

Review

Applications of RIM-Based Flow Visualization in Fluid-Solid Interaction Problems: A Review of Formulations and Prospects

Hanqi Zeng ¹, Deping Cao ^{1,*}, Hao Chen ^{2,*}, Qi Chai ³ and Tianze Lu ¹¹ Department of Hydraulic Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China² Faculty of Science, Agriculture and Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU, UK³ School of Environmental Science and Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China

* Correspondence: 22504@tongji.edu.cn (D.C.); hao.chen@newcastle.ac.uk (H.C.)

Abstract: Over the past three decades, optical visualization measurements based on the Refractive Index Match (RIM) method have played a significant role in the experimental studies of fluid-solid interaction. The RIM method, which coordinates the refractive indices of the liquid and solid materials in the experiment, dramatically reduces the observation error due to optical refraction. However, the existing literature on RIM has not systematically reviewed the various applications of this technique. This review aims to fill this gap by providing a comprehensive overview of the RIM technique, examining its role in material selection for fluid-solid interaction studies, and scrutinizing its applications across various engineering disciplines. The paper begins with a brief introduction to the RIM technique and then turns to material selection and its various applications in fluid-solid interaction. It also enumerates and analyzes specific RIM-based optical measurement techniques such as Laser Doppler Velocimetry (LDA), Particle Tracking Velocimetry (PTV), and Particle Image Velocimetry (PIV) from various research perspectives in previous studies. In addition, it summarizes RIM formulations categorized by different applications in liquid-solid interaction fields. RIM-based measurement techniques generally offer intuitive, non-intrusive, cost-effective, and convenient advantages over traditional methods. The paper also critically evaluates the strengths and limitations of different materials used in RIM experiments and suggests directions for future research, emphasizing the need to develop environmentally friendly and cost-effective RIM materials.

Keywords: Refractive Index Match (RIM); fluid-solid interaction; visualization; optically transparent; formulation



Citation: Zeng, H.; Cao, D.; Chen, H.; Chai, Q.; Lu, T. Applications of RIM-Based Flow Visualization in Fluid-Solid Interaction Problems: A Review of Formulations and Prospects. *Water* **2024**, *16*, 2055. <https://doi.org/10.3390/w16142055>

Academic Editor: Giuseppe Pezzinga

Received: 27 June 2024

Revised: 19 July 2024

Accepted: 19 July 2024

Published: 20 July 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In the open literature, various experimental techniques have been adopted to study the problems of fluid-solid interaction. Conventional fluid sensors are versatile but mostly intrusive setups that produce undesirable physical disturbances to the flow, which may lead to erroneous measurements of the flow. Optical techniques, including laser doppler velocimetry (LDA) (All the abbreviations in the article are summarized in Abbreviations), particle tracking velocimetry (PTV), and particle image velocimetry (PIV), are advantageous for their nonintrusive nature and have been extensively employed in experimental research concerning fluid dynamics. The PIV method, which is commonly used to observe fluid flow fields in transparent glass tanks, has been highly successful in pure fluid experiments. However, the prevalence of opaque flowing media in natural environments poses significant challenges for studying fluid-solid interactions using non-invasive optical measurement techniques. Over recent decades, researchers have begun to use transparent substances and liquids to facilitate their studies, and have achieved some remarkable results. One notable example is the use of RIM in hydraulic engineering to visualize the complex interactions within porous media. In a study by Rousseau and Ancey [1], the RIM technique was employed to align the refractive index of glass beads with that of the

interstitial fluid, allowing for detailed flow measurements within a porous matrix using PIV. This approach not only provided insights into the intricacies of flow behavior within such media but also demonstrated the practical applicability of RIM in enhancing our understanding of fluid-solid dynamics. Another case in point is the application of RIM in geotechnical engineering, where it has been instrumental in visualizing the displacement field of granular media. Mannheimer and Oswald [2] developed transparent porous media with permeabilities and porosities similar to natural soils, enabling the observation of fluid flow and soil interaction without disrupting the soil structure. This has significant implications for the design and assessment of geotechnical structures.

A significant challenge arises when alternative materials are used [3]. Optical distortions are a consequence of the reflection and refraction of light as it traverses device materials and fluids with disparate RIs. The bending of light at a boundary is attributable to the disparity in the velocity of light in the two adjacent media, which results in a change in the direction of the light's trajectory as it propagates. According to Snell's law (also referred to as the law of refraction), when there are significant relative RI mismatches between the two transmission media, the optical path transmission undergoes a significant change. Consequently, the use of optical technologies for the illumination of a specific area to observe flows through interfaces (such as fluid-liquid) with different refractive indices can result in significant uncertainties and inaccuracies in flow measurement. Therefore, the researchers attempted to use materials with the same refractive index for their experiments.

The RIM method, which entails maintaining a uniform refractive index (RI) across all fluid and solid components within an experiment, enables the avoidance of imaging distortion caused by refraction when employing optical techniques such as PIV, PTV, and PLIF. This method is particularly advantageous because it allows the observation of flow within complex geometries and through opaque media, which is not always possible without using RIM. The unique advantage of the RIM method is its ability to provide highly accurate and undistorted flow measurements, making it a versatile tool for a wide range of fluid-solid interaction studies.

The RIM method has been applied in a diverse range of fields, including hydraulic engineering, geotechnical engineering, and environmental pollution control, among others. A diverse array of materials has been used in RIM visualization experiments. The most common solid materials employed in these experiments include: glass [4–6], plastic [7–10], rubber [11–13], resin [14,15], and hydrogel [16–18]. Liquids are classified into two categories: aqueous solutions and organic solutions. Common aqueous solutions include: sodium iodide (NaI) [19–21], ammonium thiocyanate (NH_4SCN) [22], potassium thiocyanate (KSCN) [23]. Glasses are naturally transparent and chemically stable, exhibiting excellent compatibility with a wide range of aqueous and organic fluids. Tetraethylene glycol [24], Turpentine Benzene [21], benzyl alcohol [25], p-cymene [26], mineral oil, and other organic solutions were often used to match the glasses. The selection of organic solid materials (e.g., plastic, rubber, resin) is crucial for ensuring stability and compatibility with organic liquids. Hydrogels were developed with the specific purpose of matching the refractive index of water, thereby greatly expanding the range of potential applications. RIMs with various combinations of fluid-solid systems exhibit unique strengths and weaknesses. It is of great importance to select the most appropriate materials for visualization based on the experiment's objectives (for further details regarding the various materials utilized for different applications, see Section 2).

A detailed account of the various test section arrangements, fluid and solid material choices, and methods for tuning the match has been presented [27]. A broad overview of RIM in visualization techniques is provided particularly on concentrated particle suspensions [28]. Wright et al. [29] provided an overview of fluid-solid and fluid-fluid systems with refractive index matches used in various fields. Fan et al. [30] showed a comprehensive analysis of RIM techniques involving polymethyl methacrylate (PMMA) utilized in flow field visualization experiments. The paper compares various RIM fluid schemes for PMMA based on their refractive indices, densities, viscosities, and costs, thus providing

researchers with a guide for selecting appropriate RIM fluids matched to PMMA. Dai et al. [31] discussed the evolution and advancement of transparent rock soil as a solid RIM, including the experimental apparatus, optical observation techniques, and engineering applications of this technology.

To the best of our knowledge, there is a lack of a comprehensive review that summarises and discusses RIM formulations for different application scenarios and experiments. In this paper, we present a review of RIM visualization experiments for specific applications in the fields of hydraulic engineering and other areas. This review could serve as a reference for researchers in the field. The paper is organized as follows. Section 2 details the application of RIM-based optical visualization technology in research in various fields. Section 3 summarises the RIM formulations in each scenario (including access to materials and experimental operations), providing a reference for researchers seeking to carry out relevant experiments. Also, the advantages and disadvantages of various RIM formulations along with potential future work are discussed in the section. Section 4 presents the summary and conclusions.

2. Applications of RIM

As previously stated in Section 1, RIM techniques have been used across various engineering disciplines. Building on the impact of the RIM technique in elucidating fluid-solid interactions, this section embarks on an in-depth exploration of its diverse applications. We begin by examining the role of RIM in hydraulic and mechanical engineering, demonstrating its efficacy in visualizing turbulent flows in porous media and the subsequent improvement in our understanding of fluid dynamics within these complex structures. The discourse then shifts to the field of geotechnical engineering, highlighting the utility of RIM in demystifying the interactions between solid soil particles and groundwater, which is critical for informed engineering decisions. The section then moves on to environmental engineering, where RIM has proven instrumental in mapping contaminant transport and facilitating the development of targeted remediation strategies. Finally, applications extend to biological engineering, where RIM provides a novel lens for observing cellular dynamics and advancing our understanding of microscale biofluidic processes. This paper presents a comprehensive overview of this research in four subsections, which are detailed as follows.

