

Investigation of the Accuracy of the Temperature Field Calculations with Forward Projected Background Oriented Schlieren

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ABSTRACT

This study involves the investigation of the accuracy of a Forward Projected Background Oriented Schlieren (FPBOS) setup for understanding spark ignition phenomenon in internal combustion engines. The experiment is setup with the goal of measuring the temperature of the volume heated by the spark in a J-gap spark plug. This work utilizes a calibration technique which uses a known density gradient (Helium jet) of varying thickness to calibrate the experimental setup used for measuring sparks. Helium jets of diameter ranging from 1.0 mm to 2.5 mm was used for the calibration since this is the expected thickness range of the heated volume to be measured. Further investigations were also performed for understanding the sensitivity of the measurement technique on the thickness of the density gradient used for calibration. In addition to this, investigations to understand the influence of the distance between the density gradient and the background pattern was also performed. This provided insight into how the movement of the spark along the electrode gap influences the accuracy of the measurement setup. This work reports crucial information on the accuracy of measurements obtained from a particular experimental setup and presents a methodology for estimating the accuracy of an FPBOS measurement setup.

1. Introduction

The use of renewable fuels such as hydrogen in internal combustion engines is gaining traction due to their potential to significantly reduce CO₂ emissions in the transport sector with relatively little effort, thanks to the mature technology and associated supply chain of internal combustion engines. Consequently, this is a field in which significant research is being conducted. Such development requires a deeper understanding of physical phenomena such as ignition inside these engines. This improves simulation models, contributing to faster development of such engines and helping to develop combustion strategies and improve individual components, such as prechamber ignition systems, to optimise efficiency and performance. Such improvements require simulation models that faithfully represent the physical phenomenon, which can only be validated

through suitable experimental methodologies. The focus of this work lies on the study of ignition phenomenon with the help of experiments with a goal of improving ignition simulation models.

Spark ignition and spark discharge are very heavily researched fields of science. Spark discharge by a normal induction coil ignition system in internal combustion engines show three phases - the breakdown phase, followed by the arc phase and the glow phase (R. Maly, 1984). Using a standard inductive coil ignition system, these phases last for nanoseconds, milliseconds and microseconds, respectively. The third phase is of the highest interest in the case of internal combustion engines due to the large duration and energy in this phase. In addition, the spark channel is considerably longer in these phases, increasing the volume inside the combustion chamber that could ignite the combustible mixture. This is especially true in the case of lean operation. The first two phases are characterized by high temperatures and presence of a large density of charged particles (ions and electrons). The glow phase is coldest among them with temperatures typically below 3500 K (R. Maly, 1984; R. R. Maly & Herweg, 2009).

The study of spark ignition includes those investigating the plasma itself using techniques like spectrometry (Michler et al., 2020; Kim et al., 2018), as well as heated volume surrounding the plasma investigated by means of interferometry (R. Maly & Vogel, 1976; Verhoeven, 2000). Synthetic schlieren techniques like Speckle Background Oriented Schlieren has also been used for investigating spark ignition (Michalski et al., 2018).

This study investigates the spark ignition phenomenon by utilizing a variation of the BOS technique (Kottakalam et al., 2024, 2025). This technique employ the projection of a background pattern onto the focus plane of the camera, which provided the opportunity to quantitatively evaluate the heat transfer from sparks even at high pressures with a relatively simple setup. Even though this was an improvement, determining the spark-generated density field from single camera images remained difficult. A calibration method using a known density gradient (1 mm helium jet) was introduced, which reduces errors from setup tolerances. However, this method relies on highly repeatable experiments—something hard to achieve due to spark movement in standard spark plug geometries. This spark movement changes the geometry, introducing uncertainty and errors in the calculated density fields. As a result, further study was needed to understand how geometric variations affect the density gradient calculations and how to minimize or estimate the spark movement-induced errors. Additionally, since the spark-generated density gradients can be thicker than 1 mm, the influence of the helium jet's thickness on calibration accuracy also needed to be examined. This defines the scope of the present work, which reports on further investigations aimed at improving the accuracy of the measurement technique through a refined calibration methodology.

