
Plunger Pump-Based Liquid Dispensing Systems in Semiconductor Manufacturing: A Survey

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Abstract

This survey paper systematically explores the role and impact of plunger pump-based liquid dispensing systems in semiconductor manufacturing, emphasizing their critical importance in achieving high-pressure, precision fluid delivery. As semiconductor devices become increasingly complex, the demand for precision in manufacturing processes has escalated, making plunger pump technology pivotal. The integration of advanced analytics, including Machine Learning and Artificial Intelligence, has shown significant potential in optimizing manufacturing processes, enhancing both efficiency and precision. This survey highlights technological advancements and practical applications of plunger pumps, which are extensively used in industrial settings such as oil and gas production. The paper delves into the design, operation, and principles of fluid dynamics underpinning plunger pump functionality, addressing precision requirements and challenges in semiconductor applications. Key findings include the role of numerical simulations and mathematical modeling in optimizing pump design, and the importance of prototype design in mitigating cavitation. Case studies illustrate the application of plunger pumps in high-precision etching and chemical mechanical planarization, demonstrating their effectiveness in maintaining process integrity. The survey concludes by addressing challenges such as operational reliability and efficiency, and explores future directions for technological advancements, including enhancements in fault diagnosis and the development of robust predictive models. These insights underscore the potential of plunger pump systems to revolutionize precision dispensing in semiconductor manufacturing, fostering innovation and enhancing production capabilities.

1 Introduction

1.1 Purpose and Significance of the Survey

This survey systematically examines the role and impact of plunger pump-based liquid dispensing systems in the semiconductor manufacturing industry. As semiconductor devices grow more complex and miniaturized, the demand for precision in manufacturing processes intensifies. High-pressure, precision dispensing systems utilizing plunger pump technology are essential for meeting these stringent requirements. The incorporation of advanced analytics, including Machine Learning and Artificial Intelligence, has significantly optimized semiconductor manufacturing processes, enhancing both efficiency and precision [1]. This survey is significant as it investigates the technological advancements and practical applications of plunger pumps, which are extensively utilized in various industrial sectors, including gas and oil production [2]. By focusing on this technology, the survey aims to demonstrate its potential to transform precision dispensing in semiconductor manufacturing, thereby fostering innovation and improving production capabilities within the industry.

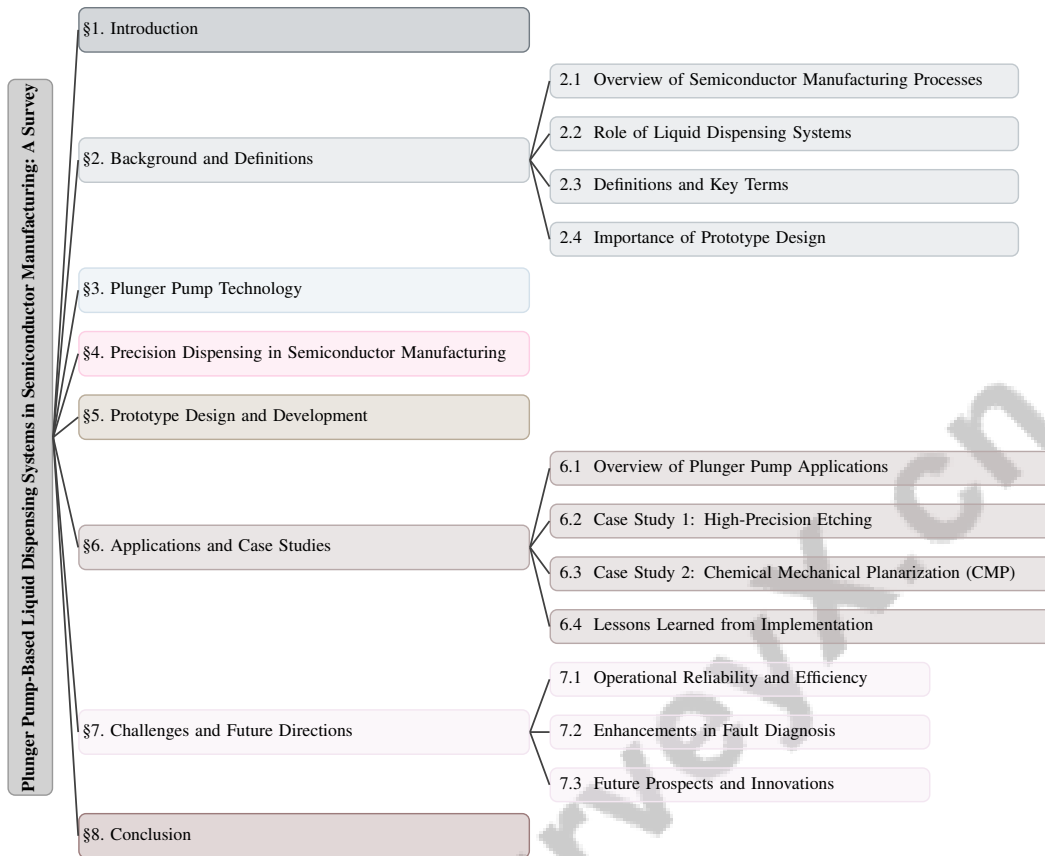


Figure 1: chapter structure

1.2 Relevance of High-Pressure, Precision Dispensing

High-pressure, precision dispensing is vital in semiconductor manufacturing, where liquid application accuracy and control are critical. The intricate processes of semiconductor fabrication—such as photolithography, etching, and chemical mechanical planarization—demand stringent precision standards to maintain the integrity and functionality of devices. Plunger pump-based systems excel in delivering high-pressure and precise fluid control, making them instrumental in achieving these standards. Continuous enhancements in plunger pump technology, including improvements in reliability, service life, and efficiency, alongside reductions in size and installation labor, significantly enhance their effectiveness in semiconductor applications [2]. These advancements not only optimize the dispensing process but also lower operational costs and downtime, thereby boosting overall productivity and competitiveness in semiconductor manufacturing.

