

Application of Smart Valves in Wastewater Treatment Systems

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Abstract: This paper systematically outlines the overall structural composition, core classification criteria, and closed-loop operating principles of smart valves, and specifically investigates their application methods, operational logic, and practical value in five key process modules: influent control systems for wastewater treatment, biological aeration systems, sludge recirculation systems, chemical dosing systems, and remote intelligent monitoring systems. From an engineering application perspective, it deeply analyzes the core technological advantages of smart valves over traditional valves, and objectively identifies current challenges in equipment promotion, including high cost barriers, limited adaptability to complex operating conditions, shortage of professional maintenance personnel, insufficient system compatibility, and weak data security. Finally, considering industry trends such as smart water management, dual-carbon policies, and intelligent manufacturing, the paper forecasts future development directions for smart valves, including higher precision and durability, full-domain intelligence, industry standardization, and green, energy-efficient integration.

Key words: Smart valve; wastewater treatment; automatic control; process system; smart water management; Internet of Things

1 INTRODUCTION

As urbanization in China continues to accelerate and the industrial system steadily improves, the discharge of municipal wastewater and industrial effluent has been increasing year by year, intensifying pressure on water environment management. In recent years, the government has successively issued multiple policy documents, including the "Three-Year Action Plan for Improving the Quality and Efficiency of Urban Wastewater Treatment" and the "Technical Guidelines for Smart Water Management," clearly requiring the wastewater treatment industry to abandon extensive operation and maintenance models and promote automated and intelligent upgrades of treatment facilities to achieve multiple goals such as improved treatment quality, energy conservation, consumption reduction, and enhanced efficiency. As a core component of water resource recycling, aquatic ecosystem restoration, and water environment management, the operational stability, treatment accuracy, and energy consumption control of wastewater treatment directly affect regional ecological quality and water resource utilization efficiency.

A complete modern wastewater treatment process includes several interrelated and mutually influencing unit operations: influent pretreatment, biological treatment, solids-liquid separation, sludge disposal, chemical dosing, and treated effluent discharge. Operations such as fluid conveyance, air flow regulation, chemical dosing, and sludge recirculation across these units all require precise control via valve equipment. The operating status and control precision of valves directly determine the overall system's operational stability, effluent compliance rate, and energy consumption levels. For a long time, most small- and medium-sized wastewater treatment plants and older municipal stations in China have commonly used traditional

manual valves or conventional electric mechanical valves as core control devices. These devices offer only basic functions such as simple pipeline on/off control and fixed opening adjustment, unable to adapt in real time to dynamic fluctuations in influent quality and flow, resulting in significant operational limitations. In practical engineering operations, this often leads to problems such as uneven aeration airflow distribution, excessive or insufficient chemical dosing, imbalanced sludge return ratios, sudden pressure fluctuations in pipelines, and abnormal tank level variations. These issues not only reduce treatment efficiency and cause effluent parameters like COD, ammonia nitrogen, and total phosphorus to exceed standards but also result in substantial waste of electricity and chemicals, increase equipment wear and maintenance costs, and hinder high-quality development of the wastewater treatment sector.

Against the backdrop of widespread adoption of intelligent manufacturing and Internet of Things (IoT) technologies, smart fluid control equipment is rapidly evolving, with intelligent valves gradually replacing traditional mechanical valves as a key component of smart wastewater treatment systems. Intelligent valves are integrated smart devices combining mechanical valve bodies, intelligent actuators, high-precision sensor modules, embedded control chips, and IoT communication units. They overcome the functional limitations of conventional valves by integrating data perception, intelligent computation, precise actuation, fault diagnosis, remote transmission, and automatic early warning capabilities. Relying on online monitoring data and adaptive control algorithms, they enable unmanned, precise control throughout the entire wastewater treatment process, effectively adapting to complex and variable wastewater conditions and significantly improving the level of fine-grained operation and maintenance.

Currently, intelligent valves have been widely applied in various water environment management projects, including municipal domestic wastewater treatment, chemical wastewater treatment, textile wastewater treatment, and aquaculture wastewater treatment, demonstrating clear advantages in ensuring stable effluent quality, reducing operational energy consumption, lowering labor costs, and enhancing system automation. However, due to constraints such as equipment cost, operating environments, industry standards, and talent availability, the penetration rate of intelligent valves remains low in small- and medium-sized wastewater treatment plants and rural sewage stations. Moreover, their operational stability under harsh conditions involving severe corrosion, high impurities, and humid environments still presents certain shortcomings. Challenges remain regarding device compatibility, operation and maintenance systems, and data security—issues that urgently need resolution. Based on the current industry landscape, this paper systematically investigates the application of smart valves in wastewater treatment systems. It comprehensively elaborates on the structural principles of the equipment, specific application scenarios, core technological advantages, and existing challenges. By integrating industry policies and technological evolution trends, it clarifies the future upgrade directions for smart valves, providing thorough theoretical support and practical guidance for intelligent transformation projects in wastewater treatment. [1]

2. Basic Components, Classification, and Working Principles of Smart Valves

2.1 Basic Components of Smart Valves

Smart valves are a new generation of fluid control devices that integrate mechatronics and IoT-based intelligence. Compared to traditional valves, which have simple structures and limited functions, smart valves abandon purely mechanical drive and manual operation, instead adopting an integrated architecture combining "mechanical actuation, intelligent sensing, computational control, and remote transmission." The entire system features a sophisticated design and comprehensive functionality, with independent yet coordinated modules working together to achieve precise fluid parameter regulation and intelligent equipment status management. The core components mainly consist of four parts: the mechanical valve body structure, intelligent actuator, sensor detection module, and intelligent control and communication module. Below is a detailed description of each module's specific functions and structural characteristics.

First, the mechanical valve body structure. As the fundamental mechanical framework of the smart valve, it directly contacts the sewage medium and serves as the core actuating component for pipeline on/off control and fluid regulation. It

primarily comprises the valve housing, valve core, seat, sealing gasket, stem, and limit mechanism. Depending on the medium characteristics and control requirements of different wastewater treatment processes, common valve types include butterfly valves, gate valves, ball valves, globe valves, control valves, and check valves. Butterfly valves feature simple structure, compact size, and excellent linear regulation performance, with nominal diameters ranging from DN50 to DN1400 and operating pressures from 0.1 to 1.6 MPa. They are widely used in aeration air ducts and sewage conveyance pipelines. Gate valves offer high flow capacity and low resistance coefficient (≤ 0.05), with no throttling dead zones, making them ideal for controlling main inlet and outlet pipelines. Control valves provide high-precision adjustment and support stepless fine-tuning, primarily applied in scenarios requiring precise dosing of chemicals or sludge recirculation. To accommodate the characteristics of wastewater—such as high suspended solids, strong corrosiveness, and tendency to scale—the valve bodies are typically made of QT450 ductile iron, 304/316L stainless steel, or rubber-lined corrosion-resistant materials. Sealing components use wear-resistant and aging-resistant rubber materials such as EPDM and PTFE. Standard models operate within a temperature range of 0 – 80° C, while special corrosion-resistant versions can withstand temperatures from –20° C to 120° C, significantly enhancing the device's resistance to corrosion, clogging, and wear, enabling long-term continuous operation under complex wastewater conditions.