Forward Projected Background Oriented Schlieren for measuring heat transferred from sparks

The Background Oriented Schlieren (BOS) technique uses the fact that a change in density leads to a change in the refractive index of a medium. Due to this change in refractive index, light passing through a volume with a different density to the surrounding medium (either due to a temperature difference or a change in the medium, e.g. helium in the surrounding air) gets refraction. This refraction is caused by a change in the density of the medium through which the light is passing and is termed a 'density gradient'. This means that when a pattern is observed through a density gradient, it is deformed due to the light rays being refracted. Background Oriented Schlieren employs algorithms (PIV, DIC, FCD, etc.) that compare images of patterns captured by cameras: one without any deformations, and one of the deformed pattern observed through the density gradient (Dalziel et al., 2000; Richard & Raffel, 2001; Raffel, 2015).

In the Forward projected background oriented schlieren technique, instead of a physical background pattern, the pattern is projected by means of a projector (Kottakalam et al., 2024, 2025). Similar technique has been presented in other studies as well (Leopold et al., 2012; Yamagishi et al., 2024; Sugisaki et al., 2022). The advantage of such a technique is that since it is not a physical pattern, it only requires optical access and does not influence the flow conditions in the measurement volume. In addition, the projector also makes the setup extremely flexible, enabling the variation of the pattern size and location of the pattern by adjusting the location of the lenses. A schematic of the measurement setup could be seen in Figure 1 with all the relevant information marked.

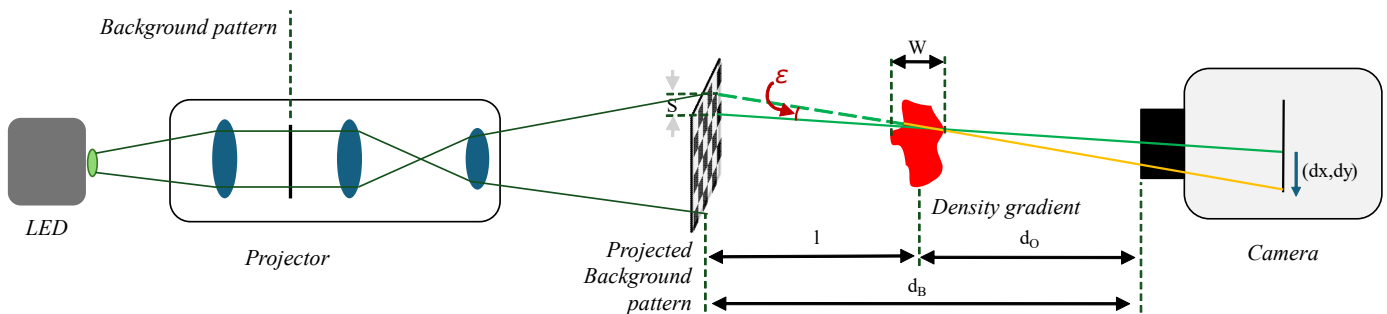


Figure 1. Schematic diagram of the FPBOS experimental setup

In addition to the visualization of the density gradients, the deformation or the deviations happening in the background pattern could be correlated to the density change or the refractive index change in the density gradient volume. Figure 1 depicts a schematic diagram of the FPBOS experimental setup along with the important geometric parameters required for the calculations. This is performed assuming several assumptions - the refraction happens in a particular plane instead of the entire volume. In reality, this happens not in a particular field, and instead along different

layers in the volume and at different planes in the line of sight of the camera. This works really well for conditions when the setup lies in the far field BOS setup. Under this situation, the thickness of the density gradient is negligible in comparison (at least 10 times smaller than the distance between the density gradient and the background pattern), which means that the refraction phenomenon is close to the assumption. However, the larger the thickness of the density gradient in comparison to the distance between the density gradient and background pattern, the lesser the agreement to the assumption. This falls in the near-field BOS, and a correction was proposed by van Hinsberg & Rösigen (2014). This, however, requires the information regarding the shape of the density gradient. Assuming symmetry, the thickness in the plane of observation can be considered as the thickness of the density gradient along the line of sight. Even this was difficult in the case of sparks due to the complex shapes and the subsequent difficulty in obtaining the thickness in a direction perpendicular to the line of sight. Therefore, the previous work (Kottakalam et al., 2024, 2025) tried to use one thickness of the density gradient and use it to calibrate the C -value instead of calculating it as per the work of van Hinsberg & Rösigen (2014) and equation 1 is the resulting modified equation showing the calibrated factor, C_{corr} .

$$\nabla^2 \rho = \frac{C_{corr}(K\rho_0 + 1)}{W(W + 2l)K} \nabla \cdot S \quad (1)$$

Equation 1 shows a Poisson equation which can be solved to obtain the density field. In this equation, the K is the Gladstone-Dale constant, ρ_0 is the ambient density, W is the thickness of the density gradient and l is the length between the density gradient and the background pattern. The term S is derived from the displacement obtained from the measurement.

