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A REVIEW OF PARTICLE IMAGE VELOCIMETRY TECHNIQUES

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Abstract. *Particle Image Velocimetry – PIV appeared approximately 40 years ago and figure as one of the most important achievements of modern experimental fluid mechanics. It has become an essential measurement procedure in fluid dynamics applied in research institutes, laboratories, large automotive and aerospace industries, it is possible to measure and evaluate an entire field of motion in different fluids and flows. Basically the technique consists in measuring the displacement of the fluid over a certain time interval, the experimental concept of the PIV uses tracer particles added to the flow and homogeneously distributed, which can be illuminated by a planar multipulsed laser obtained by an optical combination of mirrors, and a high speed camera controlled by a synchronizing trigger system combined with the laser, so the camera captures two consecutive images in a small time difference, and these images are processed and treated statistically to present the results. The diversity of equipment and practical applications for the PIV system requires a study of the technique and processing methods, aiming at greater efficiency in obtaining qualitative flow data, as well as the quantitative analysis of the velocity distribution of a flow with small rates measurement uncertainty, which can be redundantly validated with Computational Fluid Dynamics - CFD simulations. This literature review research approach is carried out in the comparative analysis of different experimental methods and procedures used for performing PIV, analyzing about 30 to 40 scientific articles published between the years 2001 to 2021. With the research it is possible to have a global view of wind tunnels, its basic characteristics of dimensions, types of open or closed circuits and maximum flow speed, and mainly the comparison between instruments and equipment needed for PIV, among them: high speed cameras, lasers and particle feeder. As a result of the study, it will be possible to characterize instruments, equipment, types and dimensions of tracer particles, image processing techniques, in addition to the advantages and limitations of the procedure. With the comparative analysis between experiments and methods used, it is possible to direct the specification of equipment and materials used in the technique, in addition to contribute with spreading knowledge for the method, which is in wide growth and possibilities for the rise of scientific knowledge in the Fluid Dynamics area.*

Keywords: *fluid dynamics, speed field, particle image velocimetry, flow data, image processing.*

1. INTRODUCTION

The study of the effects of forces in fluids called Fluid Mechanics originated in the years 287 BC by the scientist Archimedes, and over time several scientists such as Leonardo da Vinci, Galileo Galilei, Evangelista Torricelli, Blaise Pascal, Isaac Newton, Daniel Bernoulli, Osborne Reynolds, among others, left their significant contributions with studies and theories for the development and improvement of phenomena in fluid flow. This area of study in physics can be divided into two parts, one of which is hydrostatics, which studies the effects of a fluid in static equilibrium, and in hydrodynamics, also called fluid dynamics, which addresses the properties of fluid movement. Among the characteristics and properties of a flow, the study of velocimetry is of vital importance for the characterization and knowledge of the effects of this movement.

According to Xiaodong *et al.* (2014) velocimetry can be divided into point and global. Among the punctual techniques include all of Pitot, and rotary vane anemometry, which are based on the principle of pressure differential; hot wire anemometry, hot film anemometry and hot sphere anemometry based on heat transfer principles; ultrasonic anemometry (UA) based on the acoustic principle; and laser doppler velocimetry (LDV) based on the principles of doppler shift. Global techniques primarily include particle image velocimetry (PIV), particle tracking velocimetry (PTV) and particle shadow velocimetry (PSV), all of which are based on optical principles. However, it is possible to highlight the advantage of optical techniques with the possible measurement of a velocity field in a given region and not just a point measurement. Despite the similarity of measurements using optical resources, the PTV and PSV techniques are not the object of this study, and can be better described by Dracos (1996) and Sijie *et al.* (2015).

Among the characteristics of the techniques used, it is possible to characterize as non-intrusive the spot measurement by laser doppler velocimetry (LDV), and in the global measurement all the PIV, PTV, PSV techniques based on optical principles, thus preserving the original characteristics of the flow to be studied. Specifically, it is proposed to approach the study of the characteristics and possible configurations of the particle image velocimetry (PIV) technique applied in wind tunnels, through a literary survey of approximately 30 scientific articles as a theoretical reference.

The next sections are organized as follows: Section 2 deals with a review of the literature on the PIV, section 3 deals with the methodology used in the study carried out, section 4 presents a comparative analysis of the experiments carried out based on the theoretical framework, and finally section 5 presents the conclusion and section 6 the Bibliographical References.

