Experimental Evaluation of Turbidity Impact on the Fluence Rate Distribution in a UV Reactor Using a Microfluorescent Silica Detector

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Supporting Information

ABSTRACT: Turbidity is a common parameter used to assess particle concentration in water using visible light. However, the fact that particles play multiple roles (e.g., scattering, refraction, and reflection) in influencing the optical properties of aqueous suspensions complicates examinations of their effects on ultraviolet (UV) photoreactor performance. To address this issue, UV fluence rate (FR) distributions in a photoreactor containing various particle suspensions (SiO_2 , MgO , and TiO_2) were measured using a microfluorescent silica detector (MFSD). Reflectance of solid particles, as well as transmittance and scattering properties of the suspensions were characterized at UV, visible, and infrared (IR) wavelengths. The results of these measurements indicated that the optical properties of all three particle types were similar at visible and IR wavelengths, but obvious differences were evident in the UV range. The FR results indicated that for turbidity associated with SiO_2 and MgO suspensions, the weighted average FR (WAFR) increased relative to deionized water. These increases were attributed to low particle photon absorption and strong scattering. In contrast, the WAFR values decreased with increasing turbidity for TiO_2 suspensions because of their high particle photon absorption and low scattering potential. The findings also indicate that measurements of scattering and transmittance at UV wavelengths can be used to quantify the effects of turbidity on UV FR distributions.

INTRODUCTION

In recent years, ultraviolet (UV) technology has been used increasingly for disinfection, photolysis, and advanced oxidation processes in water and wastewater treatment.^{1,2} The performance of UV photoreactors is governed by fluence (dose) delivery, in particular the fluence distribution. Numerical models have been widely applied to calculate fluence delivery, generally based on integrated application of submodels to simulate the optical field (i.e., fluence rate (FR) distribution) and fluid mechanics, usually by application of computational fluid dynamics software.^{3,4} An important component of accurate simulations of fluence delivery is an accurate description of the FR distribution.^{5–7}

Several mathematical models have been developed for simulation of FR distributions in UV reactors, including the multiple point source summation (MPSS),⁸ line source integration (LSI),⁹ and extense source with volumetric emission (ESVE) models.¹⁰ Meanwhile, hardware and analytical methods to measure (local) FR have been developed to validate optical field models.^{11,12} In general, FR models are effective for quantification of the effects of dissolved compounds that may absorb UV radiation.^{13,14} The fundamental optical behavior of these dissolved compounds (i.e., absorbance) can be accurately measured using a spectrophotometer based on the Lambert–Beer Law.

When UV radiation is imposed on particle suspensions, photon absorption and scattering (or reflection) by suspended particles will occur. This complex optical behavior is difficult to simulate using existing models, and has not been examined in a systematic manner, largely because of the dispersed nature of the suspended particles. In fact, absolute scattering does not induce photon energy consumption; scattered photons remain available for disinfection or photolysis, while absorbed photons are no longer available for reactions.^{15,16} Hence the Lambert–Beer law is insufficient for FR distribution simulation in the presence of particle suspensions, and measurements based on standard spectrophotometers do not allow independent characterization of the optical behavior of suspensions. Therefore, in the absence of numerical methods to account for the optical effects of suspended particles, experimental measurements of the FR field could be used to provide direct evidence of the effects of particles.

Turbidity measurements are commonly used to characterize the particle concentration in water.^{17,18} Despite the fact that turbidity measurements are generally based on visible radiation,

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this commonly applied optical parameter has also been used to inform water quality assessments that are applied for performance analysis of UV photoreactors. At present, turbidity in water treatment is usually measured using an electronic turbidity meter, usually expressed in nephelometric turbidity units (NTUs). Multiple turbidity measurement methods have been approved by the United States Environmental Protection Agency (USEPA) and the International Organization for Standardization (ISO), including EPA Method 180.1, ISO7027, Great Lakes Instrument Method 2 (GLI 2), Hach Method 10133, etc. These methods are based on nephelometry, wherein a visible light beam and a photodetector are positioned to allow measurement of visible light scattered perpendicular to the incident beam.

