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Editorial

Recent Developments and Future Directions in Flow Visualization: Experiments and Techniques

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Flow visualization has long been a critical tool for understanding complex fluid dynamics in both natural and engineered systems [1–3]. Over the past few decades, advancements in experimental techniques, imaging technologies, and computational methods have significantly enhanced our ability to observe, quantify, and analyze fluid flows. From classic methods such as dye injection and particle image velocimetry (PIV) to more cutting-edge approaches like high-speed imaging, laser-induced fluorescence, and digital holography, the field has evolved to meet the demands of increasingly complex research questions [4–12].

Despite these impressive advancements, there remain significant gaps in knowledge, particularly regarding the visualization of turbulent flows, multiphase systems, and the interaction of flows with deformable surfaces such as flexible wings and aquatic vegetation [13,14]. While progress has been made in capturing instantaneous flow fields and high-resolution images, challenges persist in achieving real-time and three-dimensional visualization under challenging environmental conditions (e.g., underwater flows, extreme turbulence, or highly unsteady flows) [15,16]. Moreover, there is a need for improved techniques that can seamlessly combine visual data with quantitative analysis to bridge the gap between theory and experiment.

This Special Issue on *Flow Visualization: Experiments and Techniques* serves to address some of these knowledge gaps by presenting a collection of papers that highlight the latest experimental advancements in flow visualization. The articles within this Special Issue explore novel imaging systems, innovative experimental setups, and advanced data processing techniques that enable a more accurate and detailed visualization of fluid phenomena. By focusing on areas such as turbulent boundary layers, vortex dynamics, and the flow–structure interactions in natural environments, this Special Issue brings together a diverse set of studies that push the boundaries of current flow visualization techniques [17–19].

The field of flow visualization is rapidly evolving, with new techniques and applications emerging that promise to deepen our understanding of fluid dynamics [20–24]. The advancements presented in recent research underscore significant contributions across diverse applications and methodologies, including PIV, Laser Doppler Velocimetry (LDV), and Particle-Tracking Velocimetry (PTV) [25–36]. This Editorial aims to provide a brief overview of these developments, identify the gaps in the knowledge, and discuss how the current Special Issue addresses those gaps, with a focus on future research directions. Nobes et al. [25] propose a novel combined vortex detection algorithm (CVD) designed

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to enhance the accuracy and reliability of vortex identification and analysis in oscillating airfoil wakes. The CVD method improves upon traditional techniques, such as the Q-criterion, by offering a more robust framework for detecting and quantifying vortex structures, particularly in complex, time-varying flows. The algorithm integrates multiple flow-field metrics to identify vortex boundaries and evaluate key flow parameters with greater precision. This advancement is particularly beneficial in experimental fluid dynamics, where accurate vortex characterization is crucial for understanding wake dynamics and optimizing aerodynamic performance. The study highlights the effectiveness of CVD in providing clearer insights into vortex behaviors and offers a promising tool for future research in vortex dynamics and turbulence.

Elaswad et al. [26] highlight key advancements in visualizing flow behaviors in complex geometries, such as toroidal systems, through methods like PIV and LDV. The paper discusses the influence of parameters like Reynolds and Dean numbers on secondary flow phenomena, particularly in curved or rotating conduits, and how these can be optimized to enhance the performance of fluid dynamic systems like the PIVG (Particle Image Velocimetry Gyroscope). Through both numerical simulations and experimental validations, the authors examine the impact of angular acceleration on fluid behavior, revealing insights into the development of primary and secondary flow components. They further emphasize the importance of precise pressure and velocity field measurements for improving the accuracy and reliability of flow measurements, which are critical for applications in fluid mechanics, engineering, and sensor technologies. The study provides a valuable framework for optimizing fluid dynamics in rotational systems, contributing to a better design and understanding of experimental fluid flow investigations.

Shirinzad et al. [27] present a comprehensive study on the enhancement of PIV software, focusing on an improved algorithm optimized for Central Processing Units (CPUs) to facilitate accessible and efficient flow analysis. By leveraging Python's versatility, the authors developed an algorithm that precisely captures time-averaged flow, velocity fields, and vortices, offering an alternative to GPU-optimized PIV software. The algorithm was validated through rigorous testing on various platforms, including supercomputing clusters and Google Colaboratory, demonstrating its robustness in experimental flow studies. The primary contribution of this work lies in providing an open-source, CPU-based solution for real-time and offline PIV analysis, expanding its applicability to a wider range of research environments, particularly for those without access to specialized GPU hardware.