In the previous study, the calibration factor, C_{corr} was obtained by using a density gradient of a known density and finding the value that leads to a density closest to the density of the medium. A Helium jet of a 1 mm thickness was used for calibration purposes, and the C_{corr} obtained was used for the calculation of the density field generated by sparks. However, the influence of the thickness of the density gradient used for the calibration was not analysed. This work presents a more comprehensive calibration methodology with further sensitivity analysis performed with the goal of providing a better understanding of the influence of various setup parameters on the calibration of the factor C_{corr} .

2. Experimental setup

The schematic diagram shown in Figure 1 depicts the equipment utilized, namely the LED (LPS 3 from iLA5150), the projector (achromatic lenses from Edmund Optics), and the camera (LaVision CX1-25), as well as the location of the density gradient (gas jet or spark). The timing control was performed by using the Programmable Timing Unit (PTU 11 external) from LaVision. The lens

used here is a Tokina AF 100 mm f/2,8 Macro AT-X lens, with all the experiments performed with f/11 aperture opening.

The helium gas jets are produced by a metal cap with a bored hole attached to a low-pressure (approx. 5.0 mbar relative pressure) helium gas pipe. The sparks are generated between the electrodes of an automotive J-gap spark plug with 0.7 mm electrode gap using a standard induction ignition coil. The geometric setup of the experiments was $d_B = 295.5$ mm and $l = 5.0$ mm. A checkerboard pattern was used as the background pattern of size 5×5 pixels. At the focus plane, each pixel corresponds to a .00784 mm. All the experiments were performed under ambient conditions.

For the calibration, the Gladstone Dale coefficient of the air is $0.000264 \text{ m}^3/\text{kg}$ and for Helium is $0.00019607 \text{ m}^3/\text{kg}$.

3. Calibration methodology and accuracy

The FPBOS technique utilizes a relatively simple setup to detect changes in the refractive index in a medium. The deviations or deformations to a background pattern observed by a camera through a density gradient can be calculated by different algorithms (here, Fast Chequerboard Demodulation was used (Wildeman, 2018)), and this is quantitative information regarding the change in refractive index of the density gradient as given by equation 1 (van Hinsberg & Rösigen, 2014; Kaneko et al., 2021). However, these calculations require the shape of the density gradient or the thickness, W , of the density gradient for each pixel in the view field. This is a significant challenge in the case of a spark and therefore, a calibration technique which utilizes a calibration factor (C_{corr} replacing C in equation 1) instead of the calculated factor was proposed in Kottakalam et al. (2024) and Kottakalam et al. (2025). In this method, instead, the maximum thickness of the density gradient was taken as W . The calibration factor, C_{corr} , was determined with a density gradient of a known density (helium jet) and this was used to estimate the temperature field generated by sparks. As part of this work, this calibration technique was further investigated to understand the influence of the thickness (W) of the known density gradient (helium jet) on the determination of the calibration factor, C_{corr} . Additionally, the distance between the density gradient and the background pattern (I) was varied to improve understanding of how sensitive the technique is to different parameters. This was then utilized to build a characteristic diagram, which improved reproducibility in the density calculations. This was also key in the development of automated scripts used for processing of large datasets of images from high-speed cameras.

A key change in the evaluation was that, rather than taking the maximum thickness of the density gradient, an average thickness was evaluated in this present work. This significantly improved the robustness of the technique. The images for the FPBOS measurement were captured at a frequency of 5 Hz. For each measurement, 50 images were captured, making the measurement duration 10 seconds. The valve for the helium jet was opened after the start of the measurement to ensure the

first few images of each measurement could be used as reference images.

