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Super-lightweight, low-cost and wireless water quality monitor for remote chlorine rate management in water-circulating cooling facilities

Masayuki Kawakami, *[a,b] Toshihiro Kasama, *[a] Tomomi Sato, *[a]
Hidekatsu Tazawa,*[a] Madoka Takai, *[a] Daisaku Yano*[b] and Ryo Miyake*[a]

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There is a growing demand for the continuous monitoring of residual chlorine in water-circulating cooling facilities to remotely maintain concentrations within an appropriate range. This study aims to develop a lightweight, low-cost, and wireless water quality monitor. We further propose a highly simplified and miniaturized configuration based on a wet chemical analysis method, which combines a liquid delivery mechanism driven by water head pressure, rather than a high-precision pump, with a low-power latch valve. Furthermore, to prevent fluctuations in flow path resistance, we adopted a glass-made mixing and reaction flow path device fabricated using imprint processing, which offers excellent surface smoothness and high rigidity. The evaluation results demonstrated that this monitor's flow system achieves highly stable flow behaviour while reducing reagent consumption to less than 1/10 (a few μL per measurement). Under these stable flow conditions, we confirmed sufficient analytical performance for measuring the residual chlorine rate in cooling water. Furthermore, in a demonstration test using a small-scale circulating cooling unit, we confirmed that the signal response of the monitor was perfectly synchronized with changes in chlorine concentration following periodic additions at 60 min intervals. Consequently, a super-lightweight, extremely low-cost, and fully wireless water quality monitor is ready for use.

1 Introduction

For the maintenance of water infrastructure, routine water quality monitoring is essential to ensure water safety and quality and to diagnose infrastructure deterioration. Numerous parameters, such as the concentrations of viable bacteria, turbidity, and mineral content, are measured at water purification plants and sewage treatment plants, and their levels are strictly controlled.[1]

Recently, such water quality monitoring work has been extended to various fields, such as water facilities in industrial plants and buildings. In particular, in water-circulating cooling facilities installed on rooftops or outdoors in factories and office buildings, the open exposure of these systems to the atmosphere allows extraneous bacteria to enter the circulating cooling water, and if left unattended, this can lead to problems such as pipe clogging. Therefore, to suppress bacterial proliferation, disinfectants, primarily chlorine (hypochlorous acid), are added to the circulating cooling water.[2,11] However, excessive addition of chlorine may damage the circulating equipment, and the associated chemical costs are not negligible. Currently, residual chlorine concentrations are periodically checked, generally using DPD method[14]-based meters (*e.g.*, Digital PACKTEST) at cooling tower water sites. However, these methods typically require manual water sampling and are not automated. Furthermore, although automated water quality analyzers dedicated to drinking water may be available, they are not easy to install due to the size, cost and other reasons as discussed later. Thus, there is a growing demand for the continuous remote monitoring of residual chlorine concentration at individual facilities to maintain the residual chlorine concentration within an appropriate range (>0.1 ppm). The total number of such cooling facilities, including existing installations, is rapidly increasing in line with global trends of industrialization and urbanization. To address this societal demand, we propose a remote residual chlorine management system, as shown in Fig. 1. To achieve this concept, a sensor-like, compact monitor—namely, a lightweight, low-cost, and wireless water quality monitor—is an essential core component. It should be noted that, since the objective is to provide an indicator for tracking residual chlorine concentration trends, an accuracy of approximately 0.1 ppm is sufficient for this purpose.

As methods for monitoring residual chlorine content in drinking water samples, the polarographic method, based on

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[a] *Department of Bioengineering, School of Engineering, The University of Tokyo, 7-7 Shinkawasaki, Saiwai-ku, Kawasaki, Kanagawa 212-0032, Japan.*
E-mail: kawakami-m@organo.co.jp
[b] *ORGANO Corporation, 4-4-1 Nishionuma, Minami-ku, Sagamihara, Kanagawa 252-0032, Japan*