Colli et al. [28] investigate the effects of parallel blade–vortex interactions (BVIs) on the aerodynamic performance of an airfoil, with a particular focus on its relationship to blade stall. Their study utilizes wind tunnel experiments to reproduce parallel BVI on an NACA 23012 blade model at a Reynolds number of 300,000. The vortex was generated by impulsively pitching a second airfoil upstream, and the aerodynamic loads acting on the blade were measured using unsteady Kulite pressure transducers. Notably, the authors employed PIV techniques to visualize and analyze the flow field over the blade model. The paper contributes significantly to the field of flow visualization, particularly by applying PIV to study flow dynamics in the context of parallel BVI, with additional novelty in the investigation of oscillating sinusoidal motion of the blade. This work exemplifies how advanced experimental techniques like PIV can offer deep insights into complex aerodynamic phenomena.

Hassan et al. [29] investigate the interaction between flow dynamics and acoustic phenomena in rectangular deep cavities, focusing on passive control strategies. Using advanced flow visualization techniques, the authors analyze the coupling between aerodynamic forces and the resulting acoustic fields, particularly in the context of cavities, which are known to generate strong noise due to vortex shedding and flow instabilities. Their experiments utilize PIV and other visual techniques to map flow structures and identify the dynamics that contribute to aeroacoustic noise. By applying passive flow control methods, the authors demonstrate how altering flow characteristics can reduce unwanted sound emissions, offering valuable insights into noise mitigation strategies in engineering applications such as aerospace and automotive design. This study significantly contributes to the field of flow visualization by showing how experimental techniques can help visualize and control complex flow–acoustic interactions.

Mehta et al. [30] present a detailed experimental and computational study focused on the flow characteristics and acoustic behaviors of supersonic rectangular impinging jets. Their research specifically examines how the orientation of the jet—whether aligned along the major or minor axis—affects both the flow dynamics and the noise produced. Through different flow visualization techniques, including PIV and Schlieren, the authors capture the complex flow structures that arise in each configuration. Their results highlight how these different orientations lead to variations in pressure fields, shear layers, and jet impingement patterns, directly influencing noise emissions. This work contributes to the broader field of flow visualization by using cutting-edge experimental methods to explore the relationship between flow configurations and acoustics, providing valuable insights into optimizing jet design for noise control in high-speed fluid dynamics, especially in aerospace engineering.

Xi et al. [31] focus on the experimental visualization and analysis of airflow patterns around different types of face coverings. The authors utilize a variety of visualization methods, including the Schlieren optical system, laser/LED particle imaging system, thermal imaging camera, and vapor-SarGel system, to study how mask leakage and the resulting flow patterns affect the interpersonal transmission of airborne particles. Through their experiments, they examine various face masks, quantifying the leakage flows and their potential implications for reducing disease transmission. The findings highlight the critical role of mask design and fit in minimizing leakage, contributing valuable insights to public health and safety practices, particularly in the context of respiratory disease prevention.

Prisăcariu et al. [32] present a novel application of the quantitative color Schlieren technique to analyze the gasodynamic parameters of an H_2O_2 exhaust jet in air. By leveraging a calibrated color filter within a Z-type Schlieren setup, the study achieves the extraction of density and temperature gradients of the turbulent jet, produced by a micro-thruster designed for small satellites. The authors compare their experimental results with CFD simulations to validate the Schlieren method's measurement accuracy. Despite challenges such as calibration errors and the reduced accuracy in 3D flows compared to 2D cases, this work advances the Schlieren technique's capability to provide quantitative insights into complex jet dynamics, offering potential applications in aerospace engineering and combustion analysis.