The images with the gas jets were then processed with the FCD algorithm and the resulting displacement vector field in the x-direction was averaged for the calibration process. The calibration was performed by an automated Matlab script, which detects the average gas jet thickness from the maximum and minimum displacements in each image row. An example of the edges of the density gradient detected by the algorithm from the averaged displacement field in the x-direction can be seen in Figure 2. From this displacement gradient, the density gradient is obtained by solving the equation 1 by 5-point central difference scheme. On the left and right of the viewfield, a dirichlet boundary condition was applied, a zero gradient Newmann boundary condition was applied on the top and the bottom edge of the viewfield. Then, the script varies the C_{corr} value till a best match is obtained for the gas density. This was performed then for Helium jets of 4 different thicknesses and analysed.

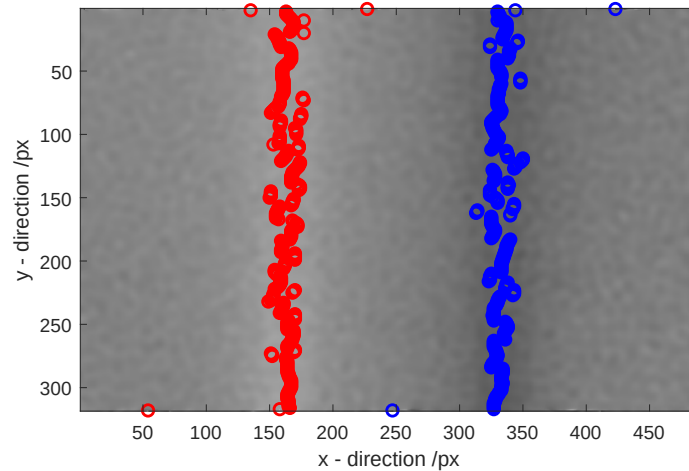


Figure 2. Displacement field magnitude obtained for the gas jet with row-wise maximum (red) and minimum (blue) displacements in x-direction

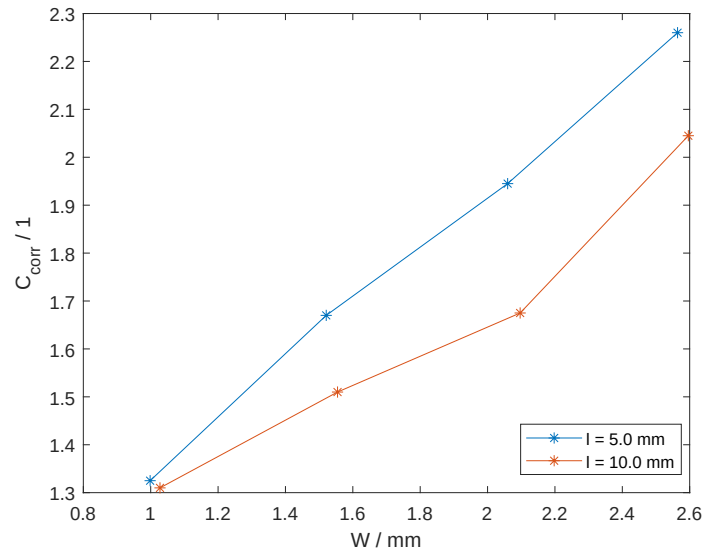


Figure 3. Characteristic diagram obtained for C_{corr} for different distances between the background pattern and the density gradients (l) with jet size variation

Figure 3 shows an example of such a characteristic diagram obtained from the aforementioned variations. It provides information regarding the sensitivity of factor C_{corr} to various parameters. It was found that for a particular thickness of the density gradient, the larger the distance between the density gradient and the background pattern (distance l in Figure 1), the smaller the error or correction required. Also, the larger the thickness of the density gradient for a particular distance l , the higher the correction factor. This was attributed to the thickness of the density gradient approaching the distance l . As a result, as can be seen from Figure 3, the slope of the two plots shows that the sensitivity of the correction factor C_{corr} is higher when the length/ distance l is smaller. From this calibration curve, a linear function was obtained for the C_{corr} calculation.

