



Comparative quantitative Schlieren for the characterization of gas- dynamic parameters of turbulent flows

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- Summary -

The present doctoral thesis describes the methods used in the past to obtain quantitative and qualitative schlieren images. The objective of the thesis is to present some schlieren methods with improved accuracy both by using optically optimized schlieren systems and from the point of view of the original pre-processing and post-processing algorithms, used to analyze the images as well as to optimize them for analysis.

The present paper could be considered to be an experimental study due to the fact that the theoretical aspects have been confirmed experimentally. The optimal methods for carrying out several quantitative methods are presented, including: the method of determining the velocity fields from schlieren images (SIV), described by 3 applied methods (the Lagrangian tracking method, the kymograph method and the method of using commercial software, dedicated to PIV), the method of determining the relationships between contrast-sensitivity-temperature (knife calibration method, thermal calibration method) and the quantitative schlieren method with calibrated color filter. All of these methods have been applied to turbulent flows, except for the knife calibration method, which was used to describe a supersonic air jet, described by shock diamonds.

By optimizing the optical systems and their parameters, images were obtained that can be processed so that between the experiment and the theoretical requirements their value of the coherence factor is at its highest.

For example, for the SIV - Lagrangian tracking method (the method which returned the greatest improvement in measurement accuracy when compared to the few existing works in the specialized literature on this topic), a sufficiently high recording speed had to be ensured, so that the method benefits from a large enough data sample to be considered relevant (this was achieved by using a high speed camera at a recording speed close to the upper limit of the equipment). It also required a special level of contrast and focus so that turbulent elements could be easily distinguished, achieved by mounting an optimally sized circular knife and using a type of camera macro lens. For all these small optimizations, both pre-calculations and pre-experimental campaigns were carried out. In order to obtain the desired results through the schlieren method with a calibrated color filter, the optimal parameters of optical nature and the implications of their characteristics in the post-processing process, as well as the manufacturing process of the color filter, were considered. Pre-experiments were also carried out in this case, to analyze the percentage transmitted by the filter, coming from the light source incorporated in the schlieren system, to the recording equipment.

Two image pre-processing and post-processing applications were created, based on original source codes, developed and optimized with the aim of obtaining the highest measurement accuracy. The present work represents the missing link between an existing visualization method and its implementation using existing and publicly available computational power at the moment. Obtaining higher accuracy indices than the existing ones confirms the importance of

automating post-processing processes, both from the point of view of the accuracy of determining certain parameters from the processed images and from the point of view of reducing processing times.

Future work perspectives include the creation of a 3D schlieren system, which would allow the real analysis of axisymmetric turbulent flows, and the comparison of its results with a statistical computational system, based on the Inverse Abel Transform, which can confirm the accuracy of the result without the need to place physical instrumentation in the studied phenomenon, thus avoiding the introduction of a measurement error.

Key words: schlieren, optical path, measurement accuracy, SIV, calibration

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1. Introduction

The present doctoral thesis describes the currently used methods for obtaining quantitative and qualitative schlieren images. The objective of the thesis is to present some schlieren methods with improved accuracy both by using optically optimized schlieren systems and from the point of view of the original pre-processing and post-processing algorithms used to analyze the images and to optimize the image sequence for further analysis.

The present work can be considered an experimental study through the prism of experimental confirmation of theoretical concepts. The optimal methods for carrying out several quantitative methods are presented, including: the method of determining the velocity fields from schlieren images (SIV), described by 3 applied methods (the Lagrangian tracking method, the kymograph method and the method of using commercial software, dedicated to PIV) , the method of determining the relationships between contrast-sensitivity-temperature (knife calibration method, thermal calibration method) and the quantitative schlieren method with color filter. All of these methods have been applied to turbulent flows, except for the knife calibration method, which was used to describe a supersonic air jet, which is described by shock diamonds.

By optimizing the optical system and their parameters, images were obtained that can be processed so that between the experiment and the theoretical requirements there is a very strong coherence factor.

For example, for the SIV - Lagrangian tracking method (the one that returned the greatest improvement in measurement accuracy compared to the few existing works in the literature on this topic), a sufficiently high recording speed had to be ensured, so that the method benefits from a large enough data sample to be considered relevant (this was achieved by using a high acquisition video camera at a recording speed close to the upper limit of the equipment).

It also required a special level of contrast and focus so that turbulent elements could be easily distinguished, achieved by mounting an optimally sized circular knife and using a type of camera-mounted macro lens . For all these small optimizations, both pre-calculations and pre-experimental campaigns were carried out. In order to obtain the desired results through the schlieren method with a calibrated color filter, the optimal parameters of an optical nature and the implications of their characteristics in the post-processing process, as well as the

manufacturing process of the color filter, were considered. Pre-experiments were also carried out in this case, to analyze the degree of transmission of the light coming from the source incorporated in the schlieren system, to the recording equipment.

Two image pre-processing and post-processing applications were created, based on original source codes, developed and optimized with the aim of obtaining the highest measurement accuracy. The present work represents the missing link between an existing visualization method and its implementation using existing and publicly available computational power at the moment. Obtaining higher accuracy indices than the existing ones confirms the importance of automating post-processing processes, both from the point of view of the accuracy of determining certain parameters from the processed images and from the point of view of reducing processing times.

Future work perspectives include the creation of a 3D schlieren system, which will allow a 3D analysis of axially symmetric turbulent jets, and the comparison of its results with a statistical computational system, based on the Inverse Abel Transform, which can confirm the obtained result without the need placement of physical instrumentation in the studied phenomenon, thus avoiding the introduction of a measurement error.

Key words: schlieren, optical path, measurement accuracy, SIV, calibration

2. Knife edge calibration quantitative schlieren

Chapter 2 of the thesis presents the schlieren method with calibration on the knife, a method that can be applied in any situation where the displacement of the knife in the plane of the source image can be measured. In general, this calibration is not very precise, the errors that occur when performing it are: the impossibility of accurately determining the position of the knife at the time of recording the images due to the small diameter of the source image (as is known, the light source has a punctiform in schlieren applications), hence the impossibility of creating a calibration curve with good accuracy, due to the small number of measurements (most

applications use between 10 and a maximum of 15 points [1]), although to create a trend a range of points between 20 and 30 values is needed, according to the Central Limit Theorem [2].

The case study carried out to confirm the theoretical aspects that confirm the hypothesis that the automatic post-processing method has a considerable influence on the accuracy of the results. This case study involves the analysis of a supersonic air jet from the point of view of density maps, and by correlating these values with the values obtained from a CFD simulation, the measurement accuracy of the method is obtained.

To calibrate the schlieren knife, intensity values are recorded in each pixel of the image. Phenomenon-free schlieren images are recorded with the calibration knife set to crop the source image by a certain percentage. This results in an experimental grid similar to the one in figure 1.

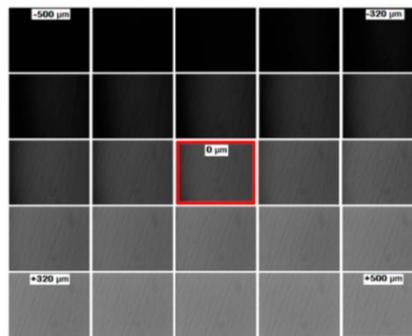


Figura 1 Grilă de imagini pentru calibrare [3]

The calibration curve obtained is similar to that in figure 2, representing the illumination per pixel in each corresponding image.

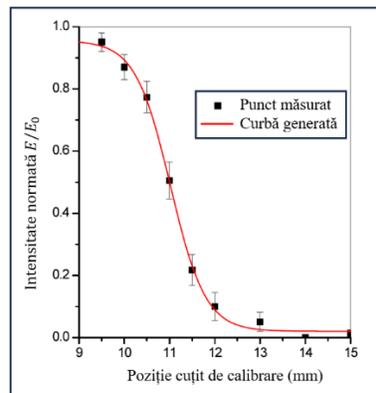


Figure 2 Illumination of the schlieren image depending on the positioning of the calibration knife

The experimental setup for obtaining schlieren images illustrating the phenomenon is shown below in figure 3. The geometry of the nozzle was determined using the Method of Features (MOC) and 3D printed using a metal powder printer. The type of equipment used is Lasertech 30 SLM, with Inconel 625 material. The nozzle was designed to evacuate the jet with an exit velocity slightly above Mach 2.6., at a pressure of 20 bar of the stream entering it. An air compressor with a capacity of 20bar was used to supply the nozzle, which means that the speed of the nozzle may decrease for a while after starting it. However, this fact can be neglected due to the high acquisition rate of the images used – 1000 images per second.

