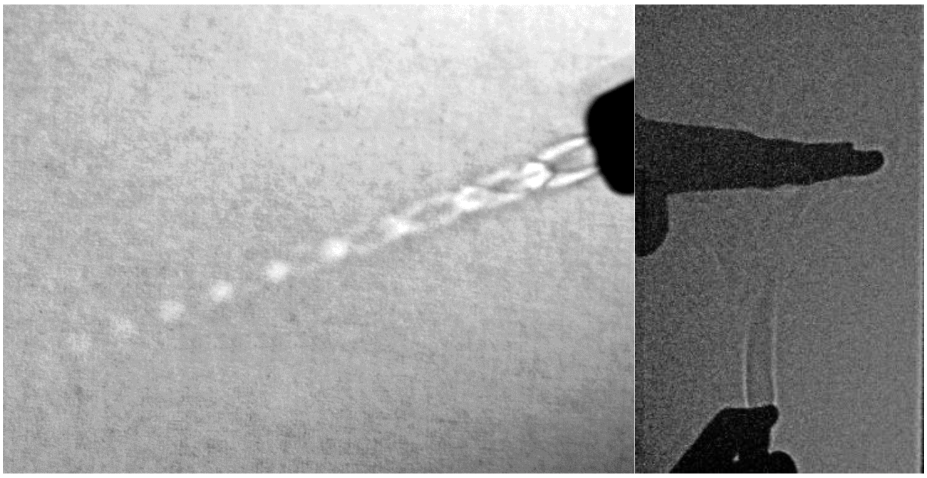


**Fig.3 a) Shadowgraphed shock diamond at the exit of an air compressor; b) lighter plume over a hand (pictures taken at INCDT Comoti)**

The distance between the nozzle and the first Mach disk of the shock diamond, can be calculated with the following formula, where x is the distance, $D_0$ is the nozzle diameter, $P_0$ is flow pressure, and $P_1$ is the atmospheric pressure:

$$\boldsymbol{x = 0.67 D_0 \sqrt{\frac{P_0}{P_1}}} \qquad \textbf{(1)}$$

For more information on the matter of diamond shock, and compressible fow in general, one can refer to J.D. Anderson**,** *Modern Compressible Flow with Historical Perspective*, 3rd Ed., 2003 [10].

The comparison between the first picture and the above-mentioned formula can be obtained after framing the jet into a background made out of millimetric paper. With the help from the previous formula, and knowing $P_0$, $P_x$ and measuring $D_0$, one can find that "the zone of silence" spreads over a distance of 4.4 mm. However, pictured below, the "zone of silence" appears to measure a bit over 4 mm, the error comes from the fact that the background, the jet and the camera are not placed perfectly parallel.

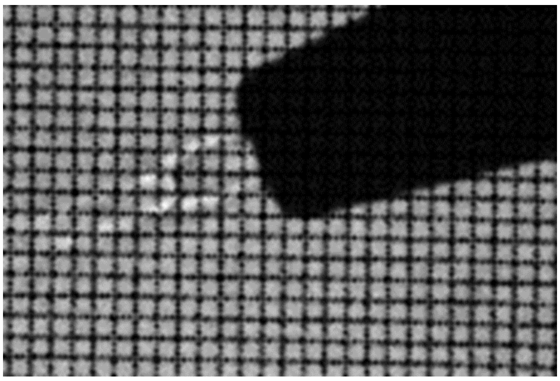


**Fig.4 Shadowgraphed shock diamond with millimetric scale (picture taken at INCDT Comoti)**

This is another error to make sure to avoid. The experiment must perfectly align with the camera, in order to obtain good results.

The shadowgraphy can be a powerful learning tool before concentrating on a schlieren system wich is more complex because of the optical elements it includes.

This paper however concentrates on the precalculation and presetting of the Z-type schlieren, the afore mentioned shadowgraphy experiment was described in order to underline the fact that by using shadowgraphy (which is less time and money consuming, but has a very poor sensitivity) some of the errors can be taken into account, when thinking about designing a schlieren system.

