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Application of Simultaneous PIV and PLIF in Study of Flow Field System

Ya'nan Gao[1], Qin Li[1,*], Yingda Huo[1], Ying Wang[1]

[1]*School of Chemical Equipment, Shenyang University of Technology, Liaoyang, Liaoning, China*
[*]*Corresponding author*

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Abstract: As a synchronous measurement technique for flow-field velocity and scalar measurements, PIV-PLIF (Particle Image Velocimetry-Planar Laser Induced Fluorescence) can provide detailed data support for complex flow with unsteady and strong three-dimensional space. The development and application of this technology in home and abroad in recent years are comprehensively reviewed. We first introduce the origin and working principle of particle image velocimetry technology and planar laser-induced fluorescence technology, and then discuss the current research status of PIV-PLIF, and then show the typical application of PIV-PLIF synchronous measurement method in engineering application. Finally, the application prospect and development trend of PIV-PLIF synchronous measurement technology are discussed. The combination of image velocimetry and planar laser-induced fluorescence is a trend of experimental hydrodynamics.

1. Introduction

Flow field measurement test provides strong support for the study of flow field structure analysis, flow law understanding, flow field control, etc. Therefore, flow field velocity measurement technology is not only directly related to the realization of internal visualization of fluid machinery, but also related to the design and optimization of fluid mechanical shape and internal structure [2]. In the 1920s, research has already started abroad for the study of flow-field velocimetry techniques. There are a variety of high-tech speed measurement technology now. Such as, Laser Doppler Velocimetry (LDV), hotline anemometer and other single-point measurement technology, Planar Laser Induced Fluorescence (PLIF), Laser Speckle Velocimetry (LSV), Particle Image Velocimetry (PIV), and other non-contact two-dimensional surface measurement techniques. There has even been Stereo Particle Image Velocimetry (SPIV) and 3-dimensional Laser Induced Fluorescence (3DLIF). And found in many literature both PIF and PLIF can be used to measure the fluid flow space velocity field and scalar field, the simultaneous measurement technology made outstanding contributions to many flow field experiment, not only can quantitatively flow field on the time resolution of flow field evolution, can also qualitatively display the flow field structure, to understand the flow mechanism and promote model development played a huge role in promoting.

Based on the current research situation at home and abroad, it is found that there are many studies on PIV and PLIF measurement technology, but some of them do not realize the real synchronous measurement [3], and the existing foreign studies do not elaborate on the synchronous measurement method itself and the data processing method of obtaining turbulence flux. This paper introduces PIV and PLIF respectively from the origin, measurement principle and their mature application, focuses on the research progress of PIV-PLIF synchronous measurement technology, summarizes the typical application of this technology at home and abroad, shows the advantages of PIV-PLIF synchronous measurement technology in complex flow field testing, combined with the existing image processing technology, applies pattern recognition technology to process flow field test images, and analyzes the development trend of PIV-PLIF synchronous measurement from the aspects of synchronous measurement method and data processing means.

2. Development and Current Status of PIV

2.1 Origin of PIV

PIV is widely used in a flow field velocity technology, which is a transient, multipoint, no contact laser hydrodynamic velocity method developed in the late 1970s. PIV has been continuously improved and developed in recent decades [1]. It is an interdisciplinary speed measurement method developed by solid mechanical speckle method [4], which integrates laser, digital signal processing, image graphics processing, computer, modern optical application and microelectronics technology.

In the history of flow field measurement, it is mainly attributed to the non-contact fine measurement named the PIV proposed by Adrian[5] in 1984. In 1992, Ronald J Adrian[6] realized the particle imaging technology of fluid mechanics, which is a great scientific progress in the fluid field.

2.2 Principle of PIV

2.2.1 Composition of PIV

A complete PIV system includes light source system [7] (dual-cavity pulse laser, guide arm and chip light source lens group), image acquisition system (high frame CCD camera, 64-bit dedicated high-speed image data acquisition board), control coordination system (synchronizer), and dedicated PIV image data processing and flow field display system (Insight software package and its external interface) (Figure 1) [8].

