A Survey on Water Drag, Air Pressure, and Two-Phase Flow Dynamics in Engineering Systems

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Abstract

This survey paper provides an exhaustive exploration of pivotal engineering concepts, including water drag, air pressure, and two-phase flow dynamics, and their substantial implications for system performance and efficiency across diverse engineering applications. The paper examines the intricate interrelationships between these phenomena, emphasizing their role in optimizing aquatic locomotion, energy conversion systems, and fluid dynamics. It highlights the integration of machine learning with computational fluid dynamics (CFD) to enhance simulation capabilities and offers insights into complex flow behaviors. The survey also delves into the impact of air pressure on system dynamics, including its effects on MEMS gyroscopes and micromechanical resonators, and explores innovative approaches for pressure monitoring. Additionally, the paper investigates two-phase flow dynamics, focusing on advancements in computational fluid dynamics and the cooperative dynamics of nanoparticles. The distribution and environmental implications of hydrogen sulfide gas and the principles of gravity-driven flow in drainage systems are also analyzed. The survey synthesizes findings from diverse studies to offer a cohesive perspective on these engineering concepts, fostering innovation and guiding future research directions. By addressing these areas, the survey aims to contribute to the enhancement of system design and operational efficiency across multiple engineering disciplines, while identifying challenges and solutions in system design and future research directions.

1 Introduction

1.1 Significance of Key Concepts in Engineering

Understanding fundamental engineering concepts such as water drag, air pressure, and two-phase flow dynamics is essential for optimizing the performance and efficiency of engineering systems. Water drag is a critical factor in aquatic locomotion and energy conversion systems. For example, analyzing the drag dynamics on an accelerating submerged rectangular flat plate is vital for enhancing performance in activities such as rowing [1]. Additionally, the oscillating water column (OWC) serves as a wave energy converter (WEC), highlighting the importance of mastering water drag to improve energy conversion efficiency [2]. In hydraulic fracturing, the effectiveness of drag reducers, particularly under saline conditions, is crucial for system performance [3].

In fluid dynamics, the integration of machine learning with computational fluid dynamics (CFD) significantly enhances simulation capabilities, providing insights into complex flow behaviors and system optimizations [4]. The interactions of nanoparticles in air further illustrate the intricate dynamics affecting system performance [5]. Air pressure is pivotal in various engineering applications, influencing the gas damping coefficient of MEMS gyroscopes, which is essential for their functionality [6]. A precise understanding of air pressure effects is also crucial in applications involving micromechanical air-filled cavities [7].

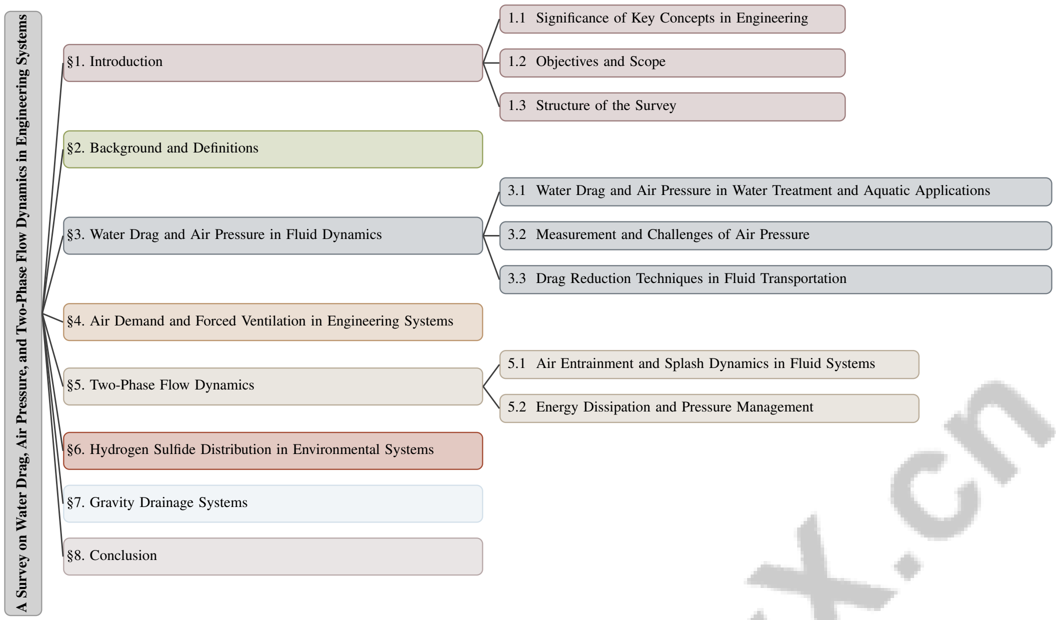

Figure 1: chapter structure

The interdependencies among meteorological variables, such as wind speed, wind direction, and air pressure, are critical for optimizing wind turbine operations and enhancing wind energy generation efficiency. Understanding two-phase flow dynamics, where liquid and gas phases coexist, is vital in energy systems. The dynamics of diving wedges entering water improve predictive capabilities in naval engineering and injury prevention [8]. Furthermore, coastal wetlands act as buffers to incident wave energy, emphasizing the importance of these dynamics for environmental protection and energy dissipation [9].

In engineering systems, internal dissipation in coated micro-cantilevers is crucial for enhancing the sensitivity and usability of cantilever-based sensors [10]. The optimization of neural network architectures is also essential for addressing the complexity of datasets and the demand for efficient models that generalize well [11]. Integrating these key concepts enhances efficiency and performance while driving innovation, laying the groundwork for future advancements across diverse applications.

1.2 Objectives and Scope

This survey aims to conduct a comprehensive exploration of the pivotal concepts of water drag, air pressure, and two-phase flow dynamics within engineering systems. It seeks to unravel the complex interrelationships between these phenomena and their significant implications for system performance and efficiency across various engineering applications. The investigation into water drag will analyze hydrodynamic efficiency in aquatic locomotion, considering factors such as finger spreading on stroke efficiency during swimming [12], as well as the influence of drag on energy conversion systems like wave energy converters [2]. This aligns with research emphasizing the importance of understanding drag forces in contexts such as wave-vegetation interactions, where porosity and inertia critically affect wave propagation [9].

Regarding air pressure, the survey will explore its impact on system dynamics, including its effect on the instability of viscous liquid drops [13] and the functioning of MEMS gyroscopes [6]. Furthermore, it will delve into the effects of air pressure on micromechanical resonators, where pressure variations influence the mechanical properties of suspended membranes [7]. Innovative approaches for pressure monitoring in low-pressure environments will be examined [14], alongside applications of air pressure in processes such as organic waste composting [15]. Additionally, the survey will investigate statistical methodologies for predicting meteorological variables essential for optimizing wind energy generation.

