# Visualization and diagnosis of hydrogen jet based on joint methods

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## ABSTRACT

Hydrogen energy has quietly become the key to dealing with various environmental problems and energy transformation. With the development of the hydrogen energy industry, safety problems caused by hydrogen leakage also occur continuously. It is particularly important to find a safe and reliable visualization technology to detect hydrogen leakage. Some issues about background oriented schlieren and laser beam profile deformation in visualizing and diagnosing flow fields are summed up and studied both theoretically and experimentally. The two optical methods are compared from two aspects of flow field structure visualization and parameter diagnosis. On this basis, the feasibility of combining the background oriented schlieren with the laser beam profile deformation method to visualize and diagnose the flow field is proposed, and an experimental device is established. In addition, the hydrogen flow field is selected as an empirical example. The experimental results show that the combination of background oriented schlieren and the laser beam profile deformation method may be a reasonable and feasible means for complex flow field structure visualization and parameter diagnosis.

**Keywords:** Hydrogen leakage, Visualization method, Background oriented schlieren, Joint monitoring

## 1. INTRODUCTION

With the continuous growth of world energy demand and the increasingly severe environmental pollution caused by fossil energy, the development and utilization of new energy has become the world's focus[1]. Hydrogen energy is a clean, efficient, and sustainable secondary energy that can be obtained in various ways. Hydrogen energy has quietly become the key to dealing with various environmental problems and energy transformation[2]. However, hydrogen is flammable and explosive, with low ignition energy, significant diffusion coefficient, and mechanical properties of biodegradable materials[3]. Hydrogen has potential leakage and explosion hazards in preparation, storage, transportation, filling, and use. Therefore, hydrogen safety is one of the essential prerequisites for the application and large-scale commercialization of hydrogen energy, which has attracted extensive attention worldwide. Hydrogen is colorless and odorless and difficult to detect after leakage[4]. If it leaks in a confined space, it is easy to gather, and there is a potential threat of fire and explosion accidents. According to the international hydrogen safety database, the number of safety accidents caused by hydrogen leakage is the highest[5]. Therefore, detecting hydrogen leakage quickly and effectively is a problem that many researchers and experts have been concerned about. There are several techniques to visualize the hydrogen jet. Han et al.[6] investigated the diffusion characteristics of hydrogen gas leaking from a high-pressure source through a small hole by irradiating a jet of $Al_2O_3$ powder doped with an Nd-YAG laser. Thawko et al.[7] studied the flow field of a pulse-started circular confined nitrogen jet. Vanselow et al.[8] evaluated the spatial distribution of quantitative

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measurement errors for inhomogeneous refractive index fields. Biswas et al.[9] used Schlieren Image Velocimetry (SIV) to study the flow field of axisymmetric turbulent helium jets. Breakey et al.[10] used the time-resolved particle image velocimetry (TRPIV) technique to study the time-space-resolved flow measurement of a free-jet aeroacoustic source. Hinsberg[11] investigated the full-field density information measurements of axisymmetric under expanded supersonic jets. Veser et al.[12] studied the horizontally-fixed hydrogen jet's concentration and flow velocity distribution. Kotchourko et al.[13] studied quantitative information on the concentration distribution of freely expanding vertical axisymmetric hydrogen jets. Tan et al.[14] combined the adaptive Fourier-Hankel(AFH) Abel algorithm to analyze the radial density distribution of axisymmetric jets. Deimling et al.[15] studied a series of hydrogen jet experiments using high-speed film photography technology, image processing technology, and background orientation technology. Miao et al.[16] summarized the optical sensing technology for hydrogen leakage detection. Roy et al.[17] used planar laser Raman imaging technology to measure the low-temperature hydrogen jet's concentration field and temperature field.

