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Research Article

Optimization and Unsteady Flow Mechanisms in Bidirectional Axial-Flow and Tubular Pump Systems: A Comprehensive Theoretical and Performance-Oriented Investigation

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Abstract

Bidirectional axial-flow and tubular pump systems play a critical role in modern hydraulic engineering applications, particularly in tidal energy conversion, flood control, irrigation drainage, and reversible pumping stations. Unlike conventional unidirectional pumps, these systems must maintain acceptable hydraulic performance, stability, and structural reliability under both forward and reverse operating modes. This dual-function requirement introduces complex challenges related to blade design, internal flow structure, pressure pulsation, vibration, and efficiency degradation. The present research article offers an extensive theoretical and analytical investigation into the optimization mechanisms, internal flow behaviors, and unsteady pressure characteristics of bidirectional shaft tubular pumps and reversible axial-flow pump devices. Drawing strictly and exclusively from the provided body of peer-reviewed literature, this study synthesizes prior experimental, numerical, and theoretical findings to construct a unified and deeply elaborated understanding of reversible pump behavior. Special attention is given to the influence of blade airfoil geometry, trailing-edge modification, rotor–stator interaction, tip clearance effects, flow separation phenomena, and pressure pulsation mechanisms under variable load conditions. The methodology of this work is grounded in qualitative synthesis and comparative theoretical analysis rather than new experimental or numerical data, allowing for a comprehensive reinterpretation of existing results. The findings highlight that performance asymmetry between forward and reverse modes is fundamentally linked to blade camber distribution, flow incidence mismatch, and wake–blade interaction dynamics. Furthermore, unsteady pressure pulsations are shown to be inseparable from geometric optimization decisions, particularly at partial load and off-design conditions. The discussion critically examines current limitations in bidirectional pump design practices and outlines future research pathways focused on integrated aero-hydrodynamic optimization, vibration mitigation, and long-term operational reliability. This article aims to serve as a definitive theoretical reference for researchers and engineers working on reversible pump technologies.

Keywords: Bidirectional axial-flow pump, tubular pump optimization, pressure pulsation, unsteady flow, reversible pump design, blade trailing-edge geometry, rotor–stator interaction

INTRODUCTION

Bidirectional pumping systems have emerged as indispensable components in contemporary hydraulic and energy infrastructure, driven by increasing demands for operational flexibility, energy efficiency, and adaptability to variable flow conditions. Unlike conventional pumps designed for a single flow direction, bidirectional axial-flow and tubular pumps are required to operate efficiently and reliably in both forward and reverse modes. This operational reversibility is particularly essential in applications such as tidal power generation, reversible drainage and irrigation systems, flood control stations, and bidirectional water transfer schemes. In these contexts, the pump often functions alternately as a turbine and a pump, or must accommodate flow reversal without mechanical reconfiguration, making bidirectional hydraulic performance a core design requirement rather than a secondary feature (Xie et al., 2015; Shi et al., 2016).

From a fluid mechanics perspective, bidirectional operation introduces a fundamentally different design problem compared to unidirectional pumps. Traditional axial-flow and centrifugal pumps rely on blade camber, stagger angle, and thickness distribution optimized for a single dominant flow direction. When the flow direction is reversed, the same blade geometry often becomes aerodynamically or hydrodynamically suboptimal, leading to severe performance degradation, increased flow separation, elevated pressure pulsations, and intensified vibration levels (Ma et al., 2014; Ma and Wang, 2017). Consequently, the core challenge in bidirectional pump research lies in reconciling the conflicting aerodynamic requirements of forward and reverse operation within a single blade and passage design.

Early research on bidirectional pumps primarily focused on achieving basic functional reversibility, often accepting significant efficiency losses in one operating direction. However, as engineering standards evolved and energy efficiency became a central concern, researchers began to investigate systematic optimization strategies aimed at narrowing the performance gap between forward and reverse modes. Studies on bidirectional shaft tubular pumps demonstrated that passage geometry, hub-to-tip ratio, and blade profile selection exert a strong influence on hydraulic performance symmetry (Xie et al., 2015). Subsequent experimental investigations further confirmed that even modest geometric refinements could yield measurable improvements in efficiency and head characteristics under dual-direction operation (Shi et al., 2016).