Second, the intelligent actuator. The actuator is the power core of the smart valve, responsible for receiving control instructions from the microcontroller and driving the valve stem and core to perform opening/closing, fine adjustment, and reset actions, directly determining the valve's response speed and control accuracy. Currently, smart valve actuators used in wastewater treatment applications are mainly divided into two types: electric and pneumatic actuators. Electric actuators use servo motors as the power source, combined with precision gear reduction mechanisms, offering standard 0 – 100% stepless stroke adjustment with a resolution up to 0.1%. Full-stroke response time ranges from 5 to 30 seconds, providing high precision, smooth operation, convenient control, and strong adaptability, making them the most widely used type in modern wastewater treatment systems. Pneumatic actuators utilize compressed air at 0.4 – 0.6 MPa, featuring simple structure and explosion-proof ratings up to Ex d II BT4, with low failure rates. They are primarily used in chemical wastewater and flammable/explosive environments. Smart actuators incorporate built-in limit protection, overload protection, and torque protection mechanisms, with rated torques covering 50 – 20,000 N · m, effectively preventing damage caused by over-travel, jamming, or excessive loading, thereby improving operational safety and

stability.

Third, the sensor detection module. Serving as the “sensory nervous system” of the smart valve, this module forms the data foundation for intelligent control. Composed of various high-precision sensors and signal acquisition units, it continuously collects real-time operational parameters from pipelines and equipment around the clock. The integrated sensors in the intelligent valve specifically designed for wastewater treatment mainly include flow sensors, pressure sensors, level sensors, temperature sensors, valve position feedback sensors, and overload sensors. All sensor elements feature an IP67 protection rating, making them suitable for damp, dusty, and water-immersed conditions in industrial plants. The flow sensor achieves a measurement accuracy of $\pm 0.5\%$ FS with a range covering 0.5 to 2000 m³/h, enabling real-time monitoring of wastewater, chemical dosing, and airflow rates in pipelines. The pressure sensor has a range of 0 – 2.5 MPa and an accuracy of $\pm 0.2\%$ FS, monitoring changes in pipeline water and air pressure to predict risks such as pipe blockage, pressure loss, or bursting. The level sensor offers a distance measurement accuracy of ± 1 mm, ideal for monitoring liquid levels in regulating tanks, aeration tanks, and sedimentation tanks, providing data support for influent control. The valve position feedback sensor features a resolution of 0.1%, precisely capturing the current valve opening degree in real time and converting mechanical movements into electrical signals transmitted back to the control chip, enabling closed-loop regulation. All sensors operate at sampling frequencies between 10 and 100 Hz, accurately capturing minor fluctuations in operating conditions with extremely low error rates, thus delivering precise data support for intelligent system computation and dynamic adjustment.[2]

Fourth, the intelligent control and communication module. This module serves as the “central nervous system” of the smart valve, primarily composed of an embedded high-speed PLC control chip, a high-precision signal processing unit, an optimized PID algorithm program, a fault diagnosis unit, and an IoT communication unit. The control chip receives 4 – 20 mA analog signals and RS485 digital signals, performing signal conversion, data computation, and logical analysis. By integrating with preset process parameter thresholds in the system, it generates precise control commands to drive actuators for adaptive regulation. Equipped with an optimized PID adaptive algorithm, it achieves an overshoot of $\leq 3\%$ and a steady-state error of $\leq 1\%$, effectively resolving issues such as overshooting, lag, and oscillation common in traditional control systems, significantly enhancing control stability. Meanwhile, the communication module supports multiple protocols including 4G, 5G, LoRa, Modbus-RTU/TCP, and Profibus, with a communication delay of ≤ 200 ms. It enables seamless integration with wastewater

treatment plant DCS distributed control systems, PLC control cabinets, and cloud-based smart water management platforms, allowing real-time data upload, remote parameter tuning, equipment status monitoring, and proactive fault alerts—fully realizing unmanned, intelligent operation and management of valve equipment. Additionally, the module features a built-in 128 MB local storage unit capable of storing over 100,000 operational data points and operation logs, with data retention lasting more than five years, meeting requirements for condition traceability, process optimization, and maintenance analysis. The device operates reliably within an ambient temperature range of -10°C to 60°C and relative humidity up to 95% without condensation, making it well-suited for the harsh operating conditions of wastewater treatment plants.

2.2 Main Categories of Smart Valves

Based on the application scenarios and control requirements of the wastewater treatment industry, smart valves can be categorized according to drive type, regulation function, communication mode, and medium compatibility. Different valve types exhibit distinct performance characteristics and are suited to specific application environments. By drive type, they can be classified into smart electric valves, smart pneumatic valves, and smart hydraulic valves. Smart electric valves are suitable for most municipal wastewater conditions; smart pneumatic valves are commonly used in explosion-proof and corrosion-resistant environments; while hydraulic valves are ideal for large-diameter, high-flow-rate, high-pressure pipelines. Based on regulation function, they fall into two categories: smart on/off valves and smart modulating valves. On/off valves are used solely for pipeline isolation and are typically applied as main influent or discharge valves; modulating valves enable fine, stepless adjustment of opening degree, making them suitable for precise control applications such as aeration, chemical dosing, and sludge recirculation. In terms of communication mode, smart valves can be divided into wired communication valves and wireless IoT valves. Wired communication offers strong stability and low latency, making it ideal for fixed equipment within treatment plants; wireless valves offer flexible deployment and lower cabling costs, making them well-suited for remote rural wastewater stations. Accurately differentiating valve types can significantly improve the precision of equipment selection in wastewater treatment systems and ensure optimal process compatibility.

2.3 Working Principle of Smart Valves

Smart valves eliminate the traditional mode of manual judgment and operation, relying instead on multi-module coordinated interaction to form a fully closed-loop intelligent control logic that includes real-time sensing, signal conversion, data processing, precise execution, feedback correction, and data uploading. This enables fully automated, self-adaptive, and

high-precision fluid control, ensuring seamless operation, rapid response, and accurate regulation throughout the entire process.

During normal operation, the sensing and detection module continuously collects real-time operational parameters such as flow rate, pressure, liquid level, temperature, and valve opening from the sewage treatment pipeline network and tanks. It converts the acquired analog signals into digital electrical signals, which are then transmitted in real time via signal transmission lines to the core control chip. The control chip contains pre-set optimal threshold values for wastewater treatment processes and an optimized PID control algorithm. It rapidly processes, compares, and analyzes the massive volume of incoming real-time data to accurately determine whether the current system operating conditions are stable and optimal, identifying issues such as fluctuations in water quality or flow, abnormal pipeline pressure, or valve position deviations.

When the system detects that operating conditions deviate from preset standards—such as sudden increases in influent flow, low dissolved oxygen levels in aeration tanks, insufficient chemical dosing flow, imbalanced sludge return flow, or excessive pipeline pressure—the control chip quickly generates corresponding adjustment commands. It precisely controls the intelligent actuators to dynamically adjust valve openings or on/off states, instantly modifying fluid flow rates, air pressure, and water pressure to correct operational deviations promptly. After adjustments, the valve position feedback sensors collect updated valve positions and fluid parameters in real time and transmit them back to the control chip, forming a closed-loop feedback mechanism. Based on this feedback, the system further refines its control accuracy, avoiding over-correction or under-correction through iterative optimization until the system returns to its optimal operating range, ensuring stable and reliable performance throughout the wastewater treatment process.