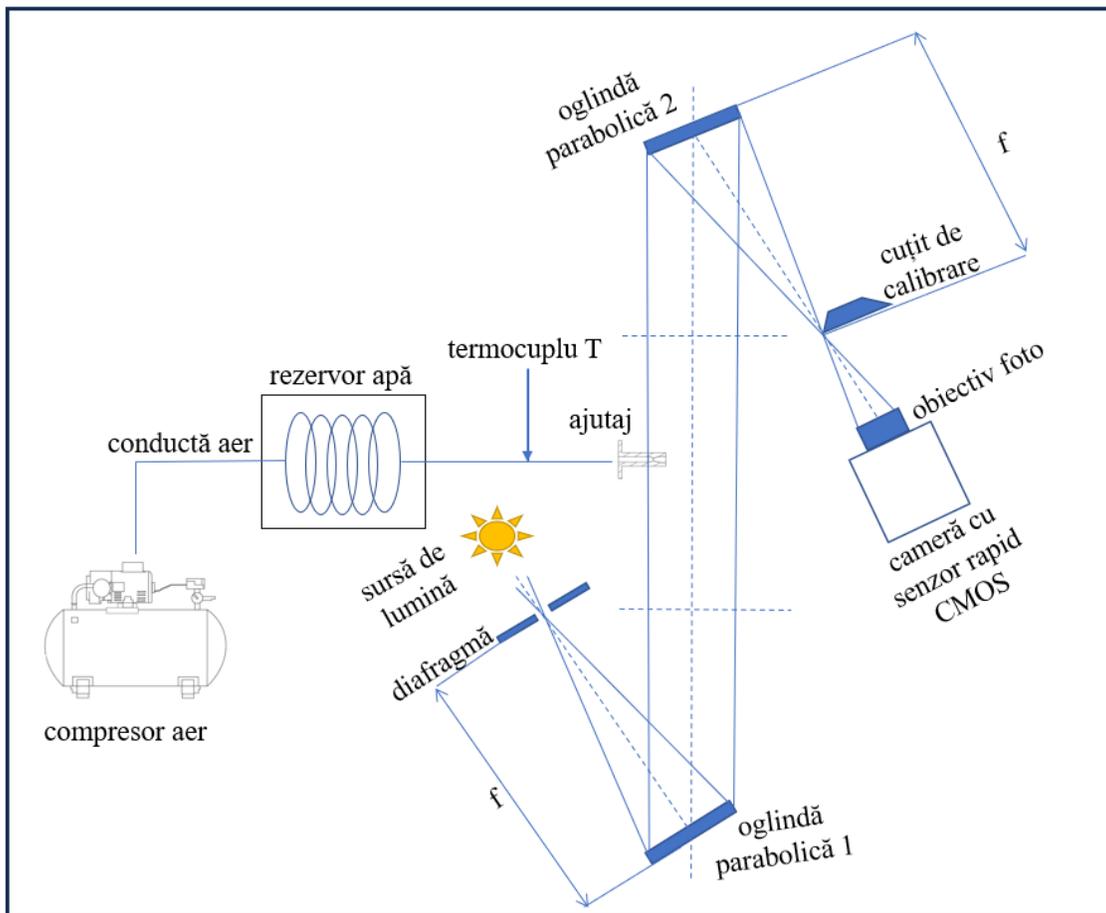


Figure 3 Experimental setup for the schlieren study of an exhaust jet generated by a supersonic nozzle [1]

Table 1. Equipment performances, used to create the experimental configuration for the study of an air jet discharged by a supersonic nozzle [1]

Nr.	Equipment type	Performances
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1.	2 x twin parabolic mirrors	Edmund Optics diameter 7.5cm EFL= 444.5mm
2.	Extended light source	LED illuminance=335 lumens wave length=440nm
3.	High speed camera	Phantom Veo 710L 1000 fps Spatial resolution: 1280x800
4.	Camera lens	Nikon Tamron Macro 28-75 SP AF, f/2.8
5.	Diaphragm	Diameter 5mm
6.	Air compressor	Brandschutztechnik Müller presiune furnizată=20 bar
7.	Termocouple	Type T

Although the schlieren images contain a variation corresponding to the evolution of the jet shown in the sequence of images in figure 4, the measurements are considered to be made when the jet can be considered fully developed.

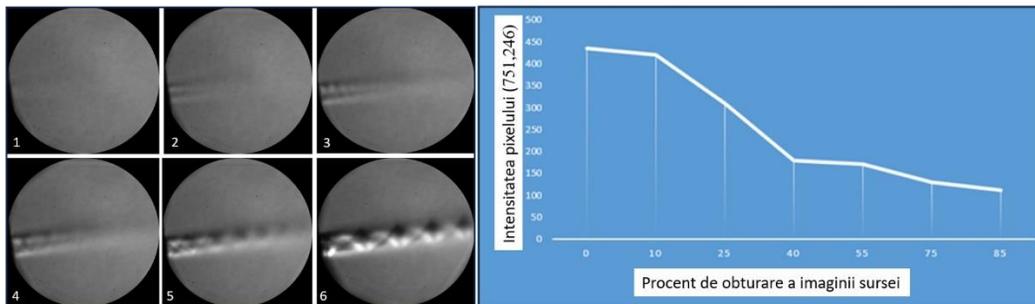


Figure 4 (a) Development sequences of the supersonic jet (b) Calibration curve obtained for 7 different positions of the calibration knife, for the pixel located at coordinates (751,246) [1]

Individual calibrations are performed for each pixel of interest. Phenomenon-free schlieren images (background images) will be recorded, corresponding to different percentages of light source image obscuration. The curve thus obtained for the pixel located at coordinates (751,246), is represented in figure 4 (b).

As can be observed in the schlieren images of the investigated jet, the presence of shock waves is represented by areas of high light intensity, which represents the displacement angle of the beam on the knife in the indicated area that exceeds the measurement capabilities of the system, and the values of the quantities in the respective areas cannot be interpreted correctly. Pixels close to that area will not be able to be part of the investigation, resulting in incorrect density values, amplifying the global error of the method. This fact represents a limitation of the present system.

The resulting density field results demonstrated an overall averaged value 15% higher than that returned by the CFD model. This fact is due to the fitting error of the calibration curve, the errors from light losses that cannot be quantified and the possible errors caused by the variable temperature in the room where the experiments were carried out.

The structure of the application and the functions used, as well as their application, are determined with the help of schlieren images designed to optimize the pre- and post-processing process. The description of the application and its capabilities will be detailed in the next chapter.

3. Development of pre and post processing applications for schlieren images

3.1. The PreQual application

The image pre-processing application PreQual is the result of observing the repetitive nature of the pre-processing of schlieren images obtained in experimental campaigns based on this visualization method. PreQual is a GUI, generated with the Matlab-AppDesigner module, whose source code is written in the Matlab programming language. This application contains both predefined and pre-optimized functions available in Matlab, but also some special functions. The structure of this application is original, specially designed to help any user familiar or unfamiliar with the schlieren technique, to obtain the best possible result from recorded images, shortening their processing time by automating the process. The graphics of the application can be seen in figure 5, detailing the operations contained in the graphical interface, as well as those running in its background.

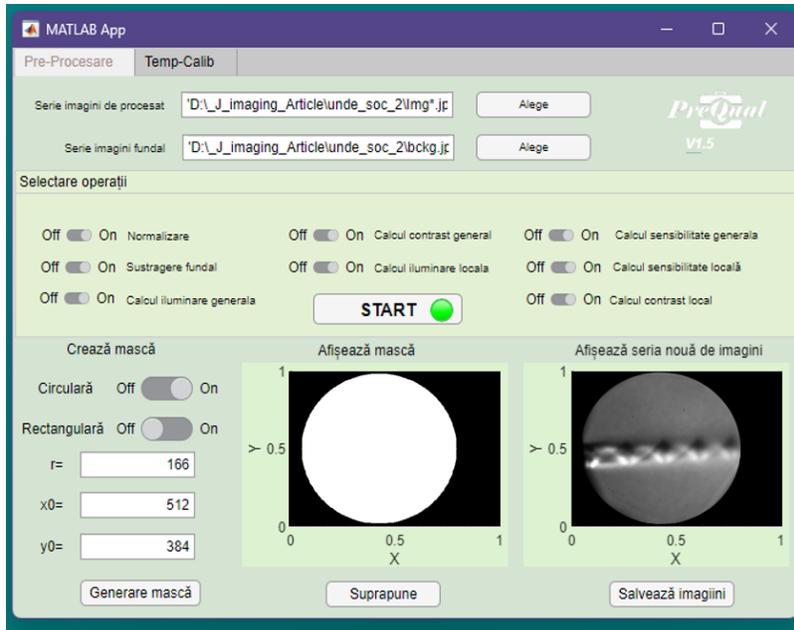


Figura 1 PreQual's graphic interface

Two case studies are presented to demonstrate how the PreQual pre-processing application works. The first is based on the processing of images containing a supersonic air jet, and the second is represented by a heated air jet. The second case is presented to emphasize the importance of the Temp-Calib module which has a simple contrast detection algorithm built in and from which both a graph of its variation and a possible calibration curve can result. These data must further be correlated with data obtained from numerical simulations.

3.2. The PostQ application

The PostQ application comprises several modules, each module developed specifically for one of the studied quantitative schlieren methods.

The PostQ application incorporates the source codes from the methods applied in this paper, intended to provide a more accurate flow characterization than existing methods, of the gas-dynamic parameters of turbulent flows, by automating the data processing process. The application is configured to operate the following options:

- to characterize the velocity field of flows by the Lagrangian SIV method

- to determine the density values by introducing a calculation module for the knife calibration method, which generates the calibration curves for each point, resulting in density maps that can be further interpreted in temperature or pressure maps, by applying the equivalent formulas
- to create optical schlieren filters by generating images conforming to the color distribution equation, entered by the user and to calculate the calibration curves in each pixel, according to the calibration method described in the next chapter.

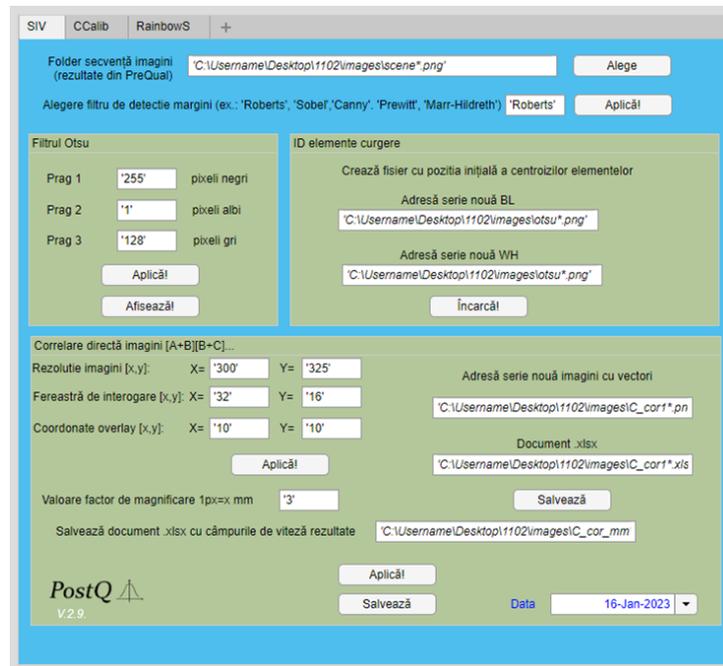


Figura 6 PostQ's graphic interface

The PostQ application contains generic functions, universally valid for a large range of images, recorded in the same schlieren system, being suitable for the automatic interpretation of several measurement campaigns, carried out on similar flow types. Changing the type of flow may require adapting the source code to the parameters of the studied flow. PreQual is a separate entity because it is most often used for the qualitative schlieren method, which aims to obtain high-quality images in which the details of the investigated phenomena can be easily observed.