2. PARTICLE IMAGE VELOCIMETRY (PIV)

Historically, an experiment created by the scientist Ludwig Prandtl in 1904 analyzed the dynamics of fluids with the creation of an apparatus by recirculating a flow of water added with mica particles visible to the human eye, in this way it was possible to add two-dimensional structures such as cylinders, prisms and wings mounted vertically in the flow channel, allowing the visualization and extraction of qualitative information regarding the experiment. However, in the Prandtl technique it was not possible to obtain quantitative data (Raffel *et al*., 2007).

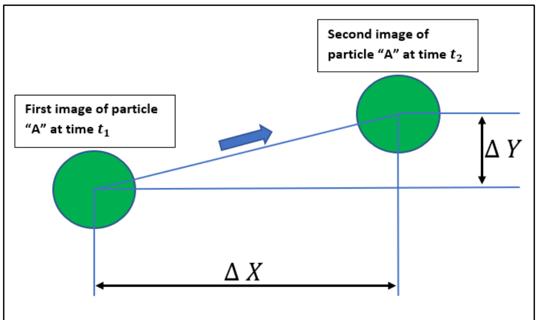
Thus, only with the advancement of technology and the emergence of new electronic components approximately 40 years ago, it was possible to create and develop a technique of particle image velocimetry (PIV) capable of obtaining relevant qualitative and quantitative information regarding fluid dynamics with optical principles.

Over the past four decades, PIV has evolved substantially into a powerful and meaningful measurement technique. This was made possible by the creativity, enthusiasm and commitment of the developers, but also by technical achievements in the field of tracer particles, light sources, recording systems, algorithms and computer performance (Scharnowski and Kahler, 2020).

The first attempts to perform PIV-like measurements were derived from optical photography based on the speckle phenomenon in 1977 (Mayinger and Feldmann, 2001). The PIV has become the most promising technique for flow field measurement, for presenting quantitative results of the velocity fields of laminar and turbulent flows and also for presenting a qualitative visualization of the flow and its effects due to its flow. The desire to use the technique by laboratories, research institutes and industries aims to obtain important and perhaps unknown data on fluid dynamics, in addition it is also possible to compare results or validate the technique through Computational Fluid Dynamics (CFD) simulation.

Currently, with adequate equipment and software, it is possible to set up a PIV technique to work in a planar measurement regime such as: 2D PIV, stereoscopic, and volumetric measurement, such as PIV-3D, Tomographic PIV (Tomo-PIV) and Holographic PIV (HPIV). It is also possible to use the technique in analysis of gas, liquid and solid flows, each of them with appropriate equipment. And in this way, each work regime and configuration establishes limitations resulting from its architecture and its devices.

The fundamental principle of PIV is easy to understand as shown in Figure 1, through two images captured in a short period of time, the software performs the processing by measuring the displacements ΔX and ΔY. The displacement ΔX/ Δt must be an approximation of the flow velocity (U). Therefore, the trajectory ΔX must be practically a straight line and the velocity constant. While ΔY/ Δt determines the velocity in the trajectory of the particle from the axis perpendicular to the flow (Dracos, 1996).



$$U = \lim_{t_2 \to t_1} \frac{X_2 - X_1}{t_2 - t_1}, \quad V = \lim_{t_2 \to t_1} \frac{Y_2 - Y_1}{t_2 - t_1}$$

Figure 1. Basic principle of the PIV technique.

The time interval for capturing images must be long to capture the displacement of the particle and short so that the particle does not leave the laser light blade and the camera focus.

The sizing of equipment and the configuration of the ideal experiment can affect the accuracy of the measurements performed. A specific study of the accuracy and precision of the PIV technique can be better studied in Lu *et al.* (2021).

2.1 EXPERIMENTAL CONFIGURATION (PIV)

The technique can be configured by combining equipment from different manufacturers, or by purchasing complete commercial systems. The first commercial applications of measurement systems based on particle image velocimetry date back to 1997, as highlighted by Raffel *et al.* (2007).

Basically, the experimental set of the particle image velocimetry technique (PIV-2D) is composed of tracer particle, a multi-pulsed laser equipped with an arrangement of mirrors with the function of converting the light beam into a planar light sheet as observed in Figure 2, and also a high-speed camera, a synchronizer to control the laser firing time and image capture, and a processing software.

Non-intrusively the laser is positioned close to the test section illuminating the tracer particles and the camera is installed perpendicular to the planar light sheet. For the PIV-2D regime, through which it is possible to obtain two velocity vectors, only one camera is used, while for the PIV-stereo two capture devices are needed, which must be positioned at a predetermined angle of so that the two frames are calibrated, guaranteeing the overlapping of the images, in this way it is possible to obtain the third vector of the three-dimensional plane. More information on the Stereo-IVP (SPIV) or Holographic-IVP (Holo-PIV) technique is found in Stanilas *et al.* (2003).