1.3 Structure of the Survey

This survey is organized to provide a comprehensive analysis of plunger pump-based liquid dispensing systems in semiconductor manufacturing. It begins with an introduction that outlines the survey's purpose and significance, emphasizing the critical role of high-pressure, precision dispensing in the industry. Following the introduction, the background and definitions section offers an overview of semiconductor manufacturing processes, clarifies the function of liquid dispensing systems, and defines key terms such as 'plunger pump' and 'fluid dynamics'. The discussion then advances to an in-depth exploration of plunger pump technology, detailing design, operation, and the underlying principles of fluid dynamics. The section on precision dispensing addresses specific requirements and challenges in achieving precision for these applications. Next, the survey delves into prototype design and development, focusing on numerical simulations, mathematical modeling, and techniques for optimizing plunger pump designs. Real-world applications and case studies illustrate the practical implementation and benefits of these systems in semiconductor manufacturing. The survey concludes

by addressing the challenges faced by plunger pump-based systems and exploring future directions for technological advancements and innovations. This structured approach ensures a thorough understanding of the subject, facilitating the identification of key areas for further research and development. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Overview of Semiconductor Manufacturing Processes

Semiconductor manufacturing is a complex sequence of processes essential for fabricating high-performance devices, initiated by silicon purification, crystallization, and wafer slicing. Key stages include photolithography, etching, doping, deposition, and chemical mechanical planarization (CMP). Photolithography uses light exposure through a photomask to imprint intricate circuit patterns on wafers, which are crucial for device functionality and reliability [3, 1, 4, 2]. Etching sculpts the wafer's surface, while doping alters its electrical characteristics. Deposition techniques such as chemical vapor deposition (CVD) and physical vapor deposition (PVD) apply essential thin films. Advanced analytics and machine learning integration enhances precision and efficiency, addressing manufacturing challenges [1]. CMP ensures wafer uniformity for further processing.

The intricate nature of semiconductor manufacturing demands stringent control and data analysis to optimize quality and efficiency. Machine learning and artificial intelligence are increasingly critical for process control, variability reduction, and yield improvement, reflecting the industry's evolution to meet technological demands.

2.2 Role of Liquid Dispensing Systems

Liquid dispensing systems are vital for the precise application of chemical solutions in semiconductor processes like photolithography, etching, and CMP. These systems must deliver exact liquid volumes with high precision to maintain stringent tolerances required for high-performance devices. The complexity of semiconductor processes and challenges such as imbalanced datasets and noise necessitate advanced optimization methods [1].

Plunger pump-based systems are preferred for high-pressure, high-precision dispensing, crucial for product consistency and quality. Computational fluid dynamics (CFD) simulations of unsteady state two-phase flow in systems using plunger pumps enhance reliability [5]. The strength and reliability of components, like those made from 09G2S steel, are crucial for efficient operation, as shown in oil and gas extraction studies [2]. These factors underscore the importance of liquid dispensing systems in semiconductor manufacturing, necessitating ongoing innovation to meet industry demands.

2.3 Definitions and Key Terms

Understanding key terms related to plunger pump-based liquid dispensing systems is crucial. A 'plunger pump' is a positive displacement pump employing a plunger mechanism to move fluids through a cylindrical chamber, achieving high-pressure fluid delivery suited for precision dispensing [6]. 'Fluid dynamics' involves the study of fluids in motion, with principles applied in plunger pump systems to optimize flow and pressure for efficient dispensing [7].

'Precision dispensing' refers to the accurate application of liquids in specified volumes, essential in semiconductor processes. Plunger pump systems enhance precision by reducing pressure pulsations that can disrupt fluid delivery uniformity. These pulsations are significant in 'reciprocating plunger pumps', where cyclical plunger motion induces pressure variations, necessitating careful design to prevent cavitation [8]. Additionally, understanding 'drag and lift coefficients' in systems with 'rarefied flows' and 'ellipsoidal particles' is vital for predicting particle behavior in fluid streams, impacting dispensing efficiency [3]. These definitions provide foundational knowledge for optimizing plunger pump-based liquid dispensing systems in semiconductor manufacturing.

2.4 Importance of Prototype Design

Prototype design is crucial for developing efficient liquid dispensing systems, especially those utilizing plunger pump technology. This phase addresses challenges like cavitation, which significantly affects

system performance and longevity. Advanced design techniques and simulations, as emphasized in [9], predict and mitigate cavitation, enhancing reliability and efficiency.

Accurate modeling of dynamic interactions within plunger pump systems is essential for effective prototype design, addressing complexities in geometry and boundary conditions reflective of plunger movements [5]. Sophisticated computational tools and simulations ensure prototypes accurately represent real-world conditions.

The integration of computer-aided design (CAD) and finite element analysis (FEA) has emerged as a primary innovation in prototype development, facilitating precise strength calculations that surpass traditional methods [2]. CAD and FEA enable designers to optimize the structural integrity and performance of plunger pump components to withstand high pressures and mechanical stresses.

Moreover, accurately modeling non-spherical particles, as discussed in [3], is significant for optimizing flow dynamics in liquid dispensing systems, leading to improved precision and efficiency. Prototype design also enhances fault diagnosis methodologies, allowing early detection and resolution of potential faults, thus improving system reliability and reducing maintenance costs and downtime in semiconductor manufacturing processes [10].