To date, most studies of the effects of turbidity on UV FR fields have involved empirical investigations based on bench-scale reactors. Passantino reported that clay turbidity up to 12 NTU does not have an obvious effect on MS2 inactivation.²⁰ Amoah found that UV inactivation of *C. parvum* and *Giardia*(oo)cysts was not impacted by 10 NTU of natural turbidity.²¹ However, Malley observed that different suspended particles have different inhibition impacts on the performance of MS2 virus inactivation by UV.²² Templeton demonstrated that humic acid and activated sludge floc particles can protect MS2 coliphage and bacteriophage T4 from UV inactivation.²³ Mamane et al. examined the effects of turbidity on the FR field using spherical actinometry and natural particles.²⁴ Their work demonstrated that particles could yield increases in local FR, depending on the nature of the particles.

A micro fluorescent silica detector (MFSD) was developed for in situ measurement of FR distributions in UV photoreactors in our previous research.^{12,25} The key features of this detector include 360-degree response, high stability, fast response, water-resistance, and small volume; these features have allowed it to be used for the examination of a wide range of optical characteristics of UV photoreactors, including the effect of inner-wall reflection,²⁵ polychromatic lamp reactor behavior,¹⁴ and multilamp reactor behavior.²⁶ Therefore, it was hypothesized that this detector would be suitable for the examination of the turbidity effect in UV photoreactors. This work aimed to clarify, by use of the MFSD, the impact of turbidity on the FR distribution in a UV reactor.

A second hypothesis was that measurements of reflectance and scattering at the characteristic wavelength of the UV source would yield better indications of the effects of suspended particles on the FR field than traditional measurements of turbidity. With this in mind, three different substituted oxide powders (SOPs, namely SiO₂, MgO, and TiO₂) with a range of reflection coefficients were examined. The optical properties of the solid particles and suspension were characterized independently, and then UV FR distributions in various particle suspensions at various turbidities were measured. This study provides experimental evidence of the effects of suspended particles on the FR field of a UV photoreactor. The results suggest promise for practical examination and monitoring of the particle effect on UV photoreactors used in water treatment.

■ EXPERIMENTAL SECTION

Chemicals and Analytical Methods. Three SOPs, namely TiO₂ (R902, DuPont Co., particle diameter (PD) ca. 400 nm), SiO₂ (Cabot M-5, PD ca. 300 nm), and MgO (Sinopharm Chemical Reagent Co., PD ca. 1000 nm, China), were used to

prepare particle suspensions with various turbidities. The reflection coefficients of the solid SOPs were measured at wavelengths of 254, 600, and 800 nm using a spectrophotometer (U-3900, Hitachi, Japan) equipped with an integrating sphere attachment; reported reflectance values were the sum of specular and diffuse measurements. Powders of all three SOPs were compressed into tablet mold individually for the reflection coefficient measurement.²⁷ Because of higher reflection coefficients of the MgO powder than that of the initial standard plate of this spectrophotometer (i.e., aluminum-evaporated plane) in the wavelength range of 240–280 nm, MgO powder was used as the standard plate in this study. Therefore, reported reflection coefficients are relative to those of MgO.

Aqueous suspensions of SOPs were prepared with deionized (DI) water. A HACH 2100N turbidity meter was employed to measure the turbidity of aqueous particle suspensions. Precision of 0.01 NTU was reported by the manufacturer for the range of 0–1000 NTU. The turbidity meter was equipped with a stable halogen-filled tungsten filament lamp (emission spectrum spanned the wavelength range 400–1800 nm) to meet the reporting requirements of EPA Method 180.1. This method is based on the principles of nephelometry, and the photodetector, whose response spectral peak was reported to be between 400–600 nm, received light scattered perpendicular to the incident light path. Additionally, because the turbidity meter did not allow measurements based on radiation in the UV portion of the electromagnetic spectrum, a fluorescence spectrophotometer (Cary Eclipse, Varian, Australia) with a 1 cm path-length cell was utilized to investigate the scattering behavior of each SOP suspension at specific wavelengths in the UVC (254 nm), visible (600 nm), and IR (800 nm) ranges. In the fluorescence spectrophotometer, as with the turbidity meter, the excitation and emission beams are perpendicular to each other. For these measurements, the excitation and emission wavelengths were both set to the same value. Hence, the receiving “fluorescence” signal was used to represent the scattering property of the test suspension at each of the chosen wavelengths. Note that in common spectrofluorometric applications, the emission wavelength is set to a longer value than the excitation wavelength, hence the excited fluorescent signal of the suspension cannot interfere the scattering property test. In addition, absorbance at each of the three characteristic wavelengths (i.e., 254, 600, and 800 nm) of each SOP suspension was measured with a spectrometer (UV2600, Shimadzu, Japan) in a 1 cm path-length cell.