Figure 2 clearly represents a PIV-2D technique being applied in a wind tunnel with a rectangular test section, a light beam emitting multi-pulsed optical laser is positioned at the top of the section, and by combining a cylindrical lens and a plane mirror it is possible to convert the light beam into planar light sheet. The acquisition of two images is performed perpendicular to planar light, and the delay time between the two images depends on the flow velocity. It is possible to notice that all components are installed outside the test section, therefore it is essential to ensure the transparency of the constructive structure of the test section.

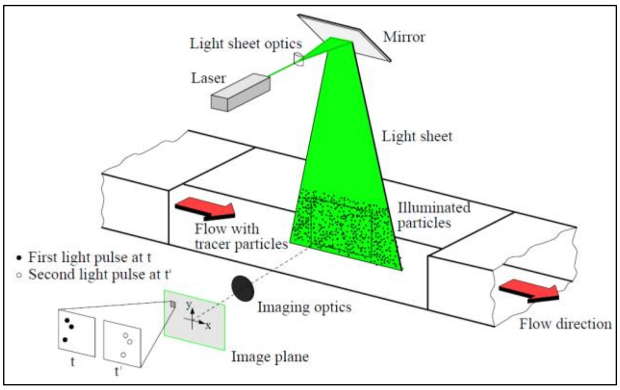


Figure 2. PIV layout configuration.

3. METHODOLOGY

The present study was designed from the search for experimental scientific articles that address experimental applications and use the PIV technique. The "Portal de Periódicos CAPES/MEC[1]" was used, it provides access to scientific information through several databases with content from national and international periodical publications covering all areas of knowledge. Only the terms: PIV and wind and tunnel were used as search keywords. Only the publication criterion from 2001 was adopted as a filter for selection, thus allowing a broad view and no choice criteria for the study, selecting only the most relevant sample of publications available on the "Portal de Periódicos CAPES/MEC".

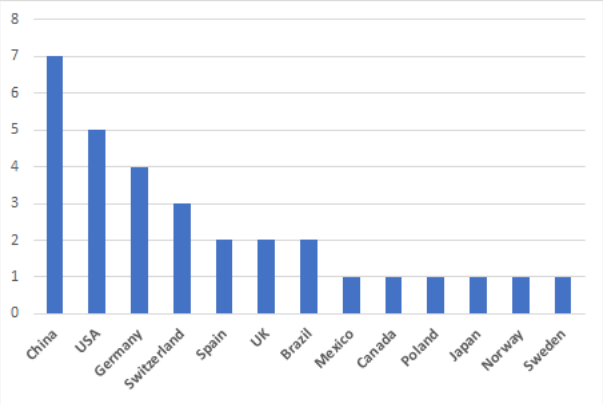
With the proposed analysis, it is possible to describe application layouts, specific characteristics of the components, parameters determined for each experiment and brands and models of the used equipment. Thus, this study is relevant for the dissemination of knowledge and applied technique.

4. COMPARATIVE ANALYSIS OF EXPERIMENTS

According to the survey carried out, it is possible to see in Figure 3a, the dispersion of the number of publications by countries of origin, highlighting the largest publications for the countries of China, USA and Germany, and in Figure 3b, it is possible to observe the dispersion of scientific articles over the years of publication, in this case most of the selected articles are more recent being 22 articles from the year 2015, it is also worth noting that these graphs do not represent any

[1] https://www-periodicos-capes-gov-br.ezl.periodicos.capes.gov.br/index.php?

trend of growth or decrease in publications in relation to the countries of origin or the year of publication, as the survey did not exhaust the published articles, but rather represent a small sample (n=32), so it cannot be taken as a parameter to trace statistical trends.