The scope extends to two-phase flow dynamics, focusing on integrating time-lapse seismic data with dynamic flow models to improve CO_2 saturation estimates [16]. The survey will spotlight

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advancements in computational fluid dynamics, particularly the application of machine learning in simulating compressible two-phase flows [4]. Moreover, it will address the cooperative dynamics of nanoparticles influenced by air pressure, which are vital for motion control in fluid systems [5]. Investigating liquid water transport in mixed-wettability gas diffusion layers and its effects on capillary pressure and water saturation will also be a focal point [17].

This survey aims to synthesize findings from diverse studies to offer a cohesive perspective on these engineering concepts, fostering innovation and guiding future research directions. It will also consider developing numerical models for simulating oscillations in systems such as sea organs, where water levels and air pressure interact [18]. By addressing these areas, the survey endeavors to enhance system design and operational efficiency across multiple engineering disciplines. Additionally, it will examine the characterization of internal dissipation in micro-cantilevers influenced by air pressure and metallic coatings, as explored in [10], to elucidate its significance in sensor technology and system optimization.

1.3 Structure of the Survey

This survey is meticulously structured to provide an in-depth exploration of critical engineering concepts such as water drag, air pressure, and two-phase flow dynamics, and their implications for system performance and efficiency. The paper is organized into distinct sections outlining the objectives, methodology, findings, and implications of the study, providing a comprehensive overview of the evolution of bacterial and fungal flora during in-vessel composting of organic household waste under controlled air pressure conditions [5, 15].

The **Introduction** section establishes the foundation by discussing the significance of these key engineering concepts, outlining the objectives, and defining the scope of the survey. This section also provides an overview of the paper's organization.

The **Background and Definitions** section offers precise definitions and explanations of fundamental terms, including water drag, air pressure, air demand, forced ventilation, two-phase flow dynamics, hydrogen sulfide distribution, and gravity drainage systems, underscoring their relevance in various engineering contexts.

In the **Water Drag and Air Pressure in Fluid Dynamics** section, we investigate the roles of water drag and air pressure within fluid dynamics, examining their effects on engineering systems. This section discusses factors influencing water drag, techniques for measuring air pressure, challenges in maintaining optimal pressure levels, and strategies for drag reduction in fluid transportation systems [19].

The **Air Demand and Forced Ventilation in Engineering Systems** section explores the significance of air demand and the role of forced ventilation in sustaining optimal conditions. It addresses mechanical systems used for air circulation and their applications, focusing on specialized environments and energy systems [15].

The **Two-Phase Flow Dynamics** section delves into the behavior of systems where liquid and gas phases coexist. It covers topics such as air entrainment, splash dynamics, energy dissipation, and pressure management, providing insights into system efficiency and design [4].

The **Hydrogen Sulfide Distribution in Environmental Systems** section analyzes the distribution and dispersion of hydrogen sulfide gas, examining its environmental implications and the methods employed to monitor and control its distribution [16].

The **Gravity Drainage Systems** section investigates the design and function of gravity-driven systems used for fluid and waste movement. It discusses the principles of gravity-driven flow, design considerations, and applications in engineering and environmental management [18].

The **Conclusion** section synthesizes the key findings and insights, emphasizing the importance of understanding these concepts for enhancing engineering systems. It also discusses the challenges and solutions in system design and identifies future research directions and emerging trends [5].

Each section of the paper is carefully crafted to build upon existing literature, incorporating innovative approaches and experimental evaluations to provide a comprehensive understanding of the topics covered. The survey's structure mirrors the methodological rigor found in studies such as those

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by Ambach et al. and Xu et al. [11], ensuring a systematic exploration of the subject matter.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Theoretical Framework and Modeling Approaches

Theoretical frameworks and modeling approaches are pivotal in deciphering the complexities of engineering systems, particularly concerning water drag, air pressure, and two-phase flow dynamics. These methodologies facilitate the examination of phenomena that significantly affect system efficiency and performance. In fluid dynamics, the integration of high-order numerical methods and automatic differentiation, as demonstrated by Bezgin et al., enhances the predictive capabilities for complex flow behaviors [4]. The Immersed Boundary Method (IBM) exemplifies computational techniques for simulating fluid flow around intricate geometries, such as hand interactions with water during swimming [20].

Modeling multiphase flows presents challenges due to unclosed terms from phase interactions, which limit the predictive power of existing turbulence models. Beetham et al. underscore the necessity of capturing complex interactions, such as particle clustering, to accurately describe fluid dynamics in these systems [21]. Moreover, understanding air-fluid interface dynamics in compliant channels reveals new propagation modes and instabilities, offering insights into multiphase system behaviors [22]. The three-dimensional volume of fluid (VOF) model, utilized by Niu et al., aids in simulating two-phase flow in gas diffusion layers (GDLs) with various PTFE treatments, enhancing water management understanding in PEM fuel cells [17].

In terms of air pressure, theoretical frameworks analyze mechanical properties under varying conditions pertinent to fluid dynamics. The Squeeze Film Effects Analysis (SFEA) method proposed by Næsby et al. focuses on these analyses [7]. Bocchi et al. introduce a nonlinear mathematical model capturing the dynamics of oscillating water columns (OWC), addressing time-dependent air pressure variations impacting energy conversion processes [2]. Additionally, controlled air pressure is crucial in environmental engineering for enhancing microbial activity during aerobic composting processes [15].

Theoretical advancements also enhance the understanding of viscous drops, with Xu et al. exploring the balance between destabilizing and stabilizing stresses during impact, critical for understanding instability conditions [23]. Models categorizing impact phenomena based on solid textures and air pressure emphasize the significance of microscopic boundary conditions on macroscopic flow dynamics [24]. Nonlinear shallow water equations with non-hydrostatic pressure, as utilized by Suzuki et al., simulate wave propagation in the presence of vegetation, accounting for drag forces from both vertical and horizontal vegetation [9].

In two-phase flow dynamics, models preserving hyperbolicity effectively capture compressible flow dynamics, allowing for accurate wave propagation across both dense and dilute regimes while ensuring thermodynamic consistency [25]. These models are crucial in understanding wave dynamics and liquid-gas phase interactions. The interplay between pore geometry and wettability, as proposed by Rabbani et al., leads to unique interfacial behaviors significantly affecting fluid recovery [26]. The integration of these theoretical frameworks and modeling approaches fosters a comprehensive understanding of complex engineering systems, driving innovation and enhancing efficiency across diverse applications.

