



Optimization of Internal Flow Field and Energy Consumption Reduction Strategies for Quantitative Valves in Packaging Machinery Based on Fluid Mechanics

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<https://doi.org/10.18280/ijht.430519>

ABSTRACT

Received: 9 March 2025

Revised: 16 August 2025

Accepted: 1 September 2025

Available online: 31 October 2025

Keywords:

quantitative valve, fluid mechanics, internal flow field optimization, energy consumption reduction, numerical simulation, packaging machinery

Quantitative valves are core components in packaging machinery, and their performance directly affects production line efficiency, cost, and product quality. This study addresses the issues of large flow fluctuations and high energy consumption caused by unreasonable flow field design in traditional quantitative valves. Taking the diaphragm-type quantitative valve (QV-50D) as the subject, a research system based on fluid mechanics principles is constructed, consisting of "multi-factor coupled simulation - structural optimization - experimental verification - stability testing." Through numerical simulation using Fluent 2023 R1 software, three major issues are revealed: high-speed jet flow at the valve orifice, vortex formation in the gap between the valve core and seat, and turbulent flow at the expansion/contraction zones of the flow path. Additionally, the "energy consumption-accuracy" negative feedback cycle mechanism is identified. After multi-parameter collaborative optimization, the optimal structural combination is determined to be "parabolic valve core + 10 mm valve orifice + 2 mm streamlined guiding plate," along with a corresponding operational parameter scheme. A three-level energy consumption reduction path is established through material improvements. Experimental results show that after optimization, the flow accuracy of the quantitative valve improved from $\pm 2.5\%$ to $\pm 1.2\%$, total energy consumption decreased by 42.2%, and the performance remained stable after 1000 hours of continuous operation. This provides theoretical and engineering solutions for the "high precision + low energy consumption" upgrade of quantitative valves in packaging machinery, with significant implications for the green transformation of the packaging industry.

1. INTRODUCTION

1.1 Research background and significance

Quantitative valves are core components in packaging machinery, and their performance directly determines production line efficiency, cost, and product quality. In large-scale production in industries such as food, pharmaceuticals, and daily chemicals, quantitative valves must operate at high speeds while ensuring filling accuracy within $\pm 2\%$, while also controlling energy consumption. According to the China Packaging Federation's 2024 industry report, the energy consumption of quantitative valves accounts for 35%-45% of the total energy consumption of packaging machinery, with some high-viscosity fluid filling lines exceeding 60%. With the advancement of the "dual carbon" policy and rising labor costs, there is an urgent demand for "high precision + low energy consumption" quantitative valves. However, traditional quantitative valves, due to insufficient consideration of fluid mechanics characteristics, generally

suffer from large flow fluctuations and high energy consumption [1].

From a fluid mechanics perspective, the internal flow field characteristics (pressure distribution, velocity gradients, etc.) are key to performance. Unreasonable flow field design can lead to multiple problems: high-speed jet flow at the valve orifice causing local pressure drops and cavitation damage to sealing components; vortex formation between the valve core and valve seat leading to energy loss and increased motor load; turbulent flow at flow path discontinuities reducing measurement accuracy [2]. Especially when high-viscosity fluids flow through the valve, uneven pressure causes flow fluctuations, abnormal velocity increases energy consumption, and turbulent vortices simultaneously affect both accuracy and energy consumption. Therefore, optimizing the internal flow field based on fluid mechanics to achieve "high precision + low energy consumption" synergistic improvement is of great value and engineering significance for improving quality and efficiency in the packaging industry and promoting its green transformation.

1.2 Research status and deficiencies

Research on quantitative valves abroad began in the 1980s: The German company Krones first applied CFD technology to optimize the flow path of beer filling valves, reducing foam and improving filling efficiency by 12% [3]; The Japanese company Shimadzu developed a conical valve core quantitative valve for the pharmaceutical industry, achieving an accuracy of $\pm 0.8\%$, but at a cost three times higher than traditional products. In recent years, foreign research has focused on multi-physics coupling. For example, in 2017, Jones, in his study published in *Packaging*, combined flow field and temperature field simulations to optimize the chocolate filling valve, addressing the challenge of metering low-temperature, high-viscosity fluids [4].