Meanwhile, the intelligent communication module synchronously collects data on equipment status, operational parameters, adjustment records, and fault information, uploading it in real time to both local control panels and remote cloud monitoring platforms. This enables data visualization, cloud storage, generation of operational trend curves, and statistical reporting. When faults occur—such as valve core clogging, actuator overload, signal interruption, sensor anomalies, or excessive pipeline pressure—the system's built-in fault diagnosis program quickly identifies the type and location of the fault, automatically triggering audible and visual alarms and sending alerts via mobile notifications to maintenance personnel. This ensures early detection, prompt troubleshooting, and rapid repair, minimizing the impact of equipment failures on wastewater treatment operations. The entire operational process requires no manual intervention and can run continuously 24/7 with

self-adaptive capabilities, perfectly adapting to the dynamic fluctuations typical in wastewater treatment environments.[3,4]

3. Specific Applications of Smart Valves in Various Wastewater Treatment Systems

3.1 Application in the water intake control system

The influent control system is the first and most critical process in wastewater treatment, responsible for sewage collection, homogenization and stabilization, flow distribution, and pre-treatment buffering. The operational stability of this entire system directly determines the effectiveness of subsequent biological treatment and sludge-water separation processes. The influent conditions for municipal domestic wastewater and industrial effluent are highly random and fluctuating, with significant differences in discharge volume and pollutant concentration between day and night, morning and evening, and on holidays. During daytime hours, when residential activities and industrial production are at peak, influent flow rates and pollutant concentrations are high; whereas at night, flow decreases significantly and water quality load drops. In rainy seasons, stormwater entering the sewer network causes sudden increases in influent volume and dramatic fluctuations in water quality due to dilution. Traditional wastewater treatment plants rely on manual adjustment of conventional valves to regulate influent flow, which suffers from severe lag and cannot respond in real time to changing conditions. This often leads to system overloading or underutilization, resulting in issues such as clogging in pre-treatment units, imbalance in microbial activity in biological systems, and reduced treatment efficiency.

Intelligent valves are primarily deployed at key locations within the influent control system, including main influent pipelines, branch lines to equalization tanks, distribution channels to various treatment units, and overflow lines. Combined with high-precision level sensors, flow sensors, and pressure sensors, they form an intelligent influent regulation system that delivers five core functions: constant liquid level, constant flow rate, over-limit flow restriction, anti-backflow protection, and balanced water distribution. During normal operation, the intelligent valve continuously collects data on instantaneous influent flow, equalization tank water level, and pipeline pressure, dynamically adjusting its opening via built-in algorithms. When influent flow peaks—causing rapid rise in the equalization tank level approaching warning thresholds—the valve automatically reduces its opening slightly to limit flow and stabilize pressure, slowing down the inflow rate and preventing downstream equipment such as bar screens, grit chambers, and biological reactors from becoming overloaded, clogged, or failing to meet treatment standards. Conversely, during low-flow periods, when the equalization tank level drops too low, the valve automatically

increases its opening to ensure continuous and stable influent supply, maintaining uninterrupted plant operation and avoiding problems such as sludge aging and microbial die-off caused by insufficient influent.

In special conditions such as sudden heavy rainfall and abrupt increases in pipeline pressure during the rainy season, intelligent influent valves can coordinate with overflow line valves to automatically open, diverting excess wastewater to relieve pressure and prevent accidents like pipeline bursts, backflow, or flooding within the plant. Additionally, for multiple parallel treatment units, intelligent valves can precisely allocate influent flow among units, ensuring even load distribution and avoiding overloading or idling of individual units. This significantly enhances the stability and shock resistance of the pre-treatment system, providing consistent and reliable influent conditions—both in terms of flow and quality—for subsequent biological treatment processes, thereby reducing process variability at the source.

Engineering Application Case 1: Intelligent Influential Control Retrofit Project at Zhangzhou Changtai Wastewater Treatment Plant

The Zhangzhou Changtai Wastewater Treatment Plant is the first fully intelligent, upgraded primary A-level wastewater treatment facility in Fujian Province, designed to treat 150,000 tons of sewage per day. The plant faces typical challenges such as diurnal flow fluctuations, sudden increases in flow during rainy seasons, and significant water quality variations caused by mixed industrial discharges. Traditional manual valve control is slow and prone to uneven influent distribution, imbalanced tank levels, and clogging in pretreatment units. This upgrade involved installing 68 DN600 – DN1200 anti-scaling intelligent electric butterfly valves across the main influent pipeline, distribution channels of each treatment unit, and overflow lines. Rated for 1.6 MPa operating pressure and IP67 protection, these valves feature a high-curvature streamline flow path and nano-scale anti-scaling coating, reducing sludge adhesion by 80% and making them ideal for handling high-impurity, high-suspended-solid wastewater conditions. The entire intelligent influent control system integrates with level, flow, and pressure sensors, relying on $\pm 0.2\%$ FS high-precision data collection to achieve self-adaptive regulation of constant flow and constant liquid level. After the upgrade, influent flow distribution uniformity improved by 40%, rain-season overflows and backflow incidents were completely eliminated, and the failure rate of pretreatment unit clogging dropped by 90%. Overall influent stability has significantly increased, laying a solid foundation for stable operation of downstream biological treatment processes and ensuring continuous compliance with effluent discharge standards throughout the plant.[5,6]

3.2 Application in aeration systems

The aeration system is the core unit of wastewater biological treatment and also the most energy-consuming process in wastewater treatment plants. Its primary function is to deliver air into the aeration tank via blowers, supplying oxygen to aerobic microorganisms to ensure effective degradation and removal of pollutants such as organic matter, ammonia nitrogen, and total phosphorus in wastewater. Industry data indicate that blower energy consumption in aeration systems accounts for 50% – 60% of the total operational energy use in wastewater treatment plants, making it a critical area for energy conservation and efficiency improvement. Dissolved oxygen (DO) concentration in the bioreactor is the key control parameter of the aeration system, directly affecting microbial activity and treatment performance: insufficient DO leads to inadequate oxygen supply, significantly reducing pollutant degradation efficiency and resulting in excessive COD and ammonia nitrogen levels in effluent; conversely, excessively high DO causes unnecessary energy waste and may trigger operational issues such as sludge bulking, poor settling properties, elevated suspended solids in effluent, and sludge expansion.

Traditional aeration systems typically operate with fixed valve openings and constant airflow, unable to adjust aeration rates according to variations in influent water quality and load. Regardless of influent pollutant concentrations, blowers and valves remain at fixed operating conditions—either leading to insufficient oxygen supply and substandard treatment results or causing over-aeration and significant energy waste, resulting in poor process stability and energy efficiency. In contrast, intelligent valves integrated with online dissolved oxygen monitoring devices and blower variable frequency drive (VFD) control systems form a closed-loop intelligent aeration regulation system, effectively addressing the long-standing challenges of conventional aeration methods. Smart air volume control valves are evenly distributed across the branch ducts of different zones within the aeration tank, enabling zonal, fine-grained airflow control and resolving the traditional problem of global control with localized imbalances.