Incorporating advanced methodologies, frameworks such as the Time-dependent numerical model for sea organ simulation (TDNSOS) proposed by Krvavica et al. couple hydrodynamic and thermodynamic equations to improve comprehension of multiphase hydrodynamic processes [18]. The application of quasilinear hyperbolic equations and the Nash-Moser inverse function theorem, discussed by Shao et al., provides a robust theoretical basis for analyzing long-term behaviors in complex systems [27]. The multivariate seasonal time-varying threshold autoregressive model with threshold ARCH (TVARX-TARCHX) introduced by Ambach et al. integrates periodicity, conditional heteroscedasticity, and interactions among meteorological variables, enhancing forecasting accuracy in air pressure-influenced systems. Additionally, controlling solid surface wettability, as explored by Hwang et al., has significant implications for drag reduction and buoyancy enhancement, further illustrating the importance of theoretical frameworks in optimizing engineering applications [28].

3 Water Drag and Air Pressure in Fluid Dynamics

In fluid dynamics, the interactions between water drag and air pressure are fundamental to both theoretical insights and practical applications. This section explores their significance, particularly in water treatment and aquatic contexts, to understand their influence on system performance and efficiency, setting the foundation for further exploration in the following subsections. Table 3 presents a comparative overview of the primary focus areas, innovative techniques, and efficiency impacts in water treatment, air pressure measurement, and fluid transportation, illustrating the integration of advanced methodologies in fluid dynamics. Figure 2 illustrates the hierarchical structure of key concepts in fluid dynamics related to water drag and air pressure, highlighting their significance in water treatment, aquatic applications, and fluid transportation. The chart categorizes the interactions and measurement challenges of water drag and air pressure, as well as innovative drag reduction techniques, emphasizing the role of chemical and physical innovations in optimizing system performance and energy efficiency.

3.1 Water Drag and Air Pressure in Water Treatment and Aquatic Applications

The interaction of water drag and air pressure is pivotal for optimizing water treatment processes and enhancing aquatic applications, significantly influencing system efficiency. In water treatment, drag dynamics are affected by factors like acceleration and submersion depth, with peak drag force observed at a 20 mm depth [1]. This understanding is crucial for optimizing filtration and sedimentation processes, where precise fluid dynamics control is essential.

The application of superhydrophobic (SHPo) surfaces and Liquid-Infused Surfaces (LIS) shows promise in reducing drag within turbulent flows. LIS offers robustness against pressure fluctuations and shear forces, providing sustained drag reduction compared to SHPo surfaces [20]. This is particularly beneficial in aquatic applications, where reducing water drag can enhance water transport efficiency and minimize energy consumption [28].

Air pressure is critical in phenomena like liquid drop splashing upon impact with solid surfaces, where ambient air pressure significantly influences the creation of thin liquid sheets [23]. In the context of oscillating water columns (OWC) as wave energy converters, time-dependent air pressure interactions with waves are crucial for water treatment and aquatic applications [2].

The Volume of Fluid (VOF) model used to simulate two-phase flow in gas diffusion layers (GDLs) highlights the importance of understanding capillary pressure and water saturation, especially with PTFE distribution [17]. This modeling approach is vital for optimizing water management in systems like PEM fuel cells.

In environmental engineering, controlled air pressure enhances microbial activity during composting, as shown by the IVCAP method, which improves compost quality and efficiency [15]. The challenge of accurately measuring pressures in the sub-pascal range, particularly in rarefied air or high vacuum conditions, emphasizes the need for advanced sensor technologies [29].

These studies underscore the complex interplay between water drag and air pressure in water treatment and aquatic applications, revealing their significant influence on system efficiency. The research highlights the urgent need for innovative strategies, such as using drag-reducing polymers and liquid-infused surfaces, to enhance fluid dynamics and optimize these processes for improved performance and energy conservation [1, 30, 20].

As shown in Figure 3, understanding the interactions between water drag and air pressure is essential, especially in water treatment and aquatic environments. The first figure illustrates a fluid flow measurement system, crucial for accurate fluid flow analysis. The second figure shows the relationship between drag ratio and Reynolds number, providing insights into variable interactions. The third image describes a flow visualization experiment setup, highlighting the components involved in analyzing fluid dynamics. Together, these elements underscore the significance of water drag and air pressure in enhancing efficiency in water treatment and aquatic applications [30, 31, 32].

3.2 Measurement and Challenges of Air Pressure

Accurate air pressure measurement is vital in engineering systems, directly influencing performance and efficiency. Advanced techniques have been developed to address measurement challenges,

Benchmark	Size	Domain	Task Format	Metric
TSPS[24]	1,000	Fluid Dynamics	Drop Impact Analysis	Splash Size, Splash Frequency

Table 1: This table presents a representative benchmark dataset used in fluid dynamics research, specifically focusing on drop impact analysis. The dataset includes key metrics such as splash size and splash frequency, which are crucial for understanding the influence of air pressure on fluid behavior.

Benchmark	Size	Domain	Task Format	Metric
TSPS[24]	1,000	Fluid Dynamics	Drop Impact Analysis	Splash Size, Splash Frequency

Table 2: This table presents a representative benchmark dataset used in fluid dynamics research, specifically focusing on drop impact analysis. The dataset includes key metrics such as splash size and splash frequency, which are crucial for understanding the influence of air pressure on fluid behavior.

especially under varying conditions. For example, evaluating air damping in MEMS gyroscopes involves analyzing the relationships between air damping and performance metrics, highlighting dependencies between air pressure and system functionality [6].

Innovative approaches, like using mechanical quality factors and resonant frequencies, address challenges in maintaining optimal pressure levels, as variations can significantly affect system performance [7]. The Time-dependent numerical model for sea organ simulation (TDNSOS) compares numerical results with experimental data, providing insights into dynamic interactions between air pressure and fluid systems [18].

Despite advancements, challenges persist in maintaining optimal air pressure levels. The impact of ambient gas pressure on dynamic wetting, observed in dip-coating experiments, complicates fluid interface control [33]. Similarly, experiments with silicone oil and ethanol drops show fluid behavior sensitivity to air pressure changes, emphasizing the need for precise regulation [23].

Modeling air pressure correlations presents challenges, as traditional methods struggle to capture complex structures in meteorological data. Innovative modeling approaches are crucial for improving air pressure prediction accuracy and process reliability [34]. Observational data analysis using metrics like RMSE and MAE further illustrates measurement difficulties across diverse conditions [35].