We found that for complex flow fields, a single method can not solve the problems of structural visualization and parameter diagnosis at the same time. Therefore, in the current situation, it may be a feasible method to realize the structure visualization and parameter diagnosis of complex flow fields by combining different techniques. Background oriented schlieren (BOS) has been widely used in the field of flow visualization because of its simple equipment, low cost, and the ability to measure the state parameters of the flow field quantitatively[18]. In addition, in our previous research, we found that when the laser beam passes the flow field to be measured, the density gradient on both sides of the gas jet acts as a lens, resulting in the deformation of the laser beam[19]. This paper introduces a method of visualizing a circular hydrogen jet by combining the contour deformation of a laser beam with BOS.

## 2. METHODOLOGY

### 2.1 Basic principle of BOS

BOS technology uses light deflection after passing through the flow field to reflect the refractive index change inside the flow field. To obtain the offset of light, first, take an image of the background lattice as the reference image without flow field interference and then take another image as the measurement image in the presence of flow field interference. Then PIV algorithm is used to extract the displacement of corresponding points in two background image sequences to obtain the deflection information of light. The experimental principle is shown in Figure 1.

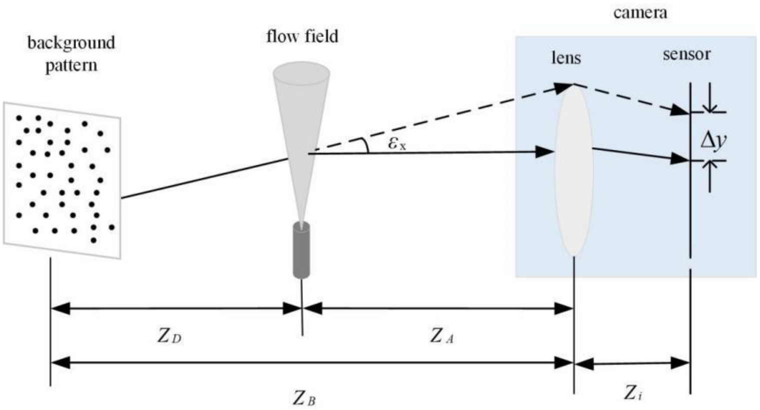


Figure1. Schematic of the BOS technique principle

In Figure 1 $Z_i$ is the image distance, $Z_B$ represents the distance between the background image and the camera, $Z_D$ represents the distance between the background image and the flow field area, $Z_A$ represents the distance between the camera and the flow field area, $\varepsilon_y$ is the deflection angle. The displacement of the ray in the y direction is $\Delta y$. The focal length of the camera lens is f. When the beam passes through the measured refractive index field, the glow will deflect due to the change in the refractive index of the medium. The following formula can express the deflection angle[20]:

$$\varepsilon_x = \frac{1}{n_0}\int \frac{\partial n}{\partial x} dz \tag{1}$$

$$\varepsilon_y = \frac{1}{n_0}\int \frac{\partial n}{\partial y} dz \tag{2}$$

Where $\varepsilon_x$ and $\varepsilon_y$ are the components of the deflection angle in the x direction and y direction respectively. $n_0$ is the refractive index of air, and n is the refractive index of the flow field through which the light passes. It can be seen from formula (1) and formula (2) that the deflection of light is only related to the refractive index gradient component perpendicular to the direction of light propagation. According to the geometric relationship shown in Figure 1, the displacement of the spot on the image plane can be obtained:

$$\Delta x = \left( \frac{Z_D}{Z_D + Z_A - f} \right) \frac{f}{n_0} \int \frac{\partial n}{\partial x} dz \tag{3}$$

$$\Delta y = \left( \frac{Z_D}{Z_D + Z_A - f} \right) \frac{f}{n_0} \int \frac{\partial n}{\partial y} dz \tag{4}$$

It can be seen from Eq. (3) to Eq. (4) that when $Z_A$, $Z_D$ and f are fixed, the displacement of the background lattice on the image is proportional to the integral of the refractive index gradient of the flow field along the ray propagation path. This shows that the displacement of the background point directly measured corresponds to the refractive index gradient of the flow field.