FR Distribution Measurement Platform. Figure 1 represents a schematic diagram of the experimental platform for measuring the FR distributions in a single-lamp UV photoreactor. A cylindrical MFSD (1.0 mm length × 0.3 mm outside diameter), whose fluorescence was received by a BPW 34 B silicon PIN photodiode, and amplified and displayed by a multimeter, was used as the FR measurement detector in this study. A cylindrical quartz-wall UV reactor (inner diameter = 190 mm and inner length = 1000 mm) wrapped in a black cotton cloth was used; UV reflectance from the air/quartz/air interfaces of this reactor had previously been estimated at approximately 8%.²⁴ A single low pressure mercury Hg lamp (GL Type, Xiashi Wanhua Co., China) with a quartz sleeve (radius = 11.5 mm) was housed in the center of the cylindrical quartz photoreactor. The lamp parameters were: arc length = 297 mm; total output power 16 W; UVC efficiency at 254 nm = 26%.

Figure 1. Schematic diagram of the experimental platform for measuring the FR distributions in a UV photoreactor.

The MFSD was fixed onto a two-dimensional guideway with its vertical axis oriented parallel to the lamp axis (Figure 1). This configuration allowed the detector to move either parallel (displacement precision of 1 mm) or perpendicular (displacement precision of 0.01 mm) to the lamp axis to measure the axial or radial FR distribution, respectively. The calibration process of the MFSD at 254 nm has been described previously.¹² A second MFSD, used as a reference detector, was inserted into the gap between the lamp and the sleeve to monitor lamp output fluctuations. Water temperature was controlled by a recirculator with precision of 0.5 °C.

FR Distribution Measurement process. The FR distributions in the reactor were measured for each of several particle suspensions. Note that for mixed suspensions of SiO₂ and TiO₂, the SiO₂ powder was first added to reach the turbidity requirement (e.g., 5.0 NTU for the SiO₂50%-TiO₂50% case with 10.0 NTU) and then the TiO₂ powder was added to reach the final turbidity requirement (e.g., 10.0 NTU for the SiO₂50%-TiO₂50% case with 10.0 NTU).

For each suspension, the test MFSD was placed parallel to the UV lamp at radial distances of 5.00 and 60.00 mm away from the quartz sleeve. For each fixed radial distance, the detector was moved parallel to the lamp axis to measure the axial FR distribution in the UV reactor. Then the detector was moved perpendicular to the lamp axis at the central cross-section of the lamp to measure the radial FR distribution. The detector was maintained at each test point for 1 min to allow a data acquisition switch unit (34971A, Agilent Co.) to collect 30 readings from the test MFSD. For each location, the last 10 readings were recorded and averaged. The final result for each test location was divided by the corresponding reading of the reference detector to correct any potential error induced by the lamp output fluctuation.

RESULTS AND DISCUSSION

Reflection Coefficients of Various Solid Particles.

Table 1 lists the reflection coefficients in the UVC region (i.e., 254 nm) and visible/IR region (i.e., 600 and 800 nm) of the three solid SOPs (i.e., MgO, TiO₂ and SiO₂) that were compressed into plates. Because MgO was used as the reference standard for reflection in this study, reflection coefficients for this material at all wavelengths were reported as 1.000. In the visible/IR light region, all three SOPs displayed similar and high reflectance, while at 254 nm the reflection coefficient of TiO₂ was substantially lower than other two SOPs. These

Table 1. Relative Reflection Coefficients of Various Materials at Different Wavelengths. At Each Wavelength, The Reflection Coefficient Was Normalized Relative to the Value Recorded for MgO

wavelength (nm)	MgO	TiO ₂	SiO ₂
254	1.000	0.135	0.849
600	1.000	0.929	0.947
800	1.000	0.916	0.954

results indicate that the all three SOPs may have similar optical behavior in the visible/IR region; however, the low UV reflection coefficient of TiO₂ may be expected to yield a different UV FR distribution as compared to the other two SOP suspensions. It should be noted that the TiO₂ particles selected for use in this study were pigment grade, which often contain other metal oxides (e.g., SiO₂, Al₂O₃, ZrO₂) as surface modifications. These surface impurities can have profound effects on the optical behavior of TiO₂ particles. As such, the optical characteristics of these TiO₂ particles may be different than those of other TiO₂ particles.

Scattering Properties of Various Suspensions. Measurements of UVT values at 600 nm as a function of the turbidity for various SOP suspensions are shown in Figure 2a.

