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Performance characterization and structural optimization of a fluid diode

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Abstract. As a passive unidirectional flow control device, Tesla valves demonstrate broad application prospects in microfluidics, thermal photovoltaics, and biomedical equipment due to their advantages of no moving parts, easy processing, and scalability. However, current research faces two major bottlenecks: first, the lack of unified performance evaluation metrics, where parameters such as flow rate ratio and pressure drop ratio are often used interchangeably, making results difficult to compare horizontally; second, structural optimization relying on empirical trial-and-error methods, where complex coupling of flow channel parameters results in low optimization efficiency, hindering deeper engineering applications. To address these issues, this paper systematically conducts research on the performance characterization and structural optimization of Tesla valves, aiming to establish a standardized evaluation system and provide efficient optimization methods. This study first established single-section and 1-8-section series models based on ANSYS Fluent, using the rectification ratio (forward/reverse flow velocity/pressure drop ratio) as the core evaluation metric. It was found that the rectification ratio of single-section valves ranges from 1.34 to 1.40 under 1000-3000Pa pressure differentials, while the 8-section series configuration achieves 1.5 times the rectification ratio of single-section valves, with improvement slowing after 4 sections. Building on these simulations, this paper innovatively introduces circuit analogy theory, mapping fluid pressure differentials, flow rates, and flow resistance to circuit voltage, current, and resistance respectively. This establishes a Tesla valve "flow-pressure" voltage-current characteristic model.

Keywords: Thermal Valve, Computational Fluid Simulation, Circuit Analog, Structural Optimization.

1. Introduction

The Tesla Valve, also known as a valveless pump or fluid diode, is a classic passive unidirectional flow control device. This invention was proposed by the renowned scientist Nikola Tesla in 1920 and granted a U.S. Patent, with a history spanning over a century. Its core design philosophy relies entirely on the geometric configuration of the flow channel to regulate fluid direction, without depending on any movable mechanical components. The valve's structure typically consists of a series of periodically arranged asymmetric units, each containing a bend with specific curvature, a fixed-length main channel (L), and connecting branch channels. This ingenious layout enables fluid to undergo distinct flow state evolution in different directions: during forward flow (low-resistance direction), the fluid passes smoothly through the main channel, generating minimal viscous resistance and pressure drop; during reverse flow (high-resistance direction), the fluid is strongly directed toward the bend region, producing complex phenomena such as large-scale flow separation, vortex generation, and flow collision, significantly increasing turbulence dissipation and local resistance, thereby effectively suppressing backflow.

Notably, the physical mechanism of generating directional flow resistance through geometric structures is widely prevalent in nature. A classic biological analogy is the intestinal architecture of certain fish species (e.g., sharks), which typically feature unique spiral valve morphologies (such as spiral valve intestines). Functionally analogous to the Tesla valve, this structure significantly enhances nutrient digestion and absorption efficiency by prolonging food retention time, intensifying fluid mixing effects, and increasing the effective absorption area of the intestinal wall. This convergent evolutionary case not only demonstrates the advanced design philosophy of the Tesla valve but also provides valuable inspiration for biomimetic fluid design and structural optimization. In recent years, Tesla valves have garnered significant research interest in fluid control due to their energy independence, ease of fabrication, and excellent scalability. They have been widely applied in various engineering fields including microfluidic chips [1], aviation management systems, chemical analysis systems [2], thermal photovoltaic systems [3], biomedical devices [4], and high-efficiency heat exchange systems [5][6], demonstrating broad prospects for both scientific research and engineering applications. Accurately evaluating the performance of Tesla valves remains a focal point in both academic and engineering communities. Early research primarily focused on establishing performance evaluation metrics and parametric analysis.

In 2001, Bendib et al. proposed using throttling efficiency as a key performance indicator for Tesla valves, laying the foundation for quantitative analysis of valve dynamics [7]. Truong et al. systematically investigated in 2003 the impact of critical geometric parameters (e.g., channel width-to-height ratio, bending radius) in basic valve configurations on flow characteristics and pressure drop behavior, revealing the intrinsic relationship between structural asymmetry and fluid rectification effects [8]. In 2007, Forster et al. conducted theoretical modeling and experimental validation to analyze the mechanism of inlet/outlet losses in valve flow, deepening the understanding of energy dissipation pathways in Tesla valves.

With the continuous advancement of numerical simulation methods, researchers have begun employing more sophisticated simulation techniques to conduct detailed studies on the internal flow structure of Tesla valves. In 2009, Fadl et al. utilized the Lattice Boltzmann method to systematically investigate the microfluidic pressure drop ratio and valve efficiency of various rectification structures (including traditional Tesla valves), revealing the microscopic mechanisms of vortex generation and energy dissipation at the mesoscale [9]. In 2010, Deng et al. conducted topological optimization design for the planar layout of Tesla microvalves, achieving structure self-generation under high-performance guidance through intelligent algorithms, providing new insights for efficient valve design [10]. In 2013, Nobakht et al. performed detailed simulations of three-dimensional incompressible flow within Tesla microvalves using Fluent software, comparing the pressure drop mechanisms of three different microvalve structures and emphasizing the significant impact of three-dimensional effects on performance evaluation [11].