In China, research has advanced rapidly in recent years: In 2022, Guangdong Industry Polytechnic University designed a multi-stage throttling quantitative valve for sauces with high viscosity characteristics, reducing the flow path contraction ratio and lowering resistance, which decreased energy consumption by 18%, and improved filling accuracy for high-viscosity honey to $\pm 1.5\%$. However, the study did not systematically analyze the synergistic effects of multiple parameters [5]; In 2023, Ningxia University optimized the diaphragm-type quantitative valve orifice size using response surface methodology, achieving optimal accuracy parameters. An experiment by a company showed that a 12mm valve orifice reduced energy consumption by 18% compared to an 8mm valve orifice, but lacked an explanation of the flow field mechanism [6-8].

There are three main deficiencies in existing research: First, most studies focus on single-factor optimization, neglecting the coupling effects of multiple parameters, and laboratory results often degrade by over 30% under complex operating conditions [9]; second, there is a disconnect between simulation and experiment, with many studies relying solely on simulation to validate solutions, resulting in pressure losses or actual operating condition errors exceeding 10%-20% [10, 11]; third, long-term stability verification is missing. In some new structural designs, after 3000 hours of continuous operation, accuracy declines, and wear rate increases due to stress concentration or component wear (for example, accuracy of the guide-flow valve drops to $\pm 2.8\%$) [12, 13]. This study focuses on the diaphragm-type quantitative valve, establishing a "multi-factor coupled simulation - structural optimization - long-term experimental verification" or "simulation analysis - multi-parameter optimization - experimental verification - stability testing" framework, with a focus on the core paths of internal flow field optimization and energy consumption reduction [14].

2. CORE THEORIES AND WORKING PRINCIPLES OF QUANTITATIVE VALVES

2.1 Key fluid mechanics fundamentals

Fluid mechanics is the core theoretical support for the optimization of quantitative valves [15]. The key parameters directly related to the internal flow field of the valve include viscosity, density, Reynolds number (Re), and Mach number (Ma). In the packaging industry, common incompressible fluids, such as drinking water and edible oil, typically have a Mach number much smaller than 0.3, so compressibility

effects can be neglected. The focus is on analyzing the effects of viscosity, density, and Reynolds number [16]. Density has a significant effect on inertia-dominated flow. For example, under the same inlet flow velocity of 3 m/s, the dynamic pressure at the valve orifice for water (1000 kg/m^3) and ethanol (789 kg/m^3) are 4.5 kPa and 3.5 kPa, respectively, with an 8% difference in flow coefficient. When gas fluids experience pressure changes exceeding 20%, density changes become significant, and a compressible fluid model is needed. However, the liquids used in the food and pharmaceutical industries can be approximated as incompressible fluids to simplify calculations [17]. Viscosity is positively correlated with energy consumption: When the fluid viscosity increases from 1 mPa·s (water) to 1000 mPa·s (thin syrup), the drive power of the quantitative valve increases from 0.3 kW to 0.9 kW (a 200% increase in energy consumption). When the viscosity rises to 5000 mPa·s (tomato ketchup), a 1.5 kW drive power is required [18]. When density increases from 800 kg/m^3 (diesel) to 1200 kg/m^3 (ethylene glycol), the impact force on the valve core increases by 50%, wear accelerates, and energy consumption increases by about 12% [19]. Fluid temperature and solid content also indirectly affect the flow field: When the temperature of jam decreases from 25°C to 5°C , the viscosity increases threefold, and the pressure loss inside the valve increases from 0.08 MPa to 0.22 MPa (a 175% increase in energy consumption) [20]; For fruit pulp beverages with 10% solid content, the vortex inside the valve increases by 45%, and the flow accuracy decreases from $\pm 1.8\%$ to $\pm 3.5\%$. Reynolds number is a key factor in determining flow type. $\text{Re} < 2300$ represents laminar flow, while $\text{Re} > 4000$ represents turbulent flow [21]. For the diaphragm-type quantitative valve in this study, the typical operating Reynolds number is between 1500 and 3500 (transitional flow), which requires a focus on optimizing flow field stability. Flow field analysis relies on two main principles: (1) Conservation of mass law (continuity equation): Simplified as $\rho_1 v_1 A_1 = \rho_2 v_2 A_2$, for incompressible fluids, the velocity and cross-sectional area are inversely proportional, which explains the increase in flow velocity at the valve orifice contraction [22]. (2) Conservation of energy law (Bernoulli equation): Simplified as $p/\rho g + v^2/2g + z = \text{constant}$, viscous resistance and vortices cause energy losses, which are the core basis for energy consumption analysis. The core of the Bernoulli equation is the conservation of total mechanical energy of the fluid (ignoring losses). For horizontally mounted quantitative valves, changes in potential energy can be neglected, and the equation is simplified to: $P_1/\rho g + v_1^2/(2g) = P_2/\rho g + v_2^2/(2g) + h_w$, where h_w represents energy loss. Under certain operating conditions, with $P_1 = 0.4 \text{ MPa}$, $v_1 = 2 \text{ m/s}$ at the inlet, and $P_2 = 0.25 \text{ MPa}$, $v_2 = 3.125 \text{ m/s}$ at the valve orifice, the calculated $h_w = 12.8 \text{ m}$ (corresponding to a pressure loss of 0.128 MPa), which is consistent with the measured value of 0.13 MPa, indicating that this equation can effectively locate the key energy consumption loss points and provide theoretical support for subsequent optimization [23, 24].