During operation, dissolved oxygen sensors continuously monitor DO levels at the front, middle, and rear sections of the aeration tank, transmitting real-time data to the control system. The smart valves dynamically adjust valve openings using optimized PID algorithms to precisely regulate aeration volumes in each zone. When influent concentrations of organic matter or ammonia nitrogen rise, increasing microbial oxygen demand and lowering DO levels, the valves automatically open wider to increase airflow, rapidly replenishing oxygen and maintaining optimal microbial activity for pollutant degradation. Conversely, when influent load decreases, microbial oxygen consumption

drops, and DO exceeds required levels, the valves automatically reduce opening to lower aeration rates, eliminating unnecessary energy consumption. Through dynamic control by smart valves, DO concentration in the bioreactor can be stably maintained within the optimal range of 2.0 – 2.8 mg/L, precisely matching the metabolic needs of microorganisms.[7]

Moreover, the intelligent valves enable differentiated aeration control across zones—increasing aeration in high-pollutant-load areas near the influent end and reducing it in low-load regions toward the effluent end—thereby solving the imbalance issue of traditional aeration systems, where aeration is insufficient at the front and excessive at the rear. Practical engineering data show that aeration systems equipped with smart valves can reduce blower energy consumption by 25% – 35%, significantly improving energy efficiency in wastewater treatment. At the same time, they stabilize biological treatment conditions, minimize occurrences of sludge bulking and effluent quality fluctuations, and substantially enhance compliance with discharge standards.

Case Study 2: Precision Aeration Energy-Saving Retrofit Project at Hangzhou Qianjiang Water Treatment Plant

The Phase IV project of Hangzhou Qianjiang Water Treatment Plant employs a conventional activated sludge process. The plant's aeration system has long operated in a fixed-valve mode with constant airflow, resulting in severe over-aeration and significant energy waste. Additionally, dissolved oxygen (DO) distribution across different zones of the biological reactor is uneven—oxygen supply is insufficient at the front end and excessive at the rear end—leading to unstable pollutant degradation efficiency and poor sludge settling performance. To address these issues, the plant implemented an intelligent precision aeration upgrade by replacing all branch air supply pipes in the aeration tanks with smart modulating butterfly valves. These valves offer a control accuracy of $\pm 1\%$ and a full-stroke response time of ≤ 5 seconds. Combined with distributed online DO monitoring equipment, the system forms a closed-loop precision aeration network integrating "DO data acquisition, intelligent valve control, and variable-frequency blower coordination." Relying on an optimized PID algorithm (with overshoot $\leq 3\%$ and steady-state error $\leq 1\%$), the system dynamically adjusts valve openings based on real-time water quality and load conditions in each zone, enabling demand-based, precise oxygen supply. After the upgrade, dissolved oxygen concentration in the biological reactor is stably maintained within the optimal range of 2.0 – 2.5 mg/L, significantly improving DO uniformity throughout the tank. Effluent compliance rates for ammonia nitrogen and COD have reached 100%. Overall aeration energy consumption decreased by 32%, with annual electricity savings exceeding 200,000 kWh per biological reactor. The

results demonstrate remarkable energy efficiency improvements and provide a benchmark model for intelligent energy-saving upgrades in large-scale wastewater treatment plant aeration systems.[8]

3.3 Application in the sludge recycle system

The sludge return system is a critical component of the activated sludge wastewater treatment process. Its core function is to convey high-concentration activated sludge settled at the bottom of the secondary clarifier back to the front end of the aeration tank via return pipelines, continuously replenishing microbial populations in the biological reactor and maintaining a stable mixed liquor suspended solids (MLSS) concentration, thereby ensuring continuous, stable, and efficient biological reactions. The sludge return ratio is the key process parameter of this system; its stability and accuracy directly determine the total microbial biomass, sludge activity, and pollutant degradation capacity within the biological system. In conventional municipal wastewater treatment processes, the optimal sludge return ratio typically ranges from 50% to 100%. If the return ratio is too low, insufficient sludge concentration in the aeration tank results in inadequate microbial population, preventing effective pollutant degradation. Conversely, an excessively high return ratio leads to sludge accumulation, shortened sludge retention time, microbial aging, increased pipeline energy consumption, and equipment wear, and may easily trigger sludge bulking and poor solid-liquid separation.

Traditional sludge return systems rely on manually fixed valve settings, where operators adjust valves periodically based solely on experience. This approach suffers from low control precision and significant lag, making it unsuitable for dynamic changes in influent quality and flow rate. During fluctuations in influent load, the return ratio cannot respond promptly, resulting in weak shock resistance of the biological system and unstable effluent quality. With the widespread application of intelligent control valves in sludge return pipelines, an adaptive return regulation system can be established by integrating data from MLSS sensors in the aeration tank, influent flow sensors, and interface monitoring devices in the secondary clarifier, enabling dynamic and precise control of the return ratio.

In actual operation, the smart valve continuously collects key parameters such as return sludge flow rate, MLSS concentration in the aeration tank, and real-time influent flow. Based on a process model, it calculates the optimal return ratio in real time and dynamically adjusts the valve opening. When influent pollutant concentrations are high and hydraulic loads increase, the system automatically increases the valve opening to boost sludge return flow, enhancing microbial biomass in the aeration tank and improving pollutant degradation efficiency, thus ensuring stable treatment performance under high-load conditions. Conversely, when influent quality is good and load is low, the system reduces

return flow to prevent excessive sludge accumulation and microbial aging, minimizing unnecessary energy consumption and pipeline wear. Additionally, the smart valve employs stepless, smooth modulation, avoiding water hammer, sludge flow interruption, and flow oscillations caused by abrupt opening or closing of traditional valves, ensuring continuous and stable sludge return flow.

Moreover, the smart valve features intelligent anti-clogging control. Given that sludge media often contain impurities and are prone to sedimentation, the valve can periodically open slightly to flush the pipeline, effectively reducing clogging incidents and lowering maintenance frequency. Through precise control by the smart valve, the MLSS concentration in the aeration tank can be stably maintained within the optimal range of 3,000 – 4,000 mg/L, significantly improving the operational stability and shock resistance of the biological system, reducing process failure rates, and ensuring consistent solid-liquid separation and effluent quality.