PostQ therefore carries out the processing processes on image sequences on which the first 6 steps have already been applied, with the help of PreQual. The PostQ application will open where you can select the desired module. All the modules available in PostQ are demonstrated and tested in the continuation of the present work.

In the next chapter, the case studies that form the basis of the PostQ application will be exemplified. These will be performed on a turbulent jet composed of high-temperature water vapor generated by a nozzle specially designed to perform position corrections for small and medium-sized satellites.

4. Velocity mapping of turbulent flows through schlieren image velocimetry (SIV)

4.1. SIV's functioning principle

The SIV (Schlieren Image Velocimetry) quantitative method has application similarities with the PIV (Particle Image Velocimetry) visualization method. The PIV method is based on the tracking of foreign particles introduced into the studied flow, thus generating velocity fields by recording two images close in time distance. These velocity fields are generated by applying a correlation algorithm. SIV is similar to the PIV method in that the post-processing of the images involves the correlation of two consecutive images, recorded shortly after each other. The schlieren optical system allows the recording of photographic frames containing the images of inhomogeneities present in the studied environment, which are revealed by the refraction of light. In the case of turbulent flows, the small-scale currents (known as "eddies") formed during the development of the flow are considered as elements to follow, replacing the classic flow seeding particles. Thus, the second method is a more direct way of tracking the flow, using elements that are part of the flow to determine the instantaneous velocity fields, and therefore can be considered as a self-seeding method.

4.2. Case study description and the lagrangian tracking method

The case study presented in this work is represented by the characterization of the velocity fields of a turbulent and axially symmetric jet of water vapor, generated by a nozzle that uses an $H_2 - O_2$ mixture as propellant. The water vapor jet has an elevated temperature and is recorded at an average acquisition speed so as to allow multiple SIV methods to be applied to the same set of images.

The experimental setup with which the images were recorded is described in figure 7.

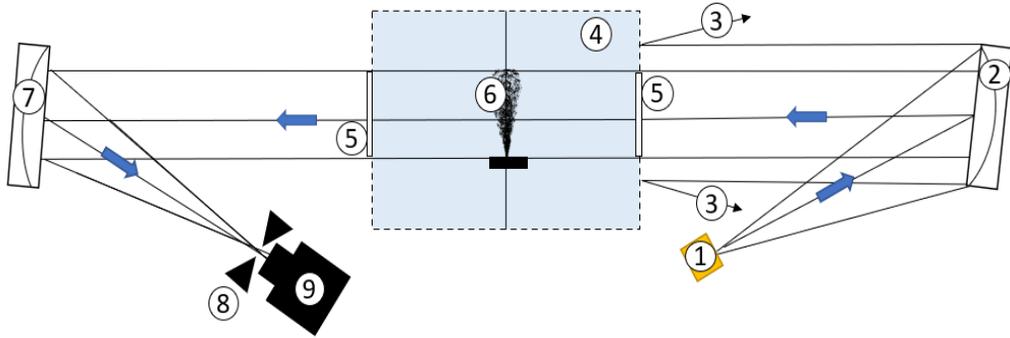


Figure 7 Experimental configuration with "U" type schlieren system: 1—LED light source; 2—first parabolic mirror; 3—light rays refracted back by the outer casing of the vacuum chamber; 4—vacuum chamber; 5—the circular viewing windows of the vacuum chamber; 6—the exhaust jet studied; 7—second parabolic mirror; 8—circular calibration knife; 9—CMOS sensor video camera.

The first SIV method applied is the Lagrangian tracking SIV method. This method involves tracking some turbulent elements that develop in the studied jet. The image processing steps required to apply this image are: reading the sequence of original images and the background image, converting them to black and white images, extracting all or part of the background elements, adjusting the intensity, scaling the image pixels and applying an intensity scale.

After applying these steps, the histograms of the images from the analyzed, processed sequence will be extracted. These are required to complete the following post-processing steps. The next step in the application of the method is to establish the parameters of the Otsu filter [5], applied to the sequence of images, so that it allows a very good demarcation of black elements from white ones. The method of evaluating the effectiveness of a filter varies depending on the desired result, therefore on the developed application, and not on general principles.

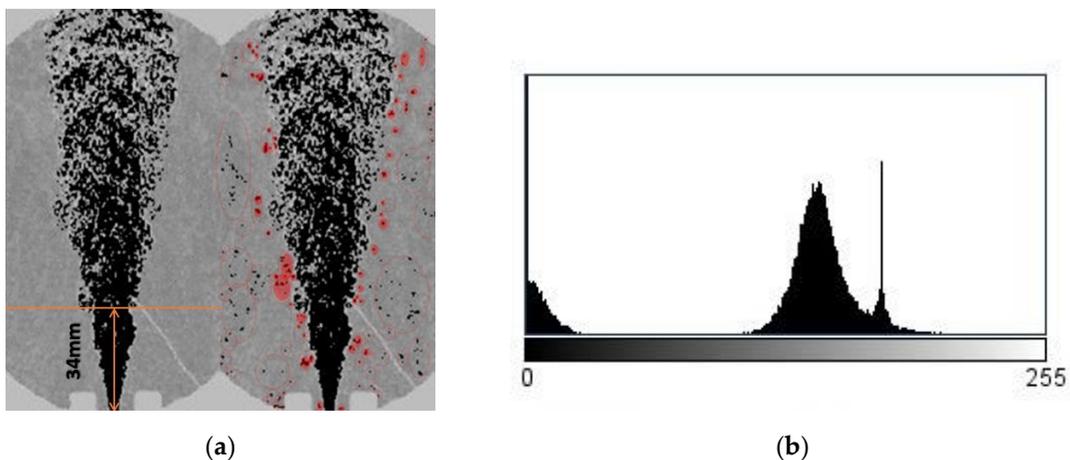


Figure 8 The studied exhaust jet (a) and (b) its histogram after applying the Otsu threshold

The results of the Lagrangian tracking method will be presented in comparison with the CFD simulation of the studied jet and with the other SIV methods.

4.3. CFD simulation of the studied jet

The experimental installation was designed to validate the feasibility of gaseous hydrogen and oxygen mixture for small-scale thrusters. It consists of a small-size thruster placed inside an experimentation chamber and connected to oxygen and hydrogen lines. The thruster was designed for a nominal value of 1 N in vacuum conditions, with an expansion ratio of 50 and a nominal mass flow of 0.3 g/s. Several tests were conducted in atmospheric and vacuum condition to determine the performance of the experimental model at near and stoichiometric mixtures. The thruster geometry consists of a convergent–divergent nozzle with a minimal section of less than 1 mm. In order to estimate the thruster’s performances and to determine the magnitude of the flow field at the thruster outlet, a 3D numerical simulation was conducted using ANSYS CFX. The computational model was created in order to reproduce the geometry of the chamber, of the thrusters, and the relative placement of these elements. The thruster’s inner geometry was modeled in order to account for the outlet of the combustion chamber and the convergent-divergent nozzle. The flow around the external geometry of the thrusters is of lesser importance; therefore, in order to lower the computational demand, a conic wall was used for the outer geometry of the experimental model, as can be seen in Figure 9. The overall dimensions of the computational model were determined by the experimental chamber dimensions, which has a cylindrical shape.

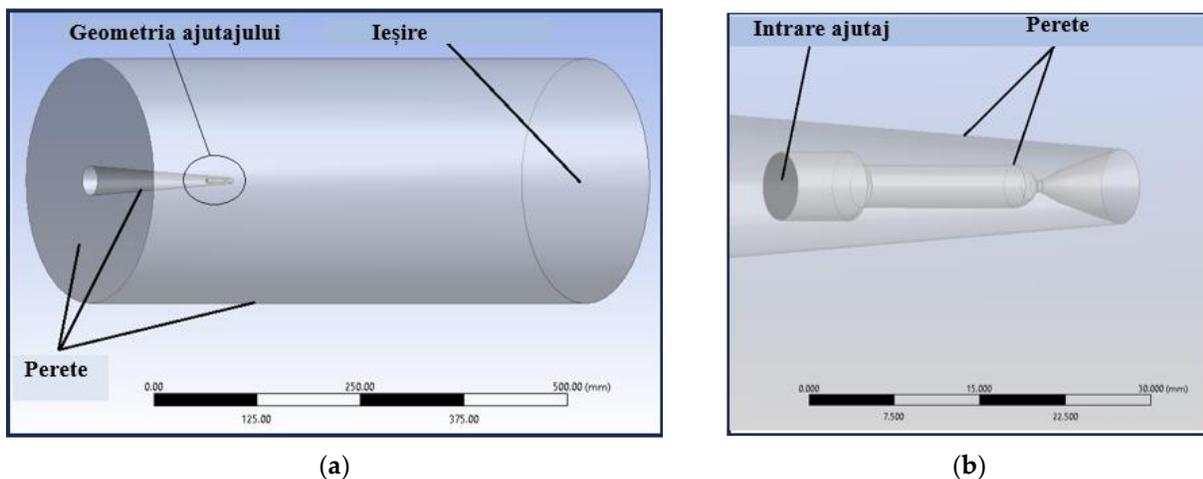


Figure 9 (a) Fluid volume; (b) thruster’s interior geometry.

