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Editorial

Taking Flow Characterization to New Heights by Fiber Bragg Gratings Array

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1. Introduction

With global warming increasing at a faster rate in recent decades than at any other moment in recorded history, nuclear power, among a wide range of energy-efficient technologies, has been identified as the primary energy source in decarbonization for the improvement of security and efficiency. Notably, the design, functionality, and safety of Generation III+, Generation IV, small modular reactor, and other cutting-edge nuclear reactor technologies depend critically on thermal hydraulics (TH) [1]. Thereby, modern TH instrumentation techniques undoubtedly play a big part in safely powering both the fleet of nuclear reactors in use today and the cutting-edge designs of tomorrow.

The Impact of sensors has arguably been nowhere more revolutionary than in nuclear instrumentation [2]. The core of flow instrumentation for measurement, diagnostics, and control, more particularly, is the accurate and effective real-time live imaging (i.e., unambiguous observation and characterization) of single or multi-phase flows and their modalities' mapping (e.g., temperature fields) through experimentation, control, and condition monitoring. To document the advancements in flow characterization using advanced instrumentation to solve both fundamental and applied TH problems that are pressing, Table 1 lays out a chronicle of the flow field imaging sensors' evolution.

Table 1. Survey of existing flow field characterization (2D/3D) approaches (beyond conventional local measurements techniques).

Technology	Advantages	Limitations	References
Particle image velocimetry	Non-intrusive for cross section	Optical access required for test region; fluid seeded with micro-particles required; high-power laser needed for reducing size of tracer particles; Suitable for low void-fraction.	[3]
Optical probes array	Simple and cheap	Accuracy sensitive to signal being measured; particularly sensitive to low void-fraction small-bubble cases.	[4]
X-ray tomography	Non-intrusive for cross section	Small field of view; radiation concern; expensive.	[5]
Optical tomography	Non-intrusive for cross section	Limited by light source and detectors; limited penetration depth.	[5]
Ultrasonic methods	Non-intrusive for cross section	Large-seeded particles required; resolution limited by separating signals from seeds and bubbles; suitable for low void-fraction.	[6]
Wire-mesh sensor	High temporal and spatial resolutions	Slightly intrusive for cross section.	[7]

Note that existing imaging technologies primarily serve current fleets of nuclear reactors, whereas new reactor designs and systems require updating and upgrading of the flow characterization techniques in terms of multi-modalities monitoring, high-speed data capture, storage, retrieval, and interference mitigation, for which the technologies mentioned in Table 1 above struggle to fulfill these more and more stringent requirements at the same time.

Fortunately, since Kenneth O. Hill's discovery of photosensitivity in optical fiber and his monumental achievement in demonstrating the first fiber Bragg grating (FBG) [8], FBG devices have gained traction in a broad mix of optical communication and sensing applications. Notably, they have the potential to become an appealing option as one of the original disruptors for flow instrumentation technology. FBGs are essentially periodic perturbations in the refractive index of an optical fiber, which act as a wavelength-selective reflector (filter). They are fabricated by exposing a photosensitive fiber to a pattern of ultraviolet laser beam via a phase mask (with a shaped diffraction grating), which causes a refractive index modulation in the fiber core. The reflected signal's wavelength is sensitive to temperature, strain, pressure, and concentration, etc., hence the formation of FBG sensors for the real-time characterization of temperature, void fraction, flow rate, pressure, and concentration, both locally and cross-sectionally (e.g., multi-phase imaging). Formidable partners in FBG manufacturing have emerged in recent years, e.g., FBGS for single-fiber multi-sensors multiplexing solutions. ITF and other researchers [9] are taking a step further in formulating FBG sensor arrays.

2. Discussion

FBGs have a host of advantages over traditional sensing technologies, including high sensitivity and accuracy (wavelength shifting dependence is not impacted by the signal's amplitude variations, and is immune to electromagnetic interference); high resolution, both spatially (for detecting small changes of small bubbles) and temporally (fast response time for transients); robustness in withstanding harsh environments (high temperatures and pressures); and multiplexing capabilities for multi-modalities monitoring (fields of temperatures, strain, and pressures) and multi-phase flow visualization at the same time.

Like the performance evolution from a single antenna to an antenna array, grouping FBG sensors into an array can revolutionize the field of fluid characterization by providing accurate and reliable measurements of various fluid properties (measuring multiple parameters simultaneously). This allows for a more comprehensive understanding of fluid behavior and properties, which can be used to identify and diagnose problems, as well as to improve the design and performance of various fluid systems. This also allows for a redefinition of fundamental limits to imaging-based flow metrology by enabling the sensing of new modalities with a multi-tasking capability, which can lead to improved efficiency and reduced downtime, i.e., significant economic benefits for complex nuclear systems.