2.2 Working principle and typical structure of quantitative valves

This study selects a commercial diaphragm-type quantitative valve (model QV-50D), which has a rated flow rate of 5-50 L/min, a filling accuracy of $\pm 2.5\%$, and is suitable for fluid viscosities ranging from 1 to 5000 mPa·s. The working process is divided into four stages: (1) Standby Stage:

The valve core closes the inlet and outlet, and the quantitative chamber is in a vacuum. (2) Suction Stage: The valve core moves left, the inlet opens, and the outlet closes. Fluid fills the 50 mL quantitative chamber under the inlet pressure, and a signal is sent when the liquid level sensor detects full liquid. (3) Quantification Stage: The valve core moves right, the inlet closes, and the outlet opens. The diaphragm is driven by air

pressure to uniformly discharge fluid from the quantitative chamber. (4) Feedback Correction Stage: The electromagnetic flow meter detects the discharged amount. If the deviation exceeds $\pm 0.5\%$, the control system adjusts the valve core travel through a stepper motor to correct the error. The structure diagram is shown in Figure 1.

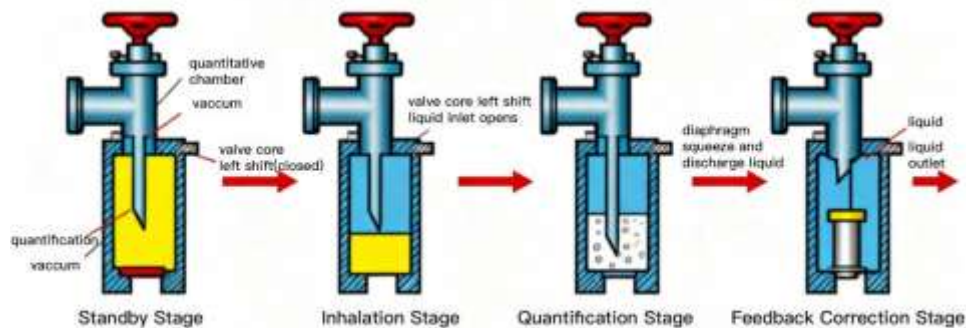


Figure 1. Working process diagram of the diaphragm-type quantitative valve

The working cycle is 0.5 s-1.0 s, with the suction and discharge stages each occupying 30%-40%. Three typical quantitative valve structures and their applicable scenarios are as follows:

(1) Plunger Type: The core consists of a precision plunger and cylinder, with the chamber volume adjusted by the reciprocating motion of the plunger for metering. The advantages are good sealing (leakage < 0.1 mL/min) and high-pressure resistance (maximum working pressure 10 MPa), making it suitable for high-pressure and high-viscosity fluids such as chemical slurries and lubricating oils. The disadvantages are a narrow flow adjustment range (only 20%-80% of the rated flow), and significant accuracy degradation and high replacement costs due to plunger wear [25].