The numerical grid was generated using ICEM software. The grid is of structured hexahedral type with smaller dimension for the thruster inside volume and the vicinity of the thruster outlet as can be determined from Figure 10. The grid independence was checked in terms of resulted y^+ values which were in the suggested intervals for the turbulence model used.

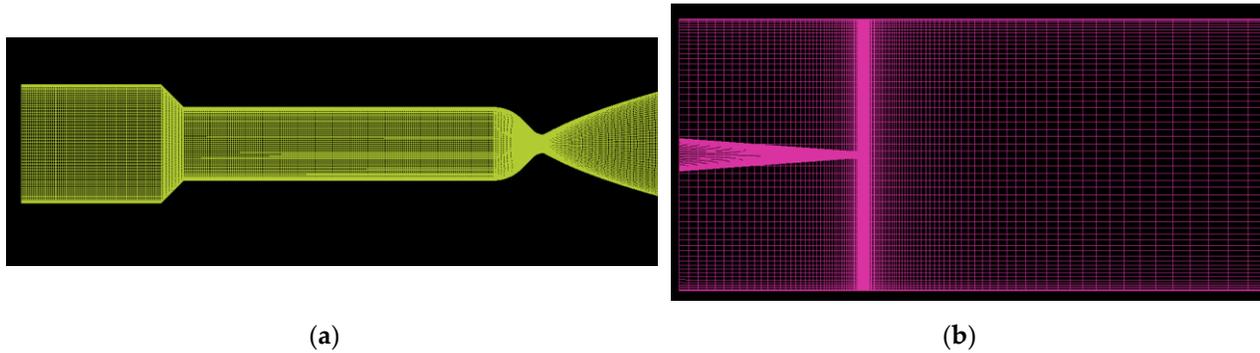


Figure 10 (a) Numerical grid for thruster internal flow; (b) Numerical grid for fluid volume.

The numerical case was set based on measurements for the respective test, thus the total mass flow was set at 0.27 g/s. In order to reduce the complexity of the numerical simulation and to lower the computational demand the combustion process was not modeled. The combustion process was considered complete at the volume inlet; with the working fluid composed of water vapor from the complete reaction of the H₂ and O₂ gases. The temperature was determined using the CEARun software for a stoichiometric reaction of gaseous hydrogen and oxygen resulting a value of 3450 K. The fluid used for this simulation was a mixture of H₂O, H₂, O₂ and N₂ in order to simulate the interaction between the water vapors and ambient air.

The boundary conditions for this study are presented in Table 1. Inlet boundary conditions were set for the thruster inlet (fixing the mass flow, total temperature and chemical components of the fluid, water vapor in this case), opening conditions for the fluid volume outlet (fixing the temperature, pressure and chemical components). For the thruster and experimental chamber walls adiabatic no slip conditions were used. RANS (Reynolds-averaged Navier – Stokes) simulations were conducted using K- ϵ turbulence model due to its known performance for high turbulent flows.

Table 2. Boundary conditions

Type	Location	Details
Inlet	Thruster inlet	Mass flow = 0.27 g/s Total Temperature = 3450 K

Wall	Thruster walls, Testing chamber walls	Adiabatic walls with no slip conditions
Opening	Testing chamber outlet	Temperature = 25°C Pressure = 1 bar

As convergent criteria three parameters were monitored: residuals, mass flow im-balance and the reaction on the thruster walls. The residuals target was fixed at 1×10^{-6} reaching at least 1×10^{-4} for each parameter. The mass flow imbalance was less than 1% with the reaction force on the thruster walls almost constant (variation less than 1% over several hundred iterations). The numerical results were compared with experimental data in terms of thruster pressures and thrust measurements, validating the numerical study.

4.4.The kymograph method

The first attempt to use this type of approach in the technique of determining the velocity field of a turbulent helium jet, from schlieren images, was made by Settles and Liberzon [7], at the end of 2022 when the results of the study on the analysis were published the averaged velocity obtained by kymograms and by the PIV method and comparing them with the ideal theoretical profile obtained from similar results of the turbulent jet (self-similarity = prediction of statistical order). Kymography is obtained in the ImageJ program by plotting the central axis ($d/2$ to x) with a 1 pixel thick line graph. The superimposition of these lines forms a spatiotemporal image of the variation of the central elements. Figure 11 shows a low resolution image, $T_{max}=100$ pixels, composed of the center lines of 100 consecutive frames.

A fast moving speed would be represented in a kymogram by means of a curve with a small slope, and elements that move slowly, would be represented by a large slope. The curves are determined by applying the same Roberts boundary determination filter used in the Lagrangian trajectory determination method.

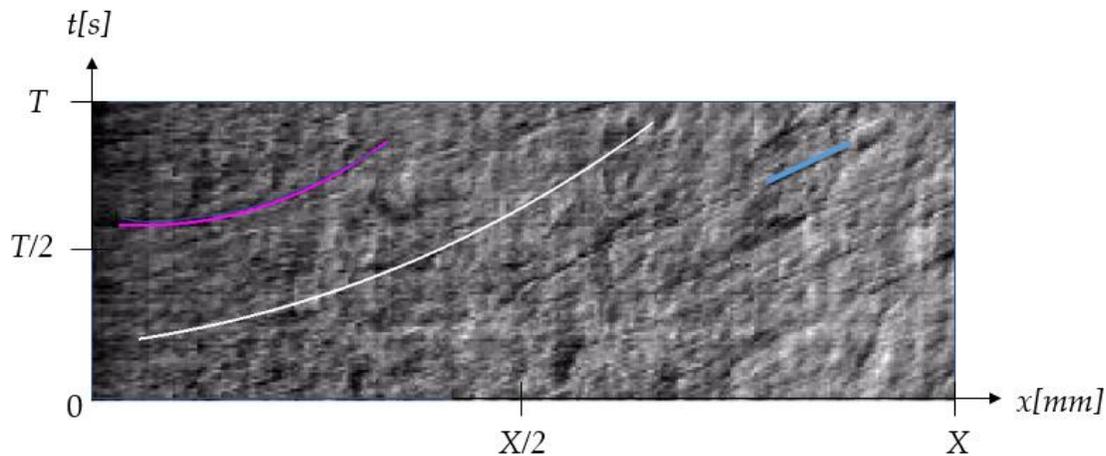


Figure 11. Kymography of the velocity on the central axis of the jet (outlined by the white curve), the path of a shallow turbulent element (blue curve) and the path of a well-defined turbulent element (pink curve)

4.5. Comparisson between CFD and SIV

In general, in the case of experimental measurements, the value of 62.5% for the measurement accuracy represents a very small value, but in the present case, it presents a value much higher than that obtained by Morales [8]. This fact is partly due to the automation of the tracking mechanism.

For more accurate descriptions of the velocity profiles, the 3D character of the jet must be taken into account. This fact can be done experimentally (by recording the images so that 2 series of images can be captured on 2 different directions of the jet, similar to the 3D PIV system) or by using a statistical method, by applying the Inverse Abel Transform to determine the velocities.

The results obtained from the CFD simulation are further compared with those obtained from the kymograph method. The overall accuracy of the kymograph method improves after the first point, but at its extreme, the velocity values seem to drop off faster than the theoretical curve. The accuracy of the method was found to be over 80% in areas located up to 80 mm away from the nozzle. The graph for this section overlaps very well with the theoretical profile, as can be seen in figure 13. The first point of the kymogram curve is considered to be an error, resulting in a maximum jet velocity of 1460 m/s, and is not included in figure 13. The velocity profile resulting from the kymograph method stops at about 85mm from the nozzle, where the curve becomes harder to identify due to the increase in density.

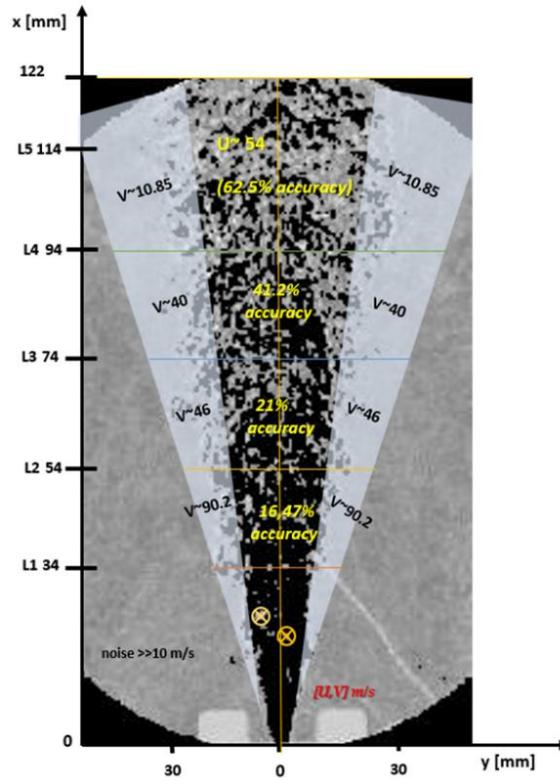


Figure 12. U and V averaged velocities, shown per region of interest, generated by the lagrangian tracking method