3.1. Influence of the calibration factor on the density calculations

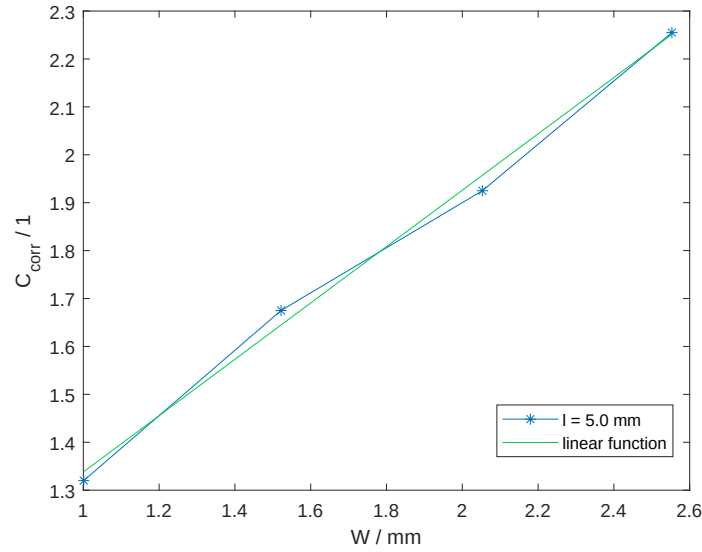


Figure 4. Linear function obtained for C_{corr} - for distance $l = 5$ mm

For accuracy estimates, this linear function was first used to obtain the C_{corr} for a gas jet of a given thickness. This was then compared to that obtained through the calibration. In addition, the resulting deviation in the density field detected was also taken in to account. Initially, this was done with a Helium jet with 1.3 mm diameter/thickness, which was not used for the generation of the linear function. It was seen that the C_{corr} obtained from the equation deviated by 0,0161 from the calibrated value of 1.545 leading to a corresponding deviation in the density calculation by -0.0112 kg/m^3 .

In addition to this, the same analysis was performed for Helium jets over the entire diameter range from 1 to 2.5 mm, to gain an understanding of the sensitivity of the measurement and calibration method to the density gradient thickness in the current experimental setup. Detailed information regarding the deviations can be seen in the Table 1. From this analysis, an average deviation in the density of Helium (0.166 kg/m^3) was calculated as 0.01374 kg/m^3 . This represents a 8.4% deviation from the reference density.

He jet diameter	1.0 mm	1.3 mm	1.5 mm	2.0 mm	2.5 mm
Z (mm)	1.00	1.32	1.52	2.06	2.57
C(calculated)	1.3369	1.5289	1.6453	1.9607	2.2613
C(calibrated)	1.32	1.545	1.67	1.945	2.26
$\delta\rho(\text{kg/m}^3)$	-0.0229	-0.0112	+0.0136	-0.0188	+0.0022

Table 1. Analysis of the accuracy of the linear function for C_{corr} compared to the reference density of Helium (0.166 kg/m^3)

3.2. Influence of the change in the location of the density gradient on the calculations

As mentioned previously, the spark moves along the electrode gap and therefore influences the accuracy of the density field measurement. For better understanding this, the Helium jet with 1.3 mm diameter was measured by varying the distance between the jet and the background pattern by upto ± 0.3 mm. This was performed to get the error in measurement that could happen due to the movement of the spark in between the electrodes. The central electrode of the J-gap spark plug used in this study has a thickness of 0.8 mm. The deviation was calculated relative to the density of the Helium jet of 0.166 kg/m^3 . The results from this test can be seen in Figure 5.

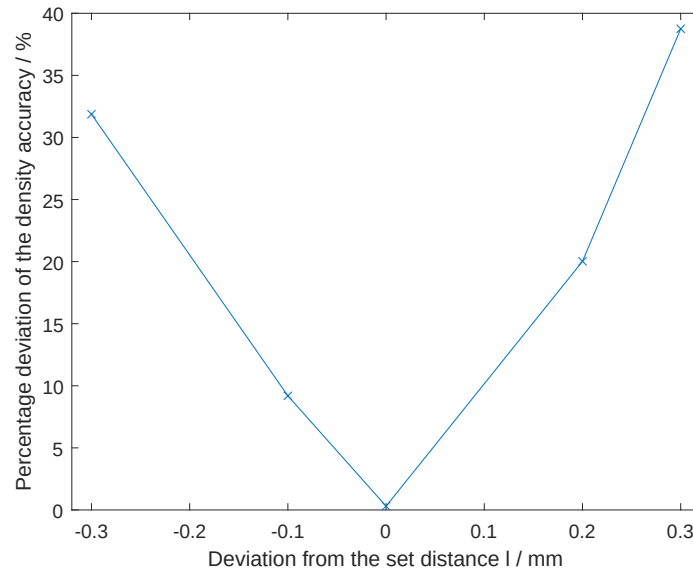


Figure 5. Relative change in the calculated density when the distance l deviates from the set distance (Reference density = 0.166 kg/m^3)

For the calculation, the C_{corr} for the 1.3 mm was initially calculated for the given setup. Then, measurements were done by varying the location of the Helium jet upto 0.3 mm in both directions. Following these measurements, the density gradient was calculated using the same parameters used for calculating the case with the correct distance. The resulting density gradient was then used for calculating the error of the experimental setup.