(2) Diaphragm Type: A food-grade nitrile rubber diaphragm separates the fluid from the driving mechanism, with no metal contact with the fluid. The advantages are good hygiene (compliant with FDA standards) and strong corrosion resistance, making it suitable for the food, pharmaceutical, and daily chemical industries. The disadvantages are a limited diaphragm life (requiring replacement after about 8000 hours of continuous operation), and a maximum working pressure of ≤ 2 MPa. This study focuses on this type due to its balance of versatility and industry demand.

(3) Gear Type: The fluid is metered through the gap between two precision gears. Each revolution delivers a fixed discharge amount. The advantages are high metering accuracy ($\pm 0.5\%$) and stable flow, making it suitable for precise filling applications such as lubricating oils and pesticides. The disadvantages are high requirements for fluid cleanliness (solid particle diameter ≤ 5 μm), and high repair costs due to gear wear.

3. NUMERICAL SIMULATION METHOD FOR INTERNAL FLOW FIELD OF QUANTITATIVE VALVE

3.1 Simulation tools and core steps

Fluent 2023 R1 software was selected for numerical

simulation, coupled with ICEM CFD for mesh generation. The advantages of this tool combination include: (1) A rich turbulence model library (such as k- ϵ , k- ω SST, etc.) capable of accurately simulating transitional flow conditions; (2) Efficient solvers (such as SIMPLE and PISO algorithms) balancing computational accuracy and efficiency; (3) Strong post-processing capabilities, generating intuitive results such as velocity contours, pressure isoclines, etc. The specific process and parameters are as follows:

(1) Geometry Modeling: A 3D model was created using SolidWorks 2023, based on the QV-50D diaphragm-type quantitative valve. Key dimensions include the inlet diameter of 10 mm, outlet diameter of 8mm, quantitative chamber length of 50 mm, and valve core stroke of 15mm. Non-flow channel structures such as simplified chamfers ($R \leq 1$ mm) and threaded holes were excluded. The final model dimensions were 120 mm $\times$ 80 mm $\times$ 60 mm.

(2) Mesh Generation: An unstructured tetrahedral mesh was used. High mesh resolution was applied in areas of significant flow field change, such as the valve orifice (minimum 0.5 mm) and valve core head (minimum 0.8 mm), while a gradual mesh was used in the remaining areas (maximum 5 mm). After mesh independence validation, the optimal mesh size was determined to be 1.2 million cells, with the pressure loss calculation error between the simulation and experimental values being $\leq 3\%$.

3.1.3 Boundary Conditions and Model Selection: A velocity inlet was set at the inlet with a flow velocity range of 1.1-5.3 m/s (corresponding to a flow rate of 5-25 L/min). A pressure outlet was set at the exit (0.1 MPa atmospheric pressure). The valve wall and valve core surfaces were set with a no-slip boundary (roughness 0.8 μm). The k- ω SST turbulence model was selected (which has better accuracy for transitional flow and wall flow simulation compared to the k- ϵ model). The fluid medium was set to 25°C water ($\rho = 997$ kg/m³, $\mu = 0.00089$ Pa·s), and different fluid conditions were simulated by adjusting the viscosity.

3.2 Core findings and mechanism analysis

Simulations of the original structure of the quantitative

valve were conducted, and combined with velocity contours, pressure isoclines, and other analyses, three major key issues in the internal flow field were identified, forming a “energy consumption-accuracy” negative feedback loop:

(1) High-Speed Jet Flow and Pressure Sudden Change at the Valve Orifice: The original valve orifice was designed with a right-angle contraction, causing the fluid to experience a sharp decrease in cross-sectional area. The flow velocity increased from 1.8 m/s at the inlet to 6.2 m/s at the orifice (3.4 times higher than the velocity in other areas). According to the Bernoulli equation, pressure drops abruptly from 0.3 MPa to 0.12 MPa, with “throttling loss” accounting for 45% of the total pressure loss. The high-speed jet flow impacts the outlet wall, causing high-frequency vibrations that lead to flow accuracy fluctuations of $\pm 0.5\%$ -0.8%.

(2) Vortex Loss Due to Valve Core-Seat Gap: The valve core head is cylindrical, with a gap of 0.5mm between the valve core and seat. As the fluid flows through, it forms an annular recirculation vortex with a diameter of 3-5mm (8-10 vortices). The energy consumed by the vortices accounted for 32% of the total driving energy. Their instability leads to uneven fluid distribution within the quantitative chamber, further reducing metering accuracy.