### 2.2 Laser beam profile deformation

Figure 2 shows our scheme for measuring the profile deformation of the hydrogen jet laser beam with a non-uniform density gradient. The He-Ne laser beam passes through a gas jet, which propagates perpendicular to the laser beam and has a density gradient in the horizontal direction. The hydrogen jet has a high gas density in the center and a low density when it moves radially outward. When the laser beam passes through the gas jet at the centerline, we find that the density gradient on both sides of the gas jet acts as a lens, leading to the deformation of the laser beam and enlarging the profile of the incident laser beam to a much larger spot. Our gas lens takes advantage of the fact that the outgoing beam is deformed relative to the incident laser beam. Due to the density gradient of the gas jet, the radial deformation of the laser beam profile is far more significant than the axial deformation, and the laser spot is elliptical. The propagation direction of the laser beam depends on the refractive index gradient; that is, the laser beam is biased towards the gas jet with higher density. For the laser beam passing through the air, the profile of the laser beam is circular, while for the laser beam passing through the gas jet, the shape of the laser beam is elliptical.

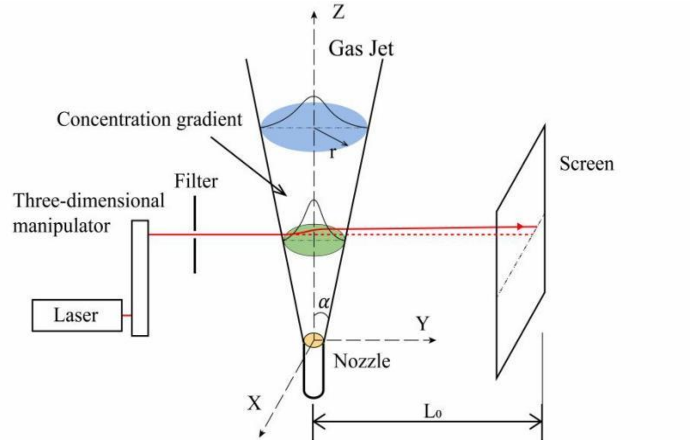


Figure2. Schematic diagram of laser beam deformation through fluid with non-uniform density gradient

## 3. EXPERIMENT

The method is applied to the experiment of a vertical circular hydrogen jet in the air. The hydrogen jet experimental system built in this experiment is shown in Figure 3. The testing equipment consists of two parts, and the gas path part consists of a 22L helium tank (UN1046, ISO11118), a proportional valve (2-WAY BALL VALVE), a high-pressure solenoid valve (SLZ), a gas mass flowmeter, and a pressure sensor (PT5403). The image acquisition and analysis includes background particle image board, LED array light source, Mercury MERCURY series industrial camera, etc. The experimental system built in this experiment can meet the control requirements for the gas path, realize the accurate real-time control of helium pressure in the gas path and the on-off function of the gas path, and install a replaceable nozzle at the end of the gas path. To simulate the low-pressure jet experiment, an air source with stable pressure and convenient adjustment is required. However, due to the unstable, flammable and explosive performance of hydrogen, helium was selected as the test gas mainly because of its high refractive index, which is vital for the sensitivity and resolution of BOS technology, and the density of helium and hydrogen is similar. Therefore, helium is used as the experimental gas instead of hydrogen in this experiment for safety.

Figure3. Hydrogen jet equipment

Figure 4 shows the schematic diagram of the experimental device integrating laser beam contour deformation and the BOS method to visualize and diagnose the hydrogen flow field. The He-Ne laser with a central wavelength of 632.8nm is used as the light source, and the maximum output power is 400 mW. After passing through the spatial filter and beam expander, the laser is divided into two beams by the beam splitter. A light beam diffuses through the ground glass after being reflected by the reflector. The speckle pattern generated by laser through ground glass is used to replace the background pattern in traditional BOS. Another ray of light directly passes through the flow field to observe the shape of the Gaussian spot. The collimating lens has a focal length of 300 mm and a diameter of 50 mm. The focal length and diameter of the imaging lens are 300 mm and 75 mm, respectively. The round nozzles with different diameters were used in the experiment, and the distance between the background pattern and the flow field to be measured and the CCD camera was changed. A total of 30 experiments were carried out. CCD camera provides $1920\times1200$ pixel image at the speed of 6000 frames/second, and the exposure time of the image is 60 milliseconds. At this speed, images can be recorded for up to 6 seconds.