Parallel to these developments, advances in computational fluid dynamics enabled detailed exploration of internal flow structures, revealing complex unsteady phenomena such as rotating stall, blade–wake interaction, and pressure pulsation amplification under off-design conditions. Numerical studies of reversible axial-flow pump units highlighted the sensitivity of internal flow patterns to operating mode, especially in relation to blade incidence angle and secondary flow development (Mao et al., 2016). These insights shifted the research focus from purely steady-state performance metrics toward a broader consideration of unsteady flow behavior and structural integrity.

Pressure pulsation and vibration have since emerged as critical performance indicators for bidirectional pumps. Excessive pulsation not only degrades hydraulic efficiency but also accelerates mechanical wear, increases noise emission, and compromises long-term reliability. Extensive investigations into centrifugal, mixed-flow, and axial-flow pumps have demonstrated that unsteady pressure fluctuations are closely linked to blade trailing-edge geometry, rotor–stator interaction, and flow separation dynamics (Gao et al., 2016; Cui et al., 2020; Lin et al., 2021). While many of these studies focus on unidirectional machines, their findings provide essential theoretical foundations for understanding similar phenomena in bidirectional systems.

Despite the growing body of literature, a persistent gap remains in the holistic integration of performance optimization, unsteady flow analysis, and bidirectional operational requirements. Existing studies often address individual aspects—such as blade profile optimization or pressure pulsation analysis—in isolation, without fully articulating their combined implications for reversible pump design. Moreover, the majority of experimental and numerical investigations are conducted under specific operating conditions, limiting their generalizability across different pump configurations and application domains.

The present article seeks to address this gap by offering an extensive, theory-driven synthesis of research on bidirectional axial-flow and tubular pumps. By systematically analyzing and interrelating findings from performance studies, internal flow investigations, and pressure pulsation research, this work aims to construct a coherent conceptual framework for understanding and optimizing bidirectional pump behavior. The scope of the article encompasses blade airfoil design, passage optimization, unsteady flow mechanisms, and vibration-related phenomena, with a particular emphasis on the underlying physical principles that govern reversible operation.

METHODOLOGY

The methodological approach adopted in this research is fundamentally analytical and interpretative, grounded in an exhaustive qualitative synthesis of the provided peer-reviewed literature. Rather than introducing new experimental measurements or numerical simulations, the study systematically reexamines existing findings to extract deeper theoretical insights and identify unifying principles applicable to bidirectional pump design. This approach is particularly well-suited to the objective of producing a comprehensive, publication-ready research article that emphasizes conceptual understanding and critical interpretation over data generation.

The first stage of the methodology involved a thematic categorization of the referenced studies. The literature was grouped into several interrelated domains: optimization of bidirectional tubular pump passages, blade airfoil and trailing-edge design, internal flow structure and performance prediction, pressure pulsation and vibration analysis, and rotor–stator interaction effects. This categorization enabled a structured comparison of research objectives, methodological assumptions, and key findings across different pump types and operating conditions.

Within each thematic domain, the methodological details reported in the original studies were carefully analyzed. For example, optimization studies on bidirectional shaft tubular pumps often employed parametric variation of geometric features such as blade angle, passage curvature, and hub diameter, combined with experimental validation or numerical performance prediction (Xie et al., 2015; Shi et al., 2016). Internal flow analyses relied heavily on computational simulations to visualize velocity distribution, vortex formation, and flow separation under forward and reverse operation (Mao et al., 2016; Ma and Wang, 2017). Pressure pulsation investigations typically utilized time-domain pressure monitoring and frequency-domain analysis to characterize unsteady behavior linked to blade passing frequency and its harmonics (Cui et al., 2021; Ji et al., 2020).

Rather than replicating these methods, the present study abstracts their core methodological principles to facilitate cross-study comparison. For instance, differences in experimental setup or numerical modeling strategy are interpreted in terms of their implications for result validity and generalizability. This abstraction allows the identification of consistent trends and recurring phenomena that transcend individual study limitations.

A critical component of the methodology is the interpretative synthesis of results across pump types. Findings from centrifugal and mixed-flow pump studies are not treated as directly transferable but are instead examined for their conceptual relevance to bidirectional axial-flow systems. Pressure pulsation mechanisms associated with trailing-edge geometry or rotor–stator interaction, for example, are analyzed in terms of their underlying fluid dynamic drivers, which are often common across pump categories (Gao et al., 2016; Zhang et al., 2020).

The methodology also emphasizes theoretical elaboration. Each major claim or observation derived from the literature is contextualized within established principles of fluid mechanics, turbomachinery theory, and unsteady flow dynamics. Counter-arguments and alternative interpretations proposed in the literature are discussed to highlight areas of ongoing debate or uncertainty. This reflective approach ensures that the analysis remains balanced and academically rigorous.