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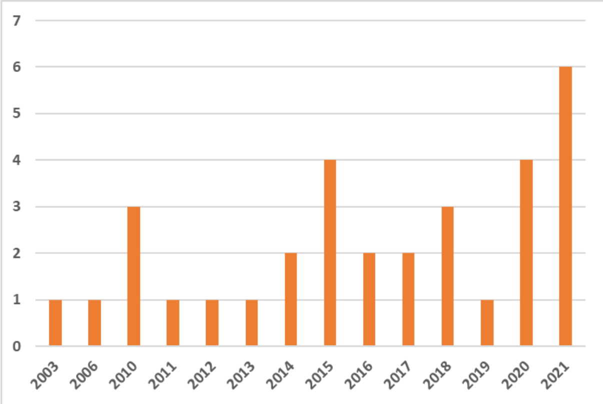


b)

Figure 3. a) An analysis about PIV publications by country and b) An historical analysis about PIV publications

4.1 Tracer Particles

Some intrusive techniques for velocity field measurement are based on direct flow measurement. As seen in Figure 2, the principle of the PIV technique is necessary to add seed particles to the flow, thus it is possible to state that the technique uses an indirect measurement. Therefore, the fluid mechanical properties of the particles must be considered, thus avoiding significant discrepancies between the movement of the fluid and particles (Raffel *et al.*, 2007).

Scharnowski and Kahler (2020) emphasize that particles must be electrically and chemically neutral, in addition to allowing buoyancy in relation to the fluid. Therefore, the ideal particle must be small and have a mass density equal to the fluid density. On the other hand, particles must be visible by the imaging system and cannot be small enough to be influenced by Brownian motion. For Melling (1997) the average size of tracer particles for gas flows is approximately 1μm.

The study evaluated experiments that basically used devices as a particulate diffuser that generated smoke or mist and an aerosol generator with the use of a Laskin nozzle. Among them stand out providers such as: Concept Vi-Count, Rosco, TSI, Martin Magnum and LaVision.

Considering the difficulty of accurately measuring these particles and the possible changes in particle sizes for each speed adjusted in the experiment. It is possible to see in Figure 4 a relation in percentage of experiments that used tracer particles with dimensions less than 1 μm and particles with dimensions greater than or equal to 1 μm. In general Dong and Wang (2004) used the smallest particles by inserting 0.1 to 0.2 nm particles of spherical quartz sand. Rolin (2018) and Raffel (2016) used particles between 50 and 130 μm. Furthermore Pires *et al.* (2010) seeded the largest particles of approximately 0.005 m using a ROSCO fog generator. Some studies did not describe information regarding particle size.

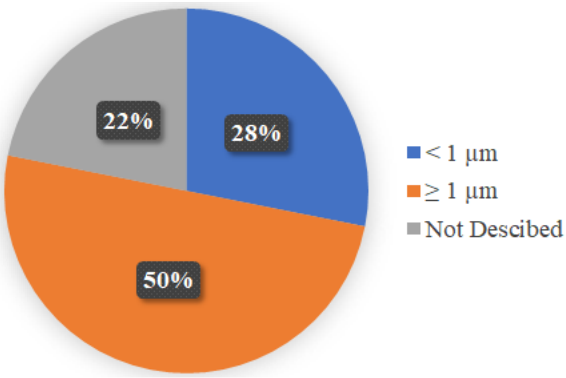


Figure 4. An analysis about particle sizes used in the PIV experimention.

The present study observed experiments that used solid particles such as: quartz sand and titanium dioxide, while other experiments used liquid particles that are dispersed in mist or smoke machines usually based on water and glycol or synthetic oils and even olive oil, too it is possible to find specific commercial solutions to be used in smoke machines as described in Helvig *et al.* (2021). Solution such as Di-Ethyl-Hexyl-Sebacat (DEHS) is often indicated for use in aerosol sprays.

4.2 Laser

Lasers are a necessary device for the application of the PIV technique, they are widely used due to their ability to emit monochromatic light with high energy density, it is also possible to analyze their working principle and their main components in Raffel *et al.* (2007).

For the emission of a planar light, it is convenient to use a cylindrical lens and, if necessary, a mirror to obtain a position perpendicular to the structural positioning of the laser. To ensure that the flow field is measured the planar light sheet should be around 1 to 3mm. However, carrying out an experiment with very thin planar light can make the SPIV technique unfeasible because the internal length is insufficient for measuring the three-dimensional flow (Xiaodong *et al.*, 2014).

In addition to the high energy density, the laser for PIV applications must be multi-pulsed, and fired at time intervals in the microsecond scale. It is possible to see in Figure 5 the sovereignty of two specific types, which the Nd: YAG represents 75% of use in experiments against 6% of the Nd: YLF. Furthermore, 19% of the articles did not describe which laser model was used. Nd: YAG (neodymium doped yttrium aluminum garnet) is a solid state laser, with an emphasis on its yttrium and aluminum oxide composition, it has a wavelength of up to 1064 nm and an energy density of approximately 200 mJ. The Nd: YLF laser (neodymium doped yttrium lithium fluoride) has a basic composition in yttrium and lithium fluoride and its advantage over YAG is the gain in energy supply for equivalent frequency rates, however its fragility and ease of breaking is a disadvantage. It is possible to highlight the use of Nd: YLF laser in the Scarano (2015) and Allegrini (2013) experiments.