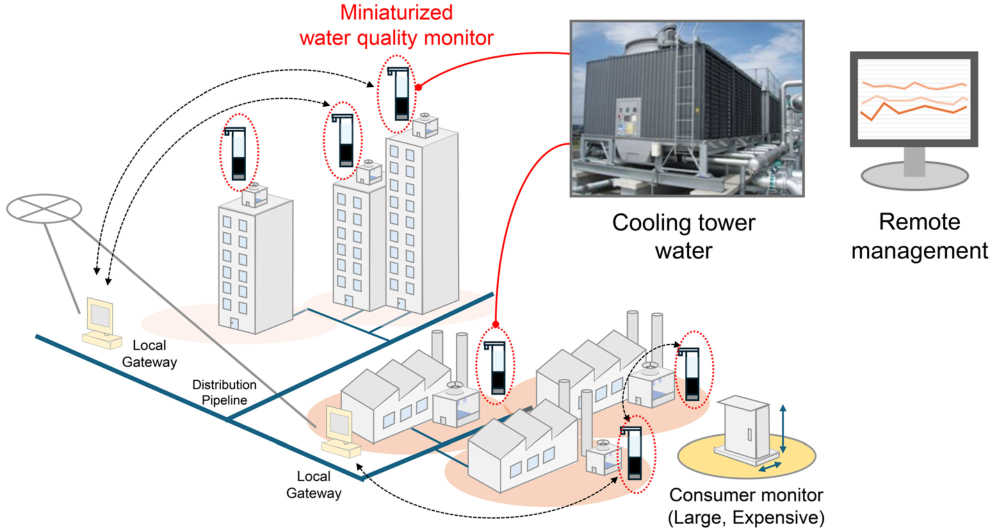


Fig. 1 Concept of a remote residual chlorine-rate management system with a compact water quality monitor.

an electrochemical reaction, and wet chemical reagent analysis, which is based on a chemical reaction between the target component and a specific reagent in the water sample, are commonly used.

The polarographic method has a fast response time and is suitable for miniaturization, and considerable efforts have been made to apply it to multipoint monitoring.[3] However, it requires countermeasures against drift and fouling, particularly when applied to water samples containing impurities, such as circulating cooling water. In contrast, the key advantage of the wet chemical reagent analysis method is its ability to selectively bind to the target component and quantify its colorimetric reaction based on absorbance. It can achieve high reliability through the use of a simple optical flow system, as well as exceptionally high selectivity and reproducibility.[20–22,24,25]

Currently, water quality monitors for drinking water that automate the wet chemical analysis method are commercially available; however, these devices are generally large, heavy (over 10 kg) and expensive (over ten thousand US dollars).[4] From the perspective of installation-site constraints and operating costs, challenges remain in applying these systems to continuous, multipoint monitoring. Therefore, this limitation motivated us to focus on a sensor-like, lightweight, low-cost, and wireless water quality monitor that is based on wet chemical reagent analysis and can be deployed at multiple locations for remote water quality monitoring.

As a method for automatically performing wet chemical analysis, FIA (flow injection analysis) has been widely adopted.[5] FIA is a technique that involves injecting minute volumes of the sample solution and reagent solution into a continuous carrier liquid flow, utilizing controlled diffusion and mixing within the flow path, as well as the accompanying chemical reaction for analysis. The system configuration is fundamentally composed of a liquid delivery and injection mechanism centred on a pump and valves, as well as a long, narrow conduit (typically with an inner diameter ≤1 mm and a length of approximately 1 m) to promote the mixing and reaction of the reagent and sample solution. This system precisely controls the fluid characteristics of small volumes of reagent and sample and delivers them together with the carrier liquid, achieving uniform mixing and reaction. This capability enables highly reproducible and stable colour development profiles. In contrast, this approach has an inherent structural limitation, in that the liquid delivery mechanism, centred on a rigid pump responsible for high-precision fluid control, inevitably results in increased system complexity and enlargement of the monitor.

Therefore, this study aims to develop a lightweight, low-cost, and wireless water quality monitor that can be deployed on-site at multiple locations by significantly simplifying the liquid delivery mechanism, while maintaining the high-precision analytical performance of FIA.

Specifically, the following were set as target specifications to enable retrofitting to existing cooling facilities: (i) a lightweight design with a hand-carriable mass of several hundred grams or less; (ii) a cost reduction guideline requiring fewer than half the number of main components used in existing water quality monitors; (iii) reagent consumption of less than 1/100th of that required for conventional manual analysis (on the order of millilitres), enabling high-frequency measurements over a defined operational period (approximately 1 month); (iv) long-term operation using battery or solar power, assuming that wired power supplies are impractical for retrofitted installations; and (v) wireless control and signal acquisition capabilities to enable remote measurement. Regarding measurement performance, the specifications were set based on the expected range of residual chlorine concentration fluctuations in cooling water, including an upper limit of 2 ppm, a limit of quantification equivalent to that of existing water quality monitors (0.1 ppm), and a measurement frequency of once every 10 min, considering the typical decreasing trend of residual chlorine in cooling water. In this paper, we first describe the fundamental concept underlying such a water monitor based on the FIA method, then discuss evaluation results, including analytical performance, and finally present the initial monitoring results obtained from a small-scale circulating cooling-water unit.