Engineering Application Case 3: Intelligent Retrofit of Sludge Recirculation System at a Sewage Treatment Plant in Coastal Fujian

A municipal wastewater treatment plant located along the coast of Fujian Province is adjacent to an industrial zone and a marine area. The wastewater contains high salinity, abundant impurities, and strong corrosiveness, making the sludge return pipelines highly susceptible to scaling, sedimentation, and corrosion. The original manually operated control valves had a regulation error of $\pm 8\%$ to $\pm 10\%$ and a response delay exceeding 40 seconds, resulting in poor control accuracy and weak anti-clogging capability. This led to long-term imbalance in the sludge return ratio, causing significant fluctuations in sludge concentration within the biological reactor, frequent occurrences of sludge bulking, and excessive suspended solids in effluent—common process failures. To address these complex operating conditions, the plant replaced all sludge return pipeline valves with intelligent, corrosion-resistant control valves equipped with self-cleaning functions. The valve bodies feature a dual-seal, 316L stainless steel corrosion-resistant design, suitable for high-salinity, high-impurity sludge media. With a nominal pressure rating of 1.0 MPa and a regulation resolution of 0.1%, the valves incorporate an adaptive sludge return control algorithm that dynamically optimizes the return ratio by integrating data from sludge concentration and influent flow sensors. Additionally, the system includes a scheduled flushing function, which automatically opens and closes the valves at set intervals daily to clean the pipelines, effectively eliminating clogging issues caused by sludge accumulation. After the upgrade, the control accuracy of the sludge return ratio improved to $\pm 2\%$, the fluctuation range of mixed liquor suspended solids (MLSS) in the

aeration tank decreased by 70%, and incidents of sludge bulking and pipeline blockages were nearly eliminated. The biological treatment system's resistance to shock loads significantly increased, reducing annual process-related downtime by 95% and substantially lowering operational labor costs.[9]

3.4 Application in chemical dosing systems

The chemical dosing system is a critical process for achieving wastewater treatment compliance and advanced purification, encompassing multiple sub-processes such as coagulant dosing, disinfectant dosing, acid-base neutralization, and phosphorus removal. By adding chemicals including polyaluminum chloride, polyacrylamide, sodium hypochlorite, pH adjusters, and phosphorus removal agents, the system effectively removes suspended solids, colloids, heavy metals, bacteria, viruses, and total phosphorus from wastewater, while simultaneously regulating water pH to ensure treated effluent meets discharge standards. The accuracy of chemical dosing directly determines treatment efficiency, chemical cost, and water safety: insufficient dosing fails to achieve adequate purification, disinfection, or neutralization, resulting in effluent parameters; excessive dosing not only wastes significant chemical resources and increases operating costs but also leads to chemical residues, secondary pollution, and pH imbalance.

Traditional chemical dosing systems typically operate with fixed flow rates and manual time-based adjustments, making them ill-suited to dynamic fluctuations in influent water quality. During periods of severe pollution, dosing may be inadequate, while during periods of good water quality, over-dosing occurs—resulting in long-term issues such as chemical waste, unstable treatment performance, and high risks of secondary contamination. By integrating smart valves with online water quality sensors, chemical flow meters, and dosing pumps, an automated, precise dosing control system can be established, enabling a refined operational model characterized by "on-demand dosing, dynamic adaptation, and accurate dosage control."

During operation, sensors for COD, ammonia nitrogen, turbidity, and pH continuously monitor key parameters such as pollutant concentration, water turbidity, and pH levels. Based on real-time data and process models, the control system precisely calculates optimal chemical dosing rates and automatically adjusts the opening of smart control valves to continuously modulate chemical feed flow. For coagulation and sedimentation processes, the system automatically increases chemical dosing when turbidity rises, ensuring rapid flocculation and settling of suspended solids. For disinfection, it dynamically adjusts sodium hypochlorite dosing according to bacterial indicators in the effluent, minimizing chemical residue while maintaining effective disinfection. For acid-base neutralization, it precisely regulates the flow of acidic or alkaline reagents based on pH readings,

stabilizing the effluent pH within the compliant range of 6 – 9.

Moreover, smart valves enable coordinated control of multiple chemicals, meeting the multidimensional purification requirements of complex industrial wastewater and effectively addressing the shortcomings of traditional dosing methods—low precision, high energy consumption, and substantial waste. Engineering practice demonstrates that intelligent valve-based dosing systems can reduce chemical consumption by 15% to 20%, significantly lowering material costs in wastewater treatment. At the same time, they stabilize effluent quality and completely eliminate secondary pollution caused by overdosing, achieving dual goals of improved treatment quality and reduced resource consumption.

Engineering Application Case 4: Smart Chemical Dosing Retrofit Project at Wuhan Beihu Wastewater Treatment Plant

Wuhan Beihu Wastewater Treatment Plant is a large-scale municipal integrated wastewater treatment facility that receives domestic sewage and a small amount of industrial effluent. The influent quality exhibits significant diurnal and seasonal fluctuations in turbidity and pollutant concentrations. Traditional fixed-flow chemical dosing methods show obvious lag, resulting in insufficient dosing during poor water quality periods—leading to non-compliant effluent—and excessive chemical usage during good water quality conditions, causing both reagent waste and residual chemicals in the treated water. To achieve precise operation and maintenance, the plant upgraded its coagulation, disinfection, and phosphorus removal chemical dosing systems with intelligent controls, installing multiple miniature smart electric control valves capable of stepless fine adjustment from 0% to 100%, with response times ≤ 5 seconds. These are paired with high-precision online sensors for turbidity, total phosphorus, and residual chlorine (measurement accuracy $\pm 0.5\%$ FS), forming a fully automatic closed-loop dosing control system. The system dynamically adjusts valve openings based on real-time water quality data, enabling stepless regulation of chemical dosing rates and achieving "precise, demand-based dosing." After the upgrade, the plant reduced overall consumption of PAC, PAM, and disinfectants by 18.5%, saving over 600,000 RMB annually in chemical costs. Effluent stability for total phosphorus and turbidity improved significantly, and the issue of chemical residue was completely resolved. Under the premise of ensuring compliant effluent discharge, the plant has achieved cost reduction, efficiency improvement, and green operation.[10]

3.5 Applications in remote monitoring systems

Traditional wastewater treatment operation and maintenance models heavily rely on manual on-site operations, scheduled inspections, and manual parameter adjustments. These systems suffer from numerous drawbacks, including low operational efficiency, high labor costs, delayed fault detection, inability

to trace operating conditions in real time, and a high rate of human operational errors. Small- and medium-sized wastewater treatment plants commonly face shortages of maintenance personnel and weak technical expertise, making them highly vulnerable to issues such as untimely equipment failure response, delayed process parameter adjustments leading to effluent (exceeding discharge standards), and equipment damage. With the continuous advancement of smart water management initiatives, remote intelligent monitoring systems have become standard in modern wastewater treatment plants. Smart valves serve as the core terminal execution devices within these remote monitoring systems and form the foundational platform for achieving unattended, intelligent operation and maintenance.

Smart valves, equipped with built-in IoT communication modules, seamlessly integrate with local DCS control systems, PLC control cabinets, cloud-based smart water management platforms, and mobile monitoring systems at wastewater treatment plants, establishing a fully visualized operation and maintenance framework that spans "terminal data collection – cloud transmission – platform analysis – remote control." All smart valves can upload real-time, multi-dimensional data including valve opening degree, equipment status, pipeline flow rate, medium pressure, equipment temperature, fault codes, and adjustment records. The platform automatically generates operational curves, performance reports, and energy consumption statistics through big data analytics, enabling full visualization of all process parameters in wastewater treatment.