2.1. Hydraulic/Mechanical Engineering: Porous Media-Fluid (Surface or Pipe Flow) Interaction

Porous media flow is prevalent in nature, engineered materials, animals, and plants. There are various types of porous media, including rocks (such as all kinds of mineral deposits), soils, vegetation, biological materials, and artificial porous media materials. It is essential to get a proper understanding of interaction characteristics when fluids flow over or through porous media because systems like this are utilized in a variety of engineering applications. For example, porous media systems can be found in topics as diverse as gravel beds of natural streams in hydraulic engineering [32,33], turbomachinery design in aerodynamics [34], fuel cells in the energy field [35], and pebble bed reactor cores [36].

In the realm of hydraulic engineering, the interactions between water and soil hold significant importance. Natural soil is a three-phase system consisting of solids, liquids, and gases. Surface water flows, when seeping through the pores of the soil, play a crucial role in regulating water movement and the transformation of aqueous solutes. In the past, engineering focused mainly on the macroscopic motion and characteristics of seepage flow, measuring average medium properties such as porosity, permeability, average velocity, and fluid pressure. For example, most previous studies in the literature [37–41] have primarily described the seepage effect on main flow or sediment transport over a porous bed based on macroscopically averaged seepage flow velocities or turbulence characteristics. This is partly because the microscopic features of pore flow were difficult to measure. Due to differences in pore structure, flow characteristics vary significantly with location. Any type of invasive measuring technique may significantly change the flow characteristics in the local porous media domain. Therefore, non-invasive optical techniques prove to be a

suitable method for measurements. Furthermore, with the aid of the RIM technique for transparency of simulated soils, nowadays researchers have been able to capture the flow field hidden in the porous media. Consequently, it can be anticipated that more precise equations may be proposed in the future to account for the effect of localized flow on sediment transport. This will be followed by a review of several RIM materials and typical applications of RIM-based flow visualization in porous media flow.

Glass beads are frequently utilized as a solid material in the examination of fluid flow in porous media due to their transparency and ease of access. Rousseau and Ancy [1] used glass beads to investigate turbulent flows over and through rough porous beds. The study utilized the RIM technique to align the refractive index of the solid beads with that of the interstitial fluid. PIV was used to visualize and measure flow within the porous matrix. Careful handling and preparation of the glass beads is crucial to maintaining the integrity of the porous structure and ensuring accurate flow measurements. Due to the intellectual property issues involved, it is not possible for us to present the images of the RIM effect from the cited papers directly here, but we have purchased solid and liquid materials for validation. RIM tests for glass beads were performed following the methodology described in this article, as shown in Figure 1. The results demonstrate the significant potential for developing RIM-based optical methods for flow visualization in porous media.

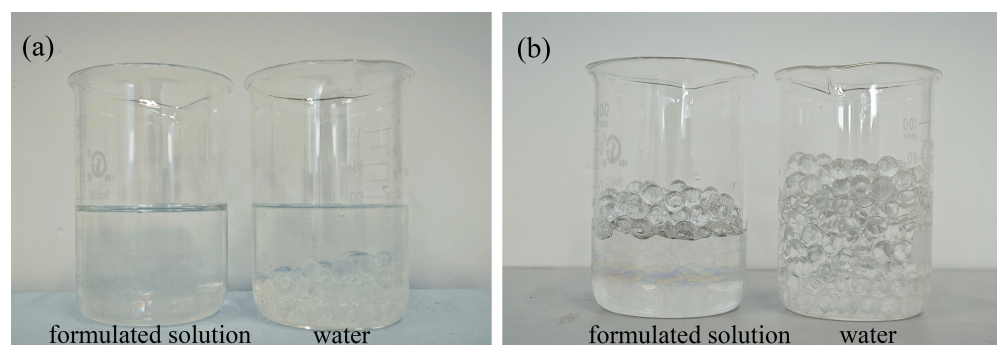


Figure 1. Comparison of optical visualization of glass beads in water and formulated solution from our validation tests following Rousseau and Ancy [1]. Glassbeads (a) fully submerged in the liquids, (b) partially submerged in the liquids.

Hydrogel beads show promise as a material for investigating porous media flow due to their optical transparency and environmental friendliness. In their research, Harshani et al. [42] used hydrogel beads made of superabsorbent polymers that expand upon hydration to imitate the refractive index of water. This characteristic enabled the observation of internal flow fields in the porous medium, providing insights into the behavior of interstitial flows in granular media. To validate the fabrication of hydrogel, various concentrations of polyacrylamide (PAC) were conducted under the methodology outlined in the cited reference [17], as shown in Figure 2. The results demonstrated great feasibility for transparent visualization experiments.

Some other solid materials used in porous media flow include: plastics, resins, and so on. Nguyen et al. [43] utilized PMMA and p-cymene in RIM to explore pore-scale turbulence, revealing intricate flow patterns. Khayamyan et al. [44] investigated inertia-dominated, transitional, and turbulent flow in a randomly packed bed of monosized PMMA spheres using an index-matched fluid with particle image velocimetry method. Fan et al. [45] used a RIM liquid, consisting of 72.2% tetrahydrofuran and 27.8% anhydrous ethanol, which effectively matches the refractive index of PMMA at 25 °C. The RIM match minimizes the impact of refractive index discrepancies between the working fluid and the fuel assembly model in flow field visualization experiments.

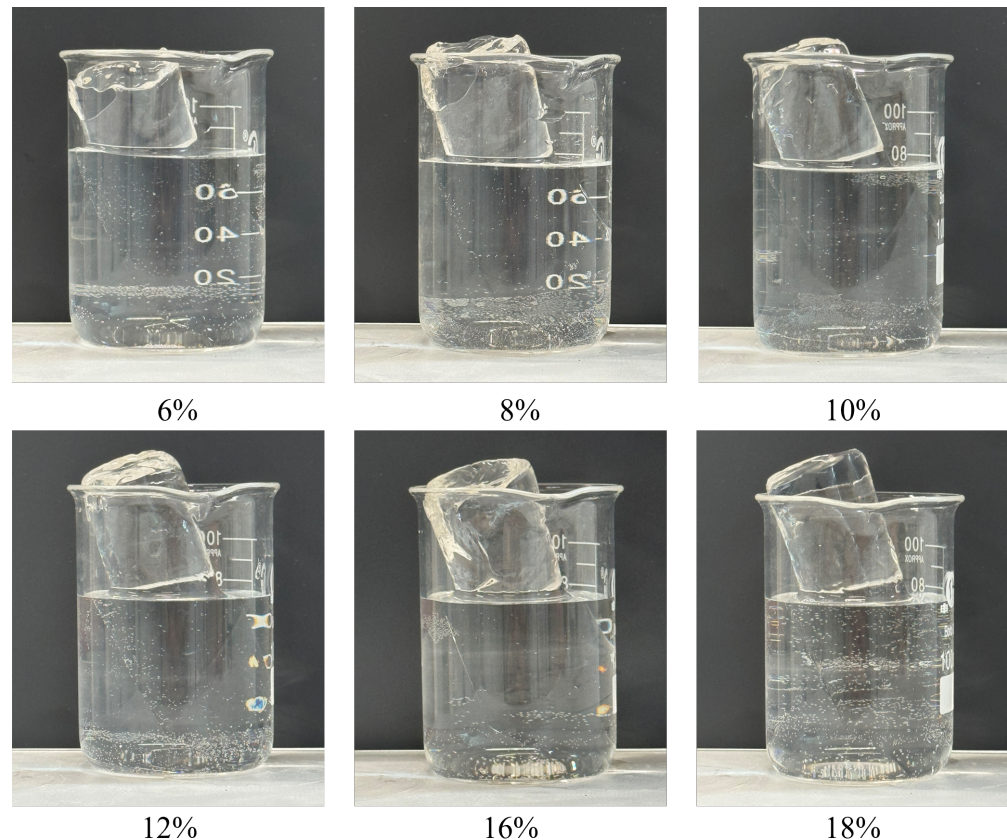


Figure 2. Demonstration in our validation experiments following the procedure given by Byron and Variano [17]. The hydrogels prepared with varying concentrations of PAC exhibited satisfactory optical transparency. The strength of the hydrogels exhibited a positive correlation with the concentration of PAC.