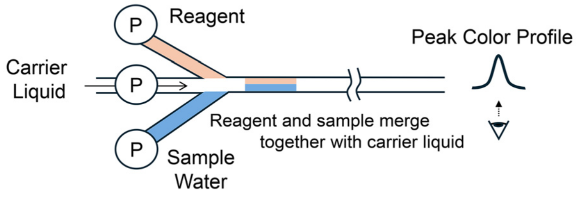
2 Materials and methods

2.1 Simplification and miniaturization method of the water quality monitor

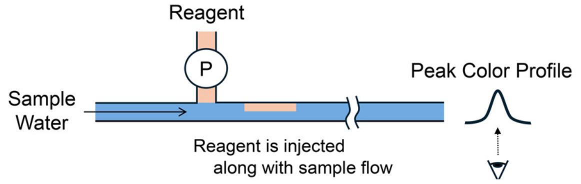
The typical flow path configuration of a conventional FIA (Fig. 2a) and the simplified configuration proposed by our group, which reduces the reliance on the pump, are shown in Fig. 2b. In conventional FIA, the sample liquid volume is often limited and small, and the standard procedure involves merging the sample liquid and reagent with precise timing, by sandwiching the sample liquid between carrier liquid segments before and after, allowing it to flow downstream. The reagent and sample liquid diffuse and mix while being sandwiched by the carrier liquid, and colour development occurs according to the concentration of the analytes in the sample liquid.

In contrast, in our proposed method, because the circulating cooling water, which serves as the sample, is abundant, we employ a simple approach of directly adding the reagent to the sample water flow at the time of analysis. This eliminates the need for a pump to deliver the carrier liquid.

Furthermore, with the aim of further simplification, we newly devised the flow path configuration, as shown in Fig. 3. An tank open to the atmosphere for storing the sample water is provided at the upper part of the device. By supplying the sample water at a flow rate exceeding that required for measurement, the excess water overflows. This structure is designed to keep the water level constant.

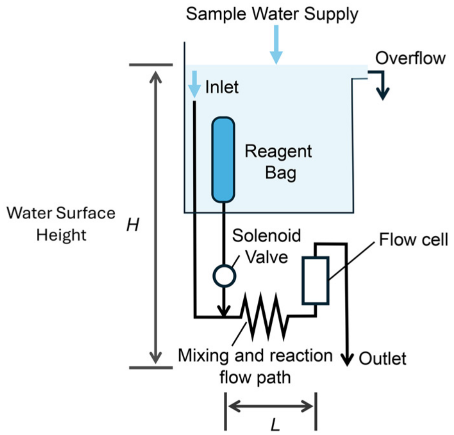


(a) Conventional FIA method

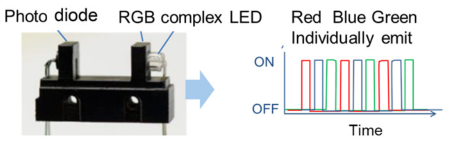


(b) Proposed FIA method

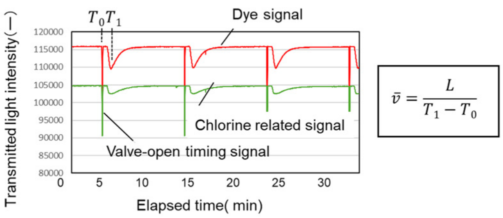
Fig. 2 Flow system configurations of the FIA method.



(a) Flow diagram of simplified and minimized FIA system



Time-divided light emission method by RGB complex LED



Time-course data obtained by the above emission method

(b) Flow stability monitoring method

Fig. 3 Highly simplified and miniaturized FIA flow system and method for monitoring flow stability.

A sample water collection pipe is positioned immediately below the water surface and is connected to the mixing and reaction flow path for FIA located at the lower part of the device. Additionally, a bag containing the reagent is held at a fixed height inside the tank. A tube for introducing the reagent connects the lower part of the reagent bag to the aforementioned mixing and reaction flow path *via* a solenoid valve. Downstream of the mixing and reaction flow path, a flow cell is installed to detect the degree of colour development of the reaction liquid coloured by the reagent. A drainage tube connects the flow cell outlet to an open end located outside the water quality monitor. By fixing the height of this open end, the water head pressure from the water surface to the open end remains constant.

Therefore, as long as the fluid resistance in the lower mixing and reaction flow path remains unchanged, the sample water flows through the path at a constant flow rate. The reagent bag is pressurized by the sample water in the tank, and by opening the solenoid valve for a predetermined duration, a fixed amount of reagent is added to the sample liquid flow.

Therefore, the pump for reagent supply is unnecessary, allowing the FIA flow shown in Fig. 2b to be realized under an extremely simplified fluidic configuration.

As the target measurement in this study is residual chlorine in circulating cooling water, we used DPD (*N*,*N*-diethyl-*p*-phenylenediamine) as the reaction reagent.[6,15] The analysis method using DPD reagent conforms to the official analytical method for quantifying residual chlorine in drinking water.

Notably, when inducing flow by water head pressure, the fluid resistance within the mixing and reaction flow path must remain constant. However, there is a concern that over the long term, the fluid resistance may change due to adhesion or accumulation of impurities in the flow path or due to the deformation or distortion of the flow path. Therefore, a mechanism was added to monitor overall changes in flow speed.

