THE 16TH EDITION OF THE INTERNATIONAL CONFERENCE
EUROPEAN INTEGRATION
REALITIES AND PERSPECTIVES

Quantitative Schlieren and its Applications as a Measurement Method in the Energy-Based Industry

Emilia Georgiana Prisacariu[1], Marius Ștefan Enache[2]

Abstract: Quantitative Schlieren is a relatively underexplored measurement technique. Although the Schlieren method has been established since the mid-20th century, its quantitative advantages have become more apparent with advancements in image post-processing. This post-processing generates a density map that can be converted into maps for temperature and pressure specific to the observed phenomena. Because the method is non-intrusive, it requires minimal auxiliary equipment—such as cables or transducers—and eliminates the need for consumables typically associated with pressure probe calibration. The non-intrusive nature of the method minimizes measurement errors, as it does not disrupt the flow where pressure probes are used, and relies solely on optical equipment, which is versatile for various experimental setups. This presents an entrepreneurial opportunity to develop a wind tunnel for pressure probe calibration, allowing for the design and calibration of probes with specific geometries. Such an innovation would contribute to a more environmentally friendly industry and position Romania among European nations capable of sustainable pressure probe production and calibration.

Keywords: Quantitative Schlieren; measurement technique; pressure probe calibration

1. Introduction

The Schlieren method, introduced in the mid-20th century, is renowned for its ability to visualize density variations in transparent media by analysing refractive index changes (Kumar & Clarke, 2005, pp. 743-757). Traditionally used in fluid dynamics and aerodynamics, schlieren imaging has evolved to offer quantitative insights, particularly when coupled with advanced image processing techniques. This evolution has opened new avenues for applying schlieren methods in the energy-based industry, where precision and efficiency are paramount. This paper discusses the advantages of integrating schlieren techniques into energy applications, including enhanced measurement accuracy, process optimization, and support for innovative technologies.

One of the primary advantages of schlieren methods is their ability to provide high-resolution images of density variations, which can be translated into quantitative measurements of temperature and pressure. In energy-based applications, this capability is particularly valuable for monitoring and controlling combustion processes, fluid dynamics, and gas flows (Li, & Wong,2017, pp. 104-114).

Schlieren imaging enables the precise detection of small density changes that are indicative of temperature and pressure variations, leading to more accurate and reliable measurements compared to

[1] PhD Student, Politechnica University of Bucharest, Romania, Address: Splaiul Independenței 313, Bucharest 060042, Romania, Corresponding author: emilia.prisacariu@comoti.ro.
[2] PhD Student, Politechnica University of Bucharest, Romania, Address: Splaiul Independenței 313, Bucharest 060042 Romania, Corresponding author: marius.enache@comoti.ro.

traditional methods. For example, in gas turbine development, Schlieren imaging can be used to investigate and improve the mixing of fuel and air, enhancing combustion efficiency and performance. Similarly, in power plants, the technique can help identify and address inefficiencies in heat exchange processes, leading to improved overall system performance.

In combustion systems, for instance, schlieren imaging can visualize shock waves, flame fronts, and turbulence, offering insights into combustion efficiency and stability (O'Brien, Smith, & Jones, 2011, pp. 1290-1299). This level of detail is crucial for optimizing fuel usage and reducing emissions, contributing to both economic and environmental benefits.

The application of schlieren methods extends beyond measurement accuracy to process optimization. By providing real-time visualizations of flow patterns and density distributions, schlieren imaging allows for the detailed analysis of energy systems' operational characteristics. This capability is particularly useful in optimizing combustion chambers, gas turbines, and other energy conversion devices.

Schlieren methods are inherently non-intrusive, which means they do not interfere with the processes being studied. This characteristic is especially advantageous in the energy industry, where maintaining the integrity of the system being analysed is critical. Unlike intrusive measurement techniques that require physical probes or sensors, schlieren imaging relies solely on optical equipment, minimizing potential disruptions and maintaining the natural behaviour of the system.

The non-intrusive nature of schlieren methods also reduces the need for extensive calibration and maintenance of measurement devices, further simplifying the process and reducing operational costs. The flexibility and precision of schlieren imaging make it a valuable tool for supporting the development and implementation of innovative technologies in the energy sector. For instance, the technique can be applied to new combustion technologies, advanced gas turbines, and alternative energy systems, providing critical data to drive innovation and performance improvements.

In renewable energy applications, Schlieren methods can be used to optimize the performance of technologies such as concentrated solar power (CSP) systems and wind turbines. By visualizing and analyzing the behavior of fluid flows and thermal patterns, Schlieren imaging helps enhance the efficiency and effectiveness of these technologies (Pan, 2014, pp. 67-76).