It can be seen from Figure 5 that the larger the distance from the set distance l , the larger the deviation. However, in the setup used for this study, it can be seen that the influence of the density gradient is significant and extreme caution need to be taken for accurate results. Nevertheless, this provides valuable information regarding the measurement accuracy if the range of movement of the spark is known.

4. Results

From the calibration curve obtained from section 3 and the same experimental setup, the density gradients generated by sparks in a J-gap spark plug was measured. Figure 6 shows the timeline of the experiment and it can be seen that the background taken for evaluation was illuminated by an LED pulse of 10 microseconds. The images were captured at a frequency of 5 Hz and the images were captured over a duration of 20 seconds. The first few images in this series were captured without a spark. The first image was taken as a reference. The images with a spark were first evaluated individually using the FCD algorithm, and then averaged to produce a good statistical displacement field.

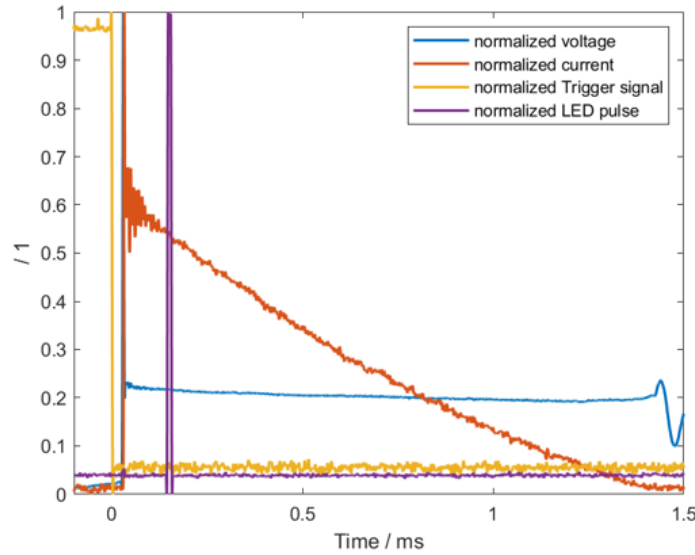


Figure 6. Timing plot for the spark observation

From this averaged density gradient field, an average thickness of the density gradient in between the electrodes were calculated using the same method mentioned in section 3. The calibration factor was obtained from the linear equation shown in Figure 3. A binary mask was used to remove the noise in the location of the electrodes and then, the poisson equation 1 was solved by applying dirichlet conditions on all the edges of the viewfield.

Figure 7 depicts the temperature field obtained for the measured sparks at 0.15 ms after the breakdown. The sparks were produced by an ignition coil dwell time of 1.2 ms. It can be seen that the temperature estimates seem plausible and within the expectations of the literature. It was found that the temperature distribution follows the same trend as detected in the previous works (Kottakalam et al., 2024, 2025). From the plot, it can be seen that the temperature is higher near the anode (lower electrode) than the cathode. It can also be seen that the temperature is the highest in the middle of the electrodes and gradually falls toward the electrodes. In addition it can be seen

that the density gradient is mostly symmetric along the x direction as well.

