Design and Performance Validation of a High-Flow Water Disinfection Module Based on UVC LED Technology

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Abstract. Water disinfection serves as a critical barrier against waterborne pathogenic microorganisms. Conventional disinfection modules are constrained by limited flow capacity, ozone byproduct formation and insufficient pressure tolerance, which hinder their stable performance in high-flow, high-pressure scenarios. This study presents a novel high-flow UVC LED water disinfection module with a rated capacity of 48 L/min, featuring ozone-free operation. With a high-strength integrated hydraulic structure and optimized light source arrangement, it maintains structural integrity without leakage or deformation under 1.0 MPa. Validated by international standards using *E. coli* 8099 and ATCC 25922, the module achieves a stable 5-log (99.999%) inactivation efficiency at 48 L/min continuous flow, offering a reliable scalable solution for industrial and municipal pressurized water disinfection.

1 Introduction

Driven by rapid urbanization and the expanding scale of industrial water treatment, the demand for high-throughput, highly efficient, and residue-free disinfection systems has surged across applications including centralized water supply, industrial circulating water systems, and point-of-entry (POE) residential purification. Currently, mainstream water disinfection technologies predominantly rely on chlorination, ozonation, and mercury (Hg)-based ultraviolet (UV) irradiation[1-3]. However, these conventional approaches exhibit significant limitations under high-flow operational conditions: chemical disinfectants such as chlorine and ozone readily react with naturally occurring organic matter and inorganic ions in water, leading to the formation of carcinogenic disinfection byproducts (DBPs), including trihalomethanes [4, 5]. Furthermore, ozonation requires complex auxiliary systems, and residual ozone poses risks to water quality safety, while maintaining seal integrity under high-pressure conditions remains technically challenging. Although conventional Hg disinfection modules operate as a purely physical treatment method—offering advantages such as instantaneous microbial inactivation, absence of chemical additives, and no persistent byproducts, and have been widely adopted in water treatment—they are inherently constrained by hydraulic architecture and lamp configuration. Their operational flow rates typically remain below 10 L/min. Increasing the flow rate often induces hydraulic short-circuiting (flow channeling) and insufficient UV fluence, resulting in a precipitous decline in disinfection efficacy. Additionally, most

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conventional units exhibit pressure ratings below 0.6 Mpa, rendering them incompatible with high-pressure piping networks [6]. More critically, conventional mercury-based UV disinfection technology is undergoing a global regulatory phase-out. Enacted in 2017, the United Nations Minamata Convention on Mercury explicitly lists mercury-containing UV lamps on its phase-out schedule, mandating a comprehensive ban on their production, sale, and use in major markets such as the European Union and China by 2025–2026. Each mercury lamp contains 3–15 mg of highly toxic elemental mercury. Breakage or improper disposal can release mercury into aquatic environments, where it bio-transforms into methylmercury, a potent neurotoxin that biomagnifies through the food chain and causes irreversible neurological damage [7]. Regulatory frameworks classify spent mercury lamps as hazardous waste (e.g., HW29 category per China's National Catalogue of Hazardous Wastes), characterized by high recycling/disposal costs and uncontrollable environmental risks. Consequently, with the full implementation of the Convention, mercury-based UV disinfection equipment is being systematically phased out of the global market, underscoring the urgent need for sustainable, high-performance alternatives such as solid-state UVC LED technology.