A dye reagent is included to serve as a flow indicator. Here, BB (Brilliant Blue FCF) dye,[7] which has a wavelength that does not interfere with the residual chlorine reagent, is mixed with the reagent. The light source for absorbance measurement uses an RGB colour LED capable of switching wavelengths, allowing the reactions of the DPD reagent and the dye reagent to be detected independently and simultaneously.

As the response of the dye is monitored, the flow speed (average velocity: $\bar{v}$) is calculated from the difference between the time the reagent is injected (T_0) and the time the dye reaches and responds in the flow cell (T_1), as well as the distance (L) between them, as shown in the following equation:

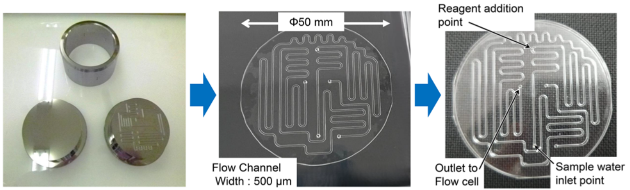
$$\bar{v} = \frac{L}{T_1 - T_0} \tag{1}$$

2.2 Glass-made mixing and reaction device

To achieve a stable flow driven by water head pressure, it is necessary to implement measures to prevent changes in the fluid resistance of the mixing and reaction flow path. Specifically, rigidity to prevent easy deformation of the flow path and smoothness of the inner wall to inhibit the adhesion and accumulation of fouling are required.

Therefore, instead of the resin tubes generally used in conventional flow systems, this study newly fabricated a mixing and reaction device in which fine flow paths were formed on a glass substrate. The fine grooves that form the flow path were created using imprint processing, which offers excellent mass productivity.[8] By using a precise mold, a fine and narrow flow path with a smooth inner surface can be reliably fabricated.

Fig. 4 shows the metal mold used for forming the path grooves (Fig. 4a), the glass substrate with fine path grooves (Fig. 4b), and the mixing and reaction device (Fig. 4c) with the top cover bonded and the flow path enclosed inside. The dimensions of the flow path were set to a width of 500 μm and a depth of 300 μm to accelerate molecular diffusion, which is smaller than the inner diameter of flow paths used in conventional FIA systems (≤1 mm).[16] By closely arranging the meandering flow path on a circular plate, which enhances convective flow as well, it was successfully folded to integrally form such a long flow path of 700 mm on a small glass surface with a diameter of 50 mm.



(a) Imprint mold for flow channel structures onto large-area glass substrate

(b) Polish the surface of the substrate to remove irregularities

(c) Bond the polished substrate using thermal fusion

Fig. 4 Glass-made mixing and reaction device.

2.3 Prototype of compact water quality monitor

Fig. 5 shows the external appearance of the water quality monitor with the glass-made mixing and reaction device installed at its base. The upper section contains a cylindrical tank for storing sample water. Sample water is supplied by falling from the top into this tank, and excess water overflows and is drained out. Inside the tank, a stainless-steel pipe (inner diameter 1.8 mm) for collecting sample water is fixed vertically, and its lower end is connected *via* a fine tube to the glass-made mixing and reaction device at the bottom.

A reagent bag is installed inside the tank in an inverted state. The mouth of the bag is made of rubber, and when the bag is replaced, it can be attached to and detached from the mixing and reaction flow path using a piercing mechanism.

The DPD reagent (DPD-25, DPD Manufacturing Corporation, Japan[28]) inside the bag is colourless and transparent, but as explained above, blue BB dye has been added to monitor flow stability.

The inner components of the lower part of the cylindrical tank are shown in the top right of Fig. 5a. The fine tube for the sample water supply is connected to the glass mixing and reaction flow path, and the fine tube for reagent supply is connected to the glass flow path *via* a solenoid valve (a latch-type valve requiring power only during operation, NLV-2-MFF, Takasago Electric). An absorbance measurement flow cell is connected directly above the outlet of the glass flow path and then to an external drain tube. By adjusting the height of the open end of the drain tube, the water head pressure between the open end and the water surface in the upper tank can be controlled, allowing the sample water flow rate to be increased or decreased.

With the above composition, the monitor weighs only 510 g (excluding stored sample water), and the pump, which is the main component for liquid delivery control, has been reduced from three units in conventional systems to a single simple latch valve (purchase cost less than $100).