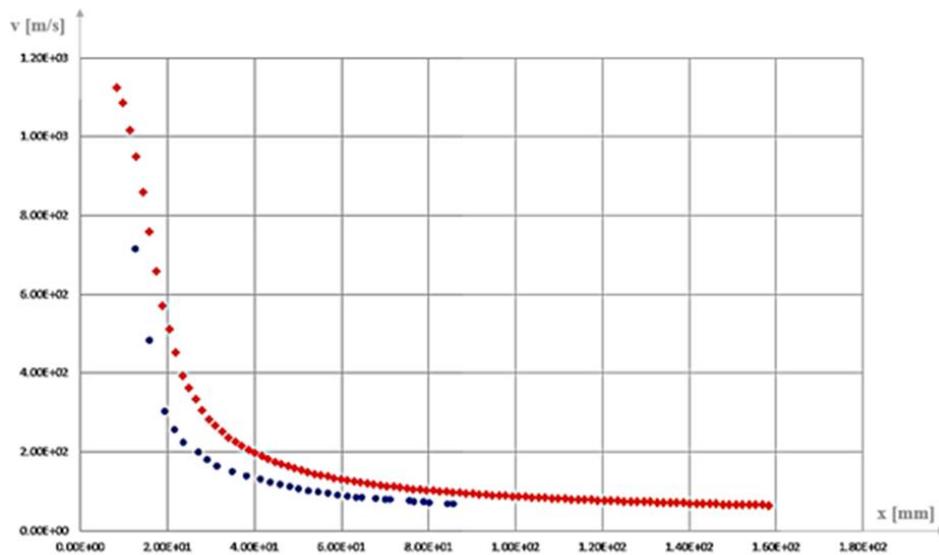


Figure 13. Axial velocity curve obtained by CFD simulation (red) and axial velocity curve obtained by the kymograph method (blue)

The results from the kymograph method can be improved if images are recorded at a slower recording speed, which would cause smaller density differences to be distinguished and

included in the jet velocity curve, so that its plot can extend from the origin to the upper limit of the parabolic mirror.

4.6. The results of the cross-correlating method, applied on a commercial software

Most PIV images are analyzed either on the software provided by the manufacturer of the visualization system, or on those made in-house, optimized specifically to fit the requirements of the observed experiments. By optimizing the properties of commercial PIV post-processing software to lend themselves to rendering the results of the SIV method, the time spent developing a dedicated post-processing application can be shortened. PIVlab offers three possible correlation mechanisms: by using FFTs, direct image correlation (DCC) or ensemble correlation. FFT correlation follows the steps described above, while DCC performs direct image correlation in a single pass by computing the displacement matrix in the spatial domain. With ensemble correlation, PIVlab analyzes a series of sparsely seeded images and averages the resulting correlation matrices. The study performed is based on 3 variations of correlation with FFT and makes a comparison with the result of direct correlation. Table 2 shows the PIVlab settings used for image processing.

Table 3. Settings used in the PIVlab post processing sessions.

Session no.	Number of passes	Interrogation areas vs. step	Other specifications, available for all of the sessions
1	3	64x32; 32x16; 16x8	Subpixel interpolator: Gauss 2x3-point Magnification factor: 1px = 0.00054m Coordinates: x increases towards right y increases towards top Contrast stretch - active
2	3	32x16; 16x8; 8x4	
3	2	32x16; 16x8	
4	1 (DCC)	16x8	Raw image analysis

Although the data sample was smaller than that obtained by session 1 and session 2, the query window and step size were more appropriate, looking at the 4th query line. Here, the velocity U varies according to a different law, since the upper vorticities of the jet no longer vary similarly to those at the exit of the jet.

DCC analysis was performed on a set of original schlieren images, as saturation was observed to play no role in image correlation.

Although DCC performed very well in determining more accurate values of flow velocities than those provided by FFT correlation, it presents the expected problem of data scarcity because a single-step query window equal to the image size is applied. The resulting velocity at the exit of the nozzle, calculated from the image, with the specifications provided in table 2, was close to 900m/s. The prop was designed to exceed Mach 3.5 and from CFD simulation it was determined that the maximum speed is 1124m/s. Different sources of errors can be identified in the measurements performed, such as the time of separation between the images being inadequate, not allowing the capture of the entire evolutionary scale of the turbulent elements considered "tracking particles" for the SIV technique and the averaged character of the values, provided by the schlieren technique, which was not addressed in these measurements. The accuracy of the measurements in the area immediately exiting the jet from the nozzle can be considered to be a maximum of 75%.

Compared to the accuracy obtained by other measurements of this kind (20-65%), without adding other types of methods adjacent to the technique to correct it, the accuracy of the data obtained by this post-processing method can be considered superior, for the case of DCC.

For the other cases, the obtained results are irrelevant when comparing them with the CFD simulation of the water vapor jet.

4.7. Conclusions regarding SIV methods

Through this study, an estimation of the velocity profile of an exhaust jet composed of water vapor was made. The methods used provided data on the speed of the studied jet, in the sections where the physical parameters of the flow better match the experimental settings.

The Lagrangian tracking method performed better in sections where the jet was described by "floating elements". Tracking turbulent elements in a 3D jet has been shown to have poor accuracy, in some cases down to 20%. The 62.5% accuracy that resulted from Lagrangian tracking can be improved by better matching the acquisition rate to the total flow velocity. Another option is to record schlieren images at different acquisition rates, specifically dedicated to a certain section of the jet, which has a certain range of speed and density known in advance.

A post-processing code was created and integrated into the applications described in Chapter 3, to identify and track the turbulent elements, for the development of this application from the current stage it is recommended to include among its options an adaptive tracking algorithm, which can be applied to take into account the deformation of elements over time. The comparison of this method with the CFD velocity profile only applies to the upper sections, since one method is line-averaged and the other represents the velocity profile of the central axis of the jet. The option of real-time post-processing can be added to the PostQ application, its implementation depending only on the performance of the post-processing system.

The kymograph method provided more accurate and reliable results with very good accuracy compared to the Lagrangian tracking method. This method can be improved in the context of the analysis of the studied jet, by decreasing the acquisition rate to be able to record images with a better resolution, which will help to identify and describe the curve generated by the kymograph method.

The accuracy of the two applied schlieren methods is calculated by comparison with the data obtained from the CFD simulation.

However, the CFD data were compared with experimental data collected by sensors measuring total mass flow and force output. The numerical simulation results showed an error of 4% compared to the experimental data in the nozzle exit velocity value, representing slightly lower values for the numerical simulations.

In the present study, the Lagrangian tracking method was found to be useful in buoyant sections, but did not produce relevant data for velocities in the midplane of the jet, despite the method being improved using the correlation functions designated for coherent tracking of the elements. The kymograph method proved to be more suitable for determining the centerline velocity, while being rather difficult to apply in other areas of the jet without the automation of the post-processing mechanism. However, it produced results with a 20% error compared to the CFD simulation data.

The magnitude of error found in schlieren methods far exceeds the magnitude of error found in CFD simulation. Therefore, the calculated accuracy of the schlieren methods can be considered relevant even when the error of the CFD simulations is taken into account.

The main conclusion of the study involving the use of commercial PIVlab software is that although the magnitude of the velocity could not be determined within reasonable limits of accuracy, the graphical profiles on the desired lines of inquiry could be obtained, for 4 different post-processing sessions. The main reason behind the inaccuracy of the measurements when applying SIV methods is the optical path integral character of the schlieren method, which is a projection of the observed density field and can only be post-processed to render the line-averaged values of the velocities . Most specialist works find that SIV methods can provide data accuracy between 20%-100%, depending on the type of flow studied and the post-processing method. For the presented case study, SIV was performed by analyzing the axially symmetric jet using the image cross-correlation method. Four post-processing sessions were performed with different settings. The first three sessions covered the FFT method, with different values for window sizes and query steps. It was observed that the second session provided a larger sampling interval due to the size of the query windows. However, the resulting velocity map also contained an amplified number of spurious vectors, generated by the development of background natural convection. Reducing the interrogation area has a negative effect on the vectors generated on the outside, in the extremes of the jet shear layers. Shear layer elements may be confused by the algorithm with elements resulting from natural convection. This fact leads to false values of the correlation peaks, generates false vectors and increases the total measurement error. The first and third sessions yielded similar results given the similar size of the smallest pass applied. They also show spurious background vectors, but on a smaller scale compared to those found in the second session. An advantage of the larger query windows used here is that the distinction between vectors can be easily made. However, for the images presented here, the speed limits cannot be imposed to completely remove the spurious vectors, as it would also remove the real vectors and therefore reduce the data sample size. The size of the data sample is controlled by the Central Limit Theorem which states that for a data sample to be relevant it must contain between 30-50 measurement points. DCC measurements calculate the correlation matrix in the spatial domain. For the DDC method, the settings were adapted taking into account the results of previous sessions. Therefore, a query window of 16x8 was used, as this was found to be the best compromise between having a relevant sample size and the impact of spurious vectors. While providing data very close to the expected value of the exit velocity of the aircraft, the DCC method was shown to be unreliable given the data scarcity resulting from the nature of the

method that allows velocities to be calculated by performing a single search pass of the query step over the window of query. To improve the results of the method, there are two important aspects that can and must be improved. The first aspect is to provide better schlieren images, which can be achieved by providing a recording with the velocity adapted to the development time of the turbulent elements.

5. Color calibrated schlieren applied to turbulent flows (CCS)

5.1. Introduction

The schlieren method with calibrated color filter is a quantitative visualization method developed to allow the extraction of data regarding the physical parameters of the studied phenomena.

This method can be found in the specialized literature under the name "rainbow schlieren", due to the segmented filters that contain transparent strips of different colors, used in some applications, and which, in the presence of the phenomenon, due to the colors of the filter, present different colors for certain values of density gradients. It has a similar operating principle to the classic schlieren method, with a slight difference in the replacement of the calibration knife.

5.2. Designing and integrating the color filter into the schlieren system

This paper uses for the initial definition of color gradients, the calibration laws used by Elsinga in [9]. For the present study, however, the jet propagation directions are different from those considered in the shock waves studied by [9]. An important difference is also created by the method of manufacturing the physical filter, which introduces considerable errors. All these errors are however reduced by the physical calibration performed before recording the schlieren images.