The core technical challenge in high-flow disinfection equipment lies in ensuring uniform UV irradiation and adequate hydraulic retention time (HRT) at elevated flow velocities, while simultaneously maintaining structural pressure integrity and guaranteeing ozone-free operation. As a highly promising germicidal radiation source, aluminum gallium nitride (AlGaN)-based semiconductor UVC LED (Ultraviolet-C Light-Emitting Diode) emit primarily in the 200–280 nm deep-UV region [8], which is highly effective at inducing microbial cell death. According to Pattison et al., radiation at 280 nm can induce photochemical damage to aromatic amino acid residues (e.g., phenylalanine, tryptophan, and tyrosine) within cellular and membrane proteins [9, 10], compromising the functionality of DNA repair enzymes and thereby accelerating the microbial inactivation process. From an engineering perspective, UVC LEDs offer stable, monochromatic emission at 280 nm. This wavelength exhibits slightly higher UV transmittance in greywater compared to the conventional 254 nm emission band of mercury lamps, providing advantages in photon utilization efficiency and irradiation penetration depth in turbid or colored water matrices [11], making it an optimal choice for inactivating bacteria, viruses, protozoa, and fungi across diverse water sources [12]. Furthermore, UVC LED technology features instant on/off capability, a mercury-free composition, precise wavelength control, and a compact form factor [2, 13-15]. Its non-chemical disinfection mechanism, absence of harmful disinfection byproduct (DBP) generation, and elimination of overdosing risks significantly enhance its commercial viability, establishing it as a highly feasible and sustainable alternative for modern water treatment. E. coli, a canonical indicator of fecal contamination, poses severe threats to public health and industrial process stability. Consequently, highly efficient and reliable water disinfection has become an indispensable component of contemporary water treatment systems. The inactivation efficiency against E. coli serves as a core performance metric for disinfection equipment, with a 5-log reduction (99.999% kill rate) representing a stringent regulatory requirement for both drinking water and high-purity industrial process water [6, 16].

In this study, a high-flow water disinfection module with a rated capacity of 48 L/min was designed and developed. By optimizing hydraulic flow regimes via computational fluid dynamics (CFD) simulation, integrating ozone-free UVC light sources, and reinforcing the pressure-resistant sealing architecture, the module was systematically evaluated under continuous flow at 48 L/min and a sustained operating pressure of 1.0 Mpa. Performance assessments focused on E. coli inactivation efficiency, structural pressure tolerance, and ozone-free operational characteristics. The findings of this work provide a robust theoretical foundation and empirical data support for the research, development, and

practical deployment of high-flow, pressurized water disinfection equipment.

2 Materials and Methods

2.1 Disinfection Module Design and Structural Parameters

The 48 L high-flow water disinfection module, independently developed by MASSPHOTON LIMITED, adopts a straight-through, monolithic flow-through architecture that enables direct integration into pressurized water piping systems without requiring auxiliary pumping equipment, thereby facilitating straightforward installation and deployment. The module employs UVC LED technology emitting in the 270 – 280 nm spectral band. By optimizing the material composition of the UVC lamp sleeves and refining the driver circuit design, ozone generation is fundamentally eliminated, ensuring zero ozone residual in the treated effluent.

The 1.0 Mpa pressure resistance rating is achieved through high-precision welding processes, a dual-layer O-ring sealing system, and a reinforced flange configuration. The structural integrity of this design can be reliably validated via in-house hydrostatic pressure testing conducted at the manufacturing facilit. The core design features and a photograph of the prototype module are presented in Fig. 1. Sensors are integrated within the module housing and connected via a unified interface system comprising quick-connect plug-type fittings, dedicated sensor connectors, and standardized rapid-connection adapters. This integrated connection strategy minimizes the total component count of the hydraulic assembly, streamlining both manufacturing assembly and on-site installation procedures. The control circuit board acquires real-time output signals from the embedded sensors to enable automatic start/stop control of the UVC LED water disinfection module. Simultaneously, the controller continuously monitors the operating current of the UVC LED arrays and the real-time UVC output irradiance. Upon detection of anomalous operational parameters, the system triggers visual alerts via status indicator LEDs to provide immediate fault diagnosis and operational warnings.