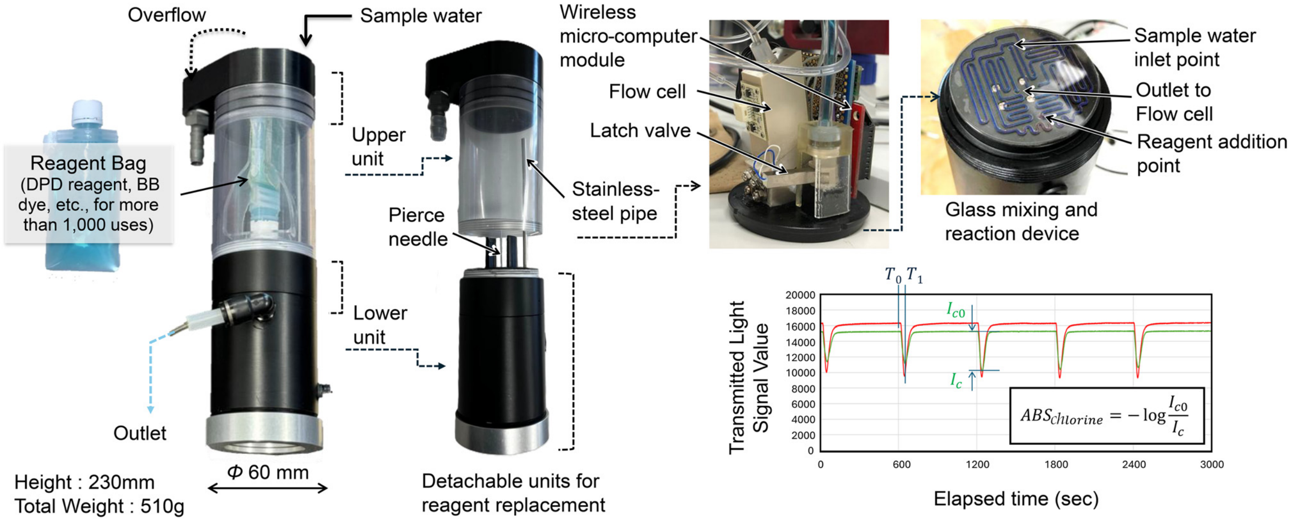


Fig. 5 Composition and components of the water quality monitor.

Fig. 6 shows the control and communication configuration diagram of this water quality monitor. According to the measurement protocol (10 min cycle), the open/close control command for the solenoid valve is transmitted to the micro-computer-embedded wireless module (Digi XBee3, Digi International) built into the lower part of the cylindrical tank (Fig. 5, top right).[12] The transmitted light intensity signal from the absorbance flow cell (comprising an SMLP34RGB2W3 LED (Rohm, Japan), an S13773 photodiode (Hamamatsu Photonics, Japan), and an in-house developed PCB) is transmitted wirelessly *via* the aforementioned module to a nearby host system. Wireless connection is possible over a distance of about 20–30 m at sites with good visibility.[26,27] By connecting the host system to the internet, the concentration signal can also be transferred to and stored on a cloud server.

Power to the water quality monitor is supplied from an external portable battery *via* a USB connector. Since there are no mechanical pumps that consume large amounts of power, the overall power consumption is less than 1 W, and operation without an external power line is possible when used in combination with a solar panel.[23]

2.4 Verification of flow stability

The flow rate of sample water in the glass mixing and reaction flow path is determined by the height difference between the water surface in the inlet tank and the open end of the drain tube. Assuming a 10 min measurement interval and considering the time required for the reaction sample water to be completely discharged from the flow cell, as well as the time for signal processing and transmission (approximately 5 min), it was deemed desirable that the time from the start of reagent addition to reaching the flow cell be within 2 min. Since the flow path length from the reagent addition point, through the 700 mm glass mixing and reaction flow path, to the flow cell is approximately 720 mm, the desired flow speed is ≥360 mm min^{-1} or more. Considering the cross-sectional area of the flow path, the desired operational flow rate is approximately ≥110 μL min^{-1}.

Therefore, we investigated the flow rate values by adjusting the water head through modification of the outlet open-end height in the prototype monitor (Fig. 7). The relationship between the height and the flow rate was experimentally checked. As a result, it was confirmed that the flow rate increases linearly in proportion to the height. This indicates the flow rate can be adjusted easily by changing the height.

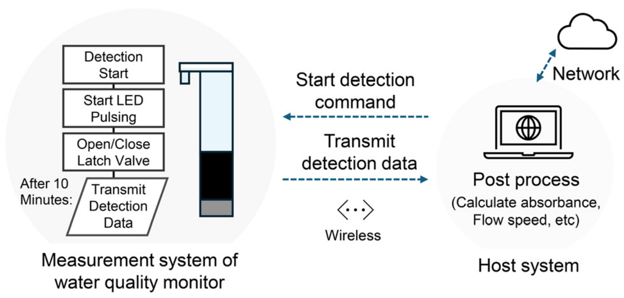


Fig. 6 Control and communication information transfer configuration diagram.