The FBG sensors array is also highly versatile and can be used in a wide range of fluid systems, including oil and gas pipelines, chemical processing plants, and biomedical applications. This versatility makes FBG sensors a valuable tool for researchers and engineers working in a variety of fields. A summary of the advantages of the FBG sensors array is portrayed in Figure 1.

Despite the many advantages of the FBG sensors array, some challenges need to be addressed. First and foremost, the cost of FBG sensors (and the interrogation/readout electronic packages) can be prohibitive for some applications. Additionally, the interpretation of FBG array data can be challenging, requiring specialized knowledge and expertise in manipulating the multiplexing readout circuits.

Overall, the departure from convention has slowed over the past decade. Crucially, continuous innovation is an essential underpinning of FBG's deployment roadmap in fluid characterization for TH applications. Nevertheless, every step towards improvement comes with trade-offs. It is necessary to integrate existing industrial competencies even more deeply into research and education to expand the current working knowledge of the literature. Back to the FBG sensor design stage, existing works [10–13] mostly involve analytical modelling coupled with experimental exploration. Contrarily, there is a need for developing semi-analytical modelling by incorporating multi-physics simulation and, notably, computational fluid dynamics (CFD) models representing the FBG array interfacing the multi-phase flow. Techniques of multi-scale modeling (space and time) need to be accounted for. Research directions are envisaged in developing customized in-house or open-source codes, a suite of models and software packages, and firmware dedicated to the FBG array-based multi-phase flow characterization with an eye on SWaP-C (size, weight, power, and cost). Accordingly, there will be a gap that must be filled in researchers' training pertaining to expert mastery in fiber optics, photonics, electronics (including array signal processing), thermal hydraulics, and CFD. Each of these technical challenges and gaps identified will occupy a PhD student for a couple of years, who will ultimately contribute to build up of technical expertise and the advancement of knowledge, from sensing devices to readout techniques.

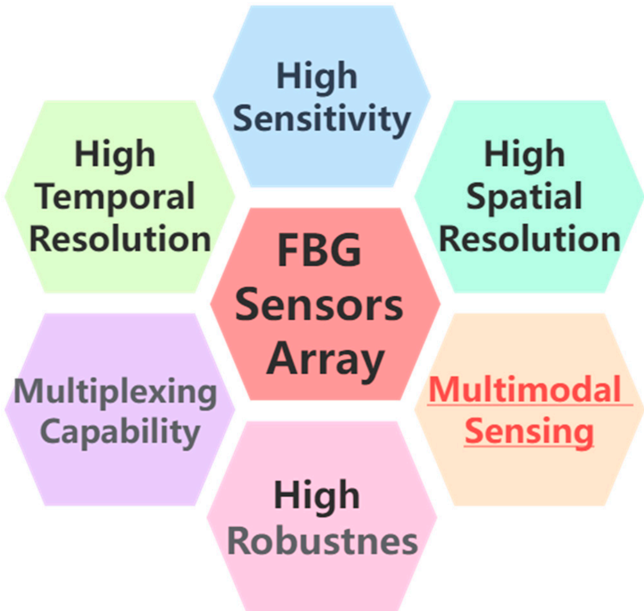

Figure 1. Advantages of FBG sensors array for flow characterization.

Unlocking the potential of FBG sensors for flow instrumentation requires a holistic and multidisciplinary approach. It is advised by this editorial that the transferrable concept of low redundancy sparse antenna array can be incorporated into the FBG sensors array design for reduced components, costs, and complexity, whilst upholding decent characterization functionality and performance. Furthermore, the FBG array topology can be formulated by unequally distributing annular rings to capture the inhomogeneous flow behavior and patterns in a pipe. It is also advisable to leverage the recent advances in active metasurface optics [14], with computation overheads being reduced by deep neural networks [15].

3. Conclusions

Real-time instrumentation of high resolution (spatial and temporal) forms an integral part of nuclear thermal hydraulics' development roadmap. Situated at the interface of optical, electrical, thermal sciences, and other research disciplines, the FBG sensors array has the potential to take flow characterization to new heights by providing accurate and reliable measurements of various properties (temperature, pressure, flow rate, void fraction, concentration, and multi-phase mapping) at the same time with single-device hardware, which reduces the cost, downtime, and uncertainties as compared with conventional sensor fusion-based approaches (requiring integration of diverse types of sensors in a system). Arguably, the use of the FBG sensors array can lead to the improved efficiency and better performance of flow systems. While there are still some challenges that remain to be addressed, the benefits of the FBG array make it a valuable tool for researchers and engineers working in a variety of fields.