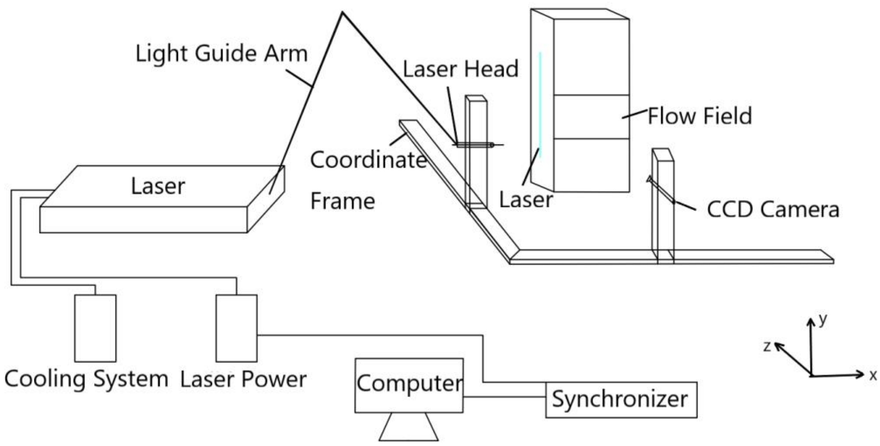

Figure 1: Schematic representation of the PIV constituent structure [8]

2.2.2 Experimental Principles of PIV

The principle of PIV test is to transmit a laser in the measured flow field filled with uniform tracer particles and use a laser light source to form a cylindrical lens; the light source illuminthe flow field with tracer particles and performs optical imaging by the image acquisition device to record the movement of particles in the flow field. Finally, processing and analyzing the acquired images by a computer and various image processing algorithms can obtain the flow information [1] of the flow field to be measured, as shown in Figure 2. In Figure, Δt is the time variable, ΔX is the displacement distance of the particle, l1 and l2 are any 2 images in the test, S is the object distance during optical imaging, and S' is the image distance during optical imaging. The d1A is the side length of a pixel.

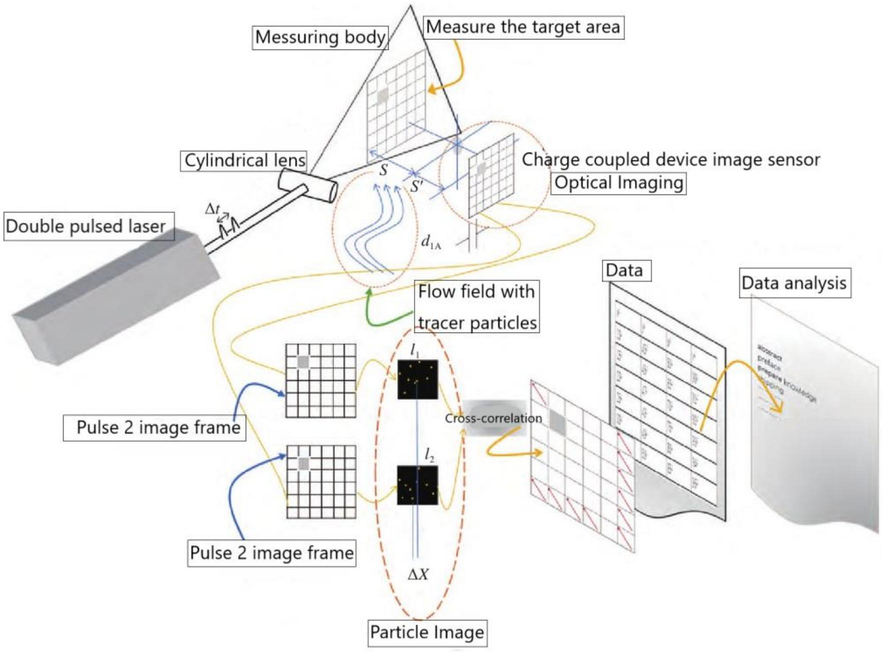

Figure 2: Principle of PIV [1]

3. Development and Current Status of PLIF

3.1 Origin of PLIF

Laser laser-induced fluorescence (LIF) technology is a new flow display and measurement method, which belongs to the non-interventional laser spectroscopy diagnostic technology. The experimental method can obtain two-dimensional or three-dimensional spatial distribution information, and make quantitative measurements combined with image processing techniques, including concentration field, temperature field, pressure field, and velocity field. It was first used by for the detection of the intermediate component of the combustion field by Kychakoff et al[9]. The technique emits photons to the flow field to be measured, and the spontaneous radiated signal is received by the imaging device.