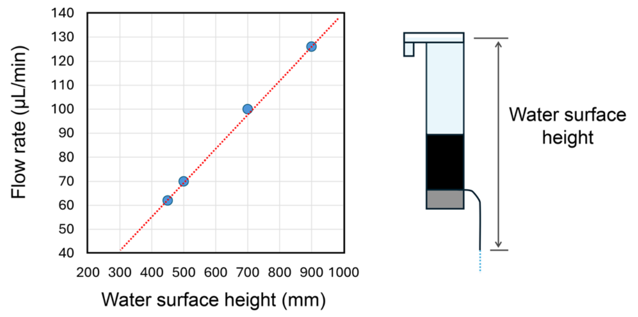


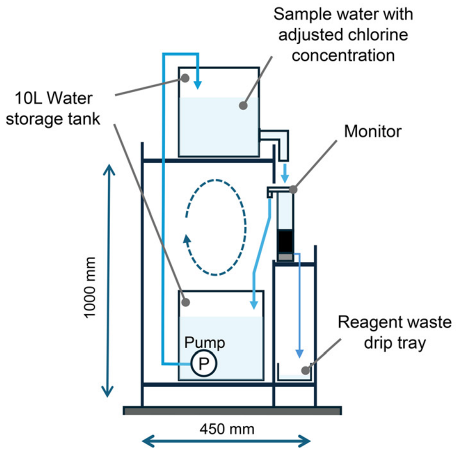
Fig. 7 Experimental results for water head and outlet flow rate.

Next, we evaluated the reproducibility and stability of the sample water flow rate. The experimental setup is shown in Fig. 8a. To enable repeated sample water supply, an experimental setup was constructed in which sample water was dropped into the water quality monitor's tank from above; the overflowed sample water was collected, returned to the top, and then supplied to the monitor in a circulating loop. Using this setup, the reproducibility of flow speed was determined from the time taken for the dye to reach the flow cell. The flow path length from the reagent injection point to the flow cell was 720 mm.

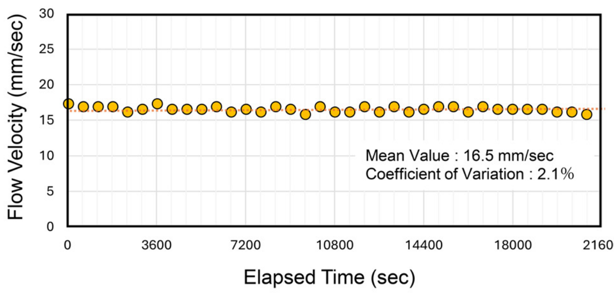
The results obtained based on eqn (1) are shown in the right panel of Fig. 8. The average flow speed for every 10 min measurement was 16.5 mm s^{-1}, the standard deviation was 0.35 mm s^{-1}, and the coefficient of variation was 2.1% over the 6 hour measurement period. This indicates that the device possesses sufficiently stable flow delivery performance. In conjunction with the rigid flow path structure, such as the glass flow path, stable flow was achieved even with liquid delivery driven by water head pressure.

2.5 Obtaining a calibration factor

In the circulating sample water supply experimental setup shown in Fig. 8, we measured the change in absorbance signal when hypochlorous acid was added sequentially into the sample water and the residual chlorine concentration varied. We then determined the calibration factor between the signal peak value and the residual chlorine concentration of the sample water obtained using an existing residual chlorine meter based on the DPD method (Digital PACKTEST,[9,10] DPM2-ClO-DP, Kyoritsu Chemical-Check Laboratory, Japan). The meter has been widely used for the periodic checking of residual chlorine concentration at cooling tower water sites. The results are shown in Fig. 9.



(a) Experimental setup



(b) Evaluation result of flow stability

Fig. 8 Experimental setup and evaluation results of flow stability.

Furthermore, the limit of quantification (10σ), calculated using repeated measurements (n = 8) of sample water without chlorine added, was 0.04 ppm. This demonstrated that the monitor possesses sufficient performance compared with the analytical performance required for monitoring circulating cooling water (0.1 ppm), as mentioned in the Introduction.

Next, using the same experimental setup, we verified whether the water quality monitor could accurately trace the decrease in residual chlorine concentration. Hypochlorous acid was added to the sample water with an initial concentration of 0.76 ppm to raise it to 1.47 ppm. The water quality monitor then monitored the trend in residual chlorine concentration over an extended period. Fig. 10 shows the change in residual chlorine concentration every 10 min. It is noted that the concentration values were obtained using the calibration factor from Fig. 9. The reference residual chlorine concentrations measured by the existing residual chlorine meter (Digital PACKTEST) are also indicated by red dots. We confirmed that the monitor is capable of accurately tracing the decrease in residual chlorine concentration. The reagent consumption per measurement, estimated from the amount of reagent used during this continuous measurement, was approximately a few µL. This demonstrates that reagent consumption can be reduced to less than 1/10th of that in conventional wet analysis (~0.1 mL).