Sabbagh et al. [46] detailed the use of RIM fluids, which presents another dimension in the study of porous media flow. The refractive index of dispersed phases was investigated by the authors using KSCN solutions and oil mixtures. This method allows for the selection of solid materials for porous media studies by matching their refractive index. The study emphasizes the importance of RIM in achieving accurate flow measurements.

Turbulent flows in natural and urban canopies are important for numerous physical and biological processes. The study by Bai et al. [47] represents a significant advance in the field of canopy flow research. The authors employed PIV in conjunction with index-matching techniques, an innovative approach that utilized transparent fractal tree models to permit unimpeded optical access. This approach yielded detailed insights into the turbulent flow structures within complex canopies. The research elucidated the importance of multi-scale elements in flow dynamics and provided a new perspective on horizontal momentum transport through the eddy viscosity model, challenging traditional views and enhancing the precision of canopy flow modeling.

In addition to some typical cases in hydraulic engineering summarized above, several cases of RIM-based porous media flow applications in other fields like mechanical engineering can also bring some insights to the study.

Hassan and Dominguez-Ontiveros [48] utilized RIM to investigate the flow and temperature fields surrounding spherical fuel pebbles in pebble bed reactors. The study introduced the use of PIV in conjunction with matched refractive index fluid to achieve optical access. This provided valuable data for code validation and enhanced the understanding of the complex flow structure within the bed. Fort and Bardet [49] reported a polymer with a refractive index similar to water, simplifying the use of existing facilities to study flows around complex geometries in polymer dynamics. Huang et al. [50] con-

ducted refractive index-matched PIV experiments and computational fluid dynamics (CFD) simulations to investigate the mixing processes in a cavity transfer dynamic mixer.

The diverse materials and techniques applied in these studies collectively enhance our understanding of porous media flow. Each material brings its own set of advantages and considerations, which must be carefully weighed in the context of the specific research objectives and experimental conditions.

2.2. Geotechnical Engineering: Solid Soil Particle-Groundwater Interaction

In the field of civil engineering, the measurement of the displacement field of granular media enables the understanding and prediction of dynamic forms of soil movement, which in turn facilitates the informed decision-making of engineers regarding displacement trends. Conventional soil measurement techniques frequently necessitate the removal of undisturbed soil samples for analysis, yet the opacity of the soil remains a persistent challenge that cannot be readily resolved. Transparent soil has been a subject of considerable interest in geotechnical engineering due to its unique advantages in visualizing soil behavior during various engineering processes. The introduction of transparent geotechnical experiment technology not only enables the visualization of deformation and seepage processes within rocks and soil but also eliminates the need for direct contact between measuring equipment and soil [51,52]. Transparent soil models that replace real soil can be viewed as the interaction and dynamic changes between solid soil particles and groundwater under different engineering situations. It serves as a surrogate for natural geotechnical materials and has been instrumental in advancing the understanding of complex interactions between soil and structures, as well as in the study of soil deformation and failure mechanisms. Consequently, this approach offers distinct advantages including minimal interference with the experimental process, cost-effectiveness, reliable repeatability, high precision, and straightforward device operation. Different kinds of geotechnical transparent soils have been prepared in the published literatures [2,31,53–60].

The pioneering work of Mannheimer and Oswald [2] laid the foundation for subsequent research in the field of transparent porous media with permeabilities and porosities similar to those of soils, aquifers, and petroleum reservoirs. The study by Song et al. [57], which focused on the preparation and geotechnical properties of transparent soil, is particularly noteworthy. They detailed the creation of a transparent soil with clay-like properties by mixing 6% fumed silica with a blend of 70% paraffin and 30% white spirit. This material, with its meticulously reported properties such as density, consolidation coefficient, and undrained shear strength, ensures reproducibility and reliability in experimental setups. Their work significantly contributes to the development of transparent soil models for geotechnical applications. Additionally, Wallace and Rutherford [58] examined LAPONITE RD[®], a synthetic smectite clay, highlighting its unique properties as a transparent soil surrogate. This synthetic clay, when hydrated and consolidated, forms a transparent slurry that allows for non-intrusive observation of soil behavior within physical models. Their research provides valuable insights into the macroscopic geotechnical properties of synthetic clay, demonstrating its potential as a soft clay surrogate for geotechnical physical model testing, especially in offshore geotechnics.

Liu and Iskander [53] compared the boundary soil displacement fields under a model footing with those from a natural soil model to investigate the modeling capacity of transparent soil. A digital image correlation (DIC) technique was employed to quantify soil deformation, which revealed that transparent soil can be utilized to investigate natural soil, albeit with certain constraints. The study demonstrated the potential of transparent soil for advanced three-dimensional deformation measurements in soil-structure interaction problems. Similarly, Yuan et al. [54] conducted an experiment on the displacement field of layered soils surrounding laterally loaded piles using transparent soil. Two particle sizes (0.1–0.5 mm and 0.5–1mm) of saturated transparent soil were achieved by mixing glass sand and transparent pore solution. The integration of transparent soil technology with particle image velocimetry has successfully demonstrated the displacement vectors

of the soil surrounding a laterally loaded pile, offering valuable insights into the soil's displacement behavior. Moreover, the application of transparent visualization technology has the potential to be extended to the monitoring of soil deformation processes and displacement patterns across a range of fields, including but not limited to retaining walls, roadbeds, and agricultural soils. This underscores the versatility and broad applicability of this innovative approach.

Wei et al. [55] prepared a transparent cemented soil (TCS) using fused quartz as the skeleton, hydrophobic fumed silica powder as the cement, and a mixed mineral oil as the pore fluid. The TCS exhibited geotechnical properties similar to those of natural soil and soft rock, making it suitable for physical modeling tests. The study presents empirical formulas for the change in shear strength parameters under varying conditions. Leng et al. [56] expanded upon this research by preparing TCS with different shear strengths and conducting unconsolidated-undrained triaxial compression tests. They analyzed the mechanical characteristics of TCS and revealed the mesoscopic mechanism of changes in its mechanical parameters.

Although transparent geotechnical model experiments provide relatively convenient experimental conditions and intuitive visualization compared to in-situ testing, they tend to simplify some of the influencing factors in real engineering, for instance, approximation of geotechnical materials and simplification of boundary conditions, etc. This will also be discussed in a future in-depth study in Section 3.3. Validation in combination with traditional observation can better help the study to be more accurate.

2.3. Environmental Engineering: Discrete Particle-Flow Interaction

As a consequence of urbanization, pollutants generated by industrial production are contaminating land and water, which will continue to impact the ecological environment and public health. The principal soil pollutants are organic compounds (such as benzene, polycyclic aromatic hydrocarbons, organochlorine pesticides, etc.) and heavy metals (including nickel, lead, zinc, chromium, copper, etc.). These pollutants vary in type, morphology, concentration, risk level, and spatial dispersion. Studying the migration patterns of pollutants and implementing appropriate management measures hold significant importance. Many researchers have conducted studies using RIM to investigate the transport of pollutants through soil [61–65] or in pure water [66,67].

To understand soil contamination, it is essential to visualize the transportation of pollutants. Liu et al. [61] conducted an experiment on the permeation process of grout inside soil using transparent soil made of fused silica and calcium bromide solution with the same refractive index. The study implemented a combined grouting and optical measurement system to visualize grout permeation, revealing that the grout body radius is proportional to grouting time, thus verifying Maag's permeation grouting formula. The findings underscore the importance of matching the refractive index for detailed visualization and have implications for improving grouting techniques in soil remediation and reinforcement.

Kashuk et al. [62] provided a sophisticated optical imaging technique for three-dimensional visualization and quantification of nonaqueous phase liquids (NAPL) distribution within transparent porous media. The methodology uses a transparent soil model, color space segmentation, and an innovative 3D carving algorithm to reconstruct NAPL zones from 2D projections. The results demonstrate the superior accuracy of the technique over conventional image analysis, providing an efficient and non-intrusive approach to studying NAPL behavior in geo-environmental research.

A similar approach can be applied to research on the treatment of soil contaminants. The study conducted by Wu et al. [63] delves into the migration dynamics of remediation agents in contaminated soils using high-pressure jet injection, a technique that has gained prominence for its extensive applicability and cost-effectiveness. The study meticulously investigates the influence of various factors, such as permeability pressure differences, particle size distributions, and void ratios, on the migration rate and distribution area of the

remediation agents. The RIM's significance lies in its ability to provide a real-time, visual, and non-intrusive assessment of the remediation process, which is crucial for optimizing the application of high-pressure jet injection in soil remediation efforts.