In recent years, the advancements in plunger pump technology have significantly impacted various industrial applications, particularly in semiconductor manufacturing. Understanding the intricate dynamics of these pumps is crucial for optimizing their performance. Figure 2 illustrates the hierarchical structure of plunger pump technology, encompassing design and operation, principles of fluid dynamics, and pulsation and pressure dynamics. This figure highlights key components such as pump design, operational efficiency, fluid behavior, cavitation, and mitigation techniques essential for enhancing plunger pump performance. By analyzing these elements, we can better appreciate the complexities involved in the effective utilization of plunger pumps in high-precision environments.

3 Plunger Pump Technology

3.1 Design and Operation of Plunger Pumps

Plunger pumps are integral to semiconductor manufacturing for their high-pressure fluid delivery capabilities. They consist of a cylindrical chamber and a reciprocating plunger, ensuring consistent flow rates and pressure stability under various conditions [6]. The integration of fluid-structure interaction principles, such as the Bidirectional Fluid-Structure Coupling Method, facilitates precise modeling of pump-fluid dynamics, enhancing efficiency [7].

Recent advancements in computational fluid dynamics (CFD) have optimized plunger pump design by simulating flow dynamics and pressure distribution within pump geometries [5]. Finite element analysis (FEA) further refines component design, as demonstrated by the optimization of the TWS 600 plunger pump body using Solid Works Simulation [2]. These methodologies ensure pumps withstand the mechanical stresses of high-pressure operations.

Operational efficiency is enhanced through advanced feature selection algorithms like the Dynamic Feature Selection Algorithm (DFSA), which utilizes Genetic Algorithms and Artificial Neural Networks to refine precision and efficiency in semiconductor applications [1]. Additionally, algorithms such as the cut-cell algorithm for Direct Simulation Monte Carlo (DSMC) optimize fluid-particulate interactions, crucial for maintaining pump integrity in diverse conditions [3]. Collectively, these advancements underscore the critical role of plunger pumps in delivering high-pressure, precision fluid delivery in semiconductor manufacturing.

3.2 Principles of Fluid Dynamics

Fluid dynamics principles are fundamental to the operation of plunger pumps, ensuring precise high-pressure fluid delivery in semiconductor manufacturing. These principles govern fluid behavior within the pump, facilitating efficient dispensing. Numerical simulations are crucial for analyzing flow dynamics and leakage characteristics, employing advanced computational methods to optimize performance [7]. By simulating fluid-pump interactions, insights into factors affecting flow and pressure stability are gained.

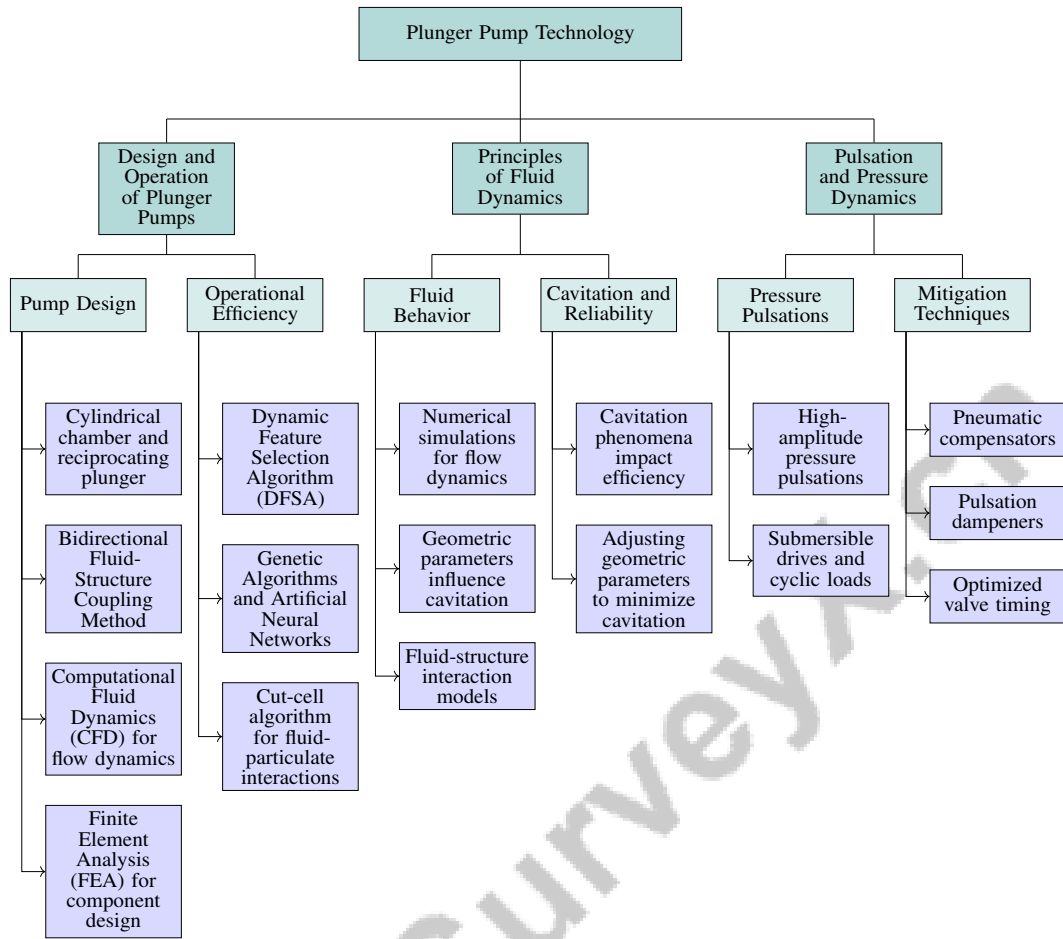


Figure 2: This figure illustrates the hierarchical structure of plunger pump technology, encompassing design and operation, principles of fluid dynamics, and pulsation and pressure dynamics. It highlights key components such as pump design, operational efficiency, fluid behavior, cavitation, and mitigation techniques essential for optimizing plunger pump performance in semiconductor manufacturing.