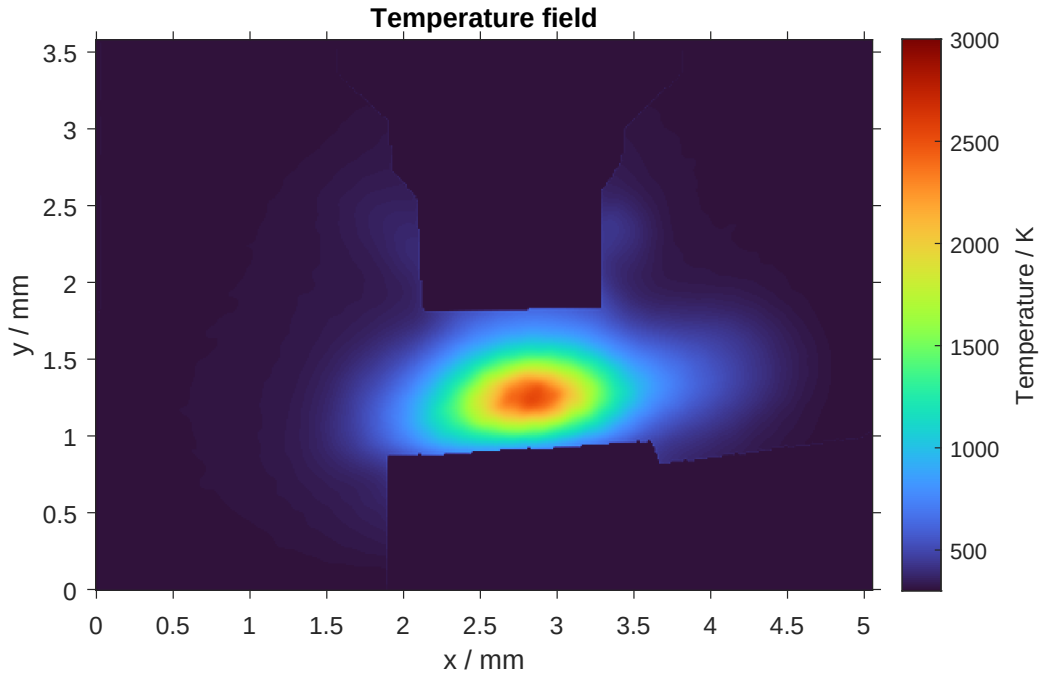


Figure 7. Temperature field calculated from the average displacement field from several sparks

From the analysis performed in section 3, the accuracy of the temperature estimation can be calculated. Taking the uncertainty in the calibration function for the C_{corr} as the only factor influencing the accuracy, taking the average deviation from table 1, the inaccuracy could be considered to be $\pm 0.0137 \text{ kg/m}^3$ leading to a relative accuracy of 8.4%. In addition to this, the movement of the density gradient for each cycle was calculated detecting the center of the density gradient for each individual sparks. The movement in the x-direction is taken to be similar to the movement in the line of sight. From the centre of the density gradient locations detected, a standard deviation value of 0.145 mm was obtained. From Figure 5, a deviation of 0.145 mm corresponds to an inaccuracy of 14.6 %. The combined accuracy is calculated by error propagation from these two uncertainties, i.e. $\sqrt{8.4^2 + 14.6^2}$ to be 16.8% of the measured density. Based on this, the accuracy of the measurement at different temperatures were calculated and has been tabulated in Table 2.

Measured Temperature (K)	Lower limit (K)	Upper limit (K)
3500	3022	4242
3000	2569	3607
2000	1717	2410
1000	856	1202

Table 2. Temperature calculation accuracy from the combined error

5. Conclusions

The main goal of this study was to provide an estimate of the accuracy of the temperature measurements utilizing the FPBOS technique. This study presents an improved calibration methodology for taking into consideration the change in thickness of the density gradient. Experiments showed that no two spark events are identical, primarily due to plasma movement along the electrode surface, which alters the effective geometry of the setup. A sensitivity study was performed to understand the influence of the movement of the density gradient on the measurement accuracy. From this, the deviation in the density gradient calculation was derived. Both of these deviations were used for the calculation of the combined error through error propagation and it was calculated to be 16.8% for the particular experimental setup used in this study. Therefore, this study presents insight into the influence of various experimental parameters on the measurement and provides methodologies for error estimation for a particular FPBOS experimental setup.

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Nomenclature

BOS	Background Oriented Schlieren
FPBOS	Forward Projected Background Oriented Schlieren
PIV	Particle Image Velocimetry
DIC	Digital Image Correlation
FCD	Fast Checkerboard Demodulation
d_0	Distance between density gradient and camera lens [mm]
d_B	Distance between background pattern and camera lens [mm]
l	Distance between density gradient and background pattern [mm]
W	Thickness of the density gradient [mm]
S	Displacement at the focus plane [mm]
ρ	Density [kg/m^3]
ρ_0	Ambient density [kg/m^3]
K	Gladstone-Dale constant [m^3/kg]

C_{corr} Calibration factor

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