Additionally, research on Tesla valves has expanded into multi-physical field coupling and standardized performance assessment. In 2018, Porwal, Piyush R. et al. investigated the heat transfer and fluid flow characteristics of multi-stage tandem Tesla valves, focusing on how passive flow control mechanisms (such as streamline diversion and jet impact) enhance overall heat transfer and flow performance. In 2022, Bao, Yunhao, and Huanguang Wang developed an enhanced evaluation framework integrating flow and heat transfer characteristics. Their systematic analysis of a novel Tesla valve's multi-condition performance established critical benchmarks for standardizing performance assessment and engineering selection. By 2024, Zhang, Xinchen, and colleagues conducted parametric scanning and multi-objective optimization to systematically investigate how geometric parameters (including branch angles, length ratios, and curvature radii) influence Tesla valve performance. Their study also evaluated the potential applications of these valves in unidirectional flow control systems, providing forward-looking guidance for designing high-performance Tesla valves [12].

The aforementioned research progress demonstrates that Tesla valve studies have evolved from early-stage mechanism exploration and parameter analysis to a new phase characterized by multiphysics modeling, structural optimization design, and standardized performance evaluation. This development has established a solid theoretical and technical foundation for its reliable application in more complex engineering systems. Notably, Tesla valves exhibit significant practical value in microfluidic systems—a field extensively utilized in cutting-edge domains such as biomedical and chemical analysis, where devices must meet stringent requirements for miniaturization, integration, and fluid control precision [13]. The motion-free design of Tesla valves ensures stable operation at microscopic scales, effectively preventing wear and clogging while significantly enhancing system reliability and service life. For instance, in microfluidic chips, Tesla valves enable precise control of microfluidic flow direction and volume, facilitating high-precision manipulation and analysis of biological samples, thereby providing critical technical support for disease diagnosis and drug development. In valveless pump designs, their unidirectional flow characteristics efficiently convert external energy into directed fluid motion, eliminating the complex mechanical structures of traditional pumps. This innovation not only simplifies system design but also improves energy utilization efficiency.

Despite the significant advantages of Tesla valves, current research still faces two major bottlenecks. First, there is a lack of a unified performance evaluation system. Different studies use varying parameters such as flow velocity ratio, pressure drop, or energy loss, making it difficult to compare results horizontally or conduct systematic evaluations. Second, structural optimization heavily relies on empirical trial-and-error methods. Due to the complex coupling between flow channel parameters, traditional optimization approaches are inefficient and costly, limiting their further application. However, their article only summarized and introduced the flow velocity and asymmetry of Tesla valves under a single structural configuration, without elaborating on the functional and structural optimization of Tesla valves. To better understand how Tesla valves operate and how their asymmetry primarily affects fluid flow during transportation, this paper will analyze the quantification of Tesla valve performance and structural optimization from theoretical, experimental, and simulation perspectives.

2. Principle of Operation of the Thales Valve

2.1 Evaluation of the Unidirectional Conduction Characteristics of Tesla Valve

For incompressible fluids, the relationship between pressure loss (ΔP) across a Tesla valve and the flow resistance coefficient can be expressed by the following equation (1):

$$\Delta P = K \cdot \frac{\rho v^2}{2} \tag{1}$$

ΔP denotes the pressure difference across a valve (unit: Pa). It is defined as: under forward flow conditions, ΔP=Pin−Pout; under reverse flow conditions, ΔP=Pout−Pi; Kn represents the resistance coefficient of the Tesla valve, a dimensionless parameter; ρ is the fluid density (unit: kg/m^3); and v is the average fluid velocity at the valve inlet cross-section (unit: m/s). The performance of Tesla valves is typically quantified by the rectification ratio (or pressure drop ratio). The rectification ratio (Rf) serves as a critical dimensionless parameter in evaluating the performance of Tesla valves and similar passive unidirectional fluid components. It quantitatively characterizes the unidirectional flow capacity of a device. Defined as the ratio of the volume flow (or average velocity) under forward flow to that under reverse flow at the same pressure difference, it is expressed as:

The performance of Tesla valves is typically quantified by the rectification ratio (or pressure drop ratio). In evaluating Tesla valves and similar passive unidirectional fluid components, the rectification ratio (Rf) serves as a key dimensionless parameter. It quantitatively characterizes the unidirectional flow capacity of the device, defined as the ratio of the volume flow (or average velocity) in the forward flow to the reverse flow under identical pressure differentials. The definition is:

$$D_i(\mathbf{Q}) = \frac{\int P_f (v_f \cdot n) ds}{\int \mathrm{P}_r (v_r \cdot n) ds} = \frac{\Delta P_{\mathrm{f}}}{\Delta P_r} \cdot \infty \cdot \frac{v_{\mathrm{f}}}{v_{\mathrm{r}}} \tag{2}$$