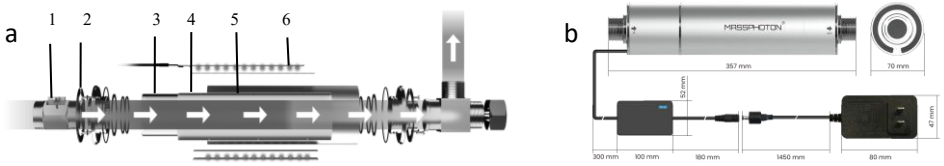


Fig. 1. Structural design and prototype of the 48 L high-flow water disinfection module. (a) Exploded-view diagram of the module assembly: 1: Water flow sensor; 2: Silicone decorative ring; 3: Quartz sleeve; 4: High-reflectivity UVC reflective materials; 5: Aluminum housing; 6: UVC LED arrays; (b)MP-UVC-48L module

Table 1 presents a comparison between the MS product and similar products available on the market. It can be seen that the MS product delivers outstanding comprehensive performance advantages in key indicators including flow rate, pressure resistance, energy consumption and service life.

Table 1. Comparison of MASSPHOTON MP-UVC-48LB with products from other brands.

UV LED modules	Flow Rate (L/min)	Press (MPa)	power consumption (W)	Service life （H）	Data sources

MASSPHOTON MP-UVC-48LB	48 - 70	1.0 MPa	43 W	10,000	Experimental data
Watersprint Core® 40	40–60	1.0 MPa	52W	20,000	Official product description
Direct Water Filters-UVC-LED-46	46	0.8 MPa	75W	7,000	Official product description
innest 30L Pro	30	0.4 MPa	24W	40,000	Official product description
Wassertechnik PURE-1.2	40	0.6 MPa	54W	8,000	Official product description

2.2 Microbial Test Strains and Cultivation

E.coli 8099 and *E. coli* ATCC 25922 were selected as indicator strains for microbiological evaluation. Both strains are recommended as reference microorganisms for assessing water disinfection efficacy in the Chinese national standard GB 28235-20200[17]and the international standard ISO 6222:1999 [18]. Strains were inoculated into Luria–Bertani (LB) liquid broth and incubated at 37 °C under constant agitation for 18–24 h. The resulting bacterial suspensions, with concentrations adjusted to approximately 5.0 × 104 – 5.0 × 10^6 (CFU/mL), served as the influent water samples for disinfection testing.

2.3 Disinfection Efficacy Testing

Protocol Disinfection performance was evaluated using a continuous-flow experimental test rig. The module was operated at its rated conditions of 48 L/min flow rate and 1.0 Mpa system pressure to simulate real-world hydraulic scenarios. Influent (pre-treatment) and effluent (post-treatment) water samples were collected aseptically and subjected to serial decimal dilutions as required. Aliquots were plated onto nutrient agar media and incubated at 37 °C for 24 h, after which visible colonies were enumerated.

Microbial inactivation efficiency was quantified using the logarithmic reduction value (LRV), calculated according to the following equation:

$$LRV = \log_{10}(N_0 / N)$$

Where N_0 denotes the viable cell concentration in the influent (CFU/mL) and N represents the viable cell concentration in the effluent (CFU/mL).

2.4 Operational Temperature Monitoring and Ozone-Free Verification

Operational temperature assessment: The module was filled with sterile deionized water and pressurized to 1.0 Mpa using a hydraulic pump. Surface temperature distribution and sealing integrity were continuously monitored over a 30 min operational period to identify potential issues, including excessive thermal rise, O-ring leakage or deformation, and abnormal pressure drops. Ozone concentration detection: Under continuous operating

conditions, effluent ozone concentration was measured in real time using a calibrated portable ozone analyzer (detection limit: ≤0.001 mg/L). This procedure verified the module's ozone-free operational performance, ensuring compliance with stringent water quality safety requirements.

3 Results and Analysis

3.1 Escherichia coli Inactivation Performance

3.1.1 Inactivation Efficacy against E.coli 8099

The microbiological performance test results of the module operated at its rated conditions of 48 L/min flow rate and 1.0 Mpa system pressure are summarized in Table 2. To ensure data accuracy, reliability, and experimental reproducibility, three independent parallel trials were conducted under identical operational parameters.

Table 2. Inactivation efficiency against *E.coli* 8099 under continuous-flow conditions.