The technique originated in the mid-1970s [10] for mixed flow display of shear layers. After years of development, from gas to water body, from qualitative to quantitative, from line measurement to surface measurement and other aspects have been continuously improved and improved. Since the 1980s, the rapid development of CCD camera technology and image processing technology has enabled LIF technology to carry out accurate quantitative measurement, and improve its measurement accuracy. So far, the most commonly used technology is the plane LIF technology. It uses the sheet light source excitation to measure the fluorescence of water, according to the fluorescence intensity and concentration or temperature, can obtain two-dimensional concentration field or temperature field.

3.2 Principle of PLIF

3.2.1 Composition of PLIF

The basic composition of the planar laser-induced fluorescence system (as shown in Figure 1) consists of light source system (laser, chip light source lens group, light guide arm), imaging system (lens, filter, CCD camera), and timing synchronization controller. The composition is basically the same as the PIV system, and the difference is that the stop filter is placed in front of the CCD lens. For the more professional function of the system, also include a flat flame furnace, spectrometer, etc. PLIF expands the laser into sheet laser through optical devices such as semi-cylindrical mirror, so that the high-speed camera can capture the fluorescence information in the two-dimensional laser plane, and realize the quantitative measurement of [11] of scalar fields such as concentration and temperature in solution. The high-speed image acquisition system based on PLIF includes a high-speed camera, a laser, and a fluorescent dye. Different fluorescent dyes need to be matched with different lasers to produce fluorescence, and the better performance of the high-speed camera is the guarantee to capture the higher quality of the fluorescence images of the liquid film.

3.2.2 Experimental Principles of PIV

The experimental principle of PLIF is that in the laser illumination flow field, the fluorescence tracer absorbs energy and emits long-wave light, and the intensity information is obtained by placing a cutoff filter in front of the PIV camera. The detection principle is shown in Figure 3 [12], the fluorescence of this system is related on energy and concentration/temperature, and quantitative information can be calculated. The trace components in the environment to be measured transition to the high energy state under the incident laser and resonate with the wavelength of the incident light. This can improve the ideal efficiency of cloth aggregation in the high-energy state, thus obtaining a high-intensity fluorescence signal. Some of the particles fall back from the excited high energy state to different low energy states and radiate fluorescence bands composed of different wavelengths, and the flow field is visualized by total fluorescence intensity measurement.

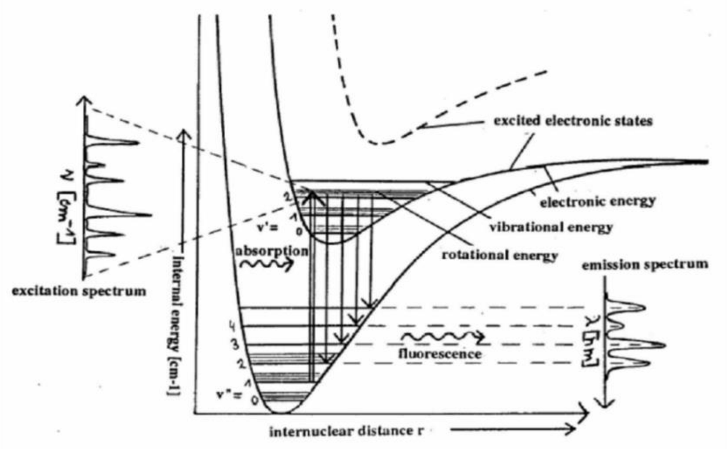

Figure 3: Detection of the Schematic [12]