The present study considers the x and y directions to be the directions of the image matrices created by Matlab, where x represents the rows and y represents the columns. Equations 1, 2, and 3 show the variation mode of the red, green, and blue colors, respectively, on the image grid. The image grid is a matrix with dimensions equal to the spatial resolution of the written image. In this case, the image has a spatial resolution equal to 400x400 pixels. Each pixel is assigned a location (row, column), a value for each of the 3 color channels (R,G,B) and a value for its intensity.

$$R = \frac{255}{1 + x_f + y_f} \quad (1)$$

$$G = \frac{255 \cdot x_f}{1 + x_f + y_f} \quad (2)$$

$$B = \frac{255 \cdot y_f}{1 + x_f + y_f} \quad (3)$$

After applying the shaping laws, the color values will be scaled to fit in the [0,1] range. This is how the image of the filter, displayed by the Matlab script, is generated.

The solution that involves the use of fine grain photographic film is used.

5.3. Determining the minimum needed parameters for CCS

The minimum required parameters for the color filter schlieren system are obtained through a series of pre-experimentation and are found in Table 3.

Table 3 Minimum parameters for recording schlieren images

Equipment type	Name	Minimum specifications
High speed camera	Phantom Veo 710L	30.000 fps, 512x384 pixels.
Twin parabolic mirrors	Edmund Optics	Al plated, minimum diameter of 200mm, EFL > 1 m.
Knife edge	Gradual color filter	Square: minim 7mmx7mm
Light source	LED, non pulsatory	Maximum diameter 5 mm Output power. 100lumens Wavelength: 400-600 nm.
Diaphragm	square	1.5 mm
Camera lens	Tamron Nikon	Macro
Data acquisition system	Internal buffer PV 710L	At least 2 seconds at 30.000 fps and the resolution of 512x348
Software and post processing equipment	Matlab- PostQ, Alienware	iCore7 Matlab 2020a, Toolbox Image Processing

5.4. Implementing the CCS

To record color filter schlieren images, it is necessary to know the position and shape of the source image accurately. For these reasons, the schlieren system had to be aligned in the Z

configuration in order to be able to image the light source without the coma effect. Its alignment involved inserting the high-speed camera inside the support frame of the vacuum camera, specifying that the two elements (vacuum camera support and video camera) did not touch each other at any point, in order not to introduce vibrations in the schlieren system, which would have made it impossible to calibrate the optical filter. The scheme of the resulting system is shown in figure 14.

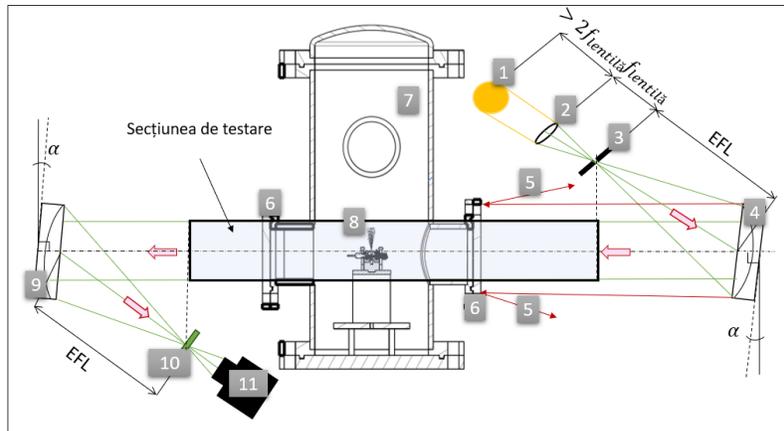


Figura 14. CCS configuration: 1—light source; 2—biconvex lens; 3—square diaphragm; 4—parabolic mirror; 5— deflected rays ; 6— glass circular windows of the vacuum chamber; 7— vacuum chamber; 8— studied jet; 9— parabolic mirror; 10—calibration mechanism; 11— CMOS sensor.

Table 4 Equipment and parameters used in the acquisition of color schlieren images

Equipment type	Name	Specifications
Twin parabolic mirrors	Al plated	EFL: 1524 mm
Light source	LS-W1	White, laser pumped Diameter: 1.5mm Optical output: 500mW
Biconvex lens	-	Diameter: 30mm FL: 250mm
Diaphragm	Custom	3D printed Dimension of the orifice: 1mmx1mm
Color filter	Custom	Square, gradual
High speed camera	Phantom Veo 1310L CMOS	30.000 fps 600x480 px Exposure time: 0.93 μ s

Camera lens	Nikon Nikkor	50mm 1:1.8G
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5.5. Calibration procedure

To calibrate the color filter, it must be translated relative to the light source as many times as is deemed necessary according to the relationship between the filter area and the light source image. This translation aims to digitally characterize the color shades existing on the physical filter.

In the present case, the investigated filter has dimensions: 5×5 mm, and the source image is 1 mm. This results in 25 positions required for the full characterization of the filter. The translation mode of the filter is done by starting with a reference image of it, where the source image is in the middle of the filter. Photographic film is calibrated without resorting to removing its optical effect. To remove the optical effect introduced by the photographic film, images can be recorded with a section that does not contain the image of the filter, but is only exposed to the light image of the screen on which the filter was projected. After obtaining this image, the average of the hue values can be determined and extracted from the schlieren images. Since the film effect is constant, the filter calibration being a physical one, it can be neglected, with the mention that the color distribution is observed to be no longer linear, as previously intended. The resulting calibration curve is illustrated in figure 15.

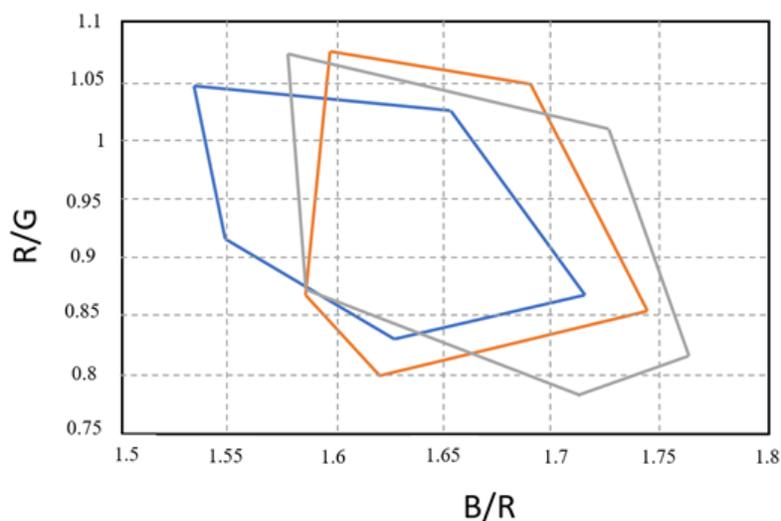


Figure 15. Calibration curves for 3 different pixels as a function of R/G and B/R color ratios

The resulting calibration function is shown in Equation 4.

$$\varepsilon = c_1 + c_2 \frac{B}{R} + c_4 \frac{B^2}{R^2} + c_5 \frac{B \cdot G}{R} + c_6 \frac{R^2}{G^2} + c_7 \frac{B^3}{R^3} + c_8 \frac{B^2 R}{G^3} + c_9 \frac{B R^2}{G^3} + c_{10} \frac{R^3}{G^3} \quad (4)$$

The purpose of the calibration function is to provide a mathematical mechanism to calculate the deflection angle of the system.

5.6. Processing the CCS images

The two sequences of color schlieren images, corresponding to the filters used, are presented below. The filters are composed of the same image, manufactured in the same way, but have different sizes. Figure 16 shows the first 6 images of the jet evolution, corresponding to the 5×5 mm filter, and Figure 17 shows the first 6 images of the sequence containing the first evolutionary moments of the jet.

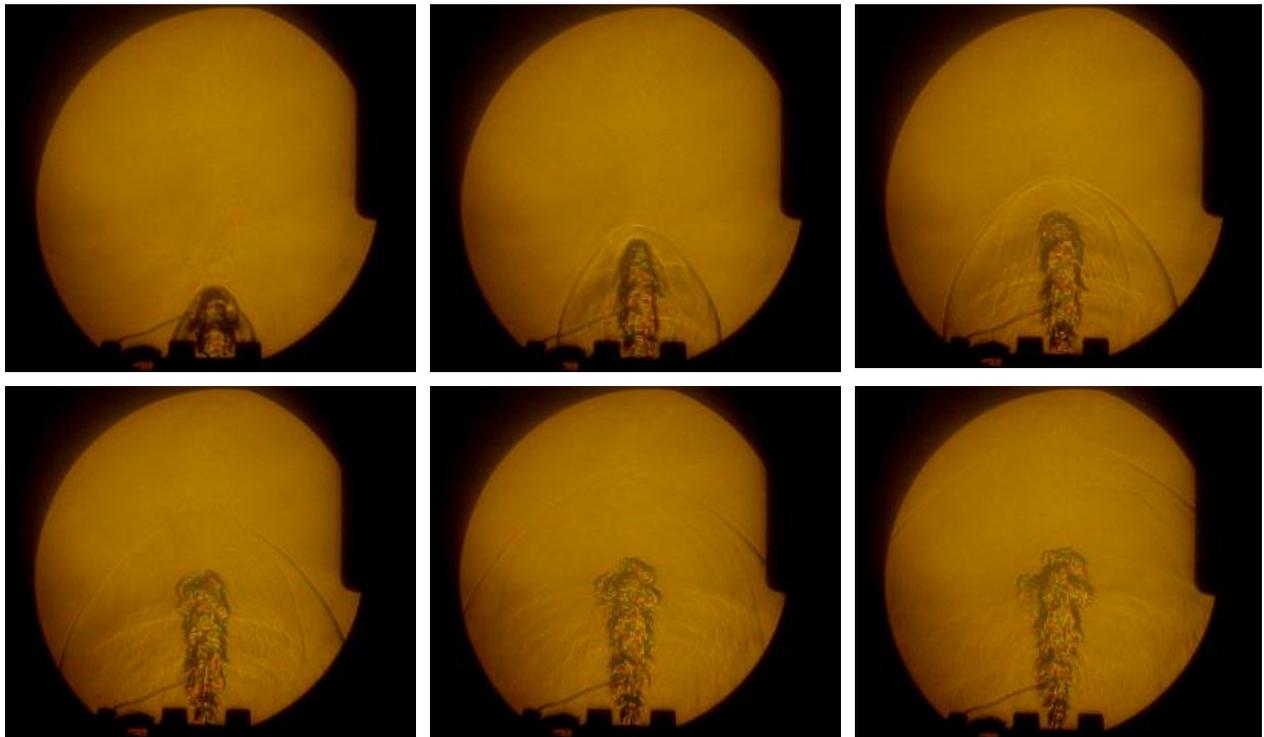


Figure 16. Sequence with 6 images recorded at the initial moment of jet development, with the color filter with dimensions of 5×5 mm