The experiments showed randomness in the trigger frequency parameter, Ferreira *et al.* (2020) performed an experiment with a 0.5 Hz repetition rate, while in Muijres (2011) a laser with a 200Hz rate was used. In the experiment by Beresh *et al.* (2015) was configured 25 to 50 Khz for Pulse-burst PIV. The thickness of the planar sheet of light presented in the studies is 0.4 to 4 mm, approaching the values according to Xiaodong *et al.* (2007).

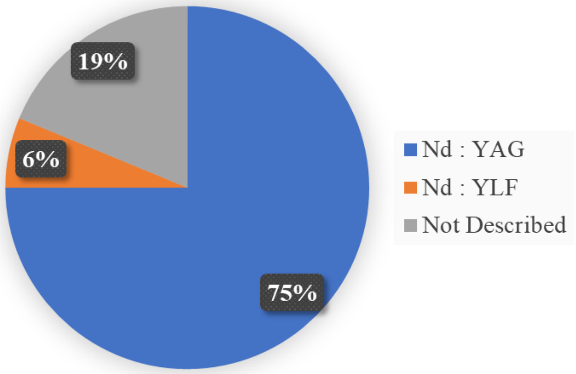


Figure 5. An analysis about type of lasers used in the PIV experimention.

4.3 High speed cameras

Currently there is a great diversity of electronic image sensors, despite the historical advance in the development of images based on vidicon tubes, technologies with solid state image sensors are widely used. It is possible to highlight two technologies among these devices, one of them is the CCD (charge-coupled device) and the other is the CMOS (complementary metal-oxide-semiconductor).

O The principle of operation and image capture is similar between sensors, they have the ability to generate small electrical charges when light falls on the component surface, and they differ in the constructive structure in which the CMOS has a circuit with nano diodes to each pixel. CMOS devices have advantages such as: lower power consumption, lower heating level, lower noise level, in addition to being more compact which allows cameras with reduced size; however CCD devices became popular in the 90s and have better resolution images compared to CMOS.

Through Figure 6 it is possible to visualize the domain of the use of CCD sensors to perform the image capture of experiments using the PIV technique. A better detail of the types of CCD sensors and their characteristics can be seen in chapter 4 of Raffel *et al.* (2007).

The experiments of Scarano (2015), Wei (2018), Wang (2003), Reyes (2015), Al-Garni (2010), Lee (2011), Chen (2021), Olasek (2021), Bardera (2020), Glick (2020), Ferreira (2020), Tominaga (2003), Faria (2019), Pires (2010), Zhu (2018), Rockel (2014), Bastankhah (2015), Sanchez (2017), Giovannetti (2017), Helvig (2021), Zheng (2021) used image capture devices with CCD technology.

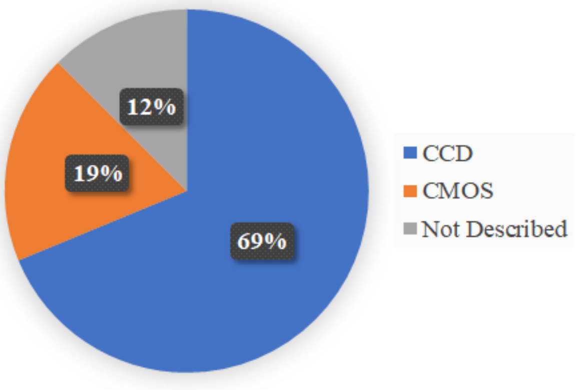


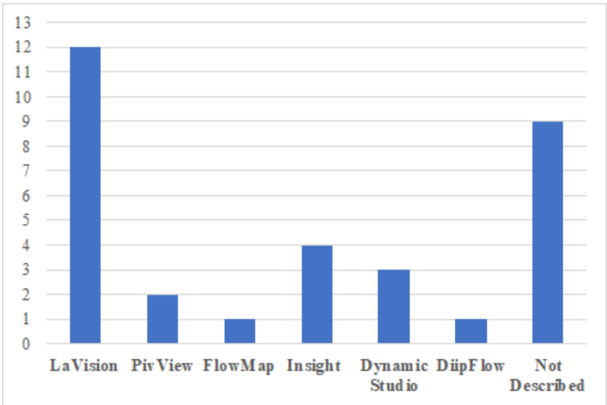
Figure 6. An analysis about type of camera used in the PIV experimention.