### 2.1. Establishing the type of mirrors to be used

The Z-type configuration draws its advantages from the mirrors'placement; the offset angle θ assures one there will be no aberrations in the system, such as coma or astigmatism (the first mirror is the negative of the second one). The aberration of the parabolic mirror grows with θ and with (f/n0).

The offset angle must be very small, especially in the one-mirror configuration, in order to avoid a double intersection of the object with the ligh: firstly, in the light's path from the source to the mirror and secondly from the mirror to the camera.

In the single-mirror configuration, the most important problem is the placement of the object to be observed. If the mirror has a small diameter, the testing area will suffer severe limitations, making it very hard to avoid the above-mentioned error.

This error, combined with the aberration of the mirror, excludes the sigle-mirror configuration as the right configuration for the experiments to be conducted.

The most sensitive configuration remains the Z-type configuration.

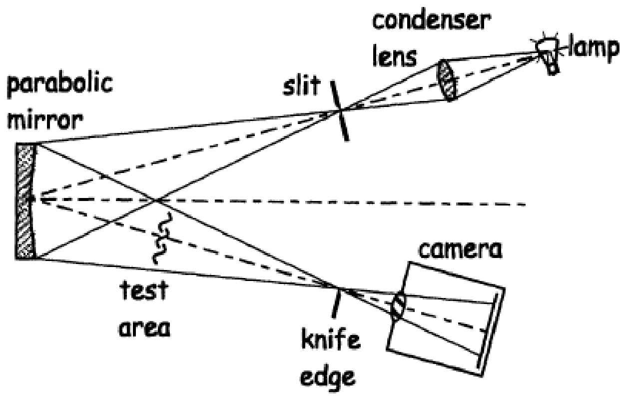



**Fig.5 Single-mirror off-axis configuration (*G.S.Settles 2001*)**

In the Z-type configuration, the same thing can happen if the distance between the mirrors is smaller than $2f_2$. The parabolic mirrors used in schlieren have a large effective focal length, that cancels the risk of a very small testing area and increases the sensitivity. The distance between the mirrors can be as large as the experiment requires, as long as the mirrors are corectly aligned. Another advantage of the parabolic mirrors is the large field of view.

The schlieren visualizing technique uses Al plated mirrors, because it emits in the spectrum of the visible light, matching the light sources's spectrum. Other options may not suit the matter, such as the gold plated mirrors which are useful only in the IR spectrum.

Based on the scale of the experiments, one can also choose the diameter of the parabolic mirrors to be used. For example, the shock diamond shadowgraphed before , only spreads on a distance of a few millimiters, so the diameter of the mirrors can be a few times bigger than that. In general, this configuration will be used to observe small perturbations.

With these facts in mind, knowing that the mirrors need to be Al plated, working in the spectrum of 400-700 *nm* (same as the light source), with a slightly bigger focal length, and a small diameter, the author decided to use the 76 mm, Al protected, parabolic mirrors from Edmund Optics.

More data about the characteristics of the mirrors can be found in the table containing the equipment's description (Table 2).

As Settles well stipulates in his iconic work [3], the Schlieren Z-type system has the advantage of a very large test area (much larger than $2f_2$) ). In that case, the use of flat mirrors is necessary, in order to reduce the laboratory space needed for conducting the experiment.

Althought, folding mirrors are not desirable unless compulsory, because they introduce a high sensitivity to vibrations in the system, impose a very big angle of offset that increases the aberration of the mirrors and also make the system very hard to be aligned. The Z-type Schlieren system's optical path is represented in the following figure.