Geometric parameters, such as the m value, significantly influence cavitation phenomena, which can detrimentally impact pump efficiency and longevity [9]. Cavitation, marked by vapor bubble formation and collapse, poses a critical challenge in high-pressure applications. Understanding the fluid dynamics governing cavitation enables engineers to adjust geometric parameters, minimizing its occurrence and enhancing pump reliability.

Furthermore, integrating fluid-structure interaction models allows for a comprehensive analysis of dynamic interactions within the pump system, facilitating the prediction and control of fluid behavior under varying operational conditions [7]. Accurate modeling and simulation of these interactions are essential for developing plunger pump systems that meet the stringent precision requirements of semiconductor manufacturing.

3.3 Pulsation and Pressure Dynamics

In semiconductor manufacturing, understanding pulsation and pressure dynamics is critical for optimizing plunger pump performance. Reciprocating plunger pumps often encounter high-amplitude pressure pulsations, leading to cyclic variable loads on components that can cause mechanical stress and potential failure [8].

Submersible drives can exacerbate pulsation characteristics, increasing cyclic loads and reducing system efficiency [11]. Mitigating pressure fluctuations requires sophisticated control mechanisms and design optimizations to minimize pulsations, thereby enhancing fluid delivery stability and reliability.

Advanced modeling techniques, including distributed parameter models and CFD simulations, predict and mitigate pulsations, ensuring smoother operation and extending equipment lifespan. The use of pneumatic compensators effectively alleviates pressure oscillations, improving pump performance and durability [8, 6, 7, 11, 5]. Techniques such as pulsation dampeners and optimized valve timing further reduce pulsation amplitudes, enhancing reliability and efficiency in fluid delivery systems.

Effective control of pulsation and pressure dynamics is essential for developing robust plunger pump systems. By applying advanced fluid dynamics and mechanical engineering principles, engineers can design high-performance pumps tailored for semiconductor manufacturing. These pumps are engineered to withstand demanding high-pressure conditions while enhancing long-term operational reliability by minimizing pressure pulsations and optimizing fluid delivery dynamics. Techniques such as pneumatic compensators and advanced hydrodynamic modeling significantly improve the efficiency and lifespan of these systems, ensuring consistent performance in critical applications [6, 8, 11].

4 Precision Dispensing in Semiconductor Manufacturing

4.1 Requirements for Precision in Plunger Pumps

Plunger pumps in semiconductor manufacturing must meet stringent precision standards in both flow rate and pressure to maintain the integrity of semiconductor devices. This precision is crucial for processes like photolithography, etching, and chemical mechanical planarization, where pressure pulsations and velocity oscillations can compromise system reliability and efficiency [9, 8, 7, 11, 5]. Techniques such as pneumatic compensators are employed to mitigate these oscillations, enhancing the operational stability and longevity of pumps in demanding environments.

To ensure precision, plunger pumps are engineered to deliver consistent flow rates and pressures across varying conditions. Deviations in fluid delivery can lead to defects and lower yield rates in semiconductor production. Advanced algorithms like the Dynamic Feature Selection Algorithm (DFSAs) improve pump precision by optimizing feature subsets to reduce classification errors while retaining critical features, thus enhancing accuracy and efficiency [1].

The integration of computational fluid dynamics (CFD) and fluid-structure interaction (FSI) models enhances the simulation and control of fluid dynamics within pump systems, allowing for accurate predictions of pressure pulsations and flow behavior. This approach addresses the complexities of unsteady two-phase flows in reciprocating plunger pumps and optimizes design parameters, thereby improving reliability and efficiency in chemical processing and oil production applications [9, 8, 6, 11, 5]. Accurate modeling is vital for developing plunger pump systems that meet the high precision requirements of semiconductor manufacturing.

4.2 Challenges in Precision Dispensing

Precision dispensing with plunger pumps in semiconductor manufacturing encounters challenges due to the complex interplay of mechanical and fluid dynamics. Excessive cavitation within the plunger cavity, especially in water axial piston pumps, is a significant issue. Cavitation, characterized by vapor bubble formation and collapse, adversely affects pump performance, causing vibrations, noise, and potential component damage [9]. This phenomenon results in fluctuations in flow rate and pressure, undermining the consistency required for precision dispensing.

Contaminated hydraulic fluids further challenge precision, as mechanical impurities reduce relative volume flow rates and accelerate component wear, compromising precise fluid delivery [6]. Rigorous filtration and maintenance protocols are essential to ensure hydraulic fluid purity and system reliability.

Additionally, excessive pressure increases during the plunger's upward movement induce fatigue wear, leading to mechanical stress and reduced operational reliability [11]. Managing these cyclic pressure variations is crucial to prevent premature failure while maintaining precision in semiconductor manufacturing.

Accurate modeling of drag and lift coefficients for ellipsoidal particles in rarefied flows is another challenge. These coefficients are critical for predicting particle behavior within the fluid stream, influencing dispensing efficiency and accuracy [3]. The complexity of these interactions necessitates

advanced computational models and simulations for precise control over fluid dynamics within the pump system.

Addressing challenges in plunger pump-based dispensing systems requires ongoing innovation in design and operational methodologies. Managing pressure pulsations is particularly critical, as they can lead to increased component wear, reduced efficiency, and reliability concerns in various industrial applications, including oil production and hydraulic systems. Advanced modeling techniques, incorporating frequency-dependent friction and pneumatic compensators, are essential for predicting and mitigating pulsations, ultimately improving system longevity and performance [6, 2, 8, 11].