While significant progress has been made in developing sophisticated air pressure measurement techniques, ongoing research is needed to address challenges in maintaining optimal pressure levels. These efforts are crucial for improving system performance, particularly in applications involving drag reduction in turbulent flows, where surface property modifications can enhance fluid dynamics and minimize drag forces. Recent studies show liquid-infused surfaces can achieve drag reductions exceeding 35

Figure 4 illustrates the hierarchical structure of research topics in air pressure measurement and challenges. It categorizes the advancements in techniques, ongoing challenges, and applications or improvements in related fields. Each category is supported by specific studies, highlighting the multifaceted nature of air pressure research. Additionally, Table 2 provides a detailed overview of a representative benchmark dataset utilized in the study of fluid dynamics and its relevance to air pressure measurement challenges.

3.3 Drag Reduction Techniques in Fluid Transportation

Drag reduction in fluid transportation systems is crucial for enhancing efficiency and minimizing energy consumption, particularly in industries like petroleum, where pipeline friction resistance can hinder capacity [30]. Advanced polymers, such as hydrophobic associating polyacrylamide (HAPAM), have demonstrated a maximum drag reduction rate of 76.7

Physical surface characteristics also play a crucial role in drag reduction. Liquid-Infused Surfaces (LIS) achieve drag reductions of up to 35

Surface roughness and air pressure significantly influence splash behavior, as experiments reveal variations based on these factors [24]. Understanding these dynamics is essential for refining drag reduction techniques, as aquatic vehicles and sports equipment design can be optimized by comprehending drag dynamics during acceleration [1]. Future research could refine splash models by incorporating detailed water pile-up dynamics and exploring different geometries, enhancing drag reduction strategies [8].

High-resolution measurements of mechanical loss tangents in micro-cantilevers provide insights into dissipation characteristics, related to drag reduction techniques in fluid transportation [10]. These measurements are crucial for understanding fluid dynamics and material properties interactions, informing effective drag reduction solutions.

Recent advancements in drag reduction techniques emphasize the interplay between chemical and physical innovations. Liquid-infused surfaces demonstrate remarkable drag reduction of over 35

As shown in Figure 5, understanding the interplay between water drag and air pressure is crucial for optimizing fluid transportation systems. The example explores innovative drag reduction techniques, pivotal in enhancing fluid flow efficiency. One approach highlighted is polymer synthesis via inverse emulsion polymerization, depicted in the first image. This chemical process involves monomer reaction with a sodium salt of a diisocyanate, resulting in a polymer that potentially alters fluid dynamics by reducing drag. The second image illustrates water flow through a channel with strategically placed air pockets, enhancing surface hydrophobicity (SHPo). This setup demonstrates how air pockets create a slip boundary condition, reducing frictional forces on the water, thus minimizing drag. These examples underscore the importance of material science and engineering in developing solutions to reduce drag, leading to more efficient and sustainable systems [30, 31].

Feature	Water Drag and Air Pressure in Water Treatment and Aquatic Applications	Measurement and Challenges of Air Pressure	Drag Reduction Techniques in Fluid Transportation
Key Focus Area	Water Treatment	Air Pressure Measurement	Fluid Transportation
Innovative Techniques	Superhydrophobic Surfaces	Advanced Sensor Technologies	Hydrophobic Polymers
Impact on Efficiency	Enhanced Transport Efficiency	Improved System Performance	Reduced Energy Consumption

Table 3: This table provides a comparative analysis of key focus areas, innovative techniques, and their impact on efficiency within the domains of water treatment, air pressure measurement, and fluid transportation. It highlights the role of superhydrophobic surfaces, advanced sensor technologies, and hydrophobic polymers in enhancing system performance and reducing energy consumption. The table serves as a synthesis of current methodologies and their contributions to fluid dynamics optimization.

4 Air Demand and Forced Ventilation in Engineering Systems

4.1 Ventilation in Specialized Environments

Specialized ventilation systems are crucial for maintaining safety and efficiency in environments where optimal conditions are necessary. In karst environments, ventilation regulates temperature, humidity, and gas concentrations to preserve subsurface ecosystems. The Milandre cave system research highlights the importance of understanding natural airflow patterns for effective ventilation strategies, ensuring ecological balance and preventing harmful gas accumulation [36].

In industrial settings, advanced ventilation systems manage hazardous airborne contaminants like hydrogen sulfide and ammonia, protecting worker health and ensuring compliance with environmental regulations. These systems are tailored to specific air quality needs in operations such as chemical manufacturing and mining, utilizing advanced sensor technologies and automated controls to optimize real-time ventilation parameters [20, 37, 15, 36].

Healthcare facilities rely on specialized ventilation for infection control and maintaining sterile environments. Hospital and laboratory designs incorporate high-efficiency particulate air (HEPA) filtration and controlled airflow patterns to prevent airborne pathogen transmission, safeguarding patient and healthcare worker health [15, 37, 38, 39].

The deployment of specialized ventilation systems across various environments underscores their role in ensuring safety, efficiency, and ecological balance. Advances in ventilation technologies are expected to address unique environmental challenges, such as optimizing airflow in karst systems and enhancing bioreactor efficiency for composting under controlled air pressure [34, 15, 26, 36].

4.2 Air Breakdown Effect and Energy Systems

Air breakdown poses significant challenges to the stability and efficiency of energy systems, especially where precise pressure measurements are critical. Disturbances such as nonlinearity and instability in mechanical systems complicate accurate pressure assessments, potentially affecting system performance and reliability [40].

Mitigating air breakdown effects requires innovative strategies, such as robust superhydrophobic coatings that reduce water drag and increase buoyancy in aquatic applications, thereby minimizing air breakdown impacts on energy systems [28]. These coatings are engineered for durability under harsh conditions, providing long-term protection.

Advancements in sensor technology, particularly through nanotechnology integration into vacuum gauges, enhance pressure measurement accuracy, improving detection and control of air breakdown phenomena [40]. Addressing energy dissipation and pressure instability issues, these technological advancements contribute to energy system efficiency and stability.

The implications of air breakdown for energy systems highlight the need for continued research and development of advanced materials and sensor technologies. These efforts are crucial for mitigating air breakdown impacts on energy systems, especially in triboelectric nanogenerators (TENGs), where high-voltage air breakdown can limit energy output. By addressing challenges related to air pressure and gas composition, these initiatives aim to enhance energy system reliability and efficiency, promoting sustainable nanogenerator operations and improving environmental safety in areas affected by toxic gas emissions [37, 41].

5 Two-Phase Flow Dynamics

5.1 Air Entrainment and Splash Dynamics in Fluid Systems

Air entrainment and splash dynamics are pivotal in two-phase flow dynamics, impacting system design and optimization. Air entrainment, occurring when air is captured within a liquid during droplet impacts, is influenced by surface tension and ambient conditions, which are crucial for determining flow regimes and system stability [33]. Effective control of these conditions is vital for managing splash dynamics [19]. Instabilities at fluid interfaces, such as fingering and pinning, complicate air entrainment and splash phenomena, influencing three-dimensional flow dynamics [42]. These instabilities are categorized into static types, like Critical Heat Flux and Ledinegg Instability, and dynamic types, such as Density Wave Oscillation and Pressure Drop Oscillation [42].