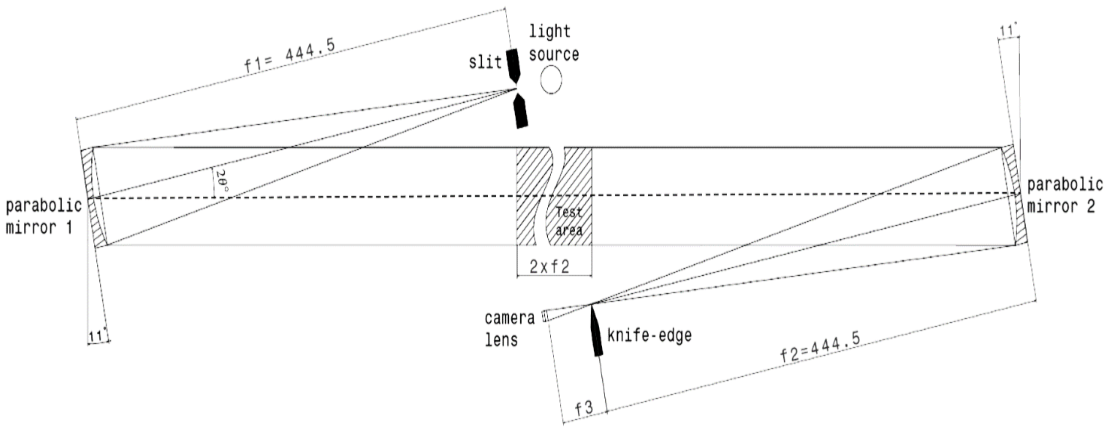



**Fig.6 Z-type configuration (author's resulting configuration)**

The sketch presents a tilt angle of the mirror equal to 11° . The angle it's exaggerated in order to better fit the equipment in the sketch. Normally, the off-axis mirrors are tilted at an angle not higher than 3° [1]. Also, *f3* represents the focal distance of the camera, which changes with the camera lens.

### 2.2. Choosing the light source

Choosing the right light source of the Schlieren system is as important as choosing the right optics. The light source needs to be point-like, so that the set-up can respect the Schlieren configuration and for the calibration knife to be effective [1], and the angle at which the rays spread from the source needs to be small, in order to form a very sharp shadow of the object that needs to be observed. In the Schlieren system, before the introduction of the knife edge into the focal point of the second mirror, the background will be illuminated uniformly, the light will be too bright and the sensitivity will be very low. The sensitivity increases while the area of the point source image decreases [1].

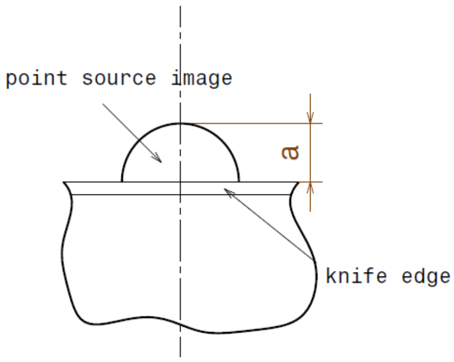



**Fig.7 Cut-off of the point source image**

The source used needs to cover the visible spectrum, and have the same wavelength as the mirrors. As mentioned before, the wavelength interval for the present configuration is 400-700 nm.
There are many options when it comes to choosing the proper light source, and as described in the literature [1], one can use either of the following: Xenon arc lamp, incandescent or halogen light bulbs, lasers, even the common laser pointer.

The main disadvantage of using an incandescent or a halogen lamp is the fact that they are spatially and temporally incoherent light sources. This characteristic can be cancelled by the use of filters or, like in this case, by adding a slit in front of the source. The slit complicates a bit the process of determinating the exact illumination on the first mirror of the system.

**Table 1. Light sources performances [2]**

| Source type | Luminous flux [lm] | Efficiency[lm/W] | Brightness [Mcd/$m^2$] | CRI | Lifetime [kh] |
|---|---|---|---|---|---|
| Incandescent 60W | 900 | 15 | 10 | 100 | 1 |
| Halogen 50W | 1000 | 20 | 20 | 100 | 2 |
| LED 2002 | 125 | 25 | 3 | 75 | 60 |
| LED 2013 | 1000 | 250 | 10 | 90 | 60 |

For this application, the matching of an H1 automotive light bulb with the optical system will be questioned. The idea of a halogent automotive light bulb can be found in an endless count of papers, all starting with the pinacle of the technique, the book writtem by G.Settles, „*Schlieren und shadowgraph techniques: visualizing phenomena in transparent media*" [1].