In their study, Lo et al. [64] investigated the possibility of visualizing multi-phase flow and surfactant flushing in soil by using transparent Aquabeads and an advanced imaging system. Upon absorption by water, the material becomes transparent and is capable of absorbing up to 200 times its weight in water. Three types of Aquabeads were used in the study to simulate soils with different relative hydraulic conductivities. The study conducted tests on multi-phase flow and surfactant flushing, using mineral oil and motor oil as contaminants. The imaging system deployed provided clear visualizations of the flushing process, highlighting the significant boost in oil recovery rates—95.8% for mineral oil and 88.5% for motor oil—attributed to the prevention of contaminant bypass and the improved efficiency of the surfactant solution. The study demonstrated the benefits of the recently developed system in geoenvironmental research.

Furthermore, RIM has also been used to study the transport of pollutants in pure water. Ni and Capart [66] developed a novel approach for visualizing and quantifying the dynamics of liquid-granular mixtures in open channel flows. The method used a combination of transverse and longitudinal laser scans with PTV to capture the in-plane velocities of both liquid tracers and solid grains in a three-dimensional volume. The study utilized PMMA spheres as the solid phase and para-cymene as the liquid phase to achieve RI matching and enhance optical access. The integrals of the mapped discharge intensities over the channel cross-section were found to be consistent with bulk outlet measurements of liquid and solid discharges, validating the accuracy of the imaging approach. The findings are of great importance for the comprehension of the intricate interactions that occur in granular flows.

In conclusion, the section highlights the RIM method's crucial role in visualizing soil contaminant transport, with applications ranging from grout permeation to NAPL distribution. The use of transparent media and matched fluids provides detailed insights and highlights the need for non-toxic, environmentally friendly materials. Future advances in imaging and RIM integration will significantly improve environmental remediation strategies.

2.4. Solid-Fluid Interaction in Biological Engineering

As researchers continue to investigate the potential applications of the RIM method, several biologically compatible materials are being employed in biological engineering. The fundamental principles underlying RIM remain consistent, yet particular attention must be paid to the materials utilized.

Biofilms are complex communities of microorganisms that adhere to surfaces and are enclosed in a matrix of extracellular polymeric substances they produce. They play a crucial role in various environmental and medical processes due to their unique properties, such as increased resistance to antibiotics and the ability to facilitate nutrient exchange. Leis et al. [68] introduced a non-destructive method for observing microbial biofilms using an optically transparent porous medium made of amorphous fluoropolymers. The biofilms were cultivated in flow cells filled with Nafion granules, which permitted visualization due to the matching of the refractive index between the solid fluoropolymer grains and the aqueous immersion medium. This method represents a significant advance in microbiological research, as it offers a novel approach to examining biofilms in their natural state. The application of confocal microscopy has enabled the real-time, three-dimensional imaging of biofilms, providing insight into the complex structure and dynamic processes within these communities at previously unattainable depths. This technique presents novel opportunities to gain a deeper understanding of the behavior and ecological significance of microbial communities in diverse environments.

In the field of biomedical fluid dynamics, flow phantoms are artificial models designed to mimic the physiological conditions of blood flow in the human body. They are used to study hemodynamics, test medical devices, and improve diagnostic and treatment

methods for vascular diseases. Ho et al. [69] presents a new method for creating flow phantoms for PIV analysis of cerebral aneurysms. The researchers utilized desktop 3D printing technology, specifically Stereolithography (SLA), to fabricate a rigid refractive-index-matched flow phantom. The team printed a cerebral aneurysm's idealized geometry using FLGPCLXX photopolymer resin. The resin was refractive-matched with a working fluid composed of deionized water and NH_4SCN . This approach overcomes the limitations of traditional investment casting techniques, providing a more efficient and cost-effective alternative. This advancement has significant implications for the study of hemodynamics in vascular diseases, with the potential to lead to improved diagnostic and treatment strategies for conditions such as cerebral aneurysms. In the field of sidewall aneurysm hemodynamics, the formation of unsteady vortices was visualized by Le et al. [70], in which a transparent acrylic replica was manufactured to simulate the aneurysm. A solution of sodium iodide, glycerin, and water was matched to the RI of this solid by specific weight percentages. The outcomes of the physical experiments and CFD numerical simulations were found to be highly concordant, demonstrating great experimental potential for flow field visualization in other medically relevant problems. Zhang et al. [71] reported an imaging platform that enables long-term, high-resolution imaging of biofilms for the study of cellular-level dynamics within bacterial biofilms. This platform employs a thin MY133-V2000 polymer film that is glued across the 3D-printed channel, effectively eliminating optical aberrations.

The application of RIM in biological engineering facilitates the study of complex solid-fluid interactions, such as microbial biofilm dynamics and blood flow in medical models. The use of biocompatible materials with tailored refractive indices enables non-invasive, high-resolution imaging, providing unprecedented insights into cellular processes and hemodynamics. This section highlights the importance of material selection and integration of RIM with advanced imaging technologies for future advances in biological and medical research.

3. RIM Formulation Summary, Discussion, and Prospects

3.1. RIM Formulation Summary

A summary of the solid and liquid materials used for RIM realization is presented according to different application areas and topics in Tables 1–4. These tables are intended for researchers to select materials relevant to their fields.

Table 1 summarizes solid and liquid materials in porous media-fluid interaction, focusing mainly on hydraulic engineering. A multitude of solid materials can be used for RIM in this field, e.g., borosilicate glass and hydrogel, among others.

Table 1. Hydraulic/mechanical engineering: porous media-fluid interaction.

Topic	Solid	Liquid	References
1. Turbulent flows over and through rough porous beds	Borosilicate beads	A mixture of 40% ethanol and 60% benzyl alcohol by volume	[1]
2. In-situ measurement of the refractive index of a porous medium in RIM experiments	Borosilicate glass beads (Sigma-Aldrich, Z273619)	(1) KSCN solutions (2) mixtures of Drakeol and soybean oil with different mass fractions	[46]
3. Flow characterization of low aspect ratio randomly packed porous bed	Beads 15 mm diameter (Pyrex®)	Aqueous solution of NH_4SCN	[72]
4. Measuring porous flow characteristics	Hydrogel beads	Water	[42]
5. Destabilization by localized fluidization of a dense granular material	Hydrogel beads	Water	[73]
6. Pore-scale turbulent characteristics in porous media	Polymethyl methacrylate (acrylic)	p-cymene	[43]
7. Foam-like porous structure; 3-D print	Epoxy resin (WaterShed® XC 11122)	Anisole (Sigma-Aldrich)	[74]
8. Mobile granular layer for the sediment transport of spherical particles	Borosilicate; PMMA	Water (15 wt%)+Triton X-100; Triton X-100	[75]

Table 1. *Cont.*

Topic	Solid	Liquid	References
9. Inertia dominated, transitional and turbulent flow	PMMA	an aqueous solution of NH ₄ SCN	[44]
10. Map interstitial flow	THV(manufactured by 3M (Maplewood, MN, USA))	Deionized water mixed with 24.2% glycerin by weight	[76]
11. Turbulent flow inside a complex canopy	UOPTIC (manufactured by Forecast 3D)	An aqueous NaI solution	[47]
12.The dynamic interplay between surface and subsurface flow in the presence of a permeable boundary	acrylic resin (Crystal Clear 204)	An aqueous NaI solution	[77]

For applications in geotechnical engineering, choices of transparent soils are listed in Table 2. Glasses (fumed silica, fused quartz, etc.) are widely used due to their low cost and ready availability. In addition, several commercially available synthetic clays facilitate the production of transparent soil.

Table 2. Geotechnical engineering: solid soil particle-groundwater interaction.