Trial	Influent Concentration, N_0 (CFU/mL)	Effluent Concentration, N (CFU/mL)	Log Reduction Value (LRV)[b]	Inactivation Efficiency (%)
Parallel 1	6.1×10^5	< 1	> 5.79	> 99.999
Parallel 2	4.5×10^5	< 1	> 5.65	> 99.999
Parallel 3	5.6×10^5	< 1	> 5.75	> 99.999
Mean	5.4×10^5	< 1	> 5.73	≥ 99.999

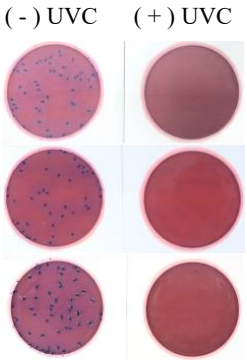


Fig. 2. Inactivation performance against *E.coli* of the 48 L high-flow water disinfection module under rated operating conditions.

The experimental results confirm that, under rated operating conditions, the module consistently achieves a minimum 5-log reduction (≥99.999% inactivation) against *E.coli 8099* (Fig. 2). The observed disinfection efficacy substantially exceeds the design specification, with effluent E. coli concentrations falling below the method detection limit (<1 CFU/mL). These findings demonstrate full compliance with the microbiological safety requirements stipulated in the Chinese national standard GB 28235-2020 for drinking water disinfection equipment [19].

3.1.2 Inactivation Efficacy against E.coli ATCC 25922

To further validate the module's disinfection reliability under independent verification, microbiological testing against *E.coli* ATCC 25922 was conducted by an accredited third-party testing institution. The module was operated at its rated conditions of 48 L/min flow rate and1.0 Mpa system pressure throughout the evaluation. The corresponding microbial inactivation results are summarized in Table 3.

Table 3. Inactivation efficiency against E.*coli* ATCC 25922 under continuous-flow conditions .

Influent Concentration, N_0 (CFU/mL)	Effluent Concentration, N (CFU/mL)	Log Reduction Value (LRV)[b]	Inactivation Efficiency (%)
1.7×10^5	< 1	> 5.23	> 99.999

The experimental results confirm that, under rated operating conditions, the module consistently achieves a minimum 5-log reduction (≥99.999% inactivation) against *E.coli* ATCC 25922. The observed disinfection efficacy substantially exceeds the design specification, with effluent E. coli concentrations falling below the method detection limit (<1 CFU/mL). These findings demonstrate full compliance with the microbiological safety criteria for drinking water and industrial process water stipulated in the World Health Organization (WHO) Guidelines for Drinking-water Quality (2023 edition) [19].

3.2 Operational Thermal Performance and Heat Dissipation Characteristics

To evaluate the module's thermal management capability under sustained high-pressure operation, a controlled heat dissipation test was conducted. The test chamber was filled with sterile deionized water, and the module was pressurized to 1.0 Mpa while operating at its rated electrical power input. Surface temperature distribution across the module housing was monitored continuously over a 30 min steady-state operational period using a calibrated digital thermocouple thermometer . Temperature readings were recorded at predefined intervals to assess thermal stability, identify potential hot-spots, and verify the effectiveness of the passive heat dissipation design under realistic hydraulic and electrical loading conditions.

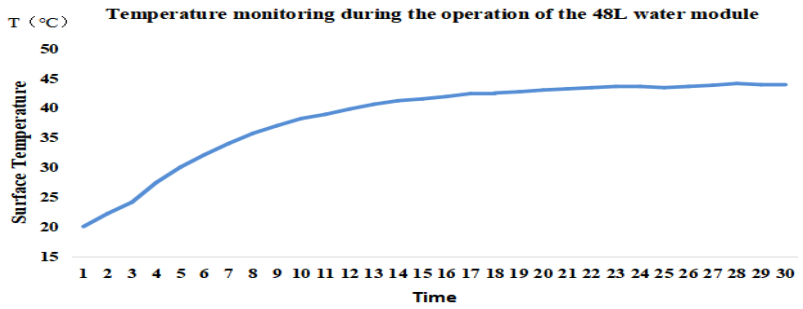


Fig. 3. Temporal evolution of housing surface temperature for the 48 L high-flow water disinfection module during continuous operation at rated condition.