4. Progress in the Simultaneous Measurement of PIV-PLIF

PIV and PLIF, the former focuses on measuring the flow field speed, while the latter focuses on measuring the scalar field (temperature, concentration, etc.). Although PIV can also be used to measure the concentration, the accuracy is not more accurate as PLIF technology, and the application of both is the flow field, which provides a prerequisite for the study of synchronous measurement technology. In the traditional synchronous measurement of flow field system, scholars at home and abroad have studied the PIV-PLIF synchronous measurement technology from the aspects of experimental application, test bench design and measurement methods.

4.1 Synchronous Measurements in the Combustion Field

In the innovative design of combustion field experiments, Petersson P et al. [13] proposed experiments with simultaneous measurement of PIV and multi-lens OH-PLIF, filtered Rayleigh temperature measurement and simultaneous measurement of multi-lens OH-PLIF and SPIV. The principle of this setup is shown in Figure 4, where two separate laser systems are used to measure PIV-PLIF simultaneously, and the backpropagating laser beam forms overlapping sheets that illuminate the flat area of the flame and pass through the vertical center line of the burner.

To study the feasibility of simultaneous measurement of multi-kHz rate PIV/OH-PLIF, Boxx I, Chterev I, and Liu L proposed [14-16] the hypothesis and realized the measurement in the study. Yamashita H, Ccacya R, Yamamoto K and other scholars [17-19] measured OH-PLIF/PIV on the flow field and flame structure, the multi-jet configuration of the turbulent flow field, and the turbulent premixed flame structure and flow field. Weinkauff J et al [20] combines acetone PLIF and SPIV to introduce an experimental study of the flame propagation through partial premixed flow, measuring the number of mixture parts, the flow field and the flame position.

In the experiment, Mao Runze et al. [21] used the flame multi-field information based on premixed CH4/H2 cyclone blunt body flame to represent the wide range of hydrogen doped ratio (0%~80%), and used OH-PLIF and PIV measurement technology to obtain the structure information and flow field information of the flame under different hydrogen doped ratios.

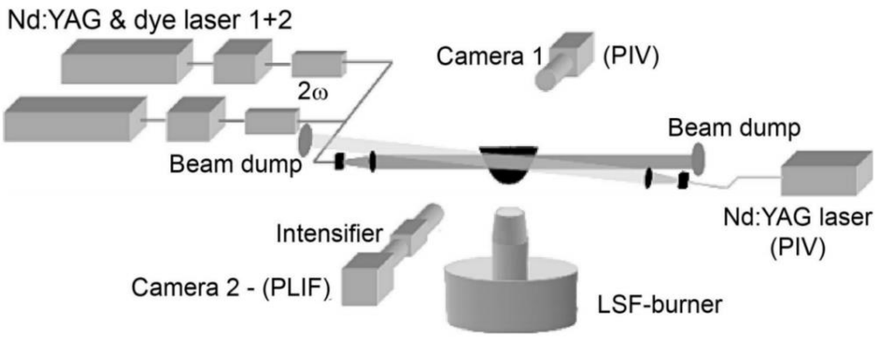

Figure 4: A Schematic representation of the experimental setup for the simultaneous measurement of PIV-OH-PLIF [13]

4.2 Synchronous Measurements in a Water-Body Scalar Field

In terms of optimizing synchronization measurement techniques, Klinner J et al. [22] provided the setup, data evaluation, and accuracy estimates of PLIF-PIV measurements. Milton-Mcgurk L et al. [23] introduced a PLIF experiment and image processing procedure that consider the power and beam profile pulse changes of Nd: YAG laser, which can reduce the measurement error of scalar concentration. See Figure 5 for the schematic diagram of the experimental test part. Mishra H et al.

[24] performed the simultaneous 2D-2C PIV and PLIF measurements to eliminate the uncertainty caused by optical distortions.

