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UV disinfection of secondary water supply: Online monitoring with micro-fluorescent silica detectors

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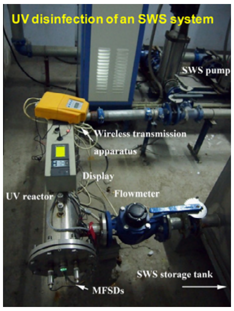
HIGHLIGHTS

- UV disinfection of secondary water supply was monitored online with three MFSDs.
- The lamp output increased by 50% due to an increase in water temperature.
- The fouling coefficient decreased by 70% due to the scaling of quartz sleeve.
- The UV fluence was strongly impacted by a large fluctuation in water flow rate.
- A periodic fluence adjustment strategy could save 35% of energy consumption.

GRAPHICAL ABSTRACT



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ABSTRACT

In past decades, secondary water supply (SWS) systems in high-rise residential buildings have seen a rapid development in China, and ultraviolet (UV) treatment has been selected as a principal disinfection technology. However, several special problems of the SWS systems, such as large daily fluctuations in water flow rate (Q) and seasonal variations in water temperature, may strongly impact the disinfection efficiency, but these issues have never been addressed before. In this study, the practical application of UV technology in an SWS system was investigated in detail. A tri-parameter monitoring system, which had earlier been developed based on three micro-fluorescent silica detectors, was installed in a UV disinfection reactor for the SWS system in a high-rise residential building. Combined with an initial fluence validation by biodosimetry, the lamp output attenuation coefficient (N), sleeve fouling coefficient (F), water transmittance (T), Q, and output fluence (U) were monitored online for about 6 months. During the long-term test period, the daily average N increased by ca. 50% due to the seasonal variation in water temperature; the F decreased by ca. 70% due to the sleeve scaling; and a large daily fluctuation of Q induced an obvious fluctuation of U. The average U over the whole operation period was as high as 169 mJ/cm^2, alerting an enormous loss of energy. Through online monitoring of the N, T, F, Q and U, this study revealed the current serious problems for UV disinfection of SWS systems, and proposed potential solutions accordingly.

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1. Introduction

In recent years, with the rapid economic development and urbanization, a large number of high-rise buildings have been built in the cities of China. As a result, the necessary secondary water supply (SWS) systems have received more and more attention. In general, drinking water is disinfected in municipal water treatment plants, and a certain level of residual disinfectant (e.g., chlorine, monochloramine) should be maintained in water distribution pipes [1,2]. For high-rise buildings, the drinking water from municipal water pipes often needs to reside temporarily in an SWS storage tank, and then pressurized by pumps to reach the high-floor users. Considering the potential depletion of residual disinfectant and the resulting re-growth of pathogenic microorganisms during the water storage period, additional disinfection of SWS is commonly required [3].

Because of its merits of little by-products formation, small space-occupancy, easy operation, and low maintenance cost, ultraviolet (UV) treatment has been selected as a principal technology for SWS disinfection and widely used in China. Since the disinfected drinking water is pumped directly to user taps, the primary problem associated with UV disinfection (i.e., no continuous disinfection ability) can be avoided.

In contrast to conventional UV disinfection applications (e.g., municipal water and wastewater disinfections) [4,5], the SWS has its own features, such as sporadic flow rates, water temperature seasonal variations, and frequent lack of quartz sleeve cleaning for UV reactors. The large daily fluctuations of water flow rate (Q) and/or water temperature will induce an obvious variation of the practical output fluence (U) of a UV reactor. Moreover, because of cost limitations, a sleeve cleaning apparatus is often not installed in UV disinfection reactors for SWS systems, which further decreases the disinfection security. These factors necessitate a detailed examination on UV disinfection of SWS systems. If the real-time fluence of the UV reactor can be obtained from a monitoring system, an online intelligent control of the output fluence can not only save the energy in the low Q period but also ensure the disinfection security in the peak Q period. However, this kind of study has never been reported.