Figure 2. UVT at 600 nm (a), UVT at 254 nm (b), and scattering intensity (SI) at 254 nm (c) as a function of turbidity. All tests were repeated three times and all values of relative standard deviation were lower than 10%.

Because of their similar reflection coefficients at 600 nm, all three SOPs displayed similar relationships between UVT₆₀₀ and turbidity. However, the particle suspensions did not display the same trends for UVT₂₅₄ vs NTU (Figure 2b) and scattering intensity (SI) at 254 nm, measured by the fluorescent spectrometer and defined by the strength of the signal scattered at an angle perpendicular to the incident beam (Figure 2c). A high particle concentration translates to high turbidity of a suspension; therefore, as turbidity increases it is reasonable to expect a decrease in UVT₂₅₄ and a corresponding increase in SI. However, among the three SOP suspensions, the SiO₂ suspension demonstrated the fastest decrease of UVT₂₅₄ and the fastest increase of SI, while the TiO₂ suspension

demonstrated opposite trends. These results suggest that these two parameters are complementary. For the measurements in the spectrometer and fluorescent spectrometer, incident UV photons will be scattered by an SOP suspension in the test cell, which would decrease the rate at which photons are received by the sensor oriented in the incident direction (i.e., UVT_{254}) and increase the rate at which photons are received by the sensor oriented perpendicular to the incident direction (i.e., SI). Therefore, these two parameters could be used to evaluate the scattering property of the suspension, and in this study the SiO_2 and TiO_2 suspensions displayed the strongest and weakest scattering ability, respectively.

Note that the results of UVT_{254} and SI_{254} for the suspensions did not absolutely agree with the relative reflection coefficient measurements reported at 254 nm in Table 1. We hypothesize that this is attributable to the fact that the scattering behavior of particles will depend on several factors, including particle size, particle shape, particle concentration, and chemical composition. The reflection coefficient data in presented in Table 1 only express the effects of chemical composition. By contrast, the scattering property test (i.e., Figures 2b and 2c) is an integral characterization for the suspension, providing a measure of optical (scattering) behavior that accounts for all of the factors listed above.

Radial FR Distribution in Various Particle Suspensions. Figure 3 illustrates the measured radial FR distributions

Figure 3. Radial FR distributions with various turbidities in (a) SiO_2 suspension, (b) TiO_2 suspension, and (c) MgO suspension.

in the central cross-section of the UV reactor filled with DI water, as well as the SiO_2 , TiO_2 , and MgO suspensions with various turbidities. When the test MFSD was moved from 10 to 70 mm from the sleeve surface, the FR decreased for all conditions. For the SiO_2 suspension (i.e., Figure 3a), the local measurements of FR for all values of turbidity were higher than the corresponding measurements in DI water. As turbidity increased, local FR values also increased. These results imply that SiO_2 particles in water will strongly reflect or redirect UV photons in various directions, thereby allowing photons to travel along a longer optical path than they would in the absence of these particles. In theory, this provides more opportunities for photons to interact with photochemical or photophysical targets in the system, such as a suspended

microorganisms, absorbing dissolved chemicals, or an MFSD detector. Therefore, the presence of suspended, reflective particles could promote photoreactor efficiency. Similar results have been reported previously with an aluminum clay suspension.²³

Similar results were also observed with the MgO suspensions shown in Figure 3b. The FR distribution in the MgO suspension increased with increasing turbidity and was consistently higher than with DI water. However, for the TiO_2 suspensions, a consistent increase of FR, relative to DI water, was evident only for the 2.0 NTU suspension. FR enhancement was more evident in the near-lamp region than for locations more distant from the lamp. As turbidity increased from 2.0 to 20.0 NTU, the FR distribution dropped. This was consistent with the relatively strong absorption at 254 nm (i.e., low reflection coefficient) and low scattering ability of the TiO_2 particles, as compared to the other two SOPs. As the MFSD approached the reactor wall, photons had more opportunities to be absorbed by the TiO_2 particles and were less likely to be scattered than with the other two particle suspensions.

Axial FR Distribution in Various Particle Suspensions. The axial FR distributions in the far-lamp region of the test UV reactor (60 mm from the sleeve surface) for each SOP suspension are illustrated in Figure 4. The FR decreased as the

Figure 4. Axial FR distributions in the far-lamp region (60 mm from the sleeve surface) in various particle suspensions with various turbidities of (a) 2.0 NTU, (b) 10.0 NTU, and (c) 20.0 NTU.