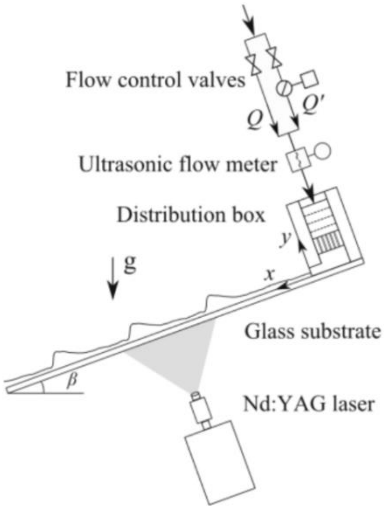

Figure 5: A Schematic diagram of the experimental trial section of Charogiannis A [30]

Xue X, Stamatova L, Wang, and other scholars [25-27] have studied PIV-PLIF synchronization measurement to study the rate variation of the flow field, and the transverse jet flow field characteristics of different sizes under different velocity ratio, the scalar field concentration distribution and observed the formation and fragmentation position of the turbulent structure. Zhiyuan Li et al. [28] used PLIF technique to study the influence of Reynolds parameters such as Reynolds number and blade phase Angle on the mixing characteristics during blade starting and operation, and tested the typical flow field characteristics using PIV technology.

In the flow properties study, Sancho I et al. [29] used PIV-PLIF to verify that the velocity and scalar field at the vortex appearance are very similar to the velocity profile of the laminar flow field at Re=1500. Charogiannis A et al. [30] for PIV-PLIF synchronization measurements observed a linear variance of film thickness for the mean and fluctuating components. Huang Fenglei [31] used PIV-PLIF technology to obtain the velocity and concentration field in the mixing process of intersoluble fluids of Newton system, and studied the influence of density difference and viscosity on the mixing process of two intersoluble fluids in the square cavity. Lacassagne T et al. [32] used SPIV and PLIF, respectively, to measure the local liquid phase velocity and dissolved gas concentration field to study turbulent mass transfer and mixing in a weak shear thinning fluid, compared with the Newtonian, water situation.

4.3 Synchronous measurements in the other fields

Compared with the application of flow field —— combustion field, water scalar field, gas-solid particles mixed flow field —— sand field, etc., have some difficulty in research. Yang et al. [33] in sand flow two phase velocity field of PIV-PLIF measurement study, combined with particle image velocity technology and plane laser induced fluorescence method, the velocity field, the experimental device is shown in Figure 6.

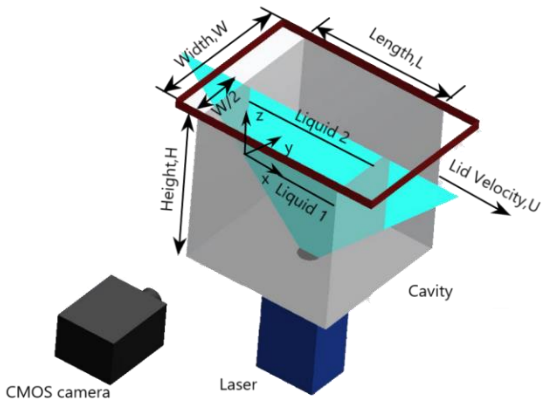

Figure 6: Schematic diagram of the experimental device, coordinate system and shooting area (red rectangle) [33]

In Min Seop Song [34], the turbulence intensity, pressure drop and local velocity field in the 19-needle beam wrapped in the sodium rapid reactor (SFR) line, and compared with the CFD simulation based on the Reynolds average Navier-Stokes equation (RANS). It shows that the computational fluid dynamics simulation results are in good agreement with the PIV measurement in specific flow characteristics such as vortex structure, vortex flow, and flow velocity direction change.

5. Trends in Simultaneous PIV-PLIF Measurements

In order to obtain flow field information more accurately, efficiently and intelligently and accurately, PIV-PLIF technology can serve more complex flow field conditions better, and the hardware system, image processing technology, and the application in flow field test still need to be improved. The flow field test experiment is influenced by many factors, such as tracer particles, device layout and image processing algorithm. Especially in some special and complex test scenarios (such as turbulence, multi-phase flow and microscale flow, etc.), the measurement accuracy is difficult to meet the requirements. So it is a problem to improving the performance of hardware equipment that must be overcome.