Topic	Solid	Liquid	References
1. Displacement field of the soil around the laterally loaded pile	Glass sand	Mixing n-dodecane and No. 15 white oil with the transparent pore solution with a mass ratio of 1:12	[54]
2. Observation of square anchor rotation	Fumed silica	A mix of 70% paraffin and 30% white spirit by volume	[57]
3. Geotechnical properties	A synthetic smectite clay (LAPONITE RD®)	Distilled water	[58]
4. Internal displacement field during pile-soil interaction	Fused quartz	Mixture of Norpar 12 and white mineral oil	[60]
5. Sand surrogate for use in physical modeling	Fused quartz	Waterbased sucrose solution	[59]
6. Surrogate soil for geotechnical laboratory modelling	Fused quartz	A mixture of hydrophobic fumed silica powder and mineral oil	[55]
7. Transparent cemented soil for physical modeling	Fused quartz (purchased from Xinyi Wanhe Mining Co., Ltd.)	A mixture of n-dodecane and 15# white oil at a mass ratio of 1:3.5 to 1:8 (both purchased from Guangdong Wengjiang Chemical Reagent Co., Ltd.)	[56]

Table 3 provides a summary of the RIM formulations used to study the transport of contaminants in flow or soil.

Table 3. Environmental engineering: discrete particle-flow interaction.

Topic	Solid	Liquid	References
1. Surfactant flushing in remediation of contaminated soils	Aquabeads (produced by Kuraray Chemical Co.)	White mineral oil and motor oil	[78]
2. Remediation of soil contamination	Amorphous silicon powder	Mineral oil solution	[63]
3. NAPL 3D distribution	Fused quartz	A mineral oil blend; low color sucrose (LCS)	[62]
4. Grout permeation	fused silica	Calcium bromide solution	[61]
5. Groundwater contamination by non-aqueous phase liquids	Aquabeads	Mineral oil and motor oil	[64]

Table 4 also illustrates some applications of the RIM method in the fields of biology and medicine. The topics are mainly observations at the cell membrane level in biology and blood flow dynamics in medicine. Excellent biocompatibility is often required in the materials used for RIM formulation.

Table 4. Biological engineering and other applications.

Topic	Solid	Liquid	References
1. Visualization of microbial biofilm architecture and transport dynamics	Nafion (Sigma-Aldrich 495786)	Water	[68]
2. Biomedical fluid dynamics using optical flow visualization	Clear photopolymer resin (FLGPCLXX)	A fluid composed of 66% NH ₄ SCN and 34% deionised water	[69]
3. Vortex phenomena in sidewall aneurysm hemodynamics	Urethane rubber	A solution of sodium iodide, glycerin, and water by weight percentages of 54.3%, 20.8%, and 24.9%	[70]

3.2. Discussion

Each combination of solid and liquid materials used in RIM visualization experiments has its own advantages and disadvantages. Next we will discuss their relative merits and demerits from the perspective of solids and liquids, respectively.

(1) Solid

Glasses, such as those used by Rousseau and Ancey [1], Sabbagh et al. [46], are readily available and exhibit a broad range of RIs, spanning from 1.45 to 1.51. They demonstrate excellent chemical stability, allowing for the matching of a diverse range of aqueous and organic fluids within the system. Additionally, glasses demonstrate robust mechanical properties suitable for stress experiments. Conversely, glass is brittle and susceptible to damage, and its shaping and molding are constrained by numerous limitations. The glass most commonly utilized is spherical or cylindrical in shape.

Plastics are easily obtainable, cost-effective, and can be conveniently produced in various shapes and sizes for RIM experiments. Extrusion, casting, 3D printing, and other processes make plastics widely applied. Commonly used plastics include the following: fluorinated ethylene propylene (FEP), polyvinyl acetate (PVA), PMMA, nylon, and polystyrene (PS). It is crucial to emphasize that plastics are organic materials, and selecting RIM-matching fluids necessitates careful attention to compatibility and stability. Otherwise, plastics and organic liquids dissolve and react, causing changes in refractive index, which makes experiments fail. Resins, which are widely used on eyeglasses in daily life, demonstrate the distinctiveness of being RI-adjustable. A relatively accurate RI ranging from 1.49 to 1.74 can be modulated after the solidification of a mixture of different liquids. However, the cost of utilizing resins is relatively high.

Hydrogels, a novel and convenient material in RIM experiments, exhibit the superior characteristic of being almost RI-equivalent with water, which can be expected to have a broad application prospect. Hydrogels significantly reduce the difficulty of seeking RIM fluids; however, the relatively low strength of hydrogels limits their applications to a few specific scenarios. Also, a salient edge effect appears when hydrogel particles are millimetres in size. The two drawbacks above for hydrogels still require continuous research efforts.

(2) Liquid

The liquids used in the RIM visualization experiments are generally divided into two categories: water and organic liquid. Water is a convenient and accessible medium, while solid materials with a refractive index matching that of water are scarce and must be sought out.

Organic liquid matches are usually configured for solids that have already been identified in experiments. In previous studies, numerous organic liquids and mixtures

thereof have been tested for their suitability as working materials. Organic RIM solutions tend to have several common problems.

(i) Toxicity. Some organic liquids are both toxic and volatile, which necessitates the implementation of appropriate ventilation and security measures during experimentation. (ii) Cost. Whether they are purchased off the shelf or prepared in the laboratory, the cost of the organic RIM solutions is often quite high, compared with the easily obtained natural fluid like water. (iii) Differences in the physical properties of the fluid. The RIM method addresses the fundamental issue of optical errors between fluids and solids. Nevertheless, there are discrepancies in the physical properties of the matching fluids and the actual fluids, including hydraulic characteristics such as density, viscosity, surface tension, and so forth. Consequently, researchers must select suitable matching fluids to ensure flow similarity. It is also necessary to consider other physical differences. (iv) Relatively low stability. Some studies have proposed that experiments be conducted in a shorter time frame to prevent changes in the properties of the organic liquid, such as density and viscosity. Additionally, there have been studies conducted on the stability of the matching fluids. (v) Relatively low compatibility with other materials. Organic liquids are easily intermiscible or reactive with several common materials.

When selecting a liquid for RIM experiments, it is crucial to consider both the optical matching requirements and the specific experimental conditions. Here are some practical tips and guidelines: (i) Optical matching. The primary goal is to match the refractive index of the liquid to that of the solid material used in the experiment. (ii) Temperature effects. The refractive index of liquids can change with temperature. It is advisable to perform experiments at a controlled temperature or to select liquids with minimal temperature dependent refractive index variation. For example, in the study by Ni and Capart [66], the temperature was kept constant to ensure accurate RI matching. (iii) Pressure sensitivity. High pressure conditions can affect the density and therefore the refractive index of liquids. Select liquids with stable refractive indices under the expected pressure ranges of the experiment. (iv) Duration of the experiment. Some liquids can change their properties over time, affecting the longevity of the RIM match. Choose fluids with proven stability over the duration of the experiment. As noted in Lo et al. [64]’s study, the stability of the RIM fluid was a critical factor in the long-term visualization of multiphase flow. (v) Toxicity and Safety. Consider the toxicity and safety profile of the fluids, especially when working in a laboratory environment. Use appropriate ventilation and personal protective equipment when handling potentially hazardous fluids.

By considering these factors, researchers can make informed decisions when selecting fluids for RIM experiments, improving the accuracy and reliability of their studies.

3.3. Future Research Topics on RIM

Having enumerated the advantages and disadvantages of RIM-based optical visualization measurements, the future of RIM-based research depends on the development of materials that overcome current limitations and better serve the needs of experimental fluid dynamics. Here are potential research directions with a focus on non-toxic, environmentally friendly, and cost-effective RIM materials:

(i) Non-toxic materials. A significant area of research should be devoted to creating RIM materials that do not pose health risks. This includes avoiding toxic organic solvents and developing alternatives that are safe to handle and dispose of, thereby improving laboratory safety and reducing environmental impact.

(ii) Environmentally friendly materials. There is a need to explore the use of biodegradable or recyclable materials in RIM formulations. This could include the use of materials derived from renewable resources or those that can be degraded by microorganisms after use, thereby reducing the carbon footprint of RIM experiments.

(iii) Diversification of solid shapes and particles and implementation of 3D printing. The expansion of RIM applications requires the creation of a variety of solid shapes and particles that can be tailored to specific experimental needs. The advent of 3D printing

technologies opens up unprecedented opportunities for the precise fabrication of complex geometries, enhancing the versatility and customization of RIM solids.

(iv) Physical properties that mimic real-world fluids. A critical direction is to develop RIM materials with physical properties such as density, viscosity, and surface tension that closely mimic those of real-world fluids such as water. This would ensure that experimental results are more representative of practical engineering scenarios, thereby increasing the applicability of RIM-based research results.

(v) Integration with advanced technologies. Future RIM materials should be compatible with state-of-the-art imaging and computing technologies. This includes developing materials that can be effectively visualized using high-speed cameras, 3D scanning, and other advanced imaging techniques, as well as those that can be accurately modeled in computational fluid dynamics simulations.