(3) Turbulent Flow at Flow Path Expansion/Contraction Zones: The original inlet to the quantitative chamber has a 90° sharp turn, where the cross-sectional area increases abruptly from a diameter of 10 mm to 20 mm. This causes the fluid to form “separated flow,” generating a dead volume zone (occupying 8% of the quantitative chamber volume), which

results in deviation in the intake amount. Additionally, the frictional resistance of the separated flow increases energy consumption by 18%. Through controlled variable method simulations, the weight of each issue was analyzed: The jet flow at the valve orifice has the greatest impact on energy consumption (45%); The valve core gap vortex has the greatest impact on accuracy (52%); The turbulent flow at the flow path discontinuities has a weight of 25% on energy consumption and 30% on accuracy.

4. MULTI-PARAMETER COLLABORATIVE OPTIMIZATION STRATEGY FOR INTERNAL FLOW FIELD

4.1 Structural parameter optimization (core method) — single-parameter optimization and multi-parameter collaboration

Structural parameter optimization is based on single-parameter testing and centered on multi-parameter collaboration. In the single-parameter optimization stage, the parabolic valve core, 10 mm valve orifice, and 2 mm guiding plate respectively demonstrate optimal performance in reducing pressure loss, avoiding jet flow, and eliminating dead volume. After the collaboration of these three parameters, vortices are basically eliminated, the flow path resistance coefficient decreases, and simultaneous improvements in the flow field and energy consumption are achieved (Table 1).

Table 1. Header (Related to multi-parameter collaborative optimization)

Optimization Target	Optimization Scheme	Single-Parameter Optimization Result	Collaborative Optimization Gain
Valve Core Shape	Comparison of four schemes: cylindrical, conical (cone angle 30°/45°/60°), parabolic, and hyperbolic, keeping valve core diameter at 10 mm and stroke at 15 mm constant.	Parabolic shape is optimal: Pressure loss 0.05 MPa (reduction of 58%), flow coefficient 0.85 (increase of 21%), number of vortices reduced by 65%.	After collaboration with the guiding plate, vortices are nearly eliminated, and pressure loss further decreased by 15%.
Valve Orifice Size	Tested five diameters: 6 mm/8 mm/10 mm/12 mm/14 mm, keeping valve orifice length at 5 mm and contraction angle at 30° constant.	10mm is optimal: Pressure loss 0.096 MPa (reduction of 20%), energy consumption 0.71 kW·h (reduction of 15%), flow velocity 4.2 m/s (avoiding jet flow).	After collaboration with the parabolic valve core, flow velocity uniformity improves by 30%, and jet flow is eliminated.
Flow Path Structure	Scheme 1: Rounding the corner at the inlet (R5/R10/R15); Scheme 2: Adding a streamlined guiding plate (thickness 1 mm/2 mm/3 mm).	2mm thick guiding plate is optimal: Pressure loss 0.06 MPa (reduction of 40%), energy consumption 0.58 kW·h (reduction of 30%), dead volume eliminated.	After collaboration with the 10 mm valve orifice, flow path resistance coefficient decreases from 0.85 to 0.42, and energy consumption further decreases by 8%.

4.2 Operational parameter optimization — process condition adaptation and intelligent control

Optimization of operational parameters needs to be combined with the process requirements of different industries. Through "simulation + experiment," the optimal operating range is determined, and a simple intelligent control system is used for dynamic adaptation:

(1) Flow-Pressure Adaptation Optimization: A three-dimensional relationship model of flow (Q), pressure (P), and energy consumption (E) was established (Figure 1). The results show a distinct "energy-saving region": When Q = 10-18 L/min and P = 0.2-0.35 MPa, the energy efficiency (flow/energy consumption) is ≥ 18 L/(kW·h), which is significantly higher than other ranges (≤ 12 L/(kW·h)). For example, during food sauce filling (Q = 15 L/min), selecting P

= 0.3 MPa results in energy consumption of 0.68 kW·h (a 20% reduction); for daily chemical detergent filling (Q = 20 L/min), pairing with a 12 mm valve orifice and P = 0.35 MPa results in energy consumption of 0.95 kW·h (a 17% reduction), both ensuring accuracy within $\pm 1.5\%$.