Here, Rr and Rf denote the pressures during reverse and forward flow respectively, while vr and vfrepresent the velocity vectors of the liquid in these two flow states. n is the unit normal vector of the vertical element, and ΔPr and ΔPf denote the pressure differences at the valve inlet and outlet under a given flow rate for reverse and forward flow. When Rf=1, it indicates equal flow capacity in both directions, meaning the device lacks rectification capability. If Rf>1, forward flow is more easily achieved, with higher values indicating superior unidirectional flow guidance. Theoretically, Rf <1 suggests the device actually favors reverse flow.

3. Results

3.1 The establishment of simulation model

This section employs numerical simulation methods to systematically investigate the flow characteristics of single-section and multi-section (with 1, 2, 4, and 8 sections in series) Tesla valves under varying pressure differentials (structural schematics are shown in Fig.1). First, for the single-section Tesla valve, the flow field structure and pressure drop-flow relationships during forward and reverse flows were analyzed under three different inlet/outlet pressure differentials (1000 Pa, 2000 Pa, and 3000 Pa) to reveal the pressure differential-dependent unidirectional conduction effect. Subsequently, the study was extended to multi-section series configurations, with particular focus on the outlet velocity variations of 2-,4-, and 8-section valves under identical pressure differential conditions. This aims to quantitatively evaluate the impact of series configuration numbers on the system's overall flow performance and rectification efficiency.

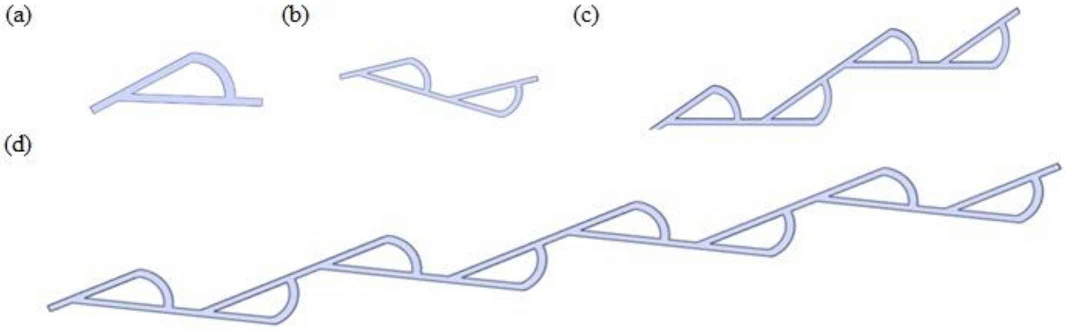

Fig. 1 Modeling of Multi-segment Tesla Valve

The modeling simulation of a single Tesla valve is presented in Fig.2. The results demonstrate that as the inlet-outlet pressure differential increases (1000 Pa, 2000 Pa, 3000 Pa), the rectification ratio (Rf = V positive / V negative) consistently exceeds 1 across all pressure differentials. This confirms that the forward flow outlet velocity remains significantly higher than the reverse flow velocity, indicating that the single-valve structure effectively achieves unidirectional flow rectification.

While the overall flow velocity increases with rising pressure differentials, the rectification ratio exhibits relatively minor fluctuations. This phenomenon indicates that under the specific geometric configuration, although enhanced fluid inertia effects facilitate forward flow, they simultaneously intensify dissipative mechanisms in reverse flow—including bypassing, secondary flow, and flow separation—resulting in concomitant increases in reverse velocity. Consequently, the overall rectification efficiency demonstrates only a gradual upward trend with increasing pressure differentials, suggesting that the single-valve structure in this study exhibits low sensitivity to pressure differential variations in its rectification capability.

Moreover, the Tesla valve demonstrates stable and significant rectification effect (Rf>1.35) within a specific pressure differential range (particularly 2500–3000 Pa), demonstrating its structural design's capability to effectively induce asymmetric flow and generate differential flow resistance between forward and reverse directions.

As shown in Fig.2, the rectification performance of the Tesla valve exhibits a positive correlation with the operating pressure differential. The rectification ratio increases monotonically from 1.34 at

1000 Pa to 1.40 at 3000 Pa, representing a 4.5% rise. This demonstrates that the valve achieves superior unidirectional conductivity under higher pressure differentials (2500–3000 Pa range). While the curve shows slight fluctuations near 2000 Pa where flow regime transition may occur, the overall upward trend remains consistent, confirming the valve's reliable and effective rectification characteristics within its designed pressure differential range.