At present, the domestic and foreign in the hardware system, the stereo PIV technology, the holographic PIV technology, PIV technology and micro PIV technology, PLIF technology, 3 DLIF technology, the future development trend of hardware system should be on the basis of guarantee timing measurement, vigorously develop can obtain high resolution large range of spatial flow field information system, to extend the image acquisition of spatial resolution and spatial scale level.

5.1 The ects of tracer particles

Trtracer particle is a kind of applied substance that can follow the fluid movement and show the phenomenon of fluid flow. Because of its strong following and optical characteristics, it provides great convenience for researchers to study the flow field characteristics. Common tracer particle [35-36] are shown in Table 1.

The existing tracer methods: solid state tracer, liquid tracer, and other tracer methods have their own advantages and disadvantages. For example, the solid-state tracer method uses hollow glass beads, which can be combined with PIV technology to observe the fluid flow velocity distribution. Another example, the selection of sodium powder as a tracer material, combined with PLIF technology, can observe the relevant state of the combustion field. Therefore, when selecting the tracer particles, theoretical calculations and experiments are also needed to obtain the best test results.

Table 1: Tracer particles commonly used in the flow field

Flow field type	The type of tracer particle	Matter	Average diameter(μm)
Liquid flow field	Solid	polystyrene	10-100
		aluminite powder	2-7
		glass drops	10-100
		Synthetic cotton particles	10-500
	Fluid	All kinds of oil	50-500
	Gas	Oxygen bubble	50-1000
Gas flow field	Solid	polystyrene	0.5-10
		aluminite powder	2-7
		powdered magnesium	2-5
		glass drops	30-100
		Synthetic cotton particles	10-500
		titanium dioxide	5-20
	Fluid	All kinds of oil	0.5-10
	vapour	Oxygen bubble	<1

In addition, in different ways, adding tracer particles can also affect the experimental results. Qiu Yilong et al.[37] studied the addition method of tracer particles, and obtained the scheme of filling particles in bypass pipeline through numerical simulation, it showed that the concentration distribution quality of particles in this way was better than other methods. Then, the results of the numerical simulation are accurate through examination to verify.

When studying the tracking properties of tracer particles in PIV measurements in supersonic flows, Fang C et al. [38] also found that the seeding system enables tracer well-controlled and reproducible dispersion of the particles under storage and humidity.

Therefore, this four-pass seeding can enable the tracer particles to be more uniform and randomly obtained the real flow characteristics of the reaction flow field.

5.2 The Influence of the Camera Layout

In the PIV-PLIF synchronous measurement, the construction of the experimental platform is also a key link, and in addition to the powerful computer processor, laser head, camera and other important equipment, the camera layout is also an important step that cannot be ignored. According to the comprehensive reading literature, most of the experiments were made by purchasing experimental tables customized by merchants and directly designed and produced by merchants. However, dating back to 2006, Chen Zhao and others of Chongqing University in 2006, they found the key influencing factor of camera layout when studying the oxidation ditch model.

Literature [41] simulates the principle of binocular ranging of human eyes. It uses two cameras into a certain Angle to obtain the particle images, and then the velocity component can be calculated by processing the particle images according to the geometric imaging relationship. At present, the common camera layouts are: lens translation (Len Translation) and lens tilt (Angular Len Displacement). As shown in Figure 7(a), the advantage of the lens translation method is that the optical magnification is constant, but the camera common field of view is limited. The lens tilt method (shown in Figure 7(b)) increases the common field of view range, especially the camera layout meeting Schemiflug conditions, and is currently used by most commercial PIV systems. According to the Mie scattering theory, generally, the forward scattered light of particles above the order of micrometers is stronger than the lateral and backward light intensity. In addition to the mode of the camera on the same side of the light source, when conditions permit, the scheme of the camera on both sides of the light source (as shown in Figure 7(c)) can be used to obtain greater scattered light intensity.