4. Conclusions

RIM-based optical visualization measurements have become an important research topic in the field of fluid-solid interactions with a broad application prospect. This paper presents an overview of the application of the RIM method, with a focus on the formulation and prospects. RIM formulations for different fluid-solid interaction application areas are summarized. Furthermore, this paper discusses the advantages and disadvantages of different materials. Finally, the possible research directions on RIM are also given.

To sum up, the following conclusions can be drawn:

(i) Compared with the traditional engineering measurements of fluid flow and fluid-solid interaction in hydraulic engineering, RIM-based optical visualization measurements have the great advantages of being intuitive, non-intrusive, low-cost, and convenient. Combined with image processing techniques, this method can obtain and display the flow field information in real-time and quickly, which has a broad application prospect.

(ii) The selection of suitable solid and liquid materials for optically transparent visualization is crucial. When water is used as the liquid in RIM configurations, it is necessary to identify reliable solids for refractive index matching. Furthermore, the careful selection of RIM-matched liquids, particularly organic ones, for common solid materials is of the utmost importance to ensure the accuracy and reliability of experimental results. Due to the demerits of organic solutions (toxicity and cost, etc) as illustrated previously, one of the future research directions is to develop the RIM technique so that natural water can be used as RIM fluid.

(iii) Continued advances in imaging and computational analysis techniques are critical to improving the capabilities and applicability of RIM-based methods. As the resolution and sensitivity of imaging systems improve and as the capabilities of computational models and data processing algorithms increase, RIM techniques will achieve higher levels of accuracy and detail in the visualization of complex fluid-solid interactions. Future research should focus on integrating state-of-the-art imaging modalities such as high-speed cameras, 3D scanning, and holography with powerful image processing and machine learning tools to gain deeper insights from RIM-based experiments.

(iv) The interdisciplinary nature of RIM-based research provides opportunities for collaboration across different scientific and engineering domains. The convergence of materials science, fluid dynamics, optical engineering, and computational physics can yield innovative solutions that address current challenges and open new frontiers in the research and application of RIM methods.

In general, the accuracy of RIM-based visualization measurement methods is steadily improving with the continuous advancement of image acquisition and processing technologies. By emphasizing the importance of material selection, technology integration, and interdisciplinary collaboration, we aim to inspire a new wave of innovation that will advance the understanding and application of fluid-solid interaction studies. With this development, it is foreseeable that the RIM method will be applied in many more fields in the future.

Author Contributions: Conceptualization, H.Z. and D.C.; methodology, H.Z. and D.C.; formal analysis, H.Z. and D.C.; investigation, H.Z. and D.C.; writing—original draft preparation, H.Z.; writing—review and editing, D.C., H.C., Q.C. and T.L.; supervision, D.C. and H.C.; project administration, D.C.; funding acquisition, D.C. All authors have read and agreed to the submitted version of the manuscript.

Funding: The authors would like to acknowledge the support provided by the Fundamental Research Funds for the Central Universities (22120240016) and the National Key Research and Development Program of China (2022YFC3106205).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

RIM	Refractive Index Match
LDA	Laser Doppler Velocimetry
PIV	Particle Image Velocimetry
PMMA	Polymethyl methacrylate
DIC	Digital image correlation
NAPL	Nonaqueous phase liquids
KSCN	Potassium thiocyanate
PVA	Polyvinyl acetate
THV	Tetrafluoroethylene hexafluoropropylene vinylidene fluoride
RI	Refractive indices
PTV	Particle Tracking Velocimetry
PLIF	Planer Laser Induced Fluorescence
PAC	Polyacrylamide
TCS	Transparent cemented soil
NH ₄ SCN	Ammonium thiocyanate
FEP	Fluorinated ethylene propylene
PS	Polystyrene

Reference

1. Rousseau, G.; Ancey, C. Scanning PIV of turbulent flows over and through rough porous beds using refractive index matching. *Exp. Fluids* **2020**, *61*, 172. [\[CrossRef\]](#)
2. Mannheimer, R.; Oswald, C. Development of Transparent Porous Media with Permeabilities and Porosities Comparable to Soils, Aquifers, and Petroleum Reservoirs. *Groundwater* **1993**, *31*, 781–788. [\[CrossRef\]](#)
3. Tang, J.; Wang, C.; Liu, F.; Yang, X.; Wang, R. A Refractive Index- and Density-Matched Liquid–Liquid System Developed Using a Novel Design of Experiments. *Processes* **2023**, *11*, 1922. [\[CrossRef\]](#)
4. McIlroy, H.M., Jr.; McEligot, D.M.; Pink, R.J. Measurement of turbulent flow phenomena for the lower plenum of a prismatic gas-cooled reactor. *Nucl. Eng. Des.* **2010**, *240*, 416–428. [\[CrossRef\]](#)
5. Dietze, G.F.; Al-Sibai, F.; Kneer, R. Experimental study of flow separation in laminar falling liquid films. *J. Fluid Mech.* **2009**, *637*, 73–104. [\[CrossRef\]](#)
6. Hirsch, D.; Graff, E.C.; Pereira, F.; Gharib, M. Influence of common transparent materials on the accuracy of image-based velocimetry. *Meas. Sci. Technol.* **2015**, *26*, 087002. [\[CrossRef\]](#)
7. Amini, N.; Hassan, Y.A. An investigation of matched index of refraction technique and its application in optical measurements of fluid flow. *Exp. Fluids* **2012**, *53*, 2011–2020. [\[CrossRef\]](#)
8. Tomac, M.N.; Gregory, J.W. Internal jet interactions in a fluidic oscillator at low flow rate. *Exp. Fluids* **2014**, *55*, 1730. [\[CrossRef\]](#)
9. Fort, C.; Fu, C.D.; Weichselbaum, N.A.; Bardet, P.M. Refractive index and solubility control of para-cymene solutions for index-matched fluid–structure interaction studies. *Exp. Fluids* **2015**, *56*, 210. [\[CrossRef\]](#)
10. Zhu, W.; Knapp, Y.; Deplano, V. Low hazard refractive index and density-matched fluid for quantitative imaging of concentrated suspensions of particles. *Exp. Fluids* **2016**, *57*, 68. [\[CrossRef\]](#)
11. Buchmann, N.; Atkinson, C.; Jeremy, M.; Soria, J. Tomographic particle image velocimetry investigation of the flow in a modeled human carotid artery bifurcation. *Exp. Fluids* **2011**, *50*, 1131–1151. [\[CrossRef\]](#)
12. Kefayati, S.; Poepping, T.L. Transitional flow analysis in the carotid artery bifurcation by proper orthogonal decomposition and particle image velocimetry. *Med. Eng. Phys.* **2013**, *35*, 898–909. [\[CrossRef\]](#)