Understanding flow regimes and interfacial phenomena is essential for predicting two-phase flow behavior. Ghiaasiaan's methodologies categorize flow regimes based on thermodynamic principles and geometry, providing insights into flows in microchannels [43]. Hendrix emphasizes innovative approaches to quantify air entrapment during liquid drop impacts, crucial for performance optimization [44]. Advanced modeling techniques, such as those proposed by Saurel et al., reduce wave speeds needed for accurate modeling, aiding in the management of dense and dilute phases [45]. The phase-field method by Liang offers numerical stability advantages, essential for simulating high-density-ratio flows [46].

Air entrainment and splash dynamics have broad implications across engineering applications, affecting processes like heat transfer, fluid mixing, and chemical reactions. A comprehensive understanding of these phenomena allows for system designs that minimize energy loss and enhance operational stability. Integrating advanced modeling techniques and visualization tools enhances fluid system predictability and control. Liquid-Infused Surfaces, as explored by van der Veen et al., show promise for innovative surface treatments to improve drag reduction and system performance [20].

5.2 Energy Dissipation and Pressure Management

Optimizing two-phase flow systems requires effective energy dissipation and pressure management, as interactions between liquid and gas phases introduce complexities affecting stability and efficiency. Understanding governing dynamics under intermediate-wet conditions and employing advanced modeling techniques, such as high-resolution direct numerical simulations and machine learning-integrated computational fluid dynamics, are crucial for capturing pore-scale physics in applications like enhanced oil recovery and CO2 sequestration [4, 26]. Incorporating non-equilibrium effects, like Maxwell slip at gas boundaries, into continuum models is necessary for precise energy dissipation predictions [33].

Two-phase flow instabilities, differing in macro and micro-channels, present challenges for pressure management, necessitating predictive tools to mitigate their effects [42]. Future research should focus on experimental investigations of these instabilities in micro-channels and refining predictive models to enhance pressure management strategies [42]. Advanced modeling techniques, such as the Phase Field Lattice Boltzmann Method (PFLBM), offer robust frameworks for simulating large-density-ratio two-phase flows, improving control over energy dissipation and pressure regulation [46]. Despite advancements, challenges remain in modeling non-conservative terms, which can yield unphysical results in extreme flow regimes [45]. Addressing these requires developing adaptive numerical methods for multiscale simulations and refined equations of state for phase changes to enhance two-phase flow models' fidelity [45].

The computational demands of simulating larger gas diffusion layer (GDL) structures in fuel cells underscore the need for improved model efficiency and stability [47]. Incorporating component transport and phase changes into these models will further enhance understanding of water transport phenomena, facilitating improved pressure management and energy dissipation strategies [47].

6 Hydrogen Sulfide Distribution in Environmental Systems

Understanding hydrogen sulfide (H_2S) dynamics in environmental systems requires examining the mechanisms of its distribution and emission factors. This section explores modeling methodologies for H_2S emissions, emphasizing the need for precise predictive frameworks to assess environmental impacts, which are crucial for effective emission management.

6.1 Modeling Hydrogen Sulfide Emissions

Modeling H_2S emissions is essential for understanding its distribution and environmental impact, with accurate predictions vital for mitigating associated health and environmental risks. A two-stage mathematical approach enhances emission predictions from environmental discharge channels (EDCs), incorporating air pressure dynamics and droplet behavior [37, 19]. This integration is critical for improving model precision.

The use of sulfide dibimane (SDB) in quantifying H_2S in biological matrices represents a methodological advancement, enhancing emission monitoring and analysis [38]. This approach aids in calibrating predictive models, ensuring a comprehensive understanding of H_2S emissions across environments.

These methodologies underscore the necessity of integrating advanced modeling with precise measurement strategies for effective H_2S emission management. As research progresses, developing sophisticated models and tools will be crucial for addressing environmental challenges posed by H_2S emissions, particularly in wastewater management and composting, thereby safeguarding public health and promoting sustainability [37, 26, 15, 39, 38].

6.2 Environmental Impact and Safety Thresholds

Hydrogen sulfide (H_2S) poses significant environmental risks, particularly when concentrations exceed safety thresholds, threatening human health and ecosystems. Emission assessments from EDCs show H_2S levels can surpass safety limits, necessitating vigilant monitoring and management to prevent adverse effects [37].

Establishing safety thresholds is crucial for public health, determined by concentration levels, exposure duration, and environmental conditions. Advanced measurement techniques, such as LC-MS/MS, enhance monitoring accuracy and provide insights into H_2S's biological roles, essential for refining safety standards [38].

Assessing emissions in wastewater transport highlights the need for robust monitoring and regulatory frameworks to mitigate health risks and set safe operational thresholds near high-emission facilities. Comprehensive modeling, like finite element analysis, predicts the impact of wastewater flow velocities on H_2S concentrations, informing infrastructure design to minimize hazards [37, 23]. Integrating analytical methods with predictive modeling is crucial for effective H_2S emission management, essential for public health and sustainability.

6.3 Hydrogen Sulfide Measurement Techniques

Accurate measurement of hydrogen sulfide (H_2S) concentrations is crucial for compliance with safety standards and mitigating environmental and health impacts. Recent advancements, particularly LC-MS/MS, have significantly improved H_2S quantification sensitivity and specificity, allowing precise measurement across various biological matrices [37, 15, 38, 23].

Mathematical dependencies from simulations assess H_2S measurement performance in EDCs, evaluating concentrations at multiple points to understand distribution and impact [37]. This method, integrating simulation data with real-world measurements, provides a robust framework for monitoring emissions and ensuring safety threshold compliance.

In addition to environmental measurements, high-sensitivity analytical methods like LC-MS/MS facilitate H_2S quantification in biological samples, offering high specificity for accurate measurement in various contexts [38]. These methodologies enhance detection capabilities and deepen understanding of H_2S's biological interactions.

Collectively, these measurement techniques emphasize the importance of combining advanced analytical methods with simulation-based approaches for effective monitoring and management of H_2S concentrations. As research advances, innovative methodologies, such as in-vessel composting and advanced modeling for gas emissions, will be crucial for enhancing environmental safety and regulatory compliance, improving waste management, and mitigating harmful emissions [37, 26, 15, 32, 48].