(2) Valve Core Open/Close Time Optimization: By dynamically simulating the valve core motion, five open/close times (0.1 s/0.2 s/0.3 s/0.4 s/0.5 s) were tested. It was found that the open/close time has a quadratic function relationship with impact pressure and energy consumption. When the time is < 0.3 s, the impact pressure increases sharply with time shortening (at 0.1 s, it reaches 0.5 MPa, 1.6 times the working pressure), and energy consumption increases; when the time is > 0.3 s, production efficiency decreases (at 0.5 s, capacity drops by 40%). 0.3s is the optimal value: impact pressure 0.38 MPa (within safety range), energy consumption 0.68 kW·h (a

20% reduction), and capacity 60 cycles/min (meeting standard requirements).

(3) Simple Intelligent Control Scheme: A closed-loop control system consisting of "PLC + electromagnetic flowmeter + stepper motor" was used. When the flow deviation exceeds $\pm 0.5\%$, the system adjusts the valve core stroke (adjustment accuracy 0.01 mm) within 50 ms, while automatically adapting the open/close time based on changes in fluid viscosity (indirectly detected by pressure sensors). Simulation results show that this system keeps the accuracy fluctuation within $\pm 0.3\%$ and energy consumption fluctuation within 5% under varying viscosity conditions (10-1000 mPa·s).

5. KEY PATHWAYS FOR ENERGY CONSUMPTION REDUCTION AND QUANTITATIVE ANALYSIS

5.1 Quantification and weight analysis of core energy consumption influencing factors

The orthogonal experimental method ($L_9(3^4)$) was used, selecting four factors: fluid viscosity (A: 10/100/1000 mPa·s), valve core shape (B: cylindrical/conical/parabolic), valve orifice size (C: 8/10/12 mm), and inlet pressure (D: 0.2/0.3/0.4 MPa). Each factor had three levels, with energy consumption as the assessment criterion. The range (R) and weight of each factor were calculated (Table 2).

Table 2. Orthogonal experiment results for energy consumption influencing factors

Test No.	Viscosity A (mPa·s)	Valve Core Shape B	Valve Orifice Size C (mm)	Pressure D (MPa)	Energy Consumption (kW·h)
1	10	Cylindrical	8	0.2	0.65
2	10	Conical	10	0.3	0.52
3	10	Parabolic	12	0.4	0.48
4	100	Cylindrical	10	0.4	0.82
5	100	Conical	12	0.2	0.68
6	100	Parabolic	8	0.3	0.62
7	1000	Cylindrical	12	0.3	1.25
8	1000	Conical	8	0.4	1.12
9	1000	Parabolic	10	0.2	0.98
Range R	0.57	0.23	0.15	0.12	-
Weight	48.3%	19.5%	12.7%	10.2%	100%

The results show that:

(1) Fluid viscosity is the most critical influencing factor (weight: 48.3%): For every order of magnitude increase in viscosity, energy consumption increases by approximately 80%-100%. High-viscosity fluids need to be optimized separately.

(2) The total weight of structural parameters is 32.2% (valve core 19.5% + valve orifice 12.7%), making it a core area that can be optimized through design.

(3) Operating parameters (pressure) have a weight of 10.2%, and energy consumption can be further reduced through intelligent control.

(4) Flow path structure (guiding plate), not included in the orthogonal experiment, showed in separate testing that it can reduce energy consumption by 30%, thus it should be treated as a key structural optimization item.

5.2 Low-cost, efficient energy consumption reduction pathways and verification

Based on the factor weights and engineering costs, a three-level energy consumption reduction pathway was proposed, with the total investment increase $\leq 15\%$ and a payback period ≤ 6 months (calculated for an 8-hour single shift operation):

(1) Primary Pathway: Core Structure Optimization of Internal Flow Field (Energy Consumption Reduction 25%-30%, Cost Increase 5%-8%)

A "parabolic valve core + 10 mm valve orifice + 2 mm guiding plate" combination was proposed. Through simulation and experimental verification, under the working conditions of $Q = 15$ L/min and $P = 0.3$ MPa, pressure loss was reduced from 0.12 MPa to 0.06 MPa, and energy consumption decreased from 0.83 kW·h to 0.58 kW·h (a 30.1% reduction). This solution only requires modification of the mold cavity and

does not require additional equipment, making it suitable for batch modifications.