5 Prototype Design and Development

Category	Feature	Method
Numerical Simulations for Design Optimization	System Performance Analysis	FEM-PD[8], ESHP[6]
	Fluid-Structure Interaction	BFSCM[7]
	Mesh and Geometry Representation	FEM[2]
Mathematical Modeling for Cavitation Minimization	Design Optimization	FEM-CA[9]
Simulation Techniques for Complex Geometries	Mesh Generation	DFSFA[1], MSMGM[5], ET[4], DPC-CM[11]

Table 1: This table provides a detailed summary of various simulation and modeling techniques employed in the optimization of plunger pump systems. It categorizes these methods into numerical simulations for design optimization, mathematical modeling for cavitation minimization, and simulation techniques for complex geometries, highlighting specific features and methodologies referenced in recent studies.

Table 1 presents a comprehensive overview of the simulation and modeling techniques utilized in the design and optimization of plunger pump systems, emphasizing their significance in enhancing system performance and reliability. Additionally, Table 4 offers a detailed comparison of various simulation and modeling techniques utilized in the optimization of plunger pump systems, emphasizing their distinct purposes and applications across different industrial sectors. Optimizing plunger pump systems' design and performance in semiconductor manufacturing involves employing various methodologies, notably numerical simulations. These simulations provide a comprehensive framework for analyzing fluid dynamics, structural integrity, and operational efficiency, offering critical insights into pump behavior under diverse conditions. The following subsection delves into the significance of numerical simulations in design optimization, highlighting their role in developing efficient liquid dispensing systems.

5.1 Numerical Simulations for Design Optimization

Method Name	Simulation Techniques	Design Optimization	Application Scenarios
BFSCM[7]	Numerical Simulations	Refining Pump Designs	Oil Recovery Industry
MSMGM[5]	Computational Fluid Dynamics	Optimize Separator Designs	Artificial Lifting Systems
FEM[2]	Finite Element Modeling	Design Improvement	Oil And Gas
ESHF[6]	Simulating Contamination Conditions	-	Civil Aviation
FEM-PD[8]	Finite Element Modeling	Refining Pump Designs	Semiconductor Manufacturing

Table 2: This table presents an overview of various numerical simulation methodologies applied in design optimization for plunger pump-based liquid dispensing systems. It details the simulation techniques, design optimization strategies, and application scenarios associated with each method, highlighting their relevance in industries such as oil recovery, artificial lifting systems, and semiconductor manufacturing.

Numerical simulations are essential for optimizing plunger pump-based liquid dispensing systems, particularly in semiconductor manufacturing. They facilitate precise modeling of fluid behavior, structural integrity, and system dynamics, crucial for enhancing pump performance and reliability. For example, [7] presents a simulation model that identifies potential leakage points, refining designs to ensure optimal performance. The use of MATLAB coding for constructing structural hexahedral meshes to simulate complex geometries in turbulent two-phase flow exemplifies the sophistication of these techniques [5]. This method captures intricate geometries and flow dynamics, providing insights into factors affecting pump efficiency and longevity. Table 2 provides a comprehensive summary of the numerical simulation methods utilized for optimizing plunger pump systems, illustrating their application across diverse industrial sectors.

Finite element models are vital for assessing pump components' structural integrity. [2] demonstrates how creating a finite element model of the pump body and applying various loads helps evaluate mechanical stresses and potential failure points, ensuring resilience under high pressures. Additionally, simulating contamination conditions, as discussed by [6], reveals contamination's impact on flow rate and component wear, allowing for strategies to minimize related issues and enhance system reliability.

Integrating pipeline dynamics with pump dynamics through finite element modeling, as shown by [8], predicts pressure pulsations, crucial for stable fluid delivery and minimizing mechanical stress. Advanced numerical simulation techniques, including finite element modeling and computational fluid dynamics, establish a robust framework for optimizing plunger pump systems. These methods enable detailed analyses of cavitation dynamics, pressure pulsations, and two-phase flow behavior, ultimately enhancing axial piston pumps' performance and efficiency. Leveraging these simulations allows for informed design choices, reducing cavitation, minimizing vibrations, and improving volumetric efficiency, leading to more reliable pumping solutions across various industrial applications [5, 9, 8, 11].

5.2 Mathematical Modeling for Cavitation Minimization

Mathematical modeling is pivotal for minimizing cavitation in plunger pump systems, crucial for maintaining efficiency and longevity in high-pressure applications. Cavitation, marked by vapor bubble formation and collapse, can cause mechanical damage and reduced performance. The study by [9] introduces a model correlating the m value, a geometric pump parameter, with cavitation occurrence, providing a framework for adjustments to mitigate cavitation effects, enhancing reliability and efficiency.

Incorporating this model into design processes allows for predicting cavitation conditions and making informed geometric adjustments. This proactive approach optimizes parameters to minimize cavitation risk, ensuring stable fluid delivery. Accurate prediction and control of cavitation through advanced modeling are essential for optimizing plunger pump systems, especially in semiconductor manufacturing where precision and efficiency are paramount. Studies indicate that the ratio of the plunger cavity diameter to the cylinder's kidney-shaped hole diameter significantly influences cavitation levels. Dynamic and sliding mesh simulations have shown that optimizing these parameters reduces cavitation and associated vibrations, enhancing volumetric efficiency [9, 11].