7 Gravity Drainage Systems

7.1 Principles of Gravity-Driven Flow

Gravity-driven flow is a fundamental principle in fluid mechanics that enables fluid movement in drainage systems through gravitational forces, eliminating the need for external energy. This is particularly vital in wastewater management, where the dynamics of free-falling annular flow in vertical pipes are pivotal. Recent studies highlight the impact of velocity profiles and film thickness on air entrainment and pressure regimes [1, 20, 32, 44]. The effectiveness of gravity-driven flow depends on factors like flow path gradient, fluid properties, and conduit geometry.

This principle relies on potential energy differences due to elevation changes, driving fluids from higher to lower points, optimizing flow rates while minimizing energy consumption [30, 32, 26]. Designing these systems requires careful consideration of hydraulic gradients, pipe diameters, and surface roughness to influence flow capacity and velocity.

Applications of gravity-driven flow span natural environments, such as rivers, and engineered structures like wastewater treatment plants, enhancing fluid dynamics and flow efficiency [1, 31, 32, 20]. In urban stormwater management, these systems channel runoff to mitigate flooding and ensure safe water discharge, while in wastewater treatment, they transport sewage to facilities, regulated by pipe slope and network layout.

Sustainable drainage solutions leveraging gravity-driven flow principles minimize environmental impact, utilizing annular flow dynamics for efficient wastewater management and fluid transport through drag reduction mechanisms. These strategies enhance drainage system efficiency and protect ecosystems by reducing contamination risks and improving water management infrastructure resilience [1, 30, 32, 26]. By utilizing natural topography, these systems improve water quality and promote groundwater recharge.

Understanding gravity-driven flow principles is crucial for designing efficient drainage systems, particularly regarding annular flow dynamics in vertical pipes. Research shows that liquid and entrained air interactions in annular flow establish critical air pressure regimes in drainage systems, especially in Building Drainage Systems (BDS). The configuration of inlets, such as Tee-junctions, significantly affects entrainment profiles and overall performance [32, 26]. By applying these

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principles, engineers can enhance fluid transport, reduce energy consumption, and support sustainable environmental management.

7.2 Design Considerations in Gravity Drainage Systems

The effective design of gravity drainage systems is essential for optimizing fluid transport and minimizing energy consumption. Key considerations include hydraulic gradient, pipe diameter, surface roughness, and drainage network layout, all of which are crucial for optimizing flow rates and ensuring reliability. These factors influence immiscible fluid displacement dynamics in porous media, the stability of two-phase flow patterns in heat pipes, and overall fluid dynamics performance in various applications [39, 24, 4, 26].

The hydraulic gradient, determined by the elevation difference between the inlet and outlet, is a primary driver of flow. A well-engineered gradient is critical for maintaining adequate flow velocity and minimizing sediment deposition and clogging. Studies suggest that modifying surface characteristics, such as superhydrophobic surfaces or liquid-infused textures, enhances flow dynamics and reduces drag [20, 31]. Additionally, selecting appropriate pipe diameters is essential to accommodate expected flow rates and minimize overflow risk during peak conditions.

Surface roughness significantly influences frictional resistance; smooth surfaces enhance flow efficiency, while rough surfaces increase turbulence and energy loss. Choosing materials with optimal surface characteristics, such as liquid-infused or superhydrophobic treatments, is crucial for achieving efficient fluid dynamics, as these can reduce turbulent drag by over 35

The drainage network layout must be strategically planned to ensure effective fluid transport, considering natural topography and potential obstacles. The use of computational fluid dynamics (CFD) simulations, particularly with advanced tools like JAX-FLUIDS, enhances network design optimization by accurately predicting flow behavior across diverse scenarios. This capability improves system performance and resilience, facilitating the integration of machine learning techniques for end-to-end optimization [22, 21, 31, 20, 4].

Integrating sustainability principles into gravity drainage system design is increasingly critical, emphasizing the management of wastewater flow dynamics, minimizing toxic gas emissions, and optimizing fluid interactions within porous media [37, 26, 15, 31, 32]. This includes incorporating green infrastructure elements, such as permeable pavements and vegetated swales, to improve water quality and promote infiltration.

Designing gravity drainage systems requires a thorough understanding of fluid dynamics, particularly multiphase flow behavior and the influence of engineering and environmental factors, such as wettability effects on fluid distribution in porous media, annular flow dynamics in vertical pipes, and surface characteristics on drag reduction in turbulent flows. Addressing these considerations enables engineers to develop efficient and sustainable drainage solutions that meet modern infrastructure demands [20, 31, 32, 26].

7.3 Applications in Engineering and Environmental Management

Gravity drainage systems are integral to various engineering and environmental management applications, efficiently transporting fluids using gravitational forces. In urban infrastructure, these systems are essential for stormwater management, mitigating flooding risks by channeling excess rainwater away from urban areas into natural water bodies or retention basins, which protects infrastructure and maintains water quality by reducing the load on sewage systems [18].

In wastewater treatment, gravity drainage systems transport sewage from residential and industrial areas to treatment plants, optimizing flow by incorporating natural topography to minimize energy consumption and operational costs. Utilizing gravitational forces facilitates efficient wastewater movement, crucial for treatment processes aimed at minimizing pollutants and safeguarding water resources. This process leverages natural particle settling behavior, influenced by size, shape, and density, ensuring optimal flow dynamics [1, 30, 48].

In agricultural water management, gravity drainage systems regulate water flow for irrigation and drainage, ensuring optimal soil moisture levels necessary for healthy crop production. These systems utilize advanced technologies and fluid dynamics principles to manage water distribution effectively,

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enhancing agricultural productivity and sustainability [11, 30, 26]. By facilitating excess water removal, these systems prevent waterlogging and salinization, which adversely affect crop yields and soil health.

In environmental management, gravity drainage systems are employed for wetland reclamation and restoring natural hydrological cycles. They effectively move water through various soil types and porous media, enhancing two-phase flow dynamics and promoting ecosystem resilience. These systems leverage fluid dynamics principles to optimize hydrological processes necessary for sustainable land management and environmental recovery [32, 26]. They help re-establish natural water flow patterns, supporting biodiversity and enhancing ecosystem services such as flood control, water purification, and carbon sequestration.

The applications of gravity drainage systems in engineering and environmental management illustrate their versatility and efficiency in addressing challenges related to fluid transport and resource conservation. By leveraging natural gravitational forces, these systems provide innovative and sustainable solutions that enhance economic viability and promote environmental stewardship. They play a crucial role in bolstering the resilience and sustainability of contemporary infrastructure and ecosystems, particularly in contexts like water treatment processes, where understanding natural particle behavior is essential for effective operation. Furthermore, integrating vegetation in coastal engineering highlights the importance of considering complex interactions, such as drag and inertia effects, in wave propagation, emphasizing the multifaceted benefits of these natural systems [9, 49, 48].