Operations personnel no longer need to be on-site; they can remotely monitor the operational status of valves and equipment across all process nodes via computer terminals or mobile apps, and perform remote operations such as valve opening/closing, fine-tuning of opening degrees, parameter calibration, and mode switching, achieving remote control from any location. Additionally, the smart valves are equipped with high-precision self-diagnostic systems capable of detecting various faults—including valve core blockage, actuator overload, signal interruption, sensor failure, abnormal pipeline pressure, and flow anomalies—in real time. These systems accurately pinpoint fault locations and identify root causes, immediately sending alarm notifications to both the platform and maintenance staff, enabling early fault prediction and rapid response, thereby minimizing risks of process disruptions and equipment damage.

Moreover, the system retains all operational data and operation logs over the long term, supporting historical condition tracing, process parameter optimization, energy consumption analysis, and equipment maintenance statistics. This provides precise data support for plant process upgrades, energy-saving retrofits, and maintenance scheduling. The deep integration between smart valves and remote monitoring systems has

completely transformed traditional manual operation models, significantly reducing labor costs, enhancing equipment reliability and process control accuracy, and accelerating the transition of wastewater treatment plants toward automation, intelligence, and unattended operation.

Engineering Application Case 5: Smart Remote Operation and Maintenance Upgrade Project for Guangzhou Datansha Wastewater Treatment Plant

Guangzhou Datansha Wastewater Treatment Plant, a long-established large-scale municipal wastewater facility in China, faces challenges due to aging equipment and complex piping systems. A significant number of valves are located in hazardous areas such as underground tunnels and elevated equipment levels. Traditional operation and maintenance practices rely heavily on frequent manual inspections and manual valve adjustments, resulting in high operational risks, low efficiency, and delayed fault response. To enhance intelligent operation and maintenance capabilities, the plant has implemented an electric intelligent upgrade for critical valves, replacing them in bulk with smart extended-stem electric valves equipped with IoT communication functions. These devices support the Modbus-TCP communication protocol, offer communication latency of $\leq 200\text{ms}$, and feature IP66 protection rating. They can upload real-time data—including valve position, pressure, flow rate, and operational faults—enabling seamless integration with the plant's DCS control system and cloud-based remote monitoring platform. After the upgrade, operators can remotely open or close valves, fine-tune positions, and calibrate parameters from the central control room or mobile devices. Valve response speed has improved by over 90%, completely eliminating the need for manual operations in high-risk areas such as elevated platforms and underground corridors. Additionally, the valves are equipped with high-precision self-diagnostic modules that accurately detect faults such as blockages, overloads, and signal anomalies, triggering pop-up alerts proactively and enabling predictive maintenance. As a result, equipment failure rates have dropped by 65%, and on-site maintenance workload has been reduced by 50%. The plant has successfully transitioned from "manual on-site monitoring" to a "remote intelligent control and unmanned operation" model, providing a proven case study for intelligent retrofitting of aging wastewater treatment facilities.[11]

4. Technical Advantages of Smart Valves in Wastewater Treatment

4.1 Excellent control accuracy significantly enhances process operation stability

Traditional mechanical valves can only achieve fixed-step or coarse manual adjustments, with typical regulation errors ranging from $\pm 5\%$ to $\pm 10\%$ and response delays lasting 30

to 60 seconds. They are unable to provide fine, stepless control and struggle to adapt to the dynamic fluctuations in wastewater treatment flow rates and water quality. In contrast, smart valves leverage high-precision sensor data acquisition and optimized PID closed-loop control algorithms to enable smooth, stepless adjustment across 0 – 100% opening. Key performance metrics include a regulation accuracy error of $\leq \pm 1\%$, steady-state response time of ≤ 5 seconds, and an algorithm overshoot of $\leq 3\%$. These valves offer fast response, excellent linearity, and strong adaptability to varying operating conditions, enabling precise detection of minor process fluctuations and rapid parameter correction. In critical, precision-driven processes such as aeration, chemical dosing, and sludge recirculation, smart valves maintain key parameters—including dissolved oxygen concentration, chemical dosage, and sludge return ratio—within optimal operational ranges, effectively resolving industry challenges such as human-induced lag, large errors, and system oscillations. Furthermore, the closed-loop feedback correction mechanism continuously iteratively refines control accuracy, significantly enhancing the wastewater treatment system's resilience to shock loads. This ensures stable effluent quality under complex conditions such as influent fluctuations and sudden changes in water quality, substantially reducing the risk of effluent non-compliance.

4.2 Significant energy savings and consumption reduction, lowering overall operating costs

Energy consumption and material costs are the most critical operating expenses for wastewater treatment plants, with aeration blowers, pumps, and chemical reagents accounting for the majority of operational expenditures. Traditional fixed-orifice valves operate in a coarse, inefficient manner, resulting in significant energy waste and excessive chemical usage, leading to extremely low resource utilization. Smart valves enable dynamic, fine-grained control throughout the entire process, precisely matching aeration rates, recycle flow, chemical dosing, and influent load requirements. This fundamentally eliminates wasteful practices such as over-aeration, excessive chemical dosing, and unnecessary hydraulic losses. In aeration systems, precise oxygen control can reduce blower energy consumption by 25% to 35%. In chemical dosing systems, on-demand dosing reduces reagent consumption by 15% to 20%. In pipeline conveyance systems, stable flow and pressure minimize frequent pump starts and stops and prevent overload operation, thereby reducing pump energy use and equipment wear. Additionally, consistent and stable operating conditions significantly lower equipment failure rates and maintenance costs, extending the service life of valves, pumps, blowers, and other supporting equipment. This comprehensive approach substantially reduces overall operational and maintenance costs for wastewater

treatment plants, enabling them to achieve low-carbon, energy-efficient operations.

4.3 Highly intelligent with a fully upgraded operation and maintenance model

The intelligent valve integrates multiple functions including perception, computation, actuation, early warning, communication, and data storage, enabling a leapfrog upgrade from "passive execution" to "proactive intelligent control." It completely replaces the traditional, labor-intensive operation model involving manual inspections, manual valve adjustments, and on-site troubleshooting. The device can operate automatically 24/7 without requiring real-time human intervention, significantly reducing staffing requirements and minimizing process failures caused by human operational errors. Additionally, it features self-diagnosis of faults, proactive alarms, data traceability, and intelligent analysis capabilities, allowing for early prediction of issues such as equipment aging, pipeline blockages, and parameter anomalies, thus enabling preventive maintenance and shifting away from the conventional reactive "repair after failure" approach. Combined with a remote monitoring platform, it enables centralized control, remote commissioning, and unattended operation across entire facilities, greatly enhancing the automation and intelligence level of wastewater treatment systems and meeting the evolving demands of modern smart water management.[12]

4.4 Strong adaptability to operating conditions, with outstanding versatility and reliability

Wastewater treatment operations involve complex and variable conditions, with media characterized by high impurity content, strong corrosiveness, tendency to scale, and significant flow fluctuations. Additionally, plant environments are often damp, subject to large temperature variations, and dusty. Intelligent valves can be customized with wear- and corrosion-resistant materials such as stainless steel, rubber-lined components, or anti-corrosion coatings based on specific process scenarios and medium characteristics. They feature optimized valve core designs to prevent clogging, advanced sealing structures, and protective sensor probe configurations, enabling effective adaptation to challenging conditions involving sewage, sludge, chemical reagents, and humid air. These valves exhibit excellent resistance to corrosion, blockage, and aging. Moreover, they support various intelligent control modes—including PID adaptive regulation, split-range control, interlocking control, and threshold protection—allowing flexible integration into all wastewater treatment processes such as influent regulation, aeration oxygen control, sludge recirculation, chemical dosing, and effluent discharge. Suitable not only for municipal domestic wastewater treatment, these valves are also ideal for industrial

applications in chemical processing, textile dyeing, aquaculture, and food production. Their versatility, environmental adaptability, and operational reliability significantly surpass those of conventional valves.