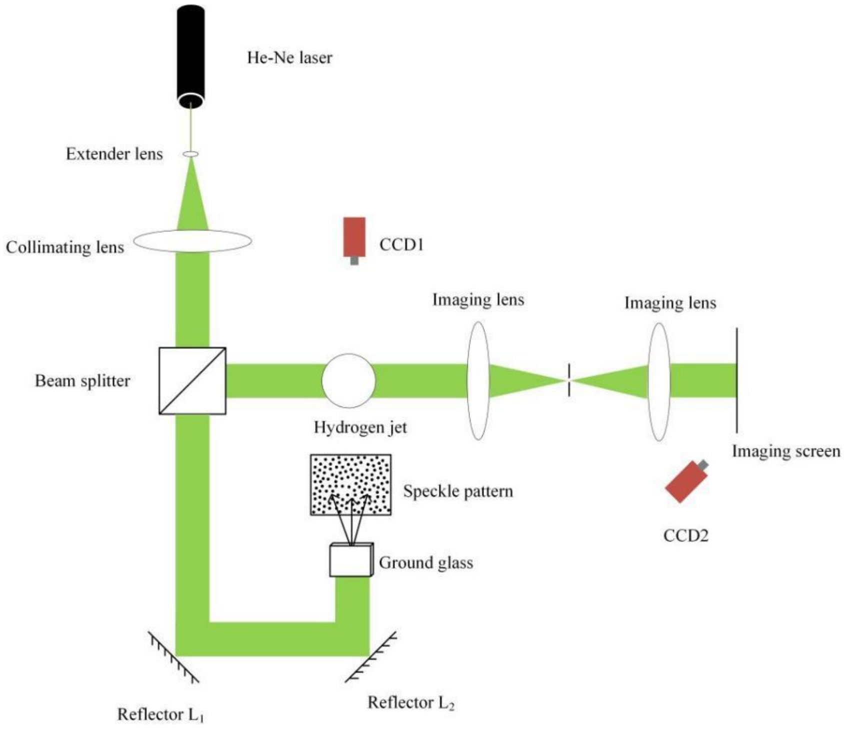
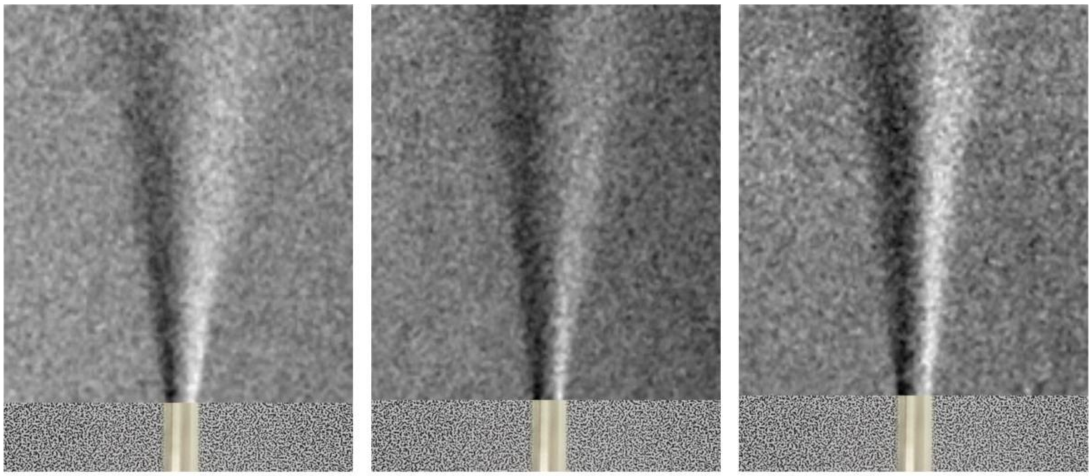


Figure4. The schematic diagram of the experimental device integrating laser beam contour deformation and BOS method to visualize and diagnose the hydrogen flow field