8 Conclusion

8.1 Challenges and Solutions in System Design

Incorporating water drag, air pressure, and two-phase flow dynamics into engineering systems presents various challenges that require innovative solutions to improve system performance and reliability. A significant hurdle is the limited scope of pressures and viscosities typically examined, which can constrain the applicability of findings in viscous liquid dynamics. Broadening the range of tested conditions could enhance the relevance of these findings across diverse engineering applications.

In aquatic engineering, quantifying the effects of finger spreading on drag is challenging due to their subtle impact in real-world swimming. Developing advanced simulation models that accurately capture these dynamics is crucial for optimizing aquatic system performance.

Predicting splash dynamics during droplet impacts is complex, as current benchmarks may not fully capture these phenomena's intricacies. Improving splash prediction models could lead to more precise simulations and better system designs.

Air entrainment studies often overlook the compressibility of air, limiting their ability to accurately depict three-dimensional impact dynamics. Incorporating compressibility and extending models to three dimensions could provide a more comprehensive understanding of air entrainment processes.

Theoretical analyses and simulations of gas damping in MEMS gyroscopes highlight the need for experimental validation to confirm theoretical predictions. Conducting empirical studies can bridge the gap between theory and practice, ensuring system designs are grounded in real-world observations.

Forecasting meteorological variables like wind speed, direction, and air pressure is complicated by the complex interactions among these variables and the limitations of current models. Developing more sophisticated models that account for these interactions could improve prediction accuracy and system performance.

The RoGuE-Tree method relies on accurate environmental models, akin to the challenges faced in engineering systems requiring precise modeling for optimal performance. Enhancing model accuracy and robustness is critical for overcoming these challenges.

In time-dependent numerical models, simplifying dynamics and assuming incompressible water flow can limit applicability. Addressing these limitations through more complex and realistic modeling approaches can enhance the utility of these models in engineering applications.

Finally, the computational cost and potential overfitting associated with evolutionary modeling methods present significant challenges. Developing more efficient algorithms and ensuring model generalizability are essential steps toward overcoming these obstacles.

Addressing these challenges requires a multifaceted approach that combines advanced modeling techniques, empirical validation, and innovative design strategies, enabling engineers to create systems that effectively integrate key concepts and enhance performance and reliability across various applications.

8.2 Future Directions and Emerging Trends

The study of water drag, air pressure, and two-phase flow dynamics is poised for significant advancements, with emerging trends and future research directions offering promising opportunities for innovation. Enhancing machine learning techniques in fluid dynamics simulations is a key focus area. Expanding the capabilities of frameworks like JAX-FLUIDS to incorporate more complex physical models and exploring additional machine learning methodologies are expected to improve simulation accuracy and provide deeper insights into fluid behaviors.

In surface technologies, future research should emphasize evaluating Liquid-Infused Surfaces (LIS) in boundary layer flows, particularly at higher Reynolds numbers and varying groove lengths, to confirm their effectiveness in practical applications. Additionally, exploring robust superhydrophobic surfaces that maintain plastron stability under real-world conditions remains critical, with potential applications in drag reduction and buoyancy enhancement.

Investigating nanoscale manipulation techniques, such as optimizing the Spontaneous Continuous Orbital Motion of Colloids (SCOMC) method for various nanoparticle materials and understanding the mechanisms behind orbital motion, aligns with emerging trends in nanoscale engineering and offers potential for innovative applications in fluid systems.

In two-phase flow dynamics, future research should integrate vegetation flexibility into models and examine the impacts of current-wave interactions to refine predictions in submerged vegetation scenarios. Furthermore, incorporating turbulent effects and optimizing pipe geometries in time-dependent numerical models promises to enhance acoustic performance and system design.

Exploring additional variables, such as different liquid properties, surface textures, and gas compositions, on thin-sheet creation and splashing dynamics represents another promising research direction. Such studies could provide a more comprehensive understanding of splash phenomena and inform the development of improved predictive models.

In forecasting, integrating numerical weather prediction models with multivariate forecasting approaches could enhance medium-term forecasting capabilities, yielding more accurate predictions of meteorological variables that influence fluid dynamics.

Future work should also focus on refining fitness functions and exploring transfer learning to reduce the search space in computational models, which is crucial for optimizing model efficiency and performance. Additionally, improving coating procedures and investigating the effects of different coating materials on dissipation in micro-cantilevers will be essential for advancing sensor technology and system optimization.

These emerging trends and future research directions highlight the potential for significant advancements in the study of water drag, air pressure, and two-phase flow dynamics, promising improvements in system efficiency and performance across a wide range of engineering applications.