3 Results and discussion

3.1 Evaluation of chlorine injection monitoring function using a circulating cooling unit

To further set conditions closer to those of an industrial environment for evaluating this monitor, a small-scale circulating cooling

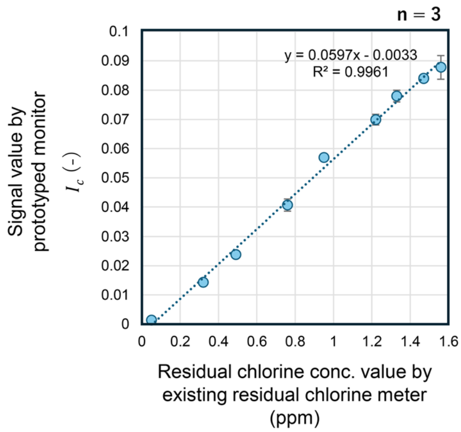


Fig. 9 Obtaining a calibration factor based on the DPD method.

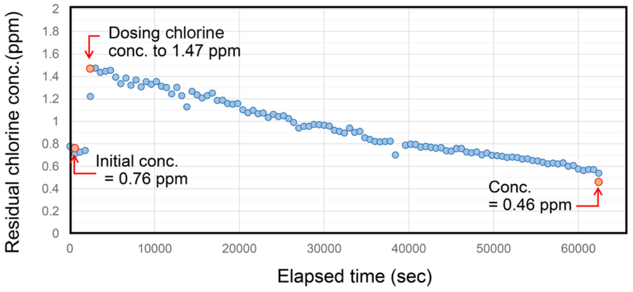


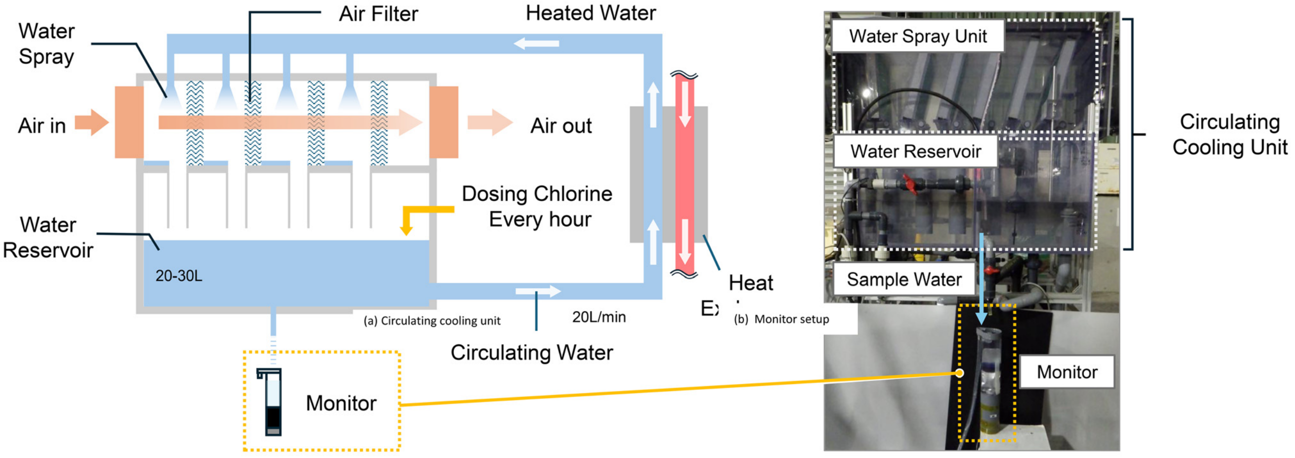
Fig. 10 Change in residual chlorine concentration every 10 min.

unit installed semi-outdoors was targeted.[13,18,19] Specifically, the evaluation focused on the continuous monitoring of the residual chlorine concentration in the unit's circulating water.

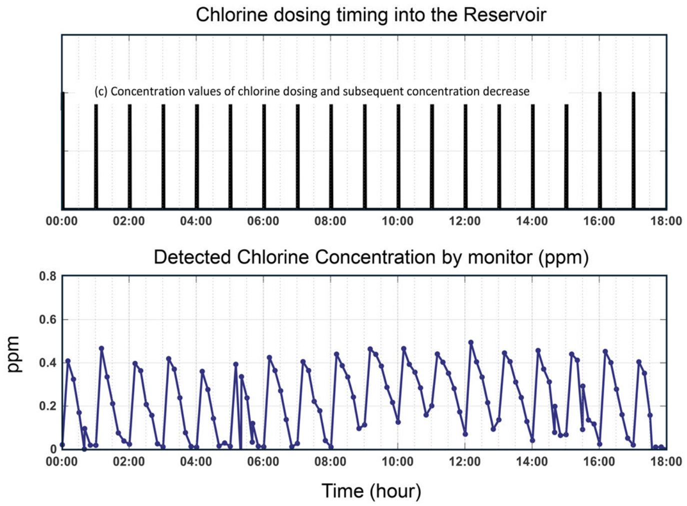
This unit cools water by circulating it, converting it into a mist, and exposing that mist to ambient air. Since circulating water exhibits significant proliferation of microorganisms (bacteria) due to contact with ambient air, chlorine is quantitatively added every 60 min to suppress this proliferation.