MFSD was moved from the lamp center to the lamp end. In the central lamp region, the FR values of all three SOPs were similar for conditions of turbidity of 2.0 NTU; at this relatively low value of turbidity, the effects of suspended particles on the FR field were limited. For turbidities of 10.0 NTU and 20.0 NTU, the FR values for the SiO_2 and MgO suspensions were higher than those of the TiO_2 suspension at the same turbidity. These results were also consistent with the previously described scattering behavior of the particles (Figure 2b and c). The axial FR distributions in the near-lamp region (5 mm from the sleeve surface) for each particle suspension are shown in Figure S1. Because of the short path-length, FR values of all three SOPs were similar in all turbidity cases.

Mixed Particle Suspensions. The particles in practical waters come principally from soil (erosion).^{18,19} The composition of natural particles is variable and depends largely on local geology and land use practices. Natural particle suspensions likely comprise mixtures of silica and metal oxides, as well as organic materials. Hence, for the practical applications of UV photoreactors, it is relevant to examine the behavior of mixed particle suspensions involving mixtures of highly reflective (e.g., SiO₂) and minimally reflective (TiO₂) particles. To address this issue, mixed suspensions of TiO₂ and SiO₂ particles were prepared. Radial FR distributions for mixtures of SiO₂ and TiO₂ with turbidity of 10.0 NTU are shown in Figure 5. Turbidity contribution ratios of SiO₂ to TiO₂ were 7:3, 5:5,

Figure 5. Radial FR distributions in mixed particle suspensions with turbidity of 10.0 NTU.

and 3:7. Because of the stronger scattering property of SiO₂ as compared to that of TiO₂, the FR distribution of the suspension with SiO₂70%–TiO₂30% was higher than that of suspension with SiO₂30%–TiO₂70%, and the FR distribution of the suspension with SiO₂50%–TiO₂50% was intermediate to the other two suspensions. Similar results were observed in the suspensions with turbidity of 20.0 NTU, as shown in SI Figure S2.

Weighted Average FR and Minimum FR. Table 2 and SI Table S1 illustrate the weighted average FR (WAFR) values

Table 2. Weighted Average Fluence Rates for Various Particle Suspensions

suspensions	weighted average fluence rate (mW cm ⁻²)			
	0 NTU	2.0 NTU	10.0 NTU	20.0 NTU
deionized water	5.824			
SiO ₂		6.120	6.386	7.784
TiO ₂		6.278	4.870	3.979
MgO		5.973	6.244	6.454
		5.0 NTU	10.0 NTU	20.0 NTU
SiO ₂ 30%–TiO ₂ 70%		5.911	4.890	3.996
SiO ₂ 50%–TiO ₂ 50%		N/A	5.111	4.831
SiO ₂ 70%–TiO ₂ 30%		5.985	5.314	5.213

and the FR values at 70 mm distance to the sleeve surface in the central cross-section (regarded as the minimum FR) for DI water, as well as for the SiO₂, TiO₂, and MgO suspensions with various turbidity values. The WAFR values for the SiO₂ suspensions with turbidity values of 2.0, 10.0, and 20.0 NTU were 1.05, 1.10, and 1.34 times higher than those of DI water,

respectively. Similarly, the minimum FR values for the SiO₂ suspensions with turbidity values of 2.0, 10.0, and 20.0 NTU were 1.02, 1.12, and 1.29 times higher than those in DI water, respectively. The minimum FR will be related to the minimum dose (or low-dose end of the dose distribution), which limits the performance of UV disinfection.²⁸

The results reported herein, which were developed through the use of the MFSD, demonstrate that the presence of reflective suspended particles (i.e., particles that scatter UV photons) can actually enhance the FR field and the overall performance of a photoreactor. A previous study also demonstrated this enhancement effect.²³ This seems contrary to the conventional view of UV photoreactors in the sense that turbidity is commonly regarded as an inhibiting factor for performance of these systems. In fact, the reflection by the particles could extend the photon path length in the reactor.²³

The low photon energy loss during the absorption/reflection process on SiO₂ particles (high UV reflection coefficient) could reduce interactions of UV photons with the reactor wall where they would be absorbed or inefficiently reflected, thereby enhancing WAFR in the reactor. Note that for UV disinfection, suspended particles can shield microbes from UV exposure, thereby counteracting the benefits described above. Therefore, the effects of suspended particles (turbidity) on the performance of UV disinfection systems can be quite complex.^{20–23,29}

The WAFR values and minimum FR values for the MgO suspensions increased with increasing turbidity, and all WAFR values and minimum FR values for the MgO suspensions were higher than those for DI water. For each turbidity condition (i.e., 2.0, 10.0, or 20.0 NTU), because the MgO particles were less effective at scattering UV₂₅₄ radiation than SiO₂ particles (Figure 2c), its WAFR value and minimum FR values were lower than the corresponding values for the SiO₂ suspension.