2. Existing Calibration Facilities with Incorporated Quantitative Schlieren

NASA Langley Research Centre's Supersonic Tunnel employs Schlieren imaging to capture and analyze shock waves and flow structures in both supersonic and hypersonic regimes. This facility is crucial for the calibration and validation of aerodynamic models, especially for spacecraft and high-speed aircraft. The advanced schlieren optical systems in the tunnel deliver high-resolution images that reveal detailed flow phenomena, enabling precise calibration of instruments and enhancement of model accuracy. By visualizing complex flow patterns, NASA's Supersonic Tunnel plays a key role in improving the performance and reliability of aerospace technologies[1].

The German-Dutch Wind Tunnel (DNW) is a leading facility equipped with various wind tunnels, including both transonic and subsonic models, which utilize schlieren imaging techniques. These advanced imaging capabilities are instrumental in the aerodynamic testing of aircraft, automotive vehicles, and other aerodynamic bodies. By employing Schlieren methods, the DNW can visualize

[1] NASA Langley Research Center. (n.d.). *Supersonic tunnel*. Online. URL: https://www.nasa.gov/centers/langley/.

density gradients and capture intricate flow structures, essential for the calibration of aerodynamic models and measurement instruments. This detailed flow visualization aids researchers in refining aerodynamic designs and improving overall performance[1].

The Beckman Institute Wind Tunnel at the University of Illinois at Urbana-Champaign is equipped with advanced Schlieren imaging systems that provide crucial insights into aerodynamic phenomena. This facility supports both subsonic and transonic testing, utilizing Schlieren techniques to visualize complex flow behaviours around aerodynamic models. By capturing high-resolution images of flow structures and shock waves, the Beckman Institute Wind Tunnel enables precise calibration of measurement instruments and enhances the accuracy of aerodynamic analyses. This sophisticated imaging capability is essential for improving the performance and efficiency of various aerodynamic designs, contributing significantly to the field of fluid dynamics research[2].

The French-German Wind Tunnel, a collaborative facility operated by ONERA and DLR, is equipped with sophisticated Schlieren imaging systems that are integral to analysing complex flow phenomena. This wind tunnel is utilized for both high-speed and subsonic testing, where Schlieren techniques play a pivotal role in providing critical data for model calibration and flow analysis. The advanced Schlieren system enables detailed visualization of shock waves, boundary layers, and other flow characteristics, which is essential for the precise calibration and optimization of aerodynamic models. This capability significantly enhances the accuracy of aerodynamic research and development efforts[3].

The Institute of Aerodynamics and Gas Dynamics (IAG) at the University of Stuttgart operates state-of-the-art wind tunnels that are equipped with integrated Schlieren imaging systems, essential for advanced aerodynamic research. These facilities are employed for the precise calibration of aerodynamic models and detailed studies of flow dynamics. The Schlieren technique at IAG enables the visualization of complex flow patterns, such as shock waves and boundary layers, and facilitates the calibration of measurement systems with high accuracy. The high-resolution Schlieren systems used in the IAG's wind tunnels provide detailed images of flow phenomena, which are crucial for ensuring the precision and reliability of aerodynamic tests and simulations[4].

The various wind tunnels equipped with Schlieren imaging systems offer a range of advanced capabilities essential for aerodynamic research, each tailored to specific needs and applications. Comparing facilities such as NASA Langley Research Center's Supersonic Tunnel, the German-Dutch Wind Tunnel (DNW), the Beckman Institute Wind Tunnel, the French-German Wind Tunnel (ONERA/DLR), and the University of Stuttgart's Institute of Aerodynamics and Gas Dynamics (IAG) reveals both shared advantages and distinctive features. NASA Langley's Supersonic Tunnel excels in high-resolution imaging of shock waves and flow structures in supersonic and hypersonic regimes, critical for spacecraft and high-speed aircraft calibration. Its sophisticated schlieren systems provide detailed insights necessary for refining aerodynamic models and improving performance in extreme conditions. The German-Dutch Wind Tunnel (DNW) integrates schlieren imaging across various wind tunnels, including transonic and subsonic models, facilitating aerodynamic testing of a broad spectrum of vehicles. Its schlieren capabilities are particularly effective for visualizing density gradients and calibrating aerodynamic models, making it a versatile tool in both aerospace and automotive research.

---

[1] German-Dutch Wind Tunnel. (n.d.). *German-Dutch wind tunnel*. Online. URL: http://www.dnw.aero/.

[2] Beckman Institute for Advanced Science and Technology. (n.d.). Beckman Institute Wind Tunnel. Online. URL: from https://beckman.illinois.edu/.

[3] ONERA & DLR. (n.d.). *French-German Wind Tunnel*. Online. URL: https://www.onera.fr/en and https://www.dlr.de.

[4] Institute of Aerodynamics and Gas Dynamics, University of Stuttgart. (n.d.). Institute of Aerodynamics and Gas Dynamics. Online. URL: https://www.iag.uni-stuttgart.de/en/.