4.4 Processing system

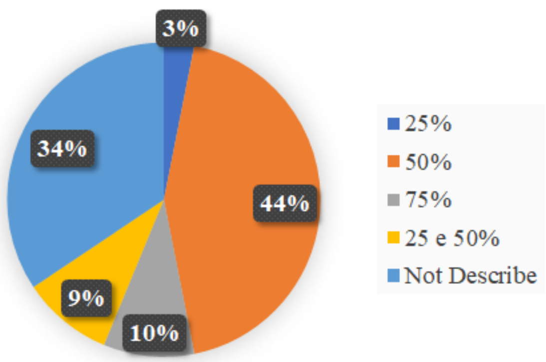
Once the digital images are captured, the files must be sent to a processing unit. Image analysis can be performed by commercial software specific for the PIV technique and fluid dynamics or even software that perform matrix calculations such as MATLAB®, and have the option of loading images.

Once these images are loaded into the processing unit, digital filtering techniques can initially be performed. Image background noise caused by light reflections can be suppressed through high-pass filtering techniques (Mayinger and Feldmann, 2001).

To perform the analysis, the digital image is subdivided into small spaces, called interrogation windows. With several defined and overlapping windows, cross autocorrelation is performed as a statistical tool. The calculation can be accelerated by applying Fast Fourier Transformation (FFT). In Figure 7a, it is possible to visualize the distribution of commercial software used in the experiments. In this case, it is important to emphasize that 9 experimental studies did not describe the software used, however they can be specific software for PIV or just matrix calculation programming software.



a)



b)

Figure 7. a) An analysis about the processing software used in the PIV experimention and b) An analysis about overlapping for Windows used in the PIV experimention

The size of the interrogation windows typically found in the experiments were square areas of 32, 64, 128 or 256 pixels, since the use of these values returns acceptable results due to camera position and resolution, optical lens arrangement, density and size of tracer particles. After defining the interrogation window, an overlay method can be applied to calculate the displacement using the cross-correlation technique. In Figure 7b, can see the distribution of the window overlap percentage parameter.

5. CONCLUSION

The present work carried out a review of the PIV technique applied to wind tunnels, presenting some characteristics and particularities of each component used and, consequently, some basic initial parameters for the configuration of a technique layout.

Despite technological evolution and advances in commercial product development, no PIV system was found with all devices from the same supplier. All experiments were performed with at least two different equipment suppliers. As a guide, it is important to emphasize that it is necessary to be judicious in the parameters adjusted for each experiment and in the selection of components to be used in the application of the PIV technique.

According to experiments carried out in the studies covered by this survey, it is possible to confirm that the PIV technique actually presents quantitative and qualitative results regarding the laminar and turbulent flow velocity field.

Even with the technological progress and commercial competition, it is possible to observe that items such as: laser and processing software have a concentration in a few product suppliers. According to Table 1, items such as acquisition cameras and smoke or fog generators have a greater number of suppliers as commercial options.

Table 1. Manufacturers of equipment used in the experiments mentioned in the studies covered by this survey.

Particles Diffuser	Lasers	Cameras	Softwares
Concept VI-Count	New Wave	Photron	Lavision
Rosco	Quantronix	LaVision	Dantec
Martin Magnum	Spectra Phisics	Roer Scientific	TSI
LaVision	Coherent	PCO	PivTec
TSI	Amplitude Laser	Dantec	
	Litron	TSI	
	Quantel Laser	Hamamatsu Photonics	
		ImperX	
		Ila	

It is possible to affirm that the PIV technique is powerful and has become an increasingly desired procedure within Laboratories and institutions that work with fluid dynamics, in addition it is still undergoing constant technological and commercial growth.

Despite the amount of relevant information from the application of the PIV technique, this study can be expanded, focusing on some specific equipment and device or even with the objective of a better detailing of some parameter. Moreover, an approach to more recent works or application of a filter with specific keywords can be performed.

Researchers must be judicious when performing a PIV measurement technique, so this study helps in the direction and sizing of equipment and the configuration to be applied, in addition to the propagation of scientific knowledge and studies in Fluid Dynamics.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Al-Garni, A. M., and Bernal, L. P., 2010. "Experimental study of a pickup truck near wake". *J. Wind Eng. Ind. Aerodyn, Vol. 98, p. 100–112.*

Allegrini, J., Dorer, V., and Carmeliet, J., 2013. "Wind tunnel measurements of buoyant flows in street canyons". *Building and Environment, Vol. 59, p. 315-326.*

Bardera, R., Sevillano, A. R., and Magariño, A. G., 2020. "Aerodynamic Investigation of a Morphing Wing for Micro Air Vehicle by Means of PIV" *Fluids*, 5.