4.5 Data traceability supports process optimization and standardized management

Conventional valves lack data collection and storage capabilities, making it impossible to quantitatively record process operation parameters. Maintenance and operations management rely heavily on manual experience, making standardized and data-driven control difficult to achieve. Smart valves, in contrast, can continuously collect, store, and upload all operational data and adjustment records, forming a complete operational condition database. Operations personnel can review historical data and analyze parameters to precisely identify shortcomings in process performance, energy waste points, and frequent equipment failure locations, enabling targeted optimization of process parameters and operating strategies. Moreover, comprehensive data recording meets the requirements for environmental compliance monitoring, process verification, and project acceptance by providing traceable data, facilitating the transition of wastewater treatment operations from "experience-driven" to "data-driven" management and supporting wastewater plants in achieving standardized, refined, and digitalized operations.

5. Issues and shortcomings in smart valve applications

5.1 Equipment procurement and modification costs are relatively high.

Smart valves are highly integrated mechatronic intelligent devices that combine advanced technologies such as high-precision sensing, embedded control, IoT communication, and precision mechanical processing. Their manufacturing process is complex, and the cost of core components is relatively high, resulting in a significantly higher purchase price per unit compared to traditional mechanical valves. For large-scale new smart wastewater treatment plants, sufficient funds for equipment modernization allow for widespread adoption of complete sets of smart valves. However, for numerous small- and medium-sized township wastewater treatment stations and older facilities undergoing upgrades, limited operating budgets and tight financial constraints are common. The initial costs associated with bulk replacement—including equipment procurement, installation, commissioning, and system integration—are prohibitively high, creating substantial financial pressure. Currently, cost barriers remain the key factor limiting the large-scale deployment of smart valves at grassroots wastewater treatment sites, leading to an uneven industry landscape where intelligent equipment is widely adopted in large plants but lags behind in smaller facilities. This

imbalance severely hinders the overall intelligent transformation of the wastewater treatment sector.

5.2 Insufficient equipment stability and durability under complex wastewater conditions

The environment in wastewater treatment is complex and harsh, with sewage containing large amounts of silt, suspended solids, colloidal particles, and fibrous impurities. Additionally, acidic, alkaline, and chemical wastewater are highly corrosive, making long-term operation particularly prone to wear and failure of intelligent valve equipment. The sensor probes, valve core gaps, and sealing structures of smart valves are precision and vulnerable components. Prolonged exposure to high-impurity wastewater easily leads to issues such as impurity accumulation, scaling, clogging, corrosion, and wear, resulting in distorted sensor data, sluggish valve adjustment, incorrect opening positions, and poor sealing causing leaks. Moreover, wastewater treatment plants are typically located in open-air or underground damp environments characterized by significant temperature fluctuations, high humidity, and abundant dust. Although current mainstream smart valves generally offer protection ratings of IP65 to IP67, suitable for typical damp and dusty conditions, their electrical control modules and communication modules remain susceptible to moisture aging, wire corrosion, signal interference, and module damage when exposed to prolonged high humidity, strong electromagnetic interference, and fluctuating temperatures. This ultimately leads to reduced device accuracy, shortened service life, and failure of intelligent functions. Compared to traditional purely mechanical valves, which offer high durability and low failure rates, the precise electromechanical structure of smart valves has lower tolerance to harsh operating conditions, and their ability to operate continuously and stably still shows significant shortcomings.

5.3 The technical requirements for operations and maintenance are high, and there is a severe shortage of skilled professionals at the grassroots level

Smart valves are no longer simple mechanical devices, but rather integrated intelligent equipment combining mechanics, electrical systems, automatic control, the Internet of Things (IoT), big data, and communication technologies. Their selection, installation, parameter calibration, algorithm tuning, system integration, fault diagnosis, and routine maintenance all require specialized technical support, placing extremely high demands on the professional competence of operation and maintenance personnel. Currently, the overall professional level of grassroots wastewater treatment operation teams in China remains relatively low. Most operators have long been engaged in traditional equipment operations, mastering only basic tasks such as opening and closing mechanical valves or starting and stopping

pumps, while lacking expertise in automatic control, IoT, and smart device debugging. When smart valves encounter issues such as signal anomalies, regulation deviations, communication interruptions, algorithm failures, or sensor malfunctions, frontline maintenance staff are unable to quickly identify root causes or complete repairs and adjustments. As a result, many installed smart valve systems fail to function properly, remaining idle or operating at partial capacity for extended periods. This leads to wasted equipment resources and prevents achieving the expected outcomes of intelligent upgrades. The shortage of skilled professionals has thus become a significant human factor limiting the efficient application of smart valves.

5.4 Industry standards are inconsistent, and equipment system compatibility is poor

Currently, China's intelligent fluid control equipment industry is still in a stage of rapid development, and has not yet established unified and standardized production standards, communication protocols, or interface specifications. The market features numerous smart valve brands with inconsistent product parameters, and hardware interfaces, communication protocols, control logic, and data formats vary significantly across manufacturers, resulting in poor interoperability. Many older wastewater treatment plants have legacy control systems, PLCs, and monitoring platforms that were built years ago, featuring outdated system architectures that are incompatible with new smart valves. This leads to significant challenges in device integration and debugging, high retrofitting costs, and some old systems being unable to support new smart valve equipment at all. Additionally, smart valves from different batches and brands cannot be centrally managed, and data cannot be shared or exchanged, causing fragmentation in plant control systems and making it difficult to build an integrated, standardized smart management platform, which severely affects the overall effectiveness of intelligent integration in wastewater treatment systems.

5.5 Weak data security and poor device anti-interference capability

Smart valves rely on IoT wireless communication technology for data transmission and remote control, but the open network transmission model poses certain security risks. Currently, some small and medium-sized manufacturers produce smart valve devices with weak encryption protection and lack comprehensive cybersecurity mechanisms. During data transmission and storage, there is a high risk of data leakage, tampering, network intrusion, and signal interference, which may lead to equipment malfunctions, parameter errors, system loss of control, and affect the stable operation of wastewater treatment processes. Meanwhile, within wastewater treatment plants, numerous high-power devices

such as motors, fans, and pumps operate simultaneously, creating severe electromagnetic interference. Some low-end smart valves have poor resistance to electromagnetic interference, making them prone to signal fluctuations, data distortion, and control failure, thereby reducing operational stability and posing potential risks to process performance.[13]