As seen in Table 1, for the halogen light bulb, the efficacy is the same as for the H1 light bulb used in this application, which has a luminous flux of 1100 and a power of 55, and can be calculated with the next formula:

$$\emptyset = \frac{\boldsymbol{lumens}}{\boldsymbol{watts}} \quad \textbf{(2)}$$

The result of the above-mentioned formula shows that for every watt used, this lamp produces 20 lumens. The radiant intensity for this bulb is given to be 105 candela, based on the manufacturer's indication, but the system will not be using all the light coming from the source. Depending on the geometry of the slit, one can calculate the illuminance on the first mirror of the system. If the slit's area is A, and the luminance (or brightness) after the slit is B, that can be approximated to $\mathbf{1,2 \cdot 10^7} \boldsymbol{candela/m^2}$ , one can calculate the illuminace on the first mirror:

$$\boldsymbol{E_0} = \frac{\boldsymbol{B \cdot A}}{\boldsymbol{f_1^2}} \quad \textbf{(3)}$$

In this case, $\boldsymbol{E_0}$ results to be 150 $\boldsymbol{candela/m^2}$ (lux), without any knife cut-off. The sensitivity is correlated to the cut-off, but literature mentiones that an experiment which does not need a very sensitive system, usually uses a 50% cut-off. This creats a good-enough contrast and also makes placing the knife-edge more exact. The second mirror will have an illuminance of 75 lux, after the knife-edge is placed.

A difference in the formula of illumination occurs if one adds new optic elements to the system. The value for contrast can be set only after the installation of the system and only after the first images are taken, because the contrast is considered to be the ratio between differential illumination ($\boldsymbol{\Delta E}$) of a point and the general illumination of the background.

$$\boldsymbol{C} \equiv \frac{\boldsymbol{\Delta E}}{\boldsymbol{E}} \quad \textbf{(4)}$$

This formula (4) can also be written as a ratio between the increment gain of illumination times the area of light that has not been cut-off by the knife edge and the magnification factor multiplied by the square of the first focal distance. The contrast is not the only quantifiable variable of importance. The sensitivity plays a very big role, and can be calculated using the next formula:

$$\boldsymbol{S} = \frac{\boldsymbol{\Delta C}}{\boldsymbol{d\varepsilon}} \quad \textbf{(5)}$$

The Schlieren sensitivity is the rate between the contrast and the refraction angle and it's the defining parameter of the technique.

After calculating all of these aspects, the conclusion is that the light source which has the highest value for the luminous flux can be considered the best one, because a lower value for illuminance can always be achieved by adjusting the slit's geometry.

As seen in this chapter, the halogen light bulb has a luminous flux of 1100 *lm*, while the other options would have been an incandescent light bulb with only 900 *lm*, or a LED, with 320 *lm*.

The halogen light bulb is the preffered choice for the system, not olny because of the luminous flux, but also for the CRI, and the higher brightness.

From this point on, the matter of calibration starts, which changes with each experiment, and does not make the subject of this paper.

## 3. EXAMPLE. SCHLIEREN VISUALIZATION OF A LOW EMISIVITY JET

The present experiment's purpose is to demonstrate otherwise the functionality of a small-geometry nozzle. The visibility of the jet is almost none, due to the fact that the chemical compound exiting the nozzle is mainly water vapours at high temperatures. Due to space limitations, the type of Schlieren used had to be a single-mirror configuration. Keep in mind that the installation was not designed for the use of optical equipment. It has 3 glass windows, but their positioning and fabric makes it hard to apply this particular technique.