Furthermore, mathematical modeling aids in simulating fluid dynamics and pressure conditions within the pump. Simulations using a finite element model of a water axial piston pump, incorporating advanced turbulence models and dynamic mesh techniques, reveal insights into fluid dynamics and component interactions. These insights help identify cavitation-prone areas influenced by the geometric ratio of the plunger cavity to the cylinder's kidney-shaped hole. Optimizing design parameters, such as the swash plate angle and cylinder block velocity, reduces cavitation severity, enhancing volumetric efficiency and minimizing vibrations. This comprehensive understanding allows for informed design modifications aimed at preventing cavitation-related issues in axial piston pumps [9, 8]. Leveraging mathematical models enables engineers to enhance plunger pump design and operation, ensuring suitability for high-precision semiconductor manufacturing applications.

5.3 Simulation Techniques for Complex Geometries

Method Name	Simulation Techniques	Geometric Complexity	Performance Optimization
MSMGM[5]	Structural Mesh Generation	Complex Geometries	Enhancing System Design
DPC-CM[11]	Hydrodynamic Modeling	Plunger Pumps	Enhance Efficiency
DFSA[1]	Genetic Algorithms	-	Model Performance
ET[4]	Emmd-Teager Method	Plunger Pump Components	Fault Diagnosis

Table 3: Overview of advanced simulation techniques used for modeling complex geometries in plunger pump systems, highlighting their application in structural mesh generation, hydrodynamic modeling, genetic algorithms, and fault diagnosis. The table details the methods employed, the associated geometric complexities, and performance optimization strategies aimed at enhancing system design and efficiency in high-pressure applications.

Designing complex geometries in plunger pump systems is crucial for optimizing performance in high-pressure applications, such as semiconductor manufacturing. Advanced simulation techniques

are employed to accurately model these geometries, ensuring precise control and optimization of fluid dynamics within the system. Creating a structured grid that accurately represents the geometry of the separator and plunger pump facilitates reliable simulations [5]. This approach enables detailed analysis of fluid flow and pressure distribution, essential for maintaining the system's precision and reliability.

Additionally, a two-stage approach involving mathematical modeling of fluid movement and parameter calculation for pneumatic compensators enhances the simulation process [11]. This method provides a comprehensive framework for predicting fluid behavior within complex geometries, enabling engineers to optimize plunger pump design and operation. By integrating these advanced simulation techniques, engineers can effectively address challenges associated with complex geometries, ensuring that plunger pumps meet the stringent requirements of semiconductor manufacturing processes.

Table 3 provides a comprehensive summary of various simulation techniques applied to complex geometries in plunger pump systems, elucidating their role in optimizing system performance and reliability.

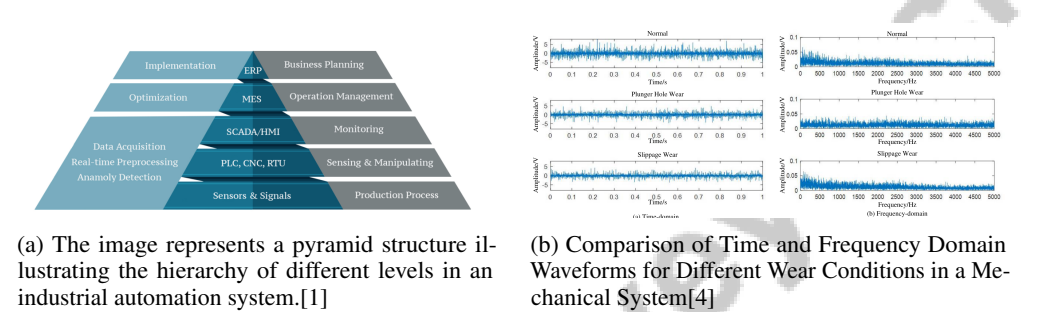


Figure 3: Examples of Simulation Techniques for Complex Geometries

As depicted in Figure 3, the examples in "Prototype Design and Development; Simulation Techniques for Complex Geometries" provide visual insights into industrial automation systems and mechanical wear analysis. The first image illustrates a pyramid structure delineating the hierarchy within an industrial automation system, ranging from "Implementation" at the apex to foundational levels like "Data Acquisition," including SCADA/HMI. This structured representation aids in understanding the layered complexity of automation systems. The second image presents a comparative analysis of time-domain and frequency-domain waveforms under various mechanical wear conditions, highlighting signal pattern differences for 'Normal,' 'Plunger Hole Wear,' and 'Slippage Wear' conditions. These visual examples underscore the importance of simulation techniques in addressing complex geometries, facilitating prototype design and development as well as effective system functionality management [1, 4].

Feature	Numerical Simulations for Design Optimization	Mathematical Modeling for Cavitation Minimization	Simulation Techniques for Complex Geometries
Purpose	Optimize Pump Systems	Minimize Cavitation	Model Complex Geometries
Techniques Used	Finite Element Modeling	Dynamic Mesh Simulations	Structured Grid Creation
Industry Application	Semiconductor Manufacturing	High-pressure Applications	Semiconductor Manufacturing

Table 4: This table provides a comparative analysis of three distinct methodologies employed in the optimization and modeling of plunger pump systems. It highlights the specific purposes, techniques used, and industry applications of numerical simulations for design optimization, mathematical modeling for cavitation minimization, and simulation techniques for complex geometries. The comparison underscores the diverse approaches and their significance in enhancing the performance and reliability of pump systems, particularly in semiconductor manufacturing and high-pressure applications.

6 Applications and Case Studies

Plunger pumps are integral to numerous industries, demonstrating their versatility in addressing unique operational challenges. This section examines specific use cases, highlighting the critical roles of plunger pumps in oil and gas, chemical processing, food and beverage, and semiconductor

manufacturing, thereby enhancing our understanding of their implementation in high-precision environments.