Calculated values of WAFR for the TiO₂ suspensions dropped from 6.278 to 3.979 mW cm⁻² as turbidity increased from 2.0–10.0 NTU. Meanwhile, the minimum FR value decreased from 4.01 to 1.95 mW cm⁻² in the turbidity range of 2.0–10.0 NTU. At turbidity values of 10.0 and 20.0 NTU, the WAFR values were lower than that of DI water. At any given value of turbidity, the TiO₂ suspensions had the highest transmittance (Figure 2b) and the lowest scattering at 254 nm (Figure 2c). Collectively, these attributes increase the likelihood of UV₂₅₄ photons being incident on and absorbed by the reactor wall. Moreover, the low reflection coefficient of TiO₂ powder at 254 nm (i.e., 0.135) implies that a large fraction of the UV photons were absorbed by the TiO₂ particles in suspension. Therefore, unlike the SiO₂ and MgO suspensions, an inhibition effect of TiO₂ particles was observed.

Table 2 also illustrates WAFR calculations for mixed suspensions with various ratios of SiO₂ to TiO₂. At a fixed value of turbidity, WAFR increased with SiO₂ content. Moreover, as turbidity increased, the WAFR values of all three mixed suspensions decreased, and the suspension with the highest TiO₂ ratio demonstrated the most rapid decrease. In addition, all WAFR values of the mixed suspensions of SiO₂ and TiO₂ at fixed turbidity (5.0 NTU and 10.0 NTU) were greater than based on TiO₂ alone, and lower than those of SiO₂ alone.

Discussion. This study illustrated the impact of turbidity, a conventional water parameter used for characterizing the concentration of suspended particles in water, on the FR field of a simple UV photoreactor. The results demonstrate that several optical properties of suspended particles can induce the

FR distribution in a UV reactor at an identical turbidity value. This is explained by the fact that conventional measurements of turbidity involve visible radiation, whereas the optical properties of particles in the UVC range are perhaps more relevant to the behavior of a UV photoreactor. Moreover, differences in particle composition are associated with differences in optical behavior in the visible and UVC ranges. Therefore, conventional turbidity measurements (based on visible light) are inappropriate for characterization of the effects of suspended particles on the FR field. As alternatives, measurements of reflectance and scattering at the characteristic wavelength of the UV source are more representative of the effects of suspended particles on the FR field.

The measurements reported herein demonstrate that the optical field (FR distribution or WAFR) was principally dependent on the photon scattering ability of the suspension, which corresponded with measurements of photon absorption and reflection by the solid powders in the suspension (reflection coefficient), as well as other factors such as the particle size and shape.²⁹ For suspensions with identical turbidity, particles that absorb poorly in a UVC wavelength range (e.g., SiO₂ and MgO) could enhance the FR distribution and performance of a photoreactor. Conversely, for particles that absorb strongly in UVC range (e.g., TiO₂), their presence in suspension could diminish the FR distribution. Meanwhile, the turbidity value could represent the particle concentration in the suspensions, implying that the increasing turbidity could amplify the effect of the particles on the FR distribution in the reactor, including positive effects (e.g., SiO₂ and MgO), and negative effects (e.g., TiO₂).

The effects of suspended particles on the optical behavior of UV radiation were also characterized by measurements of transmittance and scattering intensity developed using a spectrometer and a fluorescence spectrometer, respectively. These two tests have the potential to be used as characterization methods for evaluating the effects of turbidity on FR distributions.

■ ASSOCIATED CONTENT

■ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b02730.

Two figures and one table are provided. Axial FR distributions in the near-lamp region (5 mm from the sleeve surface) with various particle suspensions with various turbidities (Figure S1), radial FR distributions with mixed particle suspensions with various turbidities of 20.0 NTU (Figure S2), and minimum FR values (Table S1) (PDF)

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Notes

The authors declare no competing financial interest.

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