Calculations for the emissivity of the jet shows that the emissivity is very low, and the glass from the windows it's screening the jet when one tries to visualize it by means of infrared thermography. Also, while the vacuum chamber is sealed, the glass window splits the light beam in 2, causing the image to double and even triple if the distance from the jet to the parabolic mirror is too small or at the wrong angle.
The one-mirror experimental set-up is depicted in the following figure.

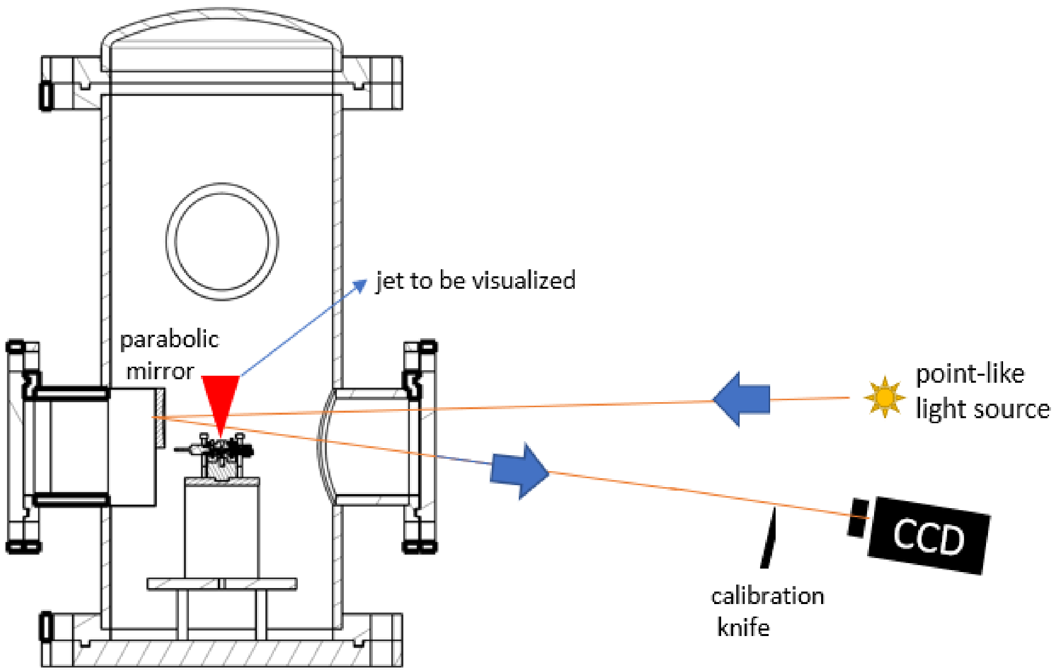



**Fig.7 Sketch of the one-parabolic-mirror configuration**

The one-mirror configuration represented the only solution for this problematic experiment. The entrance into the chamber had a very small diameter which caused the angle between the light beam going into the parabolic mirror and the light beam exiting the mirror to be really small - fact that made the optics extremely difficult to align. Another space-limiting issue was the fact that one of the parallel glass windows had little to no space between it and a very important panel that is a part of the installation and couldn't be moved at that time. Due to this fact, the Z-type configuration system, with all its advantages couldn't be applied.

The mathematical path presented before applies if one has doubts about the system sensitivity or tries to find the best configuration when space is not an issue. Giving the fact that the measured temperature of the jet reaches almost 2032K , the densitiy variation will be an important one. Also, it helps to try the shadowgraph method first, because it's less sensitive. If Shadowgraph shows the difference in density, the Schlieren will definitely "see" it too.