Concerning the above discussion, an accurate online monitoring system is fundamental for the energy-saving and safe operation of UV disinfection reactors. At present, some routine parameters, such as Q, water temperature, and UV lamp age, can be monitored readily by different commercially available sensors. Moreover, UV intensity sensors have been installed in UV facilities to monitor a lumped index of the real-time operating status [6–8]. If combined with an initial fluence validation by biodosimetry [9–11], the real-time fluence can be obtained. Recently, some researchers have also proposed some improvements of the biodosimetry method [12–15].

In our previous work, a tri-parameter online monitoring system was developed by using three micro-fluorescent silica detectors (MFSDs) installed in a UV disinfection reactor [16]. The detector signals were computed by theoretically derived mathematical equations to determine three key operational parameters: the lamp output attenuation coefficient (N), the water UV transmittance (T, at 254 nm), and the quartz sleeve fouling coefficient (F). The MFSD has obvious virtues such as high thermal and chemical stability, fast response ($\sim 1\ \mu s$) and small volume ($0.07\ mm^3$), and thus is an ideal sensor for monitoring the operational parameters of a UV facility [17–19]. Based on this novel monitoring system, this paper aimed to investigate the practical application of UV technology for an SWS system in a residential community located in Zhengzhou City of Henan Province, China. After the initial fluence validation by biodosimetry, the output fluence and the N, F, and T parameters were continuously monitored online for ca. 6 months (185 days). Through analysis of the long-term monitoring results, current problems for UV disinfection of SWS systems were identified, and potential solutions were proposed accordingly.

2. Materials and methods

2.1. Monitoring method

In the conventional monitoring methods [20–22], the UV intensity sensor reading (S), Q, and T are considered as three key parameters for the online fluence (U) determination, as expressed by the following equation:

$$U = 10^A \times \mathrm{UVA}^B \times (S/S_o)^C \times Q^D \times \mathrm{Bank}^E \tag{1}$$

$$C = m + n \times \mathrm{UVA} \tag{2}$$

where UVA = water absorption coefficient (cm^{-1}) at 254 nm [i.e., $-\log(T)$)]; Bank = multiple modules coefficient; S_o = initial UV sensor reading; and the constants A, B, D, E, m, and n can be determined from the reduction equivalent fluence (REF) data from the fluence validation process. Specifically, the values of T, S, and Q can be determined by a UV–Vis spectrometer, a UV intensity sensor, and a flow meter, respectively. Afterwards, through measuring the fluence for various operational conditions (e.g., at various S, Q, and T values) with biodosimetry, the constants (i.e., A, B, D, E, m, and n) can be obtained.

Because of its small volume, the MFSD can be inserted into the gap between the UV lamp and its associated sleeve, and thus monitor the lamp output without any interference from sleeve fouling and water T fluctuation. Two other MFSDs are installed in the UV reactor chamber. Based on the real-time readings of the three detectors, the three key parameters (i.e., T, N, and F) can be monitored individually online [16].

Since the N and F are proportional to the U, the constant C (i.e., $m + n \times \mathrm{UVA}$) in Eq. (2) is equal to 1. Hence, Eq. (1) can be simplified as follows:

$$U = 10^A \times \mathrm{UVA}^B \times N \times F \times Q^D \times \mathrm{Bank}^E \tag{3}$$

The number of constants to be determined is thus decreased from six to four. As a result, the cost and time of biodosimetry can be significantly reduced, while the monitoring accuracy can be increased.

2.2. UV reactor

A single-lamp annular UV reactor (inner diameter 140 mm × inner length 950 mm) was used in this study (Fig. 1), which contained a low-pressure high-output mercury lamp (LPHO, GL, Xiashi Co., China; arc length 786 mm, electric power 105 W, UVC efficiency 32%) centered inside a quartz sleeve (23 mm o.d.). The online monitoring system was established principally using three MFSDs that were installed at different sites in the same radial cross-section (ca. 180 mm below the top cover). Detector A was inserted into the gap between the lamp and its sleeve; and detectors B and C were placed at 10 and 18 mm radial distances from the sleeve, respectively.

2.3. Biodiosimetry test for the fitting constants determination

In this study, the term Bank^E could be eliminated because the UV reactor contained only one lamp. Further, by assuming that the water in the reactor was perfectly mixed (i.e., a perfect plug flow with ideal radial mixing), the fluence could be approximated by multiplying the volume-weighted average of the model FRs by