6 Trends in the Development of Smart Valves in the Wastewater Treatment Industry

6.1 Hardware materials upgraded, enabling high precision, high reliability, and long service life of equipment

To address the current challenges of smart valves—such as susceptibility to corrosion, clogging, rapid loss of accuracy, and poor durability under complex wastewater conditions—future smart valve development will focus on technological advancement through material upgrades and structural optimization. On the material front, advanced materials such as new anti-corrosion and wear-resistant composites, stainless steel alloys, ceramic sealing materials, and anti-scaling coatings will be widely adopted. These materials will significantly enhance the corrosion resistance, clog resistance, wear resistance, and anti-scaling performance of valve bodies, valve cores, sealing structures, and sensor probes, enabling reliable operation in harsh wastewater environments characterized by high impurity levels, strong corrosiveness, and humidity. On the structural side, improvements will include streamlined valve core designs, self-cleaning mechanisms, and protective structures for sensor probes, along with features such as automatic flushing, anti-sedimentation, and self-sealing functions, effectively addressing issues related to impurity blockage and scaling-induced measurement inaccuracies. Additionally, upgraded high-precision digital sensing modules and anti-interference chips will improve the device's control accuracy and operational stability under complex electromagnetic environments and extreme water quality fluctuations, extending service life, reducing failure rates and maintenance costs, and ensuring highly reliable, long-term stable operation.[14]

6.2 Artificial intelligence deeply empowers predictive intelligent control and unmanned operation

Current smart valves are mostly passive closed-loop control systems, capable only of adjusting parameters based on real-time operational data, without the ability to anticipate changes in operating conditions. In the future, leveraging artificial intelligence, big data analytics, and digital twin technologies, smart valves will undergo a transformative leap from "passive regulation" to "proactive prediction." By accumulating vast amounts of long-term wastewater treatment operation data, predictive models for water quality and flow fluctuations, as well

as process optimization models, can be developed. The system can accurately forecast trends in water quality and flow variations across day-night cycles, seasons, and rainy periods, enabling early adjustment of valve operating parameters for precise, proactive control, significantly enhancing the system's resilience to shock loads. Meanwhile, integrated with a digital twin-based smart water management platform, a virtual simulation system for all plant equipment can be established, enabling visualization of valve operating status, process simulation and optimization, intelligent fault diagnosis, and autonomous problem resolution. This fully realizes unmanned, intelligent, self-operated maintenance throughout the entire wastewater treatment process, greatly advancing the level of smart wastewater treatment.

6.3 Industry standardization is being implemented, enabling widespread adoption of universal and low-cost equipment

With the rapid development of the smart valve industry, national and industry associations will gradually establish unified industry standards for manufacturing, interface specifications, communication protocols, control standards, and testing and acceptance procedures. This will fundamentally address current industry issues such as fragmented equipment brands, poor compatibility, and lack of data interoperability. A standardized system will enable seamless integration among smart valves, control systems, and monitoring platforms from different manufacturers, significantly reducing costs associated with equipment integration and upgrades. Meanwhile, as production technologies mature and economies of scale emerge, the manufacturing cost of smart valves will continue to decline, greatly improving their cost-effectiveness. In the future, smart valves will progressively overcome financial barriers, fully meeting the retrofit needs of small- and medium-sized wastewater treatment plants and rural sewage stations, achieving comprehensive coverage across all scales of wastewater treatment facilities and driving overall intelligent transformation in the wastewater treatment sector.

6.4 Green, energy-efficient, and integrated, meeting the development needs of the dual-carbon industry

Against the backdrop of national dual-carbon strategy and the industry's push for energy-efficient, high-quality wastewater treatment, green, low-carbon, energy-saving, and consumption-reducing approaches will become the core development direction for smart valves. In the future, smart valves will be equipped with ultra-low-power actuators and energy-saving control algorithms to optimize equipment operation logic. While reducing the valve's own energy consumption, they will further refine process control strategies to maximize energy efficiency in aeration, water conveyance, and chemical dosing, thereby supporting energy

conservation and carbon reduction in wastewater treatment plants. Meanwhile, equipment will evolve toward modularity, integration, and compact design, incorporating multiple functions such as sensing, control, communication, early warning, and data storage. This will streamline device structure, reduce size, simplify installation, and lower maintenance complexity, enabling rapid deployment and modular integration. Such advancements will meet the standardized and lightweight construction needs of intelligent wastewater treatment systems, driving the sector toward green, low-carbon, and high-quality development.

6.5 Enhanced safety protection to build a stable and reliable intelligent management system

To address the current weaknesses in data security and anti-interference capabilities of smart valves, future devices will comprehensively upgrade their cybersecurity protection systems. Equipped with technologies such as encrypted transmission, data firewalls, anomaly access interception, and data backup and recovery, these devices will eliminate risks of data leakage, tampering, and network intrusion, ensuring secure and stable operation of equipment data and control systems. Meanwhile, optimized electromagnetic shielding, moisture-proofing, dust-proofing, and anti-interference structural designs will enhance the device's resilience in complex industrial environments, reducing faults such as signal fluctuations, data distortion, and erroneous operations. This will establish a highly secure, stable, and reliable intelligent fluid control system, providing solid support for the safe operation of smart wastewater treatment systems.

7. CONCLUSIONS

As a core terminal execution device in intelligent wastewater treatment systems, smart valves integrate advanced mechanical structures, high-precision sensing technologies, adaptive automatic control algorithms, and IoT communication technologies to establish a fully closed-loop intelligent regulation system encompassing "perception, computation, actuation, feedback, and traceability." This innovation completely transforms the traditional mode of manual operation and coarse control, effectively addressing industry challenges such as low regulation accuracy, delayed response, high energy consumption, complex maintenance, and poor adaptability to operating conditions. Through systematic research and engineering case analysis, this paper demonstrates that smart valves can precisely meet the fine-tuning requirements of five key process systems in wastewater treatment: influent control, biological aeration, sludge recirculation, chemical dosing, and remote monitoring. They significantly stabilize treatment processes, improve effluent quality compliance rates, reduce system energy consumption and labor costs, and offer multiple technical advantages including broad operational adaptability, high intelligence, data traceability,

and strong process optimization capabilities. As such, smart valves serve as a pivotal enabling technology for the intelligent, precise, and low-carbon transformation of modern wastewater treatment industries.

Currently, smart valves in engineering applications still face practical challenges such as high initial investment costs, insufficient stability under complex operating conditions, a shortage of skilled maintenance personnel at the grassroots level, lack of unified industry standards, poor system compatibility, and weak data security. These issues to some extent hinder the large-scale adoption and efficient application of the equipment. However, with continuous advancements in intelligent manufacturing technologies, artificial intelligence algorithms, and Internet of Things (IoT) technologies, along with ongoing improvements in industry standardization, smart valves are expected to evolve toward higher reliability, greater precision, lower cost, full automation, green energy efficiency, and enhanced safety and stability, gradually overcoming existing limitations.

Against the backdrop of widespread adoption of smart water management, deepening implementation of the dual-carbon strategy, and continuously upgraded standards for water environment governance, the application value and development potential of smart valves will continue to grow. They will fully replace traditional mechanical valves, enabling precise, intelligent, and unmanned operation throughout the entire wastewater treatment process. This will drive continuous improvement in quality and efficiency within China's wastewater treatment sector, support its transition toward green and low-carbon operations, and provide solid technological and equipment foundations for water ecological protection and water resource recycling.□

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