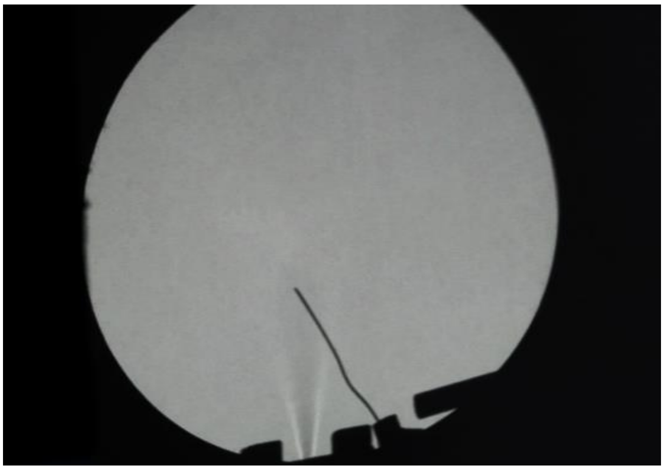


**Fig.8 Image of the jet acquired with the Shadowgraph method(pictures taken at INCDT Comoti)**

**Table 2. Equipment specification**

| | | |
|---|---|---|
| Source type | LED | 321 lumens |
| Parabolic mirror | Ø76mm | EFL 444.5mm |
| Calibration knife | Black painted | -minimum reflections |
| CCD Camera | Phantom Veo 410L | Max.7.000fps |

The difference between the sensitivity of the Shadowgraph and the Schlieren systems can be seen in Fig.8 and Fig.10, the first one does not show the entire contour of the jet, it only shows the area where the density difference is very large. This assessment is more important if one keeps in mind the fact that the jet is not at all visible by the naked eye.

The experiment was carried on under the following conditions:

- the distance between the point-like source and the parabolic mirror was approximately 1m, the distance from the parabolic mirror to the knife insertion point was the focal length of the parabolic mirror;
- the camera and the calibration knife were mounted together on a tripod, and the point like source was mounted on a different tripod. A very important aspect was mounting the two tripods at the same hight, in this way the addition of another light displacement plane was avoided.
- the calibration knife cut was nearly 80%, due to the fact that the light source was extremely powerful and extended.
- the parabolic mirror was placed inside the open chamber with a mount that guaranteed the vertical position. If the mirror was inclined, it would have been impossible to find the right angle at which to position the calibration knife.
- the Schlieren images were recorded at 8500fps, this CCD speed reduces the light intensity as well.

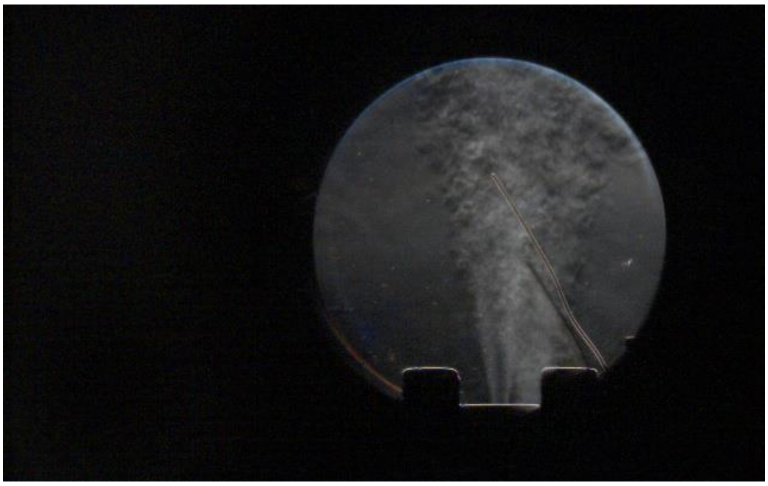
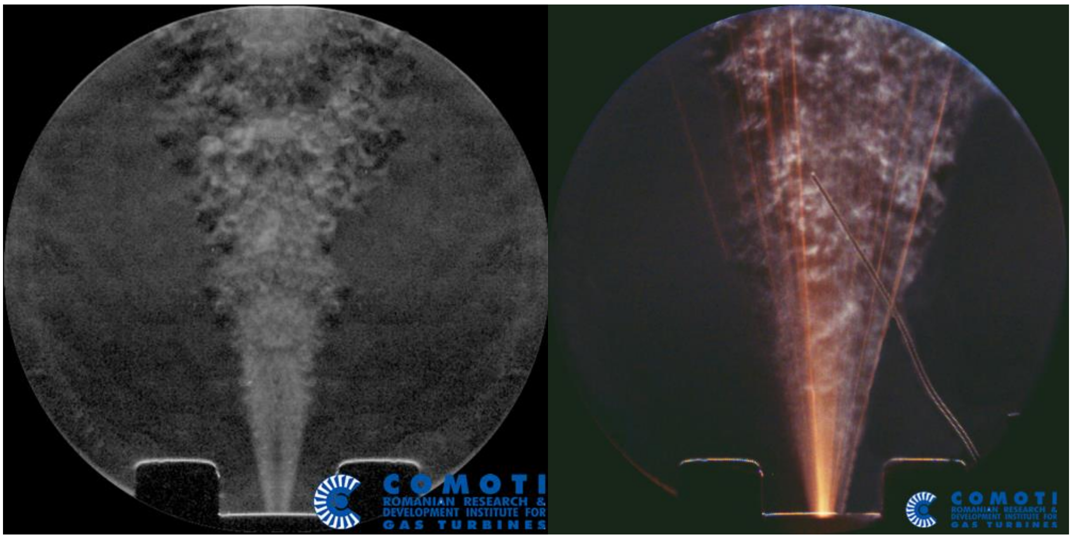