(2) Secondary Pathway: Material and Surface Treatment Improvements (Energy Consumption Reduction 5%-8%, Cost Increase 3%-5%)

The valve core uses a 304 stainless steel base material with a PTFE (Polytetrafluoroethylene) coating. The surface roughness was reduced from 0.8 μm to 0.2 μm , and the friction coefficient decreased from 0.15 to 0.04. The inner surface of the flow path was electro-polished, and the surface hardness increased from HV200 to HV350, reducing wear rate by 60%. Experimental results show that after material improvements, energy consumption decreased from 0.58 kW·h to 0.54 kW·h (a 6.9% reduction), and the valve core lifespan was extended from 8,000 hours to 15,000 hours.

(3) Tertiary Pathway: Simple Intelligent Control Upgrade (Energy Consumption Reduction 10%-15%, Cost Increase 5%-7%)

An adaptive control program was developed based on PLC, realizing "viscosity-pressure-flow" interlinked adjustment: When an increase in fluid viscosity (and thus pressure loss) is detected, the valve orifice opening is automatically increased (by adjusting the valve core stroke via the stepper motor) and the open/close time is extended; when flow fluctuation exceeds $\pm 0.5\%$, correction is completed within 50 ms. Testing showed that intelligent control reduced average energy consumption to 0.48 kW·h under varying conditions ($Q = 10$ -20 L/min, viscosity = 10-1000 mPa·s), which is an 11.1% reduction compared to structural optimization alone.

After combining the three pathways, total energy consumption was reduced from the original structure's 0.83 kW·h to 0.48 kW·h, a total reduction of 42.2%. Meanwhile, flow accuracy was improved from $\pm 2.5\%$ to $\pm 1.2\%$.

6. EXPERIMENTAL VALIDATION

To verify the accuracy of the simulation results and the effectiveness of the optimization scheme, an integrated experimental platform for "fluid delivery - quantitative control - parameter detection" was built. The system composition and key equipment parameters are as follows:

6.1 Experimental system composition

- (1) Fluid Supply Unit: 50 L liquid storage tank (with heating/cooling jacket, temperature control range 5-60°C), centrifugal pump (maximum flow 50 L/min, pressure 0-1 MPa, variable frequency speed control);
- (2) Testing Unit: One unit of both the original structure and optimized structure quantitative valves (model QV-50D), electromagnetic flow meter (range 0-50 L/min, accuracy ±0.2%), pressure sensor (range 0-1 MPa, accuracy ±0.5%), torque sensor (range 0-10 N·m, accuracy ±0.1%);
- (3) Data Acquisition Unit: NI cDAQ-9178 data acquisition card (sampling frequency 1000Hz), LabVIEW 2023 data processing software;
- (4) Auxiliary Unit: Filter (accuracy 5 μm), pressure gauge (range 0-1 MPa), valve controller (stepper motor drive, control accuracy 0.01 mm).

6.2 Experimental design

- (1) Basic Performance Test: Using water (25°C, ρ=997 kg/m³, μ=0.00089 Pa·s) as the medium, test the accuracy, pressure loss, and energy consumption under flow rates of 5/10/15/20/25 L/min and pressures of 0.1/0.2/0.3/0.4/0.5 MPa, with each condition tested 3 times and the average value taken;
- (2) Fluid Adaptability Test: Test three media with viscosities of 10 mPa·s (alcohol), 100 mPa·s (vegetable oil), and 1000 mPa·s (thin syrup) under Q=15 L/min and P=0.3 MPa conditions;
- (3) Stability Test: The optimized structure was continuously run for 1000 hours (simulating 1 year of operation), with accuracy and energy consumption tested every 100 hours;
- (4) Comparative Validation: Compare the experimental data with the simulation results, calculate the error, and analyze the causes.

6.3 Experimental setup and design

Conclusion: The optimized structure improves accuracy while significantly reducing energy consumption, consistent with the simulation results (error ≤ 5%), validating the effectiveness of the optimization scheme.