Finally, methodological limitations inherent in the source studies are explicitly acknowledged. Variations in operating conditions, geometric configurations, and measurement techniques are recognized as potential sources of discrepancy among reported results. Rather than viewing these discrepancies as weaknesses, the present study treats them as opportunities for deeper insight into the sensitivity of bidirectional pump behavior to design and operational parameters.

RESULTS

The synthesized results derived from the reviewed literature reveal a multifaceted and highly interconnected set of phenomena governing the performance and stability of bidirectional axial-flow and tubular pump systems. One of the most consistent findings across studies is the inherent asymmetry between forward and reverse operation, even in pumps explicitly designed for bidirectional functionality. This asymmetry manifests in efficiency curves, head–flow characteristics, internal flow patterns, and unsteady pressure behavior (Xie et al., 2015; Ma et al., 2018).

Optimization studies on bidirectional shaft tubular pumps demonstrate that passage geometry plays a decisive role in mitigating performance degradation under reverse operation. Adjustments to blade inlet and outlet angles, combined with refined passage curvature, were shown to improve flow uniformity and reduce hydraulic losses in both operating directions (Shi et al., 2016). However, these improvements are often accompanied by trade-offs, such as reduced peak efficiency in the primary operating mode. This highlights the fundamental design tension inherent in bidirectional systems.

Internal flow analyses provide further insight into the origins of this asymmetry. Under forward operation, the blade profile typically aligns favorably with the incoming flow, resulting in relatively smooth acceleration and minimal separation. In reverse operation, however, the same blade geometry may induce adverse pressure gradients, leading to early boundary layer separation and the formation of large-scale vortical structures (Ma and Wang, 2017). These flow disturbances contribute directly to increased energy dissipation and reduced hydraulic efficiency.

Performance prediction studies of reversible axial-flow pump units confirm that flow separation and secondary flow development are strongly dependent on operating point. At partial load conditions, both forward and reverse modes exhibit intensified unsteady behavior, but the reverse mode is particularly susceptible to instability (Mao et al., 2016). This sensitivity underscores the importance of considering off-design performance in bidirectional pump optimization.

The influence of blade airfoil selection emerges as a critical determinant of bidirectional performance. Comparative investigations of pumps equipped with different airfoil blades reveal that symmetric or near-symmetric airfoils tend to offer improved reversibility, albeit at the expense of maximum efficiency (Ma et al., 2018). Conversely, highly cambered airfoils optimized for forward operation exacerbate performance losses and unsteady flow under reverse conditions. These findings align with broader research on reversible axial fans and turbines, which emphasizes the importance of balanced camber distribution for bidirectional functionality (Abdolmaleki et al., 2019; Li et al., 2011).

Pressure pulsation analysis constitutes another major result domain. Studies across centrifugal, mixed-flow, and axial-flow pumps consistently show that unsteady pressure fluctuations are dominated by blade passing frequency and its harmonics, with amplitude strongly influenced by blade trailing-edge geometry and rotor–stator interaction (Gao et al., 2016; Cui et al., 2020). In bidirectional pumps, these effects are amplified under reverse operation due to increased flow non-uniformity and separation-induced turbulence (Ma et al., 2014).

Trailing-edge modifications, such as cutting angle adjustment or sinusoidal tubercle design, have been shown to significantly alter pressure pulsation characteristics. While these studies primarily focus on unidirectional centrifugal pumps, their results suggest that tailored trailing-edge profiles could play a vital role in mitigating unsteady behavior in bidirectional systems as well (Lin et al., 2021; Cui et al., 2020). The underlying mechanism involves the disruption of coherent vortex shedding and the redistribution of wake energy.

Rotor–stator interaction emerges as a key contributor to vibration and noise. Experimental and numerical investigations in mixed-flow pumps demonstrate a strong correlation between pressure pulsation intensity and shaft vibration, particularly under conditions of reduced tip clearance or unfavorable blade alignment (Li et al., 2020; Ji et al., 2020). In bidirectional pumps, where flow alignment varies dramatically between operating modes, rotor–stator interaction effects are likely to be even more pronounced.

Collectively, these results paint a complex picture in which geometric optimization, internal flow dynamics, and unsteady pressure behavior are deeply interwoven. Improvements in one performance aspect often influence others, sometimes in conflicting ways. This interdependence underscores the need for integrated design strategies that consider the full spectrum of hydraulic and structural phenomena.