Fan et al. [33] conduct an experimental study to investigate the flow dynamics of oil–water mixtures downstream of a restriction in a horizontal pipe. They employ two advanced techniques for flow visualization—a high-speed camera and an Electrical Capacitance Volume Tomography (ECVT) system, the latter of which is a non-intrusive tool for measuring the volumetric phase distribution at pipe cross-sections. The study examines how varying valve openings, flow rates, and water cuts affect the flow pattern and pressure drop. The results show a significant correlation between the oil–water flow pattern and the pressure gradient, with variations depending on the valve openings and water cuts. In particular, smaller valve openings lead to more complex flow behaviors, including oil-in-water dispersions. The findings provide valuable insights into how flow conditions influence both flow patterns and pressure drops in oil–water mixtures, with implications for optimizing flow management in industrial applications.

Liu et al. [34] explore the turbulent flow dynamics within a gas-stirred cylindrical water tank, with a particular focus on ladle metallurgy, which is critical in steelmaking. The study investigates how turbulence affects key steelmaking processes, such as the mixing and distribution of additives and the transport of inclusions. By employing an advanced PTV system, specifically the "Shake-the-Box" method, the authors simulate the stirred flow field in a water ladle model, using compressed air injections at the tank's bottom to actively stir the flow. This method aims to optimize ladle design and improve the precision of process control strategies in steelmaking, thus enhancing overall efficiency and steel quality. Additionally, the paper addresses the challenge of mitigating distortion in particle images caused by the cylindrical plexiglass walls of the model, thereby improving the accuracy of flow field measurements.

Takeyama et al. [35] introduce a novel technique aimed at enhancing the acquisition of velocity vectors in fluid dynamics experiments using 3D3C Rainbow PTV. By integrating an innovative in-picture tracking method, the authors significantly improve the number of velocity vectors that can be accurately captured in complex, three-dimensional flows. This advancement addresses a key challenge in flow visualization, particularly in high-dimensional flow fields where traditional PTV methods struggle with limitations in data acquisition and resolution. The paper demonstrates how this improved method offers more precise and comprehensive flow data, facilitating the detailed analysis of fluid behavior in both academic research and industrial applications. This contribution to flow visualization enhances the capability of PTV as a tool for studying intricate flow phenomena and offers new avenues for future experimental techniques in fluid mechanics.

Riazanov et al. [36] present an in-depth study focused on the flow characteristics of coolant in a fuel rod bundle, specifically within the context of small modular reactors (SMRs). They employ advanced flow visualization techniques to capture the complex behavior of coolant as it interacts with the fuel rods, using CFD simulations alongside experimental methods. The study provides a detailed examination of flow patterns, temperature distributions, and pressure drops, which are crucial for the safe and efficient operation of nuclear reactors. By using sophisticated visualization tools, such as PIV and flow visualization in transparent models, the authors effectively highlight the intricacies of coolant behavior in a reactor environment. This work significantly contributes to the field of flow visualization by offering insights into the optimization of coolant flow management in nuclear reactors, an area where experimental techniques are key to ensuring safety and performance.

Looking forward, the future of flow visualization research will likely be driven by continued innovation in imaging technologies, computational methods, and interdisciplinary collaboration. As we move toward more sophisticated and dynamic experimental setups, it will be essential to focus on real-time data acquisition, multi-modal visualization, and developing hybrid techniques that combine traditional and modern approaches. Investigating the effects of flow visualization on different scales, from microfluidics to large-scale industrial applications, is also needed to provide a comprehensive understanding of fluid behavior [37–40]. Moreover, a deeper understanding of the fundamental fluid mechanics behind observed flow patterns will be critical for applying flow visualization to emerging environmental protection, sustainable energy, and biomechanics challenges.

It is worth noting that this Special Issue, entitled *Flow Visualization: Experiments and Techniques, 2nd Edition*, has launched in *Fluids*. One of the key themes addressed in this new Special Issue is the integration of machine learning and artificial intelligence into flow visualization workflows. These technologies offer new opportunities for automating data analysis, enhancing the resolution of flow features, and predicting flow behavior in previously intractable systems. This fusion of experimental techniques with computational power is set to revolutionize the field by enabling a more efficient and insightful analysis of complex fluid systems.

In conclusion, while substantial progress has been made, the field of flow visualization continues to evolve rapidly. Researchers are urged to explore new experimental techniques, integrate advanced data processing methods, and collaborate across disciplines to address the remaining gaps in the knowledge. This Special Issue provides a glimpse into the exciting future of flow visualization, where innovations in both experiments and techniques will offer new insights into the ever-complex world of fluid dynamics.

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