13. Yagi, T.; Sato, A.; Shinke, M.; Takahashi, S.; Tobe, Y.; Takao, H.; Murayama, Y.; Umezu, M. Experimental insights into flow impingement in cerebral aneurysm by stereoscopic particle image velocimetry: Transition from a laminar regime. *J. R. Soc. Interface* **2013**, *10*, 20121031. [\[CrossRef\]](#)
14. Satake, S.I.; Aoyagi, Y.; Unno, N.; Yuki, K.; Seki, Y.; Enoeda, M. Three-dimensional flow measurement of a water flow in a sphere-packed pipe by digital holographic PTV. *Fusion Eng. Des.* **2015**, *98*–99, 1864–1867. [\[CrossRef\]](#)
15. Unno, N.; Nakata, S.; Satake, S.I.; Taniguchi, J. Three-dimensional particle tracking around microstructures in water via total internal reflection fluorescence microscopy and refractive-index-matching method. *Exp. Fluids* **2016**, *57*, 120. [\[CrossRef\]](#)
16. Kang, J.H.; Lee, K.J.; Nam, J.H.; Kim, C.J.; Park, H.S.; Lee, S.; Kwang, I. Visualization of invasion-percolation drainage process in porous media using density-matched immiscible fluids and refractive-index-matched solid structures. *J. Power Sources* **2010**, *195*, 2608–2612. [\[CrossRef\]](#)
17. Byron, M.L.; Variano, E.A. Refractive-index-matched hydrogel materials for measuring flow-structure interactions. *Exp. Fluids* **2013**, *54*, 1456. [\[CrossRef\]](#)
18. Weitzman, J.S.; Samuel, L.C.; Craig, A.E.; Zeller, R.B.; Monismith, S.G.; Koseff, J.R. On the use of refractive-index-matched hydrogel for fluid velocity measurement within and around geometrically complex solid obstructions. *Exp. Fluids* **2014**, *55*, 1862. [\[CrossRef\]](#)
19. Blois, G.; Christensen, K.; Best, J.; Elliott, G.; Austin, J.; Dutton, C.; Bragg, M.; Garcia, M.; Fouke, B. A versatile refractive-index-matched flow facility for studies of complex flow systems across scientific disciplines. In Proceedings of the 50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Nashville, TN, USA, 9–12 January 2012. [\[CrossRef\]](#)
20. Bai, K.; Katz, J. On the refractive index of sodium iodide solutions for index matching in PIV. *Exp. Fluids* **2014**, *55*, 1704. [\[CrossRef\]](#)
21. Reddy, R.K.; Sathe, M.J.; Joshi, J.B.; Nandakumar, K.; Evans, G.M. Recent developments in experimental (PIV) and numerical (DNS) investigation of solid-liquid fluidized beds. *Chem. Eng. Sci.* **2013**, *92*, 1–12. [\[CrossRef\]](#)
22. Khayamy, S.; Lundström, T.S.; Hellström, J.G.I.; Gren, P.; Lycksam, H. Measurements of Transitional and Turbulent Flow in a Randomly Packed Bed of Spheres with Particle Image Velocimetry. *Transp. Porous Media* **2017**, *116*, 413–431. [\[CrossRef\]](#)
23. Agrawal, Y.K.; Sabbagh, R.; Sanders, S.; Nobes, D.S. Measuring the Refractive Index, Density, Viscosity, pH, and Surface Tension of Potassium Thiocyanate (KSCN) Solutions for Refractive Index Matching in Flow Experiments. *J. Chem. Eng. Data* **2018**, *63*, 1275–1285. [\[CrossRef\]](#)
24. Stephenson, J.; Stewart, W. Optical measurements of porosity and fluid motion in packed beds. *Chem. Eng. Sci.* **1986**, *41*, 2161–2170. [\[CrossRef\]](#)
25. Cui, M.; Adrian, R. Refractive index matching and marking methods for highly concentrated solid-liquid flows. *Exp. Fluids* **1997**, *22*, 261–264. [\[CrossRef\]](#)
26. Huang, A.Y.; Huang, M.Y.; Capart, H.; Chen, R.H. Optical measurements of pore geometry and fluid velocity in a bed of irregularly packed spheres. *Exp. Fluids* **2008**, *45*, 309–321. [\[CrossRef\]](#)
27. Budwig, R. Refractive index matching methods for liquid flow investigations. *Exp. Fluids* **1994**, *17*, 350–355. [\[CrossRef\]](#)
28. Wiederseiner, S.; Andreini, N.; Epely-Chauvin, G.; Ancey, C. Refractive-index and density matching in concentrated particle suspensions: A review. *Exp. Fluids* **2011**, *50*, 1183–1206. [\[CrossRef\]](#)
29. Wright, S.F.; Zadrazil, I.; Markides, C.N. A review of solid–fluid selection options for optical-based measurements in single-phase liquid, two-phase liquid–liquid and multiphase solid–liquid flows. *Exp. Fluids* **2017**, *58*, 108. [\[CrossRef\]](#)
30. Fan, D.; Li, R.; He, M.; Li, X.; Li, J.; Wen, J.; Hu, Y.; Li, Y.; Li, Y.; Gu, L.; et al. Review of Refractive Index-Matching Techniques of Polymethyl Methacrylate in Flow Field Visualization Experiments. *Int. J. Energy Res.* **2023**, *2023*, 3413380. [\[CrossRef\]](#)
31. Dai, X.; He, L.; Wu, W.; Chen, J. Visualization experiment technology based on transparent geotechnical materials and its engineering application. *J. Vis.* **2023**, *26*, 145–159. [\[CrossRef\]](#)
32. Packman, A.I.; Salehin, M.; Zaramella, M. Hyporheic Exchange with Gravel Beds: Basic Hydrodynamic Interactions and Bedform-Induced Advective Flows. *J. Hydraul. Eng.* **2004**, *130*, 647–656. [\[CrossRef\]](#)
33. Bakhtyar, R.; Brovelli, A.; Barry, D.; Li, L. Wave-induced water table fluctuations, sediment transport and beach profile change: Modeling and comparison with large-scale laboratory experiments. *Coast. Eng.* **2011**, *58*, 103–118. [\[CrossRef\]](#)
34. Badum, L.; Leizeronok, B.; Cukurel, B. New Insights from Conceptual Design of an Additive Manufactured 300 W Microgas Turbine Toward Unmanned Aerial Vehicle Applications. *J. Eng. Gas Turbines Power* **2021**, *143*, 021006. [\[CrossRef\]](#)
35. Zhang, Y.; Tao, Y.; Ren, H.; Wu, M.; Li, G.; Wan, Z.; Shao, J. A metallic gas diffusion layer and porous media flow field for proton exchange membrane fuel cells. *J. Power Sources* **2022**, *543*, 231847. [\[CrossRef\]](#)
36. Reger, D.; Merzari, E.; Balestra, P.; Schunert, S.; Hassan, Y.; Yuan, H.; Lan, Y.H.; Fischer, P.; Min, M. Pressure Drop Correlation Improvement for the Near-Wall Region of Pebble-Bed Reactors. *Nucl. Technol.* **2023**, *209*, 90–104. [\[CrossRef\]](#)
37. Cao, D.; Chiew, Y.M. Suction effects on sediment transport in closed-conduit flows. *J. Hydraul. Eng.* **2014**, *140*, 04014008. [\[CrossRef\]](#)
38. Cao, D.; Chiew, Y.M.; Liu, X. Effect of suction zone length on sediment transport. *J. Hydraul. Res.* **2015**, *53*, 49–59. [\[CrossRef\]](#)
39. Cao, D.; Chiew, Y.M.; Yang, S.Q. Injection Effects on Sediment Transport in Closed-Conduit Flows. *Acta Geophys.* **2016**, *64*, 125–148. [\[CrossRef\]](#)
40. Kumar, V.S.; Shanas, P.; Dora, G.U.; Glejin, J.; Philip, S. Longshore sediment transport in the surf zone based on different formulae: A case study along the central west coast of India. *J. Coast. Conserv.* **2017**, *21*, 1–13. [\[CrossRef\]](#)