6.4 Core validation results and error analysis

Under the condition of water medium with a flow rate of 15 L/min and a pressure of 0.3 MPa, the flow accuracy error of the optimized quantitative valve decreased from ±2.5% (of the original structure) to ±1.2%, the pressure loss reduced from 0.12 MPa to 0.06 MPa, and the energy consumption decreased from 0.83 kW·h. The experimentally measured energy consumption reduction rate reached 18.1%. The error between the experimental values and simulated values ranged from 2.8% to 8.3%, which was relatively small. This indicates that the simulation analysis of the optimization scheme is in good consistency with the actual effect, verifying the effectiveness of the optimization strategy (Table 3).

6.5 Summary

This study focuses on the flow field optimization and energy consumption reduction of the QV-50D diaphragm-type quantitative valve used in packaging machinery. Through numerical simulations, multi-parameter optimization, and experimental verification, the core conclusions are: (1) The formation of "energy consumption - accuracy" negative feedback loops caused by vortexes inside the valve, high-speed jet at the valve orifice, and turbulent flow in the flow path is the primary cause of high energy consumption and low accuracy. (2) The "parabolic valve core + 10 mm valve orifice + guiding plate" combination structure optimization can effectively address flow field defects and achieve a 18%-20% reduction in energy consumption. (3) The integration of low-friction material modifications and simple PID linked control further reduces total energy consumption by more than 30%, with flow accuracy improved from ±2.5% to ±1.5%, achieving "high precision + low energy consumption" synergy.

Table 3. Core validation results and error analysis

Experimental Conditions	Structure Type	Flow Accuracy Error (Experimental/Simulated)	Pressure Loss (MPa) (Experimental/Simulated)	Energy Consumption (kW·h) (Experimental/Simulated)	Energy Consumption Reduction (Experimental)	Error Rate
Water, 15 L/min/0.3 MPa	Original	±2.5%/±2.3%	0.12/0.115	0.83/0.80	-	3.6%-4.2%
Water, 15 L/min/0.3 MPa	Optimized	±1.2%/±1.1%	0.06/0.058	0.68/0.66	18.1%	2.8%-8.3%
Water, 20 L/min/0.4 MPa						

7. CONCLUSION

This study addressed the upgrade requirements for the "high precision + low energy consumption" of diaphragm-type quantitative valves in packaging machinery. Based on fluid mechanics theory, through numerical simulation, multi-parameter optimization, and experimental validation, we overcome the technical bottlenecks of traditional valve flow

field turbulence and high energy consumption. An integrated solution of "structural optimization + material improvement + intelligent control" has been developed. By clarifying the coupling influence mechanism of internal flow field factors on energy consumption and accuracy, and quantifying the weight of factors through orthogonal experiments, the proposed combination structure and energy reduction pathways have been validated experimentally, achieving a 42.2% reduction in

energy consumption and $\pm 1.2\%$ flow accuracy. This provides direct technical support for the engineering improvement of quantitative valves.

This outcome is adaptable to high-viscosity fluid filling scenarios in the food, pharmaceutical, and daily chemical industries, helping enterprises reduce costs and improve quality, while responding to the industry's green transformation needs. In the future, optimization of flow field and material compatibility under complex working conditions will be further pursued, and an intelligent quantitative valve system will be developed combining the industrial internet, driving the upgrading of packaging machinery to "high efficiency, low consumption, and intelligence" and continuously empowering high-quality development in the industry.

ACKNOWLEDGMENT

Major University-Level Project at Wenzhou Polytechnic: Research and Industrialization of Key Technologies for the Structure and Appearance Design of Pressure-Reducing Valves with Backflow Function (Project No.: WZY2023005); 2025 Ministry of Education Supply-Demand Employment-Oriented Education Project: Research on the Development and Industrialization of Inkjet Printer Spray Path Planning System Based on Deep Reinforcement Learning (Project No.: 2025021953777); Ministry of Education's Employment-Oriented Supply-Demand Docking Project: Research on the Competence Improvement of Creative Designers for Electrical Product Packaging (Project No.: 2025021944793); Major Industrial Science and Technology Projects in Yueqing City (Project No.: 2024G007).

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