Under rated operating conditions, the module exhibited a gradual temperature increase during the initial 12 min of operation, rising from an initial ambient temperature of 20 °C to

approximately 40°C. Subsequently, the surface temperature stabilized and remained dynamically balanced below 45°C for the remainder of the 30 min test period (Fig. 3). Throughout the evaluation, no abnormalities—including water leakage at pipe fittings, weld seams, or sealing interfaces; structural deformation; or seal failure—were observed at any monitored locations.Test results verify that the module exhibits excellent pressure resistance and sealing performance. It can operate stably for 30 minutes in water pipelines under a pressure of 10 bar, and is suitable for multiple application scenarios such as high-rise water supply, industrial circulating water and pressurized water treatment with intermittent operation.

3.3 Verification of Ozone-Free Operational Performance

Effluent ozone concentration measurements demonstrated that, during continuous module operation, ozone levels in the treated water consistently remained below the analytical method detection limit of 0.001 mg/L, thereby achieving genuine ozone-free disinfection.The ozone residual concentration in both finished water and distribution system samples complies with the requirement of ≤ 0.1 mg/L specified in the WHO Guidelines for Drinking-water Quality[19]. In contrast to conventional UV disinfection modules—which may generate trace amounts of ozone due to vacuum-UV emission bands interacting with dissolved oxygen—the present module fundamentally eliminates risks associated with ozone residuals and secondary chemical contamination. This attribute renders the system particularly well-suited for applications with stringent water quality and organoleptic requirements, such as municipal drinking water supply, food and beverage processing, pharmaceutical water systems, and other sensitive industrial processes.

Table 4. Ozone concentration measurements in effluent water during continuous module operation

Time(min）	Concentration (mg/m^3)	Mean Concentration (mg/m^3)	GB 28235-2020 Standard requirement (mg/m^3)
0	0.000	0.000	0.000
5	0.000	0.000	0.000
10	0.000	0.000	0.000
15	0.000	0.000	0.000
20	0.000	0.000	0.000
25	0.000	0.000	0.000
30	0.000	0.000	0.000
35	0.000	0.000	0.000
40	0.000	0.000	0.000
45	0.000	0.000	0.000
50	0.000	0.000	0.000
55	0.000	0.000	0.000
60	0.000	0.000	0.0

4 Conclusion

This study presents the design and development of a high-flow water disinfection module with a rated processing capacity of 48 L/min, integrating three core technological advancements: (i) optimization of the UVC optical configuration and hydraulic architecture ensures consistent ≥5-log inactivation of E.coli under high-flow conditions, fully complying with stringent microbial safety standards for treated water; (ii) implementation of an ozone-free spectral emission design fundamentally eliminates the risk of secondary chemical contamination in the effluent; and (iii) integration of a high-integrity, pressure-resistant sealing structure enables stable operation at 1.0 Mpa without leakage or structural deformation over prolonged use. Furthermore, the module maintains dynamic internal thermal equilibrium, preventing temperature-induced degradation of LED irradiance output and premature aging, thereby ensuring long-term operational reliability. Collectively, this module offers a novel and robust technical solution for high-flow, pressurized water disinfection, demonstrating significant potential for deployment in municipal water supply networks, industrial process systems, and environmental remediation applications. Notably, for systems operating under intermittent or variable-duty cycles, UVC LED technology represents the most competitive alternative to conventional discharge lamps, owing to its instantaneous switching capability and insensitivity to cycling-induced lifespan degradation. Future research will focus on optimizing the energy efficiency of the system and validating disinfection efficacy under complex water quality conditions, particularly those characterized by low ultraviolet transmittance, to further expand the operational envelope and practical applicability of this technology.

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