The appropriateness of the camera layout directly affects the accuracy of the measurement results. Therefore, the best scheme of the camera layout is gradually obtained through theoretical calculation-simulation-experiment, which is the direct factor affecting the synchronous measurement results and the controllable factor.

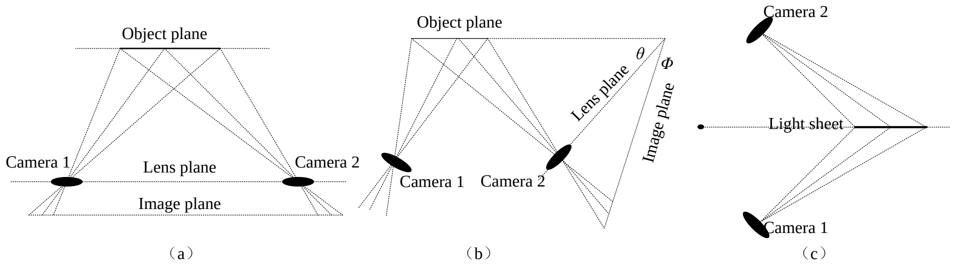

Figure 7: Camera layout of PIV [39]

5.3 The impact of image processing techniques

In terms of image processing technology, since the advent of PIV technology in 1986 and LIF technology in the 1970s, image processing technology has emerged in endlessly, such as Young's stripe method, self-correlation/cross-correlation algorithm, average correlation technology, image overlap technology, least squares (LSM) algorithm, mirror exchange method, etc., have been applied successively.

In recent years, the fast weight calculation method —— Forward Projection Area, Gaussian Radial Basis Function Interpolation and Cross-Correlation Optical Flow Algorithm, and Deconvolution Reconstruction Algorithm for Light Field μPIV have also been developed. It can be seen that the combination of artificial intelligence and PIV-PLIF technology is still a field worth exploring, which can solve the complex problem of the flow field in many fields. Therefore, it can also be proposed to improve the PIV-PLIF technology with Fuzzy Identification Algorithm.

As early as 2000, a scholar [46] proposed the fuzzy clustering identification method of non-identified PIV images, and CAI Yi et al [45] proposed the use of fuzzy recognition algorithm to identify the particle flow process, and now this algorithm has not been studied. However, for the application of PIV-PLIF synchronization measurement, due to the uncertainty of the flow field, there are many unknown situations, and the captured flow field characteristic information is characterized by things or phenomena, so the fuzzy recognition algorithm is more advanced and is more worthy of research in the future[40].

6. Conclusion

PIV-PLIF synchronous measurement technology, which can obtain low interference and small error measurement data in the unfixed complex flow field, has good development potential and broad market application prospect.

At present, the synchronous measurement mechanism of PIV-PLIF has not been truly studied in domestic research, and the application of PIV-PLIF[42] technology in the industry is still in the preliminary stage, which undoubtedly limits the broader development of this technology. The research shows that the tracer particles, hardware system, experimental design scheme and image processing technology are all the research directions to improve the measurement accuracy. In terms of the hardware system of laser fluid dynamic speed measurement method, the technical conditions of image acquisition system and lighting system have been relatively mature, but the cost is high, which makes it difficult for higher performance system to be widely used, which needs to reduce the cost from the technical level and design targeted PIV-PLIF synchronous measurement technology system[43].

Therefore, the development of low-cost PIV-PLIF synchronous measurement system and improved measurement accuracy is further development. In addition, there are relatively many studies on common flow fields such as combustion and water bodies, but the application of this technology is still underdeveloped in areas with low visibility, such as wind, sand and soil. After the technology reaches a certain stage, theoretically, other techniques can be added to make it become a complete measurement system. For example, in the cavitation impact flow field of the collision under given boundary conditions, this technology is used to observe the entire collision process, and analyzed the motion trajectory and distribution of the particles in the impact area, so then to optimize the nozzle structure and impact model. Therefore, studying the simultaneous measurement technology of PIV-PLIF is very important[44].

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