Last but not least, although achieving the trade-offs between performance, manufacturability, and cost is always crucial, it is also well worth thinking outside the box and beyond the possible, making FBG array flow imaging an art, driving a design revolution and engaging interdisciplinary collaboration to support the delivery of a vision that aspires to the development of reliable, robust, and agile flow monitoring for thermal hydraulics applications that drive the nuclear sector to continuously decarbonize the world's economic activity towards the fulfillment of the net-zero carbon mandate by 2050.

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Conflicts of Interest: The author declares no conflict of interest.

References

1. Zhang, D.; Deng, J.; Xu, Z.; Mori, M. Editorial: Thermal Hydraulics and Safety Analysis in Generation-IV Reactors. *Front. Energy Res.* **2021**, *9*, 670412. [CrossRef]
2. Wakabayashi, G.; Yamada, T.; Endo, T.; Pyeon, C.H. Nuclear Instrumentation. In *Introduction to Nuclear Reactor Experiments*, 1st ed.; Springer: Singapore, 2023; Volume 5, pp. 137–152.
3. Rohacs, D.; Yasar, O.; Kale, U.; Ekici, S.; Yalcin, E.; Midilli, A.; Karakoc, T.H. Past and current components-based detailing of particle image velocimetry: A comprehensive review. *Heliyon* **2023**, *9*, 14404. [CrossRef] [PubMed]
4. Tien, T.M.; Huang, C.J.; Lee, C.H.; Liu, K.W. Fiber-Optic Probe Array for Measuring Spatial Distributions of Air Volume Fractions in Bubbly Flows. *Sensors* **2023**, *23*, 1222. [CrossRef] [PubMed]
5. Hampel, U.; Barthel, F.; Bieberle, A.; Bieberle, M.; Boden, S.; Franz, R.; Kipping, M.N.; Köhler, S.T. Tomographic imaging of two-phase flow. *Int. J. Adv. Nucl. React. Des. Technol.* **2020**, *2*, 86–92. [CrossRef]
6. Fan, J.; Wang, F. Review of ultrasonic measurement methods for two-phase flow. *Rev. Sci. Instrum.* **2021**, *92*, 091502. [CrossRef] [PubMed]
7. Tompkins, C.; Prasser, H.M.; Corradini, M. Wire-mesh sensors: A review of methods and uncertainty in multiphase flows relative to other measurement techniques. *Nucl. Eng. Des.* **2018**, *337*, 205–220. [CrossRef]
8. Hill, K.O. Photosensitivity in optical fiber waveguides: From discovery to commercialization. *IEEE J. Sel. Top. Quantum Electron.* **2000**, *6*, 1186–1189. [CrossRef]
9. Dmitriev, A.A.; Gribaev, A.I.; Varzhel, S.V.; Konnov, K.A.; Motorin, E.A. High-performance fiber Bragg gratings arrays inscription method. *Opt. Fiber Technol.* **2021**, *63*, 102508. [CrossRef]
10. Allil, A.S.; Dutra, F.S.; Dante, A.; Carvalho, C.C.; Allil, R.C.S.B.; Werneck, M.M. FBG-Based Sensor Applied to Flow Rate Measurements. *IEEE Trans. Instrum. Meas.* **2021**, *70*, 7000608. [CrossRef]
11. Gouvêa, P.M.P.; Medeiros, K.A.R.; Ribeiro, A.S.; Barbosa, C.R.H.; Almeida, J.R.M.; Braga, A.M.B. Non-Intrusive Fluid Flow Measurement by FBG Sensing of Flow-Induced Vibrations. In Proceedings of the Advanced Photonics, Zurich, Switzerland, 2–5 July 2018.
12. Zamarreño, C.R.; Martelli, C.; Baroncini, V.H.V.; Santos, E.N.; Silva, M.J.; Morales, R.E.M.; Matias, I.R.; Arregui, F.J. Two-Phase Flow Imaging by means of an 8×8 Optical Fiber Bragg Grating Grid. In Proceedings of the Advanced Photonics, Barcelona, Spain, 27–31 July 2014.
13. Luo, C.; Wang, H.; Zhang, D.; Zhao, Z.; Li, Y.; Li, C.; Liang, K. Analytical Evaluation and Experiment of the Dynamic Characteristics of Double-Thimble-Type Fiber Bragg Grating Temperature Sensors. *Micromachines* **2021**, *12*, 16. [CrossRef] [PubMed]
14. Thureja, P.; Sokhoyan, R.; Hail, C.U.; Sisler, J.; Foley, M.; Grajower, M.Y.; Atwater, H.A. Toward a universal metasurface for optical imaging, communication, and computation. *Nanophotonics* **2022**, *11*, 3745–3768. [CrossRef]
15. An, S.; Zheng, B.; Julian, M.; Williams, C.; Tang, H.; Gu, T.; Zhang, H.; Kim, H.J.; Hu, J. Deep neural network enabled active metasurface embedded design. *Nanophotonics* **2022**, *11*, 4149–4158. [CrossRef]