41. Cao, D.; Yuan, J.; Chen, H. Towards modelling wave-induced forces on an armour layer unit of rubble mound coastal revetments. *Ocean. Eng.* **2021**, *239*, 109811. [\[CrossRef\]](#)
42. Harshani, H.; Galindo-Torres, S.; Scheuermann, A.; Muhlhaus, H. Experimental study of porous media flow using hydro-gel beads and LED based PIV. *Meas. Sci. Technol.* **2017**, *28*, 015902. [\[CrossRef\]](#)
43. Nguyen, T.; King, S.; Hassan, Y. Experimental investigation of turbulent characteristics in pore-scale regions of porous media. *Exp. Fluids* **2021**, *62*, 72. [\[CrossRef\]](#)
44. Khayamyan, S.; Lundström, T.S.; Gren, P.; Lycksam, H.; Hellström, J.G.I. Transitional and Turbulent Flow in a Bed of Spheres as Measured with Stereoscopic Particle Image Velocimetry. *Transp. Porous Media* **2017**, *117*, 45–67. [\[CrossRef\]](#)
45. Fan, D.; Peng, T.; Wen, J.; Tang, Y.; Tian, W.; Li, R.; Wang, D.; Gu, L. Study on Refractive Index Matching Liquid of Polymethyl Methacrylate Employed in Flow Field Visualization Experiment. *At. Energy Sci. Technol.* **2020**, *54*, 1604–1611. (In Chinese) [\[CrossRef\]](#)
46. Sabbagh, R.; Ansari, S.; Nobes, D.S. An imaging approach for in-situ measurement of refractive index of a porous medium. *Opt. Lasers Eng.* **2020**, *134*, 106175. [\[CrossRef\]](#)
47. Bai, K.; Katz, J.; Meneveau, C. Turbulent Flow Structure Inside a Canopy with Complex Multi-Scale Elements. *Bound.-Layer Meteorol.* **2015**, *155*, 435–457. [\[CrossRef\]](#)
48. Hassan, Y.A.; Dominguez-Ontiveros, E. Flow visualization in a pebble bed reactor experiment using PIV and refractive index matching techniques. *Nucl. Eng. Des.* **2008**, *238*, 3080–3085. [\[CrossRef\]](#)
49. Fort, C.; Bardet, P.M. Refractive-index-matched polymer for experimental fluid dynamics in water. *Exp. Fluids* **2021**, *62*. [\[CrossRef\]](#)
50. Huang, F.; Chen, P.; Wang, J.; Li, Z.; Gao, Z.; Derksen, J.J. Refractive Index-Matched PIV Experiments and CFD Simulations of Mixing in a Complex Dynamic Geometry. *Ind. Eng. Chem. Res.* **2020**, *59*, 7982–7992. [\[CrossRef\]](#)
51. Bathurst, R.J.; Ezzein, F.M. Geogrid and soil displacement observations during pullout using a transparent granular soil. *Geotech. Test. J.* **2015**, *38*, 673–685. [\[CrossRef\]](#)
52. Ferreira, J.A.; Zornberg, J.G. A transparent pullout testing device for 3D evaluation of soil–geogrid interaction. *Geotech. Test. J.* **2015**, *38*, 686–707. [\[CrossRef\]](#)
53. Liu, J.; Iskander, M.G. Modelling capacity of transparent soil. *Can. Geotech. J.* **2010**, *47*, 451–460. [\[CrossRef\]](#)
54. Yuan, B.; Li, Z.; Zhao, Z.; Ni, H.; Su, Z.; Li, Z. Experimental study of displacement field of layered soils surrounding laterally loaded pile based on transparent soil. *Journal of Soils and Sediments* **2021**, *21*, 3072–3083. [\[CrossRef\]](#)
55. Wei, L.; Xu, Q.; Wang, S.; Wang, C.; Chen, J. Development of transparent cemented soil for geotechnical laboratory modelling. *Eng. Geol.* **2019**, *262*, 105354. [\[CrossRef\]](#)
56. Leng, X.; Wang, C.; Pang, R.; Sheng, Q.; Chen, J. Material Preparation and Geotechnical Properties of Transparent Cemented Soil for Physical Modeling. *Front. Mater.* **2021**, *8*, 740388. [\[CrossRef\]](#)
57. Song, Z.; Hu, Y.; O’Loughlin, C.; Randolph, M.F. Loss in anchor embedment during plate anchor keying in clay. *J. Geotech. Geoenviron. Eng.* **2009**, *135*, 1475–1485. [\[CrossRef\]](#)
58. Wallace, J.F.; Rutherford, C.J. Geotechnical properties of LAPONITE RD®. *Geotech. Test. J.* **2015**, *38*, 574–587. [\[CrossRef\]](#)
59. Guzman, I.L.; Iskander, M.; Suescun-Florez, E.; Omidvar, M. A transparent aqueous-saturated sand surrogate for use in physical modeling. *Acta Geotech.* **2014**, *9*, 187–206. [\[CrossRef\]](#)
60. Kong, G.Q.; Cao, Z.H.; Zhou, H.; Sun, X.J. Analysis of piles under oblique pullout load using transparent-soil models. *Geotech. Test. J.* **2015**, *38*, 725–738. [\[CrossRef\]](#)
61. Liu, J.; Gao, Y.; Sui, W. *Visualization of Grout Permeation inside Transparent Soil*; American Society of Civil Engineers (ASCE): Reston, VA, USA, 2013; number 232 GSP, pp. 188–194. [\[CrossRef\]](#)
62. Kashuk, S.; Mercurio, S.R.; Iskander, M. Methodology for optical imaging of NAPL 3D distribution in transparent porous media. *Geotech. Test. J.* **2015**, *38*, 603–619. [\[CrossRef\]](#)
63. Wu, Y.; Han, Y.; Tang, X.; Chen, M.; Chen, T. Transparent Soil Test on Factors Affecting Transport of High-pressure Jet Contaminated Soil. *J. Tongji Univ.* **2020**, *48*, 1305–1311. (In Chinese) [\[CrossRef\]](#)
64. Lo, H.C.; Tabe, K.; Iskander, M.; Yoon, S.H. *Modeling of Multi-Phase Flow and Surfactant Flushing Using Transparent Aquabeads*; American Society of Civil Engineers (ASCE): Reston, VA, USA, 2008; Volume 179, pp. 846–853. [\[CrossRef\]](#)
65. Brovelli, A.; Carranza-Diaz, O.; Rossi, L.; Barry, D. Design methodology accounting for the effects of porous medium heterogeneity on hydraulic residence time and biodegradation in horizontal subsurface flow constructed wetlands. *Ecol. Eng.* **2011**, *37*, 758–770. [\[CrossRef\]](#)
66. Ni, W.J.; Capart, H. Cross-sectional imaging of refractive-index-matched liquid-granular flows. *Exp. Fluids* **2015**, *56*, 163. [\[CrossRef\]](#)
67. Dijkstra, J.A.; Rietz, F.; Lorincz, K.A.; Van Hecke, M.; Losert, W. Invited Article: Refractive index matched scanning of dense granular materials. *Rev. Sci. Instruments* **2012**, *83*, 011301. [\[CrossRef\]](#)
68. Leis, A.P.; Schlicher, S.; Franke, H.; Strathmann, M. Optically transparent porous medium for nondestructive studies of microbial biofilm architecture and transport dynamics. *Appl. Environ. Microbiol.* **2005**, *71*, 4801–4808. [\[CrossRef\]](#) [\[PubMed\]](#)
69. Ho, W.; Tshimanga, I.; Ngoepe, M.; Jermy, M.; Geoghegan, P. Evaluation of a Desktop 3D Printed Rigid Refractive-Indexed-Matched Flow Phantom for PIV Measurements on Cerebral Aneurysms. *Cardiovasc. Eng. Technol.* **2020**, *11*, 14–23. [\[CrossRef\]](#)
70. Le, T.B.; Troolin, D.R.; Amatya, D.; Longmire, E.K.; Sotiropoulos, F. Vortex phenomena in sidewall aneurysm hemodynamics: Experiment and numerical simulation. *Ann. Biomed. Eng.* **2013**, *41*, 2157–2170. [\[CrossRef\]](#)

71. Zhang, J.; Zhang, M.; Wang, Y.; Donarski, E.; Gahlmann, A. Optically Accessible Microfluidic Flow Channels for Noninvasive High-Resolution Biofilm Imaging Using Lattice Light Sheet Microscopy. *J. Phys. Chem. B* **2021**, *125*, 12187–12196. [[CrossRef](#)] [[PubMed](#)]
72. Patil, V.A.; Liburdy, J.A. Flow characterization using PIV measurements in a low aspect ratio randomly packed porous bed. *Exp. Fluids* **2013**, *54*, 1497. [[CrossRef](#)]
73. Dramé, A.S.; Wang, L.; Zhang, Y. Destabilization of Immersed Dense Granular Material Submitted to Localized Fluidization: An Experimental and Numerical Study. *J. Spectrosc.* **2021**, *2021*, 5542835. [[CrossRef](#)]
74. Butscher, D.; Hutter, C.; Kuhn, S.; Von Rohr, P.R. Particle image velocimetry in a foam-like porous structure using refractive index matching: A method to characterize the hydrodynamic performance of porous structures. *Exp. Fluids* **2012**, *53*, 1123–1132. [[CrossRef](#)]
75. Aussillous, P.; Chauchat, J.; Pailha, M.; Medale, M.; Guazzelli, E. Investigation of the mobile granular layer in bedload transport by laminar shearing flows. *J. Fluid Mech.* **2013**, *736*, 594–615. [[CrossRef](#)]
76. Hilliard, B.; Reeder, W.J.; Skifton, R.S.; Budwig, R.; Basham, W.; Tonina, D. A Biologically Friendly, Low-Cost, and Scalable Method to Map Permeable Media Architecture and Interstitial Flow. *Geophys. Res. Lett.* **2021**, *48*, e2020GL090462. [[CrossRef](#)]
77. Kim, T.; Blois, G.; Best, J.L.; Christensen, K.T. Experimental evidence of amplitude modulation in permeable-wall turbulence. *J. Fluid Mech.* **2020**, *887*, A3. [[CrossRef](#)]
78. Lo, H.C.; Tabe, K.; Iskander, M.; Yoon, S.H. A transparent water-based polymer for simulating multiphase flow. *Geotech. Test. J.* **2010**, *33*, 1–13. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.