DISCUSSION

The results synthesized in this study invite a deeper theoretical interpretation of bidirectional pump behavior, extending beyond surface-level performance metrics to the fundamental fluid dynamic mechanisms at play. At the heart of bidirectional pump design lies a compromise between aerodynamic specialization and operational versatility. Unlike unidirectional pumps, which can be optimized around a well-defined design point, bidirectional systems must accommodate two distinct and often opposing flow regimes within the same geometric framework.

One of the most significant theoretical implications concerns blade camber and incidence. Classical turbomachinery theory emphasizes the alignment of blade camber with the relative flow angle to maximize energy transfer efficiency. In bidirectional pumps, this alignment can only be optimal in one direction unless symmetric or adaptive blade designs are employed. The observed efficiency asymmetry between forward and reverse modes can thus be interpreted as a direct consequence of incidence mismatch and the resulting boundary layer behavior (Ma and Wang, 2017).

Flow separation under reverse operation emerges as a recurring theme across studies. From a theoretical standpoint, separation is not merely a local phenomenon but a global driver of unsteady behavior. Separated flow regions generate large-scale vortices that interact with adjacent blades and stationary components, amplifying pressure pulsations and vibration (Mao et al., 2016). This explains why reverse operation often exhibits higher unsteady loads even when mean performance metrics such as head and flow rate appear acceptable.

The discussion of pressure pulsation highlights the importance of unsteady flow theory in bidirectional pump analysis. Pressure fluctuations are often treated as secondary effects, yet the literature demonstrates that they are integral to understanding pump reliability and lifespan. The strong dependence of pulsation amplitude on blade trailing-edge geometry suggests that even subtle geometric features can exert disproportionate influence on unsteady behavior (Gao et al., 2016; Lin et al., 2021). This challenges traditional design approaches that prioritize steady-state efficiency over dynamic stability.

Another critical discussion point concerns the transferability of findings from centrifugal and mixed-flow pumps to bidirectional axial-flow systems. While geometric and flow differences exist, the underlying physics of rotor–stator interaction, wake dynamics, and turbulence generation share common foundations. The successful application of trailing-edge modification strategies in centrifugal pumps, for example, provides a compelling case for their exploration in bidirectional axial-flow designs (Cui et al., 2020; Zhang et al., 2020).

Despite these insights, the literature also reveals notable limitations. Many studies focus on isolated parameters or specific operating conditions, limiting their applicability to real-world bidirectional systems that experience wide-ranging flow variations. Experimental investigations are often constrained by scale effects and measurement limitations, while numerical studies depend heavily on turbulence modeling assumptions that may not fully capture complex unsteady phenomena.

Future research directions should therefore emphasize integrated optimization frameworks that combine geometric design, unsteady flow analysis, and structural response assessment. Advances in computational capability and experimental diagnostics offer promising avenues for such holistic approaches. Additionally, adaptive or morphing blade technologies, while still largely conceptual in hydraulic machinery, may offer long-term solutions to the inherent compromise of bidirectional design.

CONCLUSION

This comprehensive research article has presented an extensive theoretical and analytical examination of bidirectional axial-flow and tubular pump systems, grounded strictly in the provided body of scholarly literature. Through detailed synthesis and interpretation, the study has elucidated the complex interplay between geometric design, internal flow dynamics, and unsteady pressure behavior that defines bidirectional pump performance.

The analysis confirms that performance asymmetry between forward and reverse operation is an intrinsic challenge rooted in blade camber distribution, flow incidence mismatch, and separation dynamics. Optimization efforts focused on passage geometry and blade profile selection can mitigate but not entirely eliminate this asymmetry. Unsteady phenomena, particularly pressure pulsation and vibration, emerge as critical considerations that must be addressed alongside traditional efficiency metrics.

By integrating findings from axial-flow, mixed-flow, and centrifugal pump research, the article has demonstrated that many unsteady flow mechanisms are governed by universal fluid dynamic principles. This insight supports the cross-fertilization of design strategies across pump categories and underscores the value of trailing-edge modification and rotor–stator interaction control in bidirectional systems.

Ultimately, the study highlights the necessity of holistic design methodologies that balance efficiency, stability, and reliability under dual-direction operation. While significant progress has been made, the inherent complexity of bidirectional pump behavior ensures that this field will remain an active and challenging area of research. The theoretical framework and interpretative insights presented here aim to contribute meaningfully to that ongoing endeavor.

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