6.1 Overview of Plunger Pump Applications

Renowned for their high-pressure capabilities and precision fluid delivery, plunger pumps are indispensable across various industries. In the oil and gas sector, they manage high-pressure fluid transfer and injection processes, ensuring efficient and safe hydrocarbon extraction and transportation [2]. In chemical processing, they enable precise dosing and transfer of chemicals, handling high-viscosity fluids and corrosive materials while maintaining process integrity [7]. The integration of computational fluid dynamics (CFD) in pump design further optimizes fluid handling and process efficiency [5].

In the food and beverage industry, plunger pumps ensure sanitary and precise fluid handling, minimizing contamination risks and facilitating easy cleaning to maintain food safety. Advanced designs, such as submersible plunger pumps with pneumatic compensators, reduce pressure oscillations and cyclic loads, enhancing pump lifespan and efficiency [9, 8, 7, 11]. In semiconductor manufacturing, they are crucial for precision dispensing in processes like photolithography and etching, ensuring consistency and quality in semiconductor products [1].

The diverse applications of plunger pumps illustrate their adaptability in managing complex fluid dynamics challenges. Their robust design and advanced capabilities make them optimal for high-pressure and precision fluid delivery across various sectors. These pumps address issues of pressure pulsations and fluid contamination, enhancing operational efficiency and reliability while minimizing maintenance needs through innovative solutions like pneumatic compensators and advanced modeling techniques [8, 2, 6, 7, 11].

6.2 Case Study 1: High-Precision Etching

High-precision etching in semiconductor manufacturing requires exact delivery of chemical etchants to achieve desired microstructures on silicon wafers. Plunger pump-based liquid dispensing systems play a pivotal role in this process, ensuring consistent high-pressure and precise volumes of etchants. Advanced analytics, including machine learning and AI, optimize parameters to manage fluid contamination and mechanical impurities [6, 1].

The robust design of plunger pumps allows for accurate fluid dynamics control. Advanced CFD techniques simulate flow characteristics and optimize pump design to handle complex fluid interactions in etching [5]. Fluid-structure interaction models further stabilize fluid delivery under variable operational conditions [7], allowing engineers to predict and control pressure dynamics, minimizing fluctuations that could compromise etching quality.

Plunger pumps' reliability in high-precision etching is reinforced by their resilience against mechanical stresses and high pressures. Finite element analysis (FEA) ensures pump components withstand semiconductor manufacturing demands without performance loss [2]. This robust design, complemented by advanced simulation techniques, enables plunger pumps to meet stringent standards required for high-precision etching, contributing to the production of high-quality semiconductor devices.

6.3 Case Study 2: Chemical Mechanical Planarization (CMP)

Chemical Mechanical Planarization (CMP) in semiconductor manufacturing requires uniform and planar wafer surfaces. Plunger pump-based liquid dispensing systems ensure precise and controlled delivery of slurry solutions. Advanced hydraulic principles minimize pressure pulsations and oscillations, enhancing CMP performance and ensuring consistent results [8, 7, 11].

Plunger pumps maintain consistent flow rates and pressures, vital for desired planarization outcomes. The dynamic nature of CMP necessitates careful slurry flow management to prevent defects like dishing and erosion. Advanced computational techniques, including fluid-structure interaction models, simulate complex slurry and wafer interactions, allowing for pump parameter optimization and precise fluid dynamics control [7].

Numerical simulations enhance plunger pump reliability and performance in CMP applications, providing insights into slurry behavior under varying conditions. This enables engineers to adjust pump settings to minimize pressure fluctuations and ensure uniform material removal [5]. The robust design of plunger pumps, supported by FEA, ensures they endure mechanical stresses associated with high-pressure slurry delivery, maintaining the precision essential for effective planarization [2].

Plunger pumps handle abrasive slurry solutions without performance compromise. Advanced materials and design techniques ensure durability and longevity, reducing maintenance needs and enhancing operational efficiency. By leveraging advanced technologies, plunger pump-based systems significantly improve CMP processes, ensuring superior surface uniformity and planarity while managing velocity and pressure oscillations [4, 11].

6.4 Lessons Learned from Implementation

Implementing plunger pump systems in semiconductor manufacturing has revealed critical insights for optimizing performance and reliability. A significant lesson is the necessity of addressing the dynamic effects of plunger movements on phase separation within the pump system, highlighting the importance of comprehensive modeling to predict and manage fluid interactions [5]. Incorporating these dynamics into design and simulation processes enhances precision and efficiency.

Advanced diagnostic techniques improve operational reliability. The EEMD-Teager method, for instance, shows promise in diagnosing faults within plunger pump systems, allowing accurate classification of operational states and facilitating early anomaly detection [4]. Leveraging such diagnostic tools reduces downtime and maintenance costs, enhancing productivity and efficiency.

These lessons emphasize continuous innovation in plunger pump design and operation. Analyzing the complex dynamics of reciprocating plunger pumps and integrating advanced diagnostic techniques like EEMD decomposition and Teager energy operator demodulation enhance reliability and precision for high-performance semiconductor manufacturing. This approach addresses critical pressure pulsation issues, facilitating early fault detection and ensuring potential failures are identified and mitigated before impacting production efficiency [6, 8, 4, 11].

7 Challenges and Future Directions

7.1 Operational Reliability and Efficiency

Ensuring operational reliability and efficiency in plunger pump systems is vital for semiconductor manufacturing. A primary challenge is the accurate prediction and management of leakage within these systems, as current methods often fall short, leading to inefficiencies and potential system failures [7]. Developing comprehensive predictive models that account for complex system interactions is crucial.

Cavitation, marked by vapor bubble formation and collapse, poses additional challenges, causing mechanical damage and reduced performance. Optimizing geometric parameters in pump design can help mitigate cavitation effects, enhancing overall pump efficiency [9]. Contaminants of various sizes and concentrations further impact pump performance, with existing methods inadequately addressing these issues, leading to decreased efficiency and increased component wear [6]. Implementing advanced filtration and maintenance protocols is essential for maintaining optimal operation.