The evaluation results from the water quality monitor are shown in Fig. 11. The flow rate of circulating water is 20 L min^{-1}, and since the unit's circulating water holds approximately 20–30 L, one circulation takes about 1–2 min.

Continuous measurement of this circulating water confirmed that the residual chlorine signal response of the monitor can synchronously trace the timing of chlorine addition. The estimated residual chlorine concentration from the absorbance is approximately 0.4 ppm immediately after addition and rapidly decreases to near 0 ppm within 60 min. As shown in the test results in Fig. 10, because the rate of residual chlorine concentration decrease is gradual when the sample water is not misted, it is suggested that in a circulating cooling unit with misting, the decrease in residual chlorine concentration is primarily due to consumption resulting from the circulating water's contact with air.



(a) Circulating cooling unit (b) Monitor setup



(c) Concentration values of chlorine dosing and subsequent concentration decrease

Fig. 11 Evaluation of chlorine monitoring in a circulating cooling unit.

Table 1 Comparison between conventional technology[a] and the developed water quality monitor

Evaluation item	Water quality monitor based on the polarographic method (Hitachi AN700A[17])	Water quality monitor based on wet chemical analysis (Hitachi AN500[4])	Developed monitor
Miniaturization/simplification	Easy (handheld type possible by integrating sensor and electronics)	Requires a pump, valve, and tank for reagent supply (weight over 10 kg)	Easy (weight ≤510 g, liquid delivery key components ≤1/3, system-wide modularization possible)
Multipoint/remote monitoring applicability	Very high (long-term stability and maintenance frequency are challenges)	Difficult (installation cost, running cost, and size are challenges)	Very high (compact, low-power consumption (≤ 1 W), equipped with a simple wireless function, optimal for distributed deployment)
Maintenance load	High maintenance cost (calibration/cleaning)	Regular reagent replenishment and replacement of pumps/valves are required	Very low (low frequency of reagent replenishment; reagent consumption ≤1/10 *vs.* conventional (a few μL per test), few moving parts; low maintenance load)
Measurement frequency/responsiveness	~1 min	~1 min	~10 min
Residual chlorine analysis performance	Medium to high (highly susceptible to drift)	Very high (compliant with official methods)	High

[a] Commercialized and specialized for the analysis of drinking water.

4 Conclusion

This study aimed to develop a lightweight, low-cost, and wireless water quality monitor to meet the increasing demand for multipoint, continuous water quality monitoring necessary for remote chlorine-rate management of cooling water in factories and building facilities. To address the current structural issues of heavy weight, large size, and high cost in conventional water quality monitors specialized for drinking water, we proposed an extremely simplified and miniaturized configuration based on the wet chemical reagent analysis method (DPD method), combining a liquid delivery mechanism driven by water head pressure instead of a high-precision fluid control pump and a latch valve with low power consumption. Furthermore, to prevent fluctuations in flow path resistance, we adopted a glass-made mixing and reaction flow path device fabricated *via* imprint processing, which provides excellent surface smoothness and high rigidity.

The basic evaluation results demonstrated that this monitor's flow system can achieve extremely stable fluidity while reducing reagent consumption to less than 1/10 of that in conventional wet analysis (a few μL per measurement compared with the order of mL). Under this stable flow, we confirmed that the monitor provides sufficient analytical performance for residual chlorine concentrations in circulating cooling water (upper limit 2 ppm).

Furthermore, in a demonstration test using a small-scale circulating cooling unit close to an industrial environment, we confirmed that the monitor's signal response was perfectly synchronized with the concentration changes following chlorine addition every 60 min.

Based on the results above, Table 1 presents a comparison of the main performance and operational characteristics of the developed monitor with those of representative analytical methods (polarographic method and wet chemical analysis).

Consequently, as core equipment for remote chlorine-rate management in water-circulating cooling facilities, a super-lightweight, extremely low-cost, fully wireless water quality monitor is ready for use.

Author contributions

Masayuki Kawakami: experiments, methodology, data curation, investigation, visualization, formal analysis, and writing – original draft preparation. Toshihiro Kasama: investigation and writing – original draft preparation. Tomomi Sato: formal analysis, glass-made device control, and reviewing and editing. Hidekatsu Tazawa: glass-made device fabrication. Madoka Takai: supervision, project administration, and reviewing and editing. Daisaku Yano: supervision, project administration, and reviewing and editing. Ryo Miyake: conceptualization, visualization, investigation, supervision, project administration, resources, and writing – original draft preparation.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data that support the findings of this study are available within the article and its supplementary information (SI). Supplementary information: detailed results of the flow stability evaluations and numerical data for the calibration factor of residual chlorine. See DOI: https://doi.org/10.1039/d6an00029k.

Acknowledgements

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