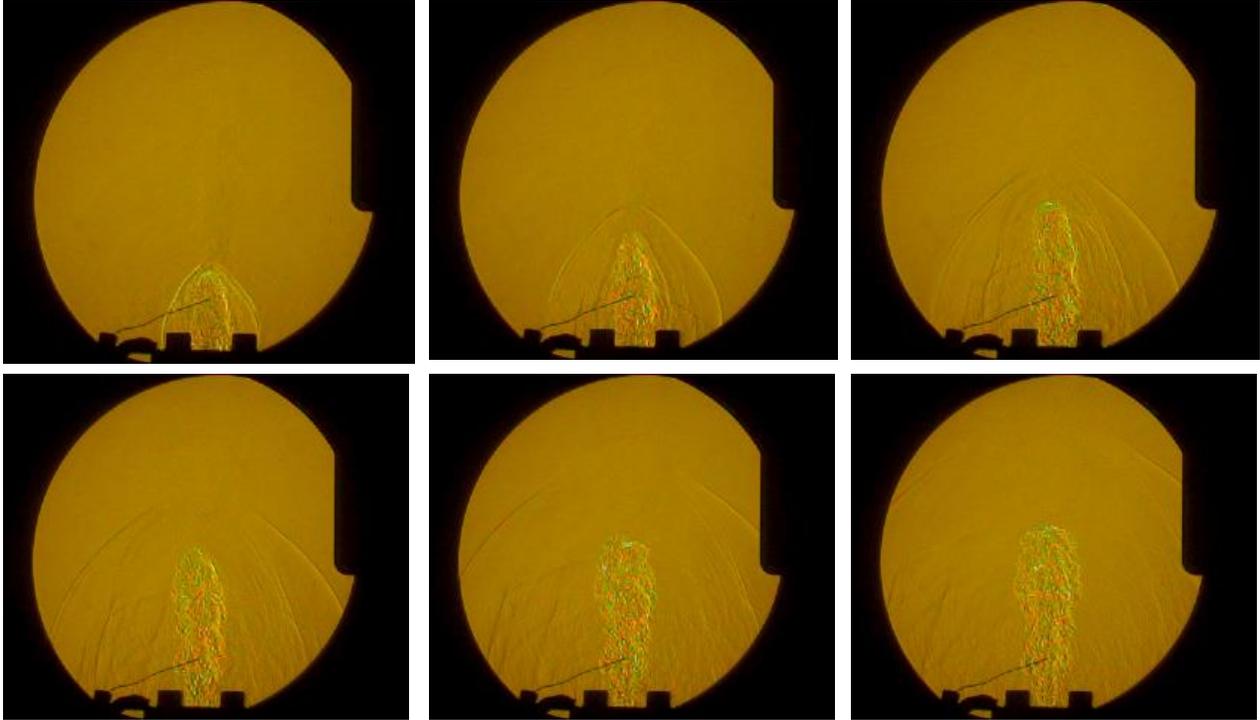


Figure 17. Sequence with 6 images recorded at the initial moment of jet development, with the color filter with dimensions of 15×15 mm

After obtaining the values for each corresponding deflection angle in each pixel, the density map is obtained using the equation known as the simplified Gladstone-Dale equation. The Gladstone-Dale constant, K varies with color wavelength, but this variation is negligible.

5.7. Results and conclusions regarding the CCS method

Control lines are used to analyze jet properties. The density distribution on the central axis of the jet is shown in figure 18. This distribution is compared with the density profile obtained from the CFD simulation, presented in Chapter 4. In figure 19, the system of axes used to quantify the results from the jet images can be seen.

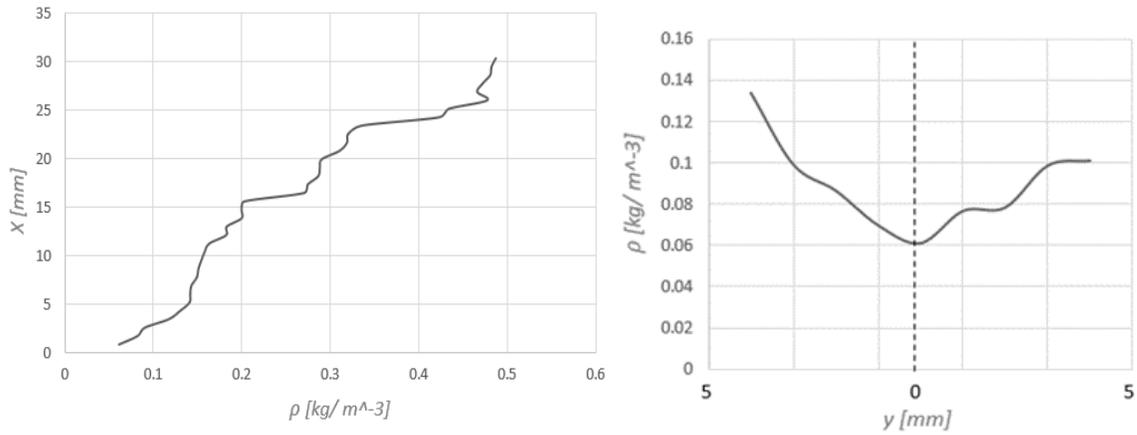


Figure 18 The curve of the density values obtained by the CCS technique, on the central axis of the jet, from the exit of the nozzle to the distance of 31 mm, on the x-axis of the water vapor jet (left) and the Density distribution on the line A crossing the jet, located near the jet exit (right)

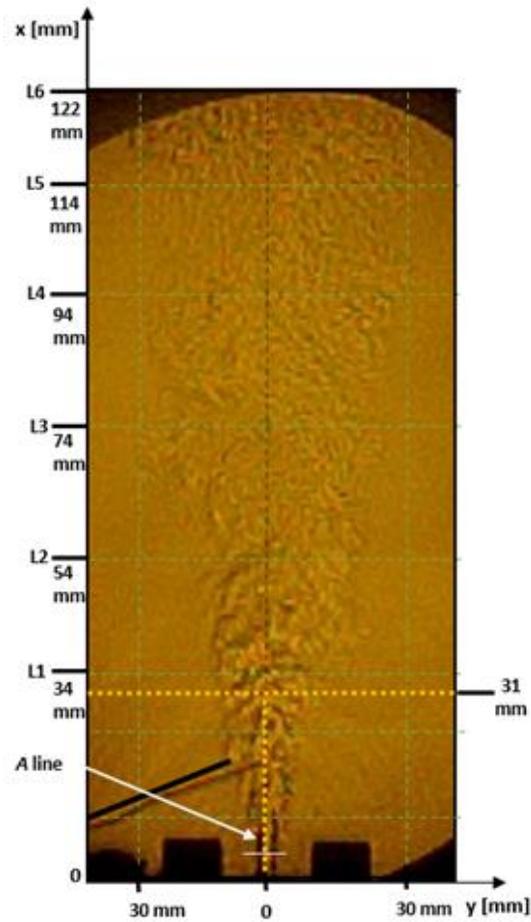


Figure 19. Axis system positioned on the water vapor jet, with control lines and physical dimensions of the jet

The results obtained by CCS analysis illustrate that the system needs increased sensitivity. However, this sensitivity must come from the characteristics of the optical system. The sensitivity from increasing the filter sizes is unnecessary, as the current system identifies color shades with relatively good accuracy. One of the sensitivities of the system is the definition of parameters per pixel. This per-location pixel shift reduces the need for subpixel-level interpolation encountered in quantitative schlieren methods designed to return values of jet velocity profiles.

Describing the density profiles of the water vapor jet can lead to revealing its other parameters. For example, one can apply the equation of state to obtain its temperature values. This calculation will however include the global error introduced by the density values.

6. Conclusions of the thesis

The aim of the present thesis was to improve the measurement accuracy of the SIV and CS quantitative schlieren methods, by automating the data pre- and post-processing process. Multiple variants of the pre- and post-processing codes were thus created, these being able to accommodate any qualitative or quantitative schlieren method.

In the case of the SIV Lagrangian method, an increase in measurement accuracy of over 20% was recorded by processing the images with a dedicated source code, specially adapted to the needs of the method, whose requirements to measure the 3D nature of the flow with the help of only 2 represented coordinates in the image could not be satisfied until the year 2018. The Lagrangian tracking method imagined by Morales addressed the subject of turbulent flows, considered axially symmetric. Morales described the method as having very poor accuracy, using a manual tracking method. The present work created both an automatic image pre-processing process in the appropriate manner in which the elements to be tracked are visible and their trajectory is easy to follow, and an algorithm capable of correlating the images and determining the center of the elements in turn necessary, to then create the path of their movement, extracting the speed profile of the jet, when confronting the data with the image acquisition speed.