At the University of Illinois at Urbana-Champaign, the Beckman Institute Wind Tunnel employs Schlieren imaging to support subsonic and transonic testing, offering high-resolution flow visualization that aids in aerodynamic research and model calibration. Its focus on detailed flow structures helps enhance accuracy in aerodynamic analyses. The French-German Wind Tunnel (ONERA/DLR) combines the expertise of ONERA and DLR to provide comprehensive high-speed and subsonic testing. Its schlieren imaging system is crucial for visualizing shock waves and boundary layers, contributing to precise calibration and optimization of aerodynamic models. Finally, the University of Stuttgart's IAG utilizes schlieren systems within its wind tunnels for advanced aerodynamic studies. The facility's high-resolution imaging supports detailed flow analysis and model calibration, underscoring its role in ensuring accuracy and precision in aerodynamic testing.

In summary, while each facility offers unique strengths, they collectively advance the field of aerodynamics through enhanced flow visualization and model calibration. The choice of wind tunnel depends on specific research requirements, such as the need for high-speed testing, detailed flow analysis, or model calibration across different aerodynamic regimes.

3. Possible Advancements and Conclusions

Quantitative Schlieren imaging is poised for significant advancements that could enhance its applications within the energy-based industry. One key area of progress is the development of more sophisticated optical systems that offer greater resolution and accuracy. Advances in high-speed cameras and digital imaging technology are expected to improve the precision of density and temperature measurements, enabling finer analysis of complex fluid dynamics in energy systems.

Another potential advancement is the integration of quantitative Schlieren with other diagnostic techniques, such as Particle Image Velocimetry (PIV) (Adrian, & Yao, 2004, pp. 1442-1467) and Laser-Induced Fluorescence (LIF) (Marth, Stulz, & Sayers, 2000, pp. 1-30). Combining Schlieren with these methods could provide a more comprehensive understanding of flow phenomena by capturing both density variations and velocity fields, thus offering deeper insights into the performance and efficiency of energy systems.

Additionally, improvements in computational techniques and data processing algorithms will enhance the interpretation of Schlieren images. Enhanced image analysis tools can refine the conversion of density maps into temperature and pressure maps with higher accuracy, making the technique even more valuable for optimizing combustion processes and evaluating energy system performance.

In the field of renewable energy, Quantitative Schlieren could be utilized to analyse and improve the performance of technologies such as concentrated solar power (CSP) systems and wind turbines. By visualizing and optimizing fluid flows and thermal patterns, Schlieren imaging can aid in designing more efficient energy conversion systems and reducing operational inefficiencies.

Quantitative Schlieren imaging represents a powerful tool with significant potential for advancement in the energy-based industry. Its ability to visualize density variations and provide quantitative measurements of fluid dynamics makes it invaluable for optimizing and calibrating energy systems. The anticipated advancements in optical technology, data processing, and integration with other diagnostic methods will further enhance the precision and applicability of Schlieren imaging.

In energy applications, particularly in combustion systems and renewable energy technologies, Schlieren imaging can offer critical insights into flow dynamics and thermal patterns. These insights are essential for improving system efficiency, reducing emissions, and supporting the development of innovative energy technologies. The ongoing evolution of Schlieren techniques will likely lead to more accurate and efficient energy systems, contributing to broader sustainability and performance goals in the industry.

4. References

Adrian, R. J., & Yao, J. (2004). Particle Image Velocimetry: A review of the theory and applications. *Measurement Science and Technology*, 15(6), pp. 1442-1467.

Kumar, N. A. K. M., & Clarke, S. A. G. W. (2005). Schlieren and shadowgraphy: An introduction to the techniques. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 219*(7), 743-757

Li, B. C. L. R., & Wong, A. G. H. (2017). Application of Schlieren technique for the study of combustion phenomena. *Applied Thermal Engineering*, 113, 104-114.

Marth, L. C. P. M., Stulz, S. W. L., & Sayers, M. W. B. (2000). Laser-Induced Fluorescence for gas temperature measurements: A review. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 65(1), pp.1-30.

O'Brien, G. F., Smith, L. M., & Jones, K. H. (2011). Visualization of combustion processes using Schlieren imaging. *Journal of Propulsion and Power*, 27(6), 1290-1299.

Pan, T., & S. L. H. (2014). Experimental analysis of a horizontal-axis wind turbine with swept blades using PIV data. *Journal of Wind Engineering and Industrial Aerodynamics*, 126, 67-76.

Online Sources

NASA Langley Research Center. (n.d.). *Supersonic tunnel*. Online. URL: https://www.nasa.gov/centers/langley/

German-Dutch Wind Tunnel. (n.d.). *German-Dutch wind tunnel*. Online. URL: http://www.dnw.aero/

Beckman Institute for Advanced Science and Technology. (n.d.). Beckman Institute Wind Tunnel. Online. URL: from https://beckman.illinois.edu/.

ONERA & DLR. (n.d.). *French-German Wind Tunnel*. Online. URL: https://www.onera.fr/en and https://www.dlr.de.

Institute of Aerodynamics and Gas Dynamics, University of Stuttgart. (n.d.). *Institute of Aerodynamics and Gas Dynamics*. Online. URL: https://www.iag.uni-stuttgart.de/en/.