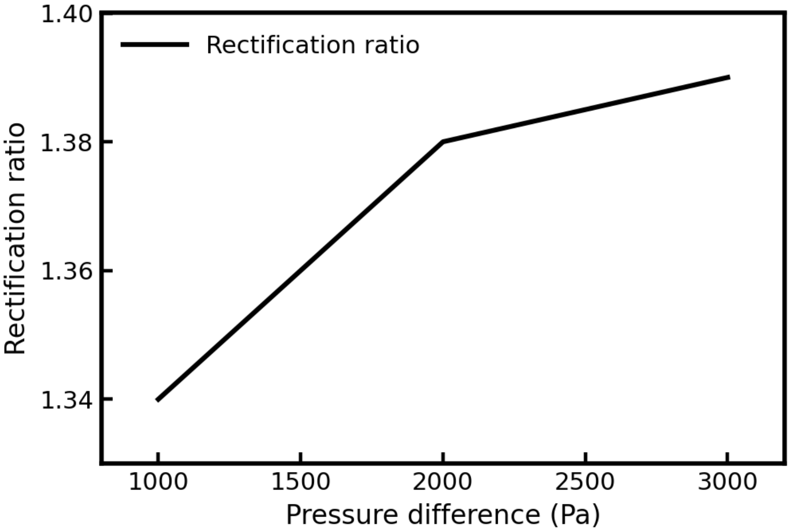

Fig. 2 Rectifier Difference of Single-Section Tesla at Different Pressures

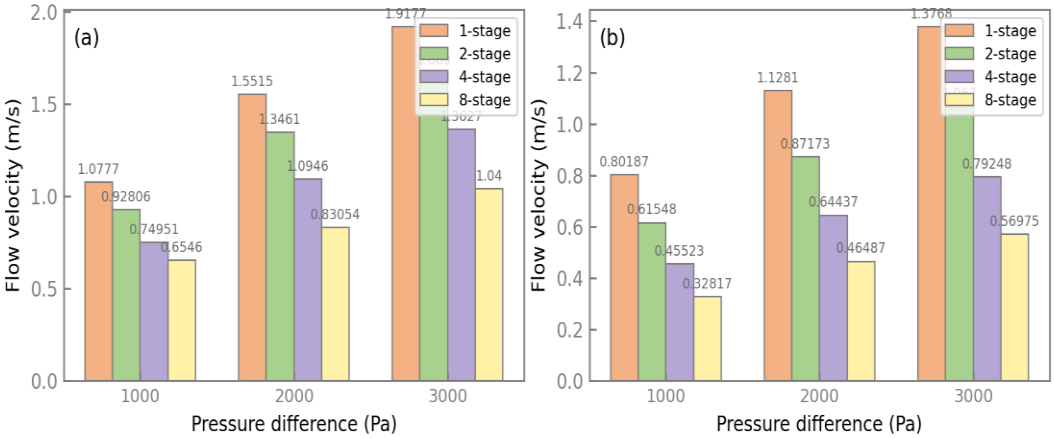

Fig. 3 Comparison of outlet velocities of different models

The modeling simulation of multi-section Tesla valves demonstrates the flow velocity comparison under varying pressure differentials, as illustrated in Fig.3. Comparative analysis of inlet velocities across different models under forward flow conditions reveals that: In forward flow, when the pressure differential increases from 1000 Pa to 3000 Pa, the inlet velocities of single-section, two-section, four-section, and eight-section models all exhibit an upward trend. Under identical pressure differentials, the single-section model consistently demonstrates higher inlet velocities than multi-section models, with lower velocities observed as the number of sections increases. The reverse flow scenario follows the same pattern: increased pressure differential correlates with higher flow velocity, where the single-section model maintains higher velocities than multi-section models, and velocities decrease with more sections. However, under identical pressure differentials and model configurations, reverse flow inlet velocities generally remain lower than those in forward flow conditions.

4. Conclusions

This study investigates the operational principles and simulation characteristics of Tesla valves, which function as passive unidirectional fluid control components. By employing an asymmetric periodic unit structure (including curves and straight sections), they create differential resistance between forward and reverse flows—forward flow exhibits smooth flowlines and minimal pressure drop, while reverse flow generates high-energy consumption due to vortex formation. Using Ansys Fluent software with the k-ε turbulence model, the study quantifies the impact of geometric parameters (e.g., curvature radius, deflection angle) and mesh refinement (curves with 0.1mm mesh density, near-wall layer treatment) on simulation accuracy. The unidirectional performance is evaluated using resistance coefficients and flow rectification ratios (forward/reverse velocity ratios). Results demonstrate stable rectification effects for single-section valves under specific pressure differentials, while multi-section series configurations (1-8 sections) enhance rectification ratios. Future performance improvements can be achieved through geometric parameter optimization.

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