The kymograph method, first published by Settles and Liberzon [7] in December 2023, followed by the author in 2023, is a method that works very well for turbulent, axially symmetric jets. This method is included in the post-processing application, whose special mode makes it easy to

identify the velocity curves corresponding to the central axis according to its slope value. Settles and Liberzon propose its visual identification, which is valid for very well-focused images of turbulent jets.

This kind of visual identification is supported by the logic of the method, although it lacks the mathematical foundation in terms of numerical comparison. The source code developed in the work fills this gap. It also includes an automation part of obtaining the kymogram velocity values, which were done manually in the only paper that described how to apply the kymograph method. Through this automation, a 5% increase in the accuracy of the method was achieved. The curve of the velocity profile on the central axis of the studied turbulent jet, obtained by the kymograph method, climbed with the mentioned percentage, almost constantly towards the curve obtained from the CFD simulation.

Additional methods for which special modules have been created, such as the thermal calibration module and the knife calibration module, are special modules that require additional modifications and are currently used for only one type of image, returning values that fall within within the limits provided by the specialized literature (2%-3%). The automation of the processes ensures the preservation of these percentages, provided that the specifications of the applications are respected.

The calibrated filter method shows a very good accuracy, obtained for a portion of the beginning of the jet. The error on this section is between 2%-5% compared to the simulation result. The main problem is, as with all schlieren methods, the integrative nature of the visualization method. With only 2 components available, the error resulting from this calculation represents a percentage well above the expectations of the specialized literature, in which it is specified that such methods are only recommended for flows that can be considered 2D. The reduction of measurement errors is due both to the high-performance optical system, with an optical path that focuses and isolates the flow very well, either through the optical elements in the optical path of the light source, or due to the reduced exposure time, which eliminates the elements of natural convection, and available post-processing power and post-processing automation. The possibility to carry out pre-experimental campaigns, which resulted in obtaining very important practical information, contributed substantially to the reduction of errors.

Most of the currently published papers describe one or more quantitative schlieren methods, used to determine a single parameter of a flow, either velocity profiles, or obtain density maps or other properties. Most of the time, the schlieren method is compared either with the PIV measurement technique or with data from numerical simulations or physical sensors.

The present work addresses the subject of determining several parameters of the same water vapor jet, also analyzing the causal relationship between the type of phenomenon investigated and the versatile character of the methods. The methods of analyzing schlieren images and even the principle of obtaining schlieren images will multiply with the increase of the available computational power - a trend that can be seen to be upward in the last decades - and the recording power of video cameras. Another influence on the method is represented by the optical elements used. In the eventuality that the manufacturing methods of optical elements will evolve (for example, they will be able to be 3D printed) and they will become more accessible, the subject of schlieren methods will become easier to approach, study and therefore improve. The automation of the post-processing process plays an important role in its use, because the trend for the implementation of existing visualization methods is based on the delivery of available "turnkey" systems that have some instructions for use and that come bundled with the software data processing. This trend is caused by the fact that both the research field and the industry focus on the description of the studied phenomenon and less or not at all on the visualization method used.

So one solution to the spread of schlieren methods is to provide systems with dedicated software that can post process large sequences of images, running analyzes for each pixel of said images.

This fact can be achieved by producing special super slides, similar to those used in old projectors. If their image were identical to the image returned by the color distribution law, then the distribution would have a linear character, and calibration would only be performed to correct small positioning errors. From an optical point of view, the most important element of the schlieren system is represented by the light source.

Containing all the described methods in a single application is very difficult because their underlying code becomes very complicated. It is recommended to break them down and make improvements individually for each method. Comparisons of the schlieren method with numerical simulations become more accurate if the simulation is of the LES or DNS type, which

can more accurately account for the character of turbulent flows, such as the DNS simulation of a supersonic jet.

After carrying out such a simulation, what is called a "pseudo schlieren" image can be obtained, by transporting the pixel-by-pixel gradient of the schlieren image on the contour resulting from the DNS simulation, with the mention that when positioning the knife horizontally, the vertical gradients will be observed and vice versa.

The present paper describes in detail the advantages and disadvantages of several experimentally tested schlieren configurations. This experimental study of optical methods offers the reader the possibility to choose the use of the schlieren configuration suitable for any type of flow investigated, without the need for further modifications of the implemented system. This comparison results from using different setups to investigate the same phenomenon. The level of detail required for the study of certain parameters can only be guessed before performing a series of pre-experiments. This paper draws the limits on the parameters required to acquire schlieren images so that the obtained images are in good agreement with the studied parameter. For example, for schlieren images analyzed with SIV methods, the jet structure must be very well focused and the resolution must be high, so that the boundary between the elements to be tracked is very well defined and so that these elements have a relevant area (larger than 1 pixel) to provide the sample data necessary for the study to be physically meaningful. The reduction of the effects of natural convection is less important, since their speed is much lower than the phenomenon and can be extracted from the images with the help of several post-processing operations recommended for the Lagrangian tracking method, while for the kymograph method, they can be completely ignored, extracting the velocity curves for the central axis and for the jet elements, performed in an automatic process that involves selecting the curves with the lowest slope and ignoring them if they exceed a certain threshold. The color schlieren method requires the use of previously calibrated filters. Although the calibration process is very laborious for the schlieren method with the color filter, its response to the study of turbulent flows on portions of interest where the phenomenon shows less influence of the optical path integration phenomenon. Another advantage of the method is the possibility to perform a visual inspection before performing the experiments, regarding the color distribution present in the images. To implement this method it is necessary to choose an optical configuration that reduces the natural convection

in the schlieren image. Strong natural convection can generate elements confused with the elements of the studied phenomenon, and the transformation of the refractive index values into corresponding density values can vitiate the final result by amplifying the obtained density profile values. Since at the extremity of the studied phenomenon the density values are very close to the values found in the ambient environment, both the shape of the flow and the data provided by the method may be flawed.

The optical setup used in the experimental tests involving the use of the calibrated filter almost completely reduces the occurrence of natural convection, both by decreasing the exposure time and by ensuring adequate sensitivity of the schlieren system.

The performance of the optical setup of a schlieren system is analyzed by acquisition and recording equipment. These two pieces of equipment constitute the bridge between the experimental tests and the theoretical process (pre- and post-processing) necessary to obtain the data. The equipment used to capture schlieren images and the influence of their performance is highlighted during the evolutionary course of the present work and can be visually analyzed, based on the improvement of the quality characteristics of the images.

7. Original contributions

The original contributions made by this work can be divided into two categories: the global contribution, - representing how the present work can be described as a step forward, intended to push the barrier of current knowledge- , and the punctual contributions, representing the intermediate stages of the global contribution .

The global contribution of the thesis is represented by the validation of the general idea of improving the accuracy of the quantitative schlieren methods by automating the image processing process and by the experimental validation of some optical configurations that use original methods to create the framework required for the tests.

The point contributions are briefly listed below:

1. Realization of an image pre-processing application, with an intuitive and easy-to-use graphical interface, called PreQual, which contains the possibility of processing any types of schlieren images, its functions being generally valid for the mentioned visualization method. Applications

with graphical interfaces on image preprocessing dedicated to the schlieren method do not exist independently. These are only found embedded in block-type schlieren systems, delivered with the physical schlieren configuration.

2. Enriching the quantitative schlieren method by explaining a relatively simple method to calibrate a dual color filter with original distribution to obtain the desired flow parameters. The presented filter calibration system is an original image translation system, necessary to obtain the calibration curves.

3. Realization of data pre- and post-processing algorithms from schlieren images, embedded in the PostQ application, which represents the most complete data post-processing application, containing the possibility of adaptation to most existing quantitative methods.

4. Characterization of the velocity field of a turbulent round jet by applying 3 different SIV methods, on a unique set of images.

5. Significantly improving the accuracy of the SIV method by automating the Lagrangian tracking process.

6. Creation of experimental configurations dedicated to each applied schlieren method, with recommendations derived from the study of specialized literature, theoretical considerations and pre-experimental campaigns.

7. The creation of optical paths for the development of the U-type schlieren system, as a variation of the Z-type method, and the exposition of the advantages and disadvantages of this new type of configuration.

8. Comparison of the measurement accuracy of 3 different SIV techniques, on the same data set with default settings, under conditions of not optimizing the data to any of them.

9. Carrying out an in-depth study of the specialized literature and of the crucial characteristics of the optical systems necessary for the application of each quantitative schlieren method, in order to obtain optimal images.

10. Detailed study on the influence of the quality of schlieren images on the quantitative data resulting from post-processing.

8. Future work

Prospects for further development are reflected by the utility of the study in the context of increasing data processing power. The biggest disadvantage of schlieren methods was considered in the past to be the need to process each pixel individually. For this reason, other measurement methods were preferred, considered to be better balanced from the point of view of the time needed to evaluate the desired characteristics versus the error caused by their intrusive nature.

By making a parallel with the evolution of the PIV visualization method, it can be seen from the evolution of the latter, the fact that the increase in conventionally available computational power resulted in easier access to various post-processing applications and obtaining quantitative data. This necessary computational power is currently available on almost any type of data acquisition/processing system (laptop, etc.), the storage of files containing numerous sequences of schlieren images and their post-processing can be performed by many individual users. PIV viewing systems usually have their own software, made by the manufacturer. A trend of the emergence of post-processing applications dedicated to PIV images, in an "open-source" regime, is observed to be growing. These post-processing applications have incorporated in their recent versions real-time PIV modules, a concept that was considered impossible not long ago. The same upward trend in post-processing of schlieren images is anticipated to develop, caused by the current compaction capacity of schlieren systems, together with the simplification of calibration procedures and the emergence of fast data post-processing solutions.

The prospects of the current work assume the continuation of the development of the PreQual and PostQ applications and their introduction into predefined schlieren systems, the patenting of the source codes of the applications and of the physical solutions described, used in the calibration of the color filter.

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