## 4. RESULTS AND DISCUSSION

In all experiments, helium was released through a nozzle with a diameter of 2mm. The investigation was conducted at a mass flow rate of about 2.2g/s and a temperature of about 293K. A total of 30 experiments were shown, and more than 300 images were obtained and processed. The three-dimensional manipulator adjusts the position between the He-Ne laser and the gas jet. The He Ne laser is moved horizontally by a three-dimensional manipulator so that it passes through several points on each cross-section line of the gas jet at equal intervals of 1.0 cm. For example, Figure 5 shows the BOS image sequence of the 2mm nozzle hydrogen jet with outlet pressures of 0.2MPa, 0.6MPa, and 1MPa obtained in our work. In addition, Figure 6 shows the laser beam profile on the screen without and with the hydrogen jet.



P=0.2MPa,α=24°

P=0.6MPa,α=23°

P=1MPa,α=22°

Fig. 5 BOS image of hydrogen jet under different outlet pressures

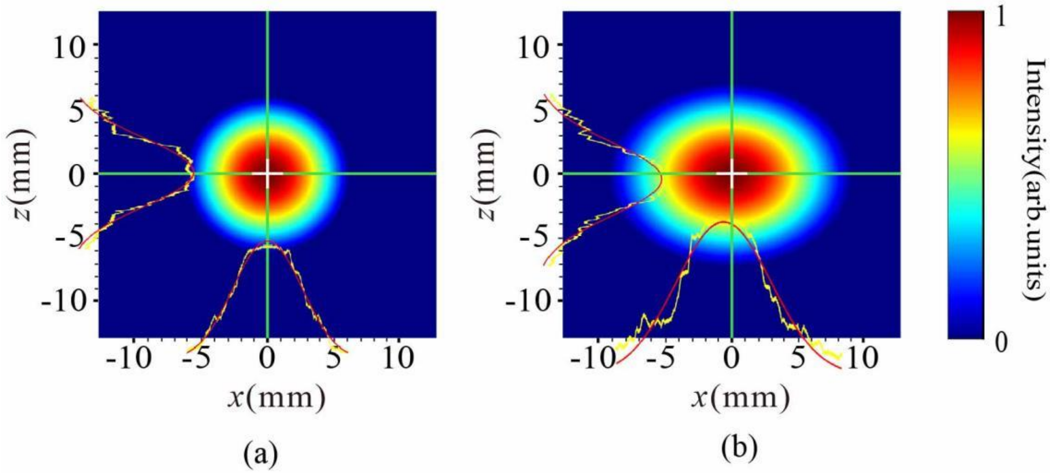


Fig. 6 Laser beam profile on the screen without and with hydrogen jet

Figure 5 shows that this improved BOS can well display the structure of the hydrogen jet. Under most pipe diameters and pressures, the average jet expansion angle is about 23° . This is very consistent with the predicted values of theoretical 21° ~30° [21]and experimental data 22° ~24° [22]. In addition, Figure 6 shows that when the laser beam passes through the gas jet at the centerline, we found that the density gradient on either side of the gas jet acted as a lens, inducing deformation of the laser beam and magnifying the incident laser beam profile to a much larger spot. Our gas lens uses the fact that this outgoing beam is deformed with respect to the incident laser beam. Because of the density gradient of the gas jet, the radial deformation of the laser beam profile is somewhat more significant than the axial component, and the laser spot is elliptical. The ovality of the laser spot depends on the refractive index. For the laser beam passing through the ambient air, the laser beam profile is circular. Whereas for the laser beam passing through the gas jet, the laser beam profile is elliptical.

## 5. CONCLUSION

In this paper, BOS and a laser beam profile deformation method are compared from two aspects of structure visualization and flow field parameter diagnosis. On this basis, the feasibility of combining BOS and a laser beam profile deformation method to visualize and diagnose the flow field is proposed, and an experimental device is established. The experimental results show that the combination of BOS and laser beam profile deformation method may be one of the reasonable means to display the flow field structure and diagnose the flow field parameters. In a word, this study is beneficial to the application of optical methods in flow visualization and parameter diagnosis.

## 6. Acknowledgement

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