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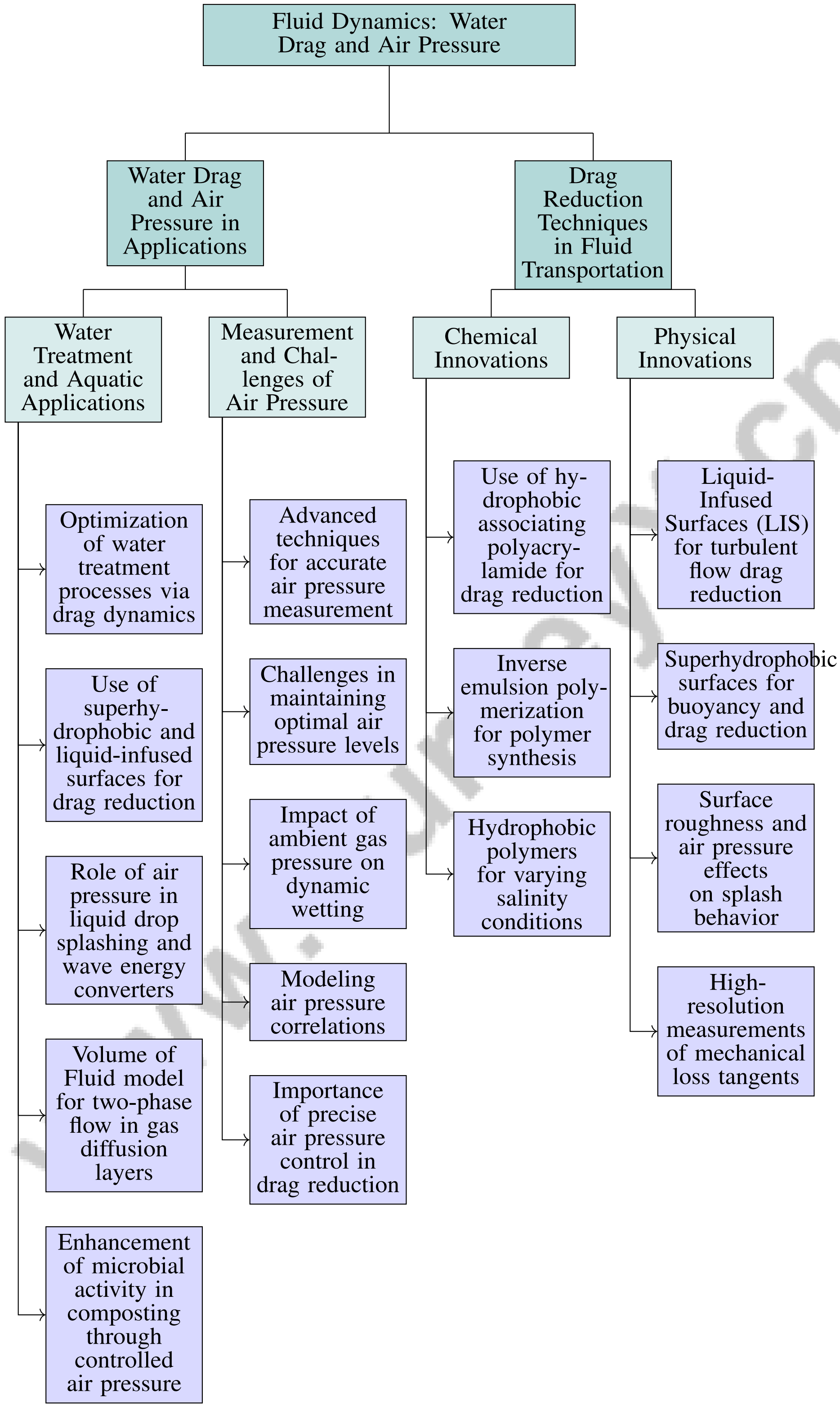
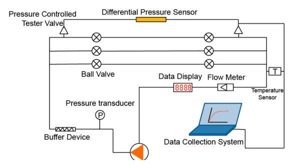
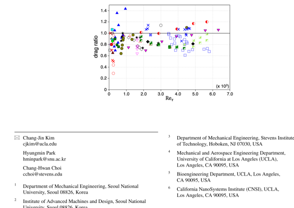


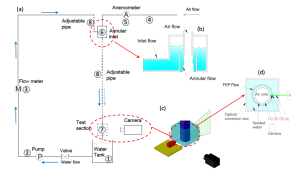
Figure 2: This figure illustrates the hierarchical structure of key concepts in fluid dynamics related to water drag and air pressure, highlighting their significance in water treatment, aquatic applications, and fluid transportation. The chart categorizes the interactions and measurement challenges of water drag and air pressure, as well as innovative drag reduction techniques, emphasizing the role of chemical and physical innovations in optimizing system performance and energy efficiency.



(a) A schematic diagram of a fluid flow measurement system[30]



(b) Drag Ratio vs. Reynolds Number[31]



(c) The image depicts a schematic of a flow visualization experiment setup.[32]

Figure 3: Examples of Water Drag and Air Pressure in Water Treatment and Aquatic Applications

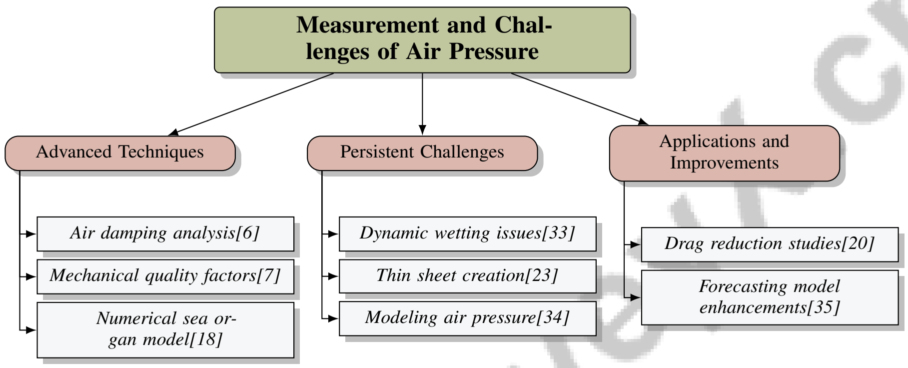
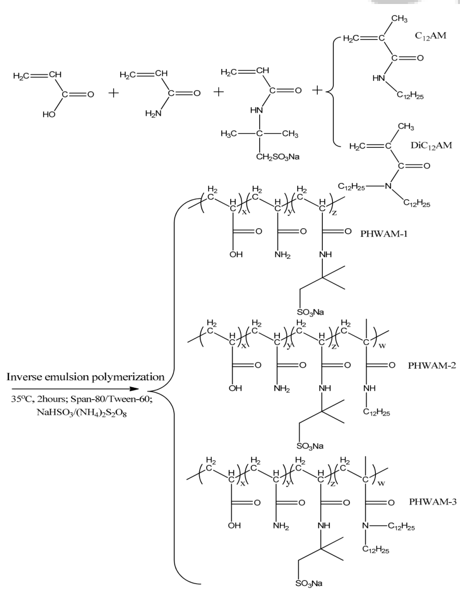
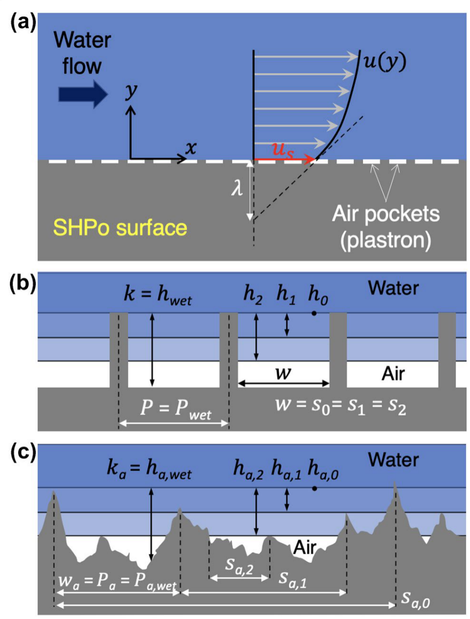


Figure 4: This figure illustrates the hierarchical structure of research topics in air pressure measurement and challenges. It categorizes the advancements in techniques, ongoing challenges, and applications or improvements in related fields. Each category is supported by specific studies, highlighting the multifaceted nature of air pressure research.



(a) The image depicts the synthesis of a polymer using an inverse emulsion polymerization process.[30]



(b) Water Flow and Surface Hydrophobicity (SHPo) in a Channel with Air Pockets[31]

Figure 5: Examples of Drag Reduction Techniques in Fluid Transportation