**Fig.9 Image of the jet before post-processing(pictures taken at INCDT Comoti)**

The post processing was focused on the next steps:

- background removal (a picture was taken before the jet, so that the pixels or eventual glares could be removed afterwards), adjusting the contrast, focusing on the phenomenon;
- in Fig.10 (b) one pixel intensity was chosen as the background substitute, and the intensity chosen was the one that underlined the jet through by creating a contrast. Also, the thermocouple could be kept in the image in this way
- the thermocouple that appears in Fig,9 was eliminated from the post-process version of the pictures (Fig.10 (a) )because it also appeard in the background image.
- the post processing tool used was the 2020a Matlab software;




**(a)** **(b)**

**Fig.10 Images of the jet after post-processing(pictures taken at INCDT Comoti)**

## 4. CONCLUSIONS AND FUTURE WORK

Before setting up a Schlieren system, one must know the scale of the phenomena to be tested, and must be able to approximate the sensitivity needed in order to capture the desired images.

The exact sensitivity can only be calculated after the system is installed, but literature offers a big variety of experiments that allows one to approximate some of the variables and then use it to precalculate the system.

The choice of optics has been motivated and the light source has been calculated, the only remaining variable right now in the system, before the experiment calibration, is the high speed camera, which in the presented case is the Phantom Veo 410L, whose characteristics (7000 fps at a resolution of 1280x720) are more than enough to capture the essence of all intended experiments, but if one does not need to capture events that happen at a high speed, a regular camera can also be used.

Setting the Schlieren system allows one to visualize the variation of density that it’s undetectable under normal visualizing conditions and can prove or disprove results obtained by numerically simulating the same phenomenon.

The experiment described in this paper is just an example of a real test-case. As in many real-life applications, the conditions of the test case, are not ideal. The Z-type configuration should always be the first choice when thinking about building a schlieren system, but sometimes one can encounter space limitations. In this case, the set-up will suffer important changes. Any set-up that respects the basic principles of the schlieren technique is viewed as such, even if the optical path has more optical elements, like for example it could include flat mirrors, a slit in front of the light source, different mirrors, no mirror, lenses or a diaphragm.

The next step in using the system is calibrating it to form a quantitative system. The post processing code will be improved to the point where it will become a in-house software through which the displacement angle will be calculated, and will allow one to fully characterize the flow.

The schlieren method of visualization is a non-intrusive method, the main disadvantage is it needs optical access to the flow. The Schlieren method can be used in both supersonic and subsonic applications, if the difference in density is big enough to be detected.

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