Pressure pulsations in reciprocating pump systems introduce mechanical stress, leading to increased wear, reduced efficiency, and a higher risk of equipment failure. These pulsations, inherent in the pumping cycle, contribute to noise and vibration, affecting the reliability and lifespan of the pump and associated systems. Effective modeling and prediction of these fluctuations during the design phase are necessary to develop mitigation strategies [8, 6, 10, 11, 4]. Current models require enhancement to improve control strategies, reduce pressure oscillations, and extend equipment lifespan.

Fault diagnosis is complicated by noise from motors and surrounding equipment, which obscures essential vibration signals [4]. The imbalance between normal and fault samples further complicates diagnosis [10]. Advanced techniques like the EEMD-Teager method can improve fault detection capabilities, enhancing system reliability.

Addressing these challenges requires a multifaceted approach, including design optimization, advanced predictive modeling, and robust diagnostic techniques. Enhancing the operational reliability and efficiency of plunger pump systems is critical for achieving stable and precise fluid delivery in semiconductor manufacturing. Solutions like pneumatic compensators can mitigate pulsations, extend pumping unit lifespan, and ensure consistent operational parameters. Optimizing the placement and technological parameters of these compensators further reduces pressure fluctuations, ensuring reliable fluid delivery in critical applications [8, 6, 7, 11, 4].

7.2 Enhancements in Fault Diagnosis

Advancements in fault diagnosis are crucial for maintaining plunger pump reliability and efficiency in semiconductor manufacturing. The EMD-Teager method effectively filters noise from vibration signals, enhancing fault diagnosis accuracy [4]. By isolating relevant features, it enables precise anomaly identification, facilitating timely maintenance and reducing downtime.

Integrating the Synthetic Minority Over-sampling Technique (SMOTE) with Tomek Link addresses sample imbalance in normal and fault datasets, enhancing fault detection reliability and classification within plunger pumps [10]. This balanced approach improves diagnostic accuracy and overall system reliability, ensuring consistent performance in high-precision applications.

Recent advancements, including SMOTE + Tomek Link for sample imbalance and EMD decomposition with the Teager energy operator for signal enhancement, highlight innovative methodologies in improving plunger pump reliability and diagnostic accuracy. These techniques facilitate failure mode identification and ensure stable performance under challenging conditions, mitigating risks associated with pump failures in critical applications like military operations and oil production [10, 4, 11].

Leveraging these techniques enables precise and efficient plunger pump operation, supporting the stringent demands of semiconductor manufacturing processes.

7.3 Future Prospects and Innovations

The future of plunger pump technology in semiconductor manufacturing promises significant advancements through innovative methodologies and new operational paradigms. Enhancing leakage prediction models by incorporating field data and examining additional operational parameters aims to refine prediction accuracy, improving system reliability and efficiency [7].

Further research is needed to understand the impact of varying contaminant hardness levels and operational pressures on wear processes in hydraulic pumps. Investigating these variables will help develop strategies to mitigate wear and extend pump operational life, enhancing performance in high-pressure applications [6].

Refining computational methods to encompass a broader range of variable conditions is another key research area. This includes applying these methods to other multiphase flow systems, potentially broadening the applicability of plunger pump technology across various industrial sectors [5]. Additionally, advancements in feature extraction techniques and their application to other mechanical systems could further enhance plunger pump diagnostic capabilities, ensuring efficient operation in diverse environments [10].

Future research will focus on improving the EMD-Teager method's robustness against noise, enhancing its applicability to a wider range of machinery and facilitating more accurate fault diagnosis and maintenance strategies [4]. Extending current models to encompass a wider variety of particle shapes and aspect ratios could lead to significant innovations in liquid dispensing technology, enabling more precise fluid dynamics control in complex systems [3].

Integrating submersible drives and pneumatic compensators in plunger pump technology holds promise for significantly enhancing efficiency and reliability. This evolution is crucial for meeting the rigorous demands of semiconductor manufacturing and other high-precision industries, where minimizing pressure pulsations and optimizing fluid dynamics are essential for operational success. Addressing velocity and pressure oscillations can lead to longer drive life, improved performance, and reduced maintenance needs, transforming industrial pumping applications [8, 10, 11, 4, 5]. By tackling current challenges and exploring new technological advancements, researchers and engineers

can ensure the continued relevance and effectiveness of plunger pumps in the evolving industrial landscape.

8 Conclusion

The survey delves into the pivotal role of plunger pump-based liquid dispensing systems within semiconductor manufacturing, highlighting their critical function in delivering high-pressure, precision fluid control. The adoption of cutting-edge technologies, including dynamic feature selection, has markedly improved the classification accuracy of manufacturing outcomes, underscoring the potential for these systems to elevate precision and operational efficiency. The application of fluid dynamics principles and finite element modeling has been crucial in refining the design and enhancing the reliability of plunger pumps. Simulations of pressure pulsations, especially in reciprocating pump setups, have contributed significantly to system reliability and efficiency. Additionally, research into cavitation phenomena has provided valuable design insights for axial piston pumps, with particular emphasis on geometric parameters that mitigate cavitation. These advancements are vital for the continued evolution of plunger pump technology. Future research directions should focus on improving leakage prediction models, understanding the effects of operational conditions on wear, and advancing fault diagnosis methodologies. The progression of computational techniques and feature extraction strategies will further augment the capabilities of plunger pump systems, ensuring their relevance and adaptability in semiconductor manufacturing and other precision-driven industries. By addressing these research areas, innovation in plunger pump technology can be propelled forward, reinforcing its essential role in high-precision sectors.

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