Bastankhah, M., and Porte-Agel, F., 2015. “A wind-tunnel investigation of wind-turbine wakes in yawed conditions”. *Journal of Physics*, Vol. 625.

Beresh, S., Kearney, S., Wagner J., Guildenbecher, D., Henfling, J., Spillers R., Pruett B., Jiang N., Slipchenko, M., Mance, J., and Roy, S., 2015. “Pulse-burst PIV in a high-speed wind tunnel”. *Measurement Science and Technology.*

Beresh, J. S., Wagner, L. J., and Smith, L. B., 2016. “Self-calibration performance in stereoscopic PIV acquired in a transonic wind tunnel”. *Exp Fluids.* Vol. 57.

Cao, X., Liu, J., Jiang, N., and Chen, Q., 2014. “Particle image velocimetry measurement of indoor airflow field: A review of the technologies and applications”. *Energy and Buildings,* Vol. 69, p. 367–380.

Chen, Z., and Wen, C. Y., 2021. “Flow control of a D-shaped bluff body using different DBD plasma actuators”. *Journal of Fluids and Structures,* Vol. 103.

Dracos, T., 1996. “Particle Tracking Velocimetry (PTV)”, Dracos T. (eds) *Three-Dimensional Velocity and Vorticity Measuring and Image Analysis Techniques*, ERCOFTAC Series, vol 4, Springer.

Faria, A., F., Avelar, A. C., and Fisch, G., 2019. “Wind Tunnel Investigation of the Wind Patterns in the Launching Pad Area of the Brazilian Alcântara Launch Center”. *Journal of Aerospace Technology and Management*, Vol. 1.

Ferreira, M. A., and Ganapathisubramani, B., 2020. “PIV-based pressure estimation in the canopy of urban-like roughness”. *Experiments in Fluids*, p. 61-70.

Giovannetti, L. M., Banks, J., Turnock, S. R., and Boyd, S. W., 2017. “Uncertainty assessment of coupled Digital Image Correlation and Particle Image Velocimetry for fluid-structure interaction wind tunnel experiments”. *Journal of Fluids and Structures,* Vol. 68, p. 125–140.

Glick, A., Ali, N., Bossuyt, J., Recktenwald, G., Calaf, M., and Cal, R. B., 2020. “Infinite photovoltaic solar arrays: Considering flux of momentum and heat transfer”. *Renewable Energy,* Vol. 156, p. 791-803.

Helvig, S. J., Vinnes, M., K., Segalini, A., Worth, N. A., and Hearst, R. J., 2021. “A comparison of lab-scale free rotating wind turbines and actuator disks”. *Journal of Wind Engineering & Industrial Aerodynamics,* Vol. 209.

Kompenhas, J., Raffel, M., Dieterle, L., Dewhirst, T., Vollmers, H., Ehrenfried, K., Willert, C., Pengel, K., Kahler, C., Schroder, A., and Ronneberger, O., 1999. “Particle Image Velocimetry in aerodynamics: Technology and applications in wind tunnels”. *Journal of Visualization*, Vol. 2, p. 229-244.

Lee, T., 2011. “PIV study of near-field tip vortex behind perforated Gurney flaps”. *Exp Fluids,* Vol. 50, p. 351–361.

Lu, J., Yang, H., Zhang, Q., and Zhouping Y., 2021. “An accurate optical flow estimation of PIV using fluid velocity decomposition” *Experiments in Fluids*, Vol. 62.

Mayinger, F., Feldmann, O., 2001. “Optical Measurements”, *Techniques and Applications*, *2º Ed.*, Springer.

Michaux, F., Mattern, P., and Kallweit, S., 2018. “RoboPIV: how robotics enable PIV on a large industrial scale”. *Measurement Science and Technology,* Vol. 19.

Muijres, F. T., Bowlin, M. S., Johansson, L. C. and Hedenstro, A., 2012. “Vortex wake, downwash distribution, aerodynamic performance and wingbeat kinematics in slow-flying pied flycatchers.” *J. R. Soc. Interface,* Vol. 9, p. 292–303.

Olasek, K., and Karczewski, M., 2021. “Velocity data-based determination of airfoil characteristics with circulation and fluid momentum change methods, including a control surface size independence test”. *Experiments in Fluids,* p. 62-108.

Pires, L. B. M., Roballo, S. T., Fisch, G., Avelar, A. C., Girardi, and R. M., and Gielow, R., 2010. “Atmospheric flow measurements using the PIV and HWA techniques”. *J. Aerosp.Technol. Manag., São José dos Campos,* Vol.2, N. 2, p. 127-136

Raffel, M., Favier, D., Berton, E., Rondot, C., Nsimba, M., and Geissler, W., 2006. “Micro-PIV and ELDV wind tunnel investigations of the laminar separation bubble above a helicopter blade tip”. *Meas. Sci. Technol,* Vol. 17, p. 652–1658.

Raffel, M., Willert, C.E., Wereley, S.T., and Kompenhans, J., 2007. “*Particle Image Velocimetry: A Pratical Guide*”, Springer.

Reyes, V. A., Espinosa, F. Z. S., Moya, S. L., and Carrillo, F., 2015. “Flow field obtained by PIV technique for a scaled building-wind tower model in a wind tunnel”. *Energy and Buildings,* Vol 107, p. 424–433.

Rolin, V. F.C., and Agel, F. P. E., 2018. “Experimental investigation of vertical-axis wind-turbine wakes in boundary layer flow”. Renewable Energy, Vol. 118, p. 1-13.

Rockel, S., Camp, E., Schmidt, J., Peinke, J., Cal, R. B. and Holling, M., 2014. “Experimental Study on Influence of Pitch Motion on the Wake of a Floating Wind Turbine Model”. *Energies,* Vol. 7, p. 1954-1985.

Sanchez, S. A., Garcia, O. L., Cuerva, A., and Meseguer, J., 2017. “Assesment of the transverse galloping stability of a railway overhead located above a railway bridge”. *International Journal of Mechanical Sciences* Vol. 131–132, p. 649–662.

Scarano, F., Ghaemi, S., Caridi, G. C. A., Bosbach, J., Dierksheide, U., and Sciacchitano, A., 2015. “On the use of helium-filled soap bubles for large-scale tomographic PIV in wind tunnel experiments”. *Exp Fluids,* Vol. 56.

Scharnowski, S., and Kähler, C. J., 2020. "Particle image velocimetry - Classical operating rules from today's perspective". *Optics and Lasers in Engineering,* Vol. 135.

Sijie, F., Pascal, H. B., Christian, M., 2015. "Particle Tracking Velocimetry for indoor airflow field: A review". *Building and Environment*, Vol. 87, p. 34-44.

Stanislas, M., Westerweel, J., Kompenhas, J., 2003. "Particle Image Velocimetry: Recent Improvements", *Proceedings of the EUROPIV 2 Workshop*, Spain. Springer.

Tominaga, Y., Okaze, T., Mochida, A., Sasaki, Y., Nemoto, M., and Sato, T., 2003. "PIV measurements of saltating snow particle velocity in a boundary layer developed in a wind tunnel". *J Vis,* Vol. 16, p. 95–98.

Ullah, H. A., Rostad, B. L., and Estevadeordal, J., 2021. "Three-cylinder rotating system flows and their effects on a downstream dimpled airfoil". *Experimental Thermal and Fluid Science.*

Wang, Z. D. H., Zhang, X., and Ayrault, M., 2003. "Height profile of particle concentration in an aeolian saltating cloud: A wind tunnel investigation by PIV MSD". *Geophisical Research Letters,* Vol. 30, N. 19.

Wei, X., Huang, B., Kanemoto, T., and Wang, L., 2017. "Near wake study of counter-rotating horizontal axis tidal turbines based on PIV measurements in a wind tunnel" J. Mar. Sci Technol, Vol. 22, p.11-24

Zheng, X., Wang, G., and Zhu, W., 2021. "Experimental study on the effects of particle–wall interactions on VLSM in sand-laden flows". *J. Fluid Mech,* Vol. 914, p. A35.

Zhixiang, L., Zhixiang, Y., Xiaoxiao, C., Ruizhou, C., and Yang, C., 2021. "Numerical and experimental studies on the airflow around the low-rise flat-roof buildings with different stable snowdrifts". *Cold Regions Science and Technology*, Vol. 187.

Zhu, Y., Lee, C., Chen, X., Wu, J., Chen, S. and Hak, M. G., 2018. "Newly identified principle for aerodynamic heating in hypersonic flows". *J. Fluid Mech,* Vol. 855, p. 152-180.

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