Impacts of SRT on Particle Size Distribution and Reactor Performance in Activated Sludge Processes

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ABSTRACT: Particle size distribution of the particulates is an essential characteristic of the wastewater quality. Particle size of activated sludge flocs may affect key sludge handling processes including sedimentation, thickening, digestion, and dewatering. This study evaluated the effects of solids retention time (SRT) on particle size distribution, sludge settleability, effluent turbidity, and removals of chemical oxygen demand (COD) and NH_4^+-N in a lab-scale Modified Ludzak–Ettinger (MLE) reactor and an integrated fixed film activated sludge (IFAS) reactor. This study also surveyed particle size distribution profile of five full-scale water resource recovery facilities (WRRFs), including high purity oxygen (HPO), step-feed nitrification/denitrification (NDN), and MLE NDN processes. This study provides direct evidence of the effects of SRT on particle size distribution and sludge settleability in lab-scale reactors and full-scale WRRFs. *Water Environ. Res.*, **90,** 48 (2018).

KEYWORDS: particle size distribution, settleability, sludge volume index, mean particle size.

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Introduction

Particle size is an important property of activated sludge that may affect sludge dewaterability (Jin et al., 2004; Karr and Keinath, 1978; Knocke and Zentkovich, 1986; Wisniewski and Grasmick, 1998), control oxygen transfer efficiency (Knudson et al., 1982, Starkey and Karr 1984), and provide useful information for the design of disinfection process (Kollu and Ormeci, 2012; Loge et al., 2002; Parker and Darby, 1995; Templeton et al., 2005).

Sedimentation of activated sludge is one of the most critical operations in activated sludge process. The performance of secondary sedimentation is crucial to overall effluent quality (Jin et al., 2003). Different parameters have been developed to characterize sludge properties in terms of sludge volume index (SVI); organic loading; sludge retention time; composition; and content of polymers, density, porosity, viscosity, and particle size distribution (Hilligardt and Hoffmann, 1997). Most modern secondary sedimentation tanks include thickening zone for sludge concentration and sludge storage in case of a high hydraulic loading period (Plosz et al., 2011). Surprisingly very few studies have investigated the relationship between particle size distributions in regard of sludge settleability. It has been observed that the SVI is related to the median floc size for nonfilamentous sludge (Andreadakis, 1993; Barber and Veenstra, 1986). Studies found that large flocs had a lower density and larger surface area (Andreadakis, 1993). Meanwhile, the presence of filaments may profoundly influence the compressibility of sludge (Wilén et al., 2003). Therefore, particle size analysis combined with morphology examination might be preferable to predict the settleability of activated sludge. Measurement of particle size can improve our knowledge of the settleability of activated sludge.

Solids retention time (SRT) has been observed to be a parameter associated with mean particle size. Early work observed the decrease of small activated sludge flocs with increased SRT (Bisogni and Lawrence, 1971; Chao and Keinath, 1979). Settling test with activated sludge with sludge ages ranging from 0.25 to 12 days shows that percent dispersion (nonflocculent or pinpoint floc) decreased exponentially with increased SRTs. Recent survey of particle size distribution at the end of the treatment chain in conventional activated sludge process, high purity oxygen process, Modified Ludzak–Ettinger (MLE) process, step-anoxic process, and oxidation ditch process shows that mean particle size of activated sludge flocs increased with increasing SRT, and the number of particles in the sedimentation supernatant decreased with longer SRT (Leu et al., 2012). Those results strongly suggest that SRT is an important parameter affecting particle size distribution in activated sludge process. However, limited information is

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Table 1—The operating condition and performance of the MLE reactor.

Reactor operation and performance	Phase (Duration in days) Phase 1 (1–10)	Phase 2 (11–80)	Phase 3 (81–120)
Influent			
DO (mg/L)	6.9 ± 0.6	6.7 ± 0.3	6.6 ± 0.1
COD (mg/L)	250 mg/L in synthetic wastewater using glucose as carbon source		
NH_4^+-N (mg/L)	40.8 ± 1.5	40.5 ± 1.7	42.0 ± 1.2
pH	7.0 ± 0.4	7.2 ± 0.1	7.2 ± 0.1
Mixed Liquor			
MLSS (mg/L)	2246 ± 210	2967 ± 361	2048 ± 134
SVI (mL/g)	106 ± 13	89 ± 9	111 ± 5
SRT (days)	4	13.3	4
Effluent			
COD (mg/L)	37.3 ± 9.0	26.9 ± 5.7	22.6 ± 6.3
NH_4^+-N (mg/L)	20.9 ± 2.1	6.9 ± 4.8	18.5 ± 1.6
DO (mg/L)	6.5 ± 0.1	6.5 ± 0.1	6.6 ± 0.1
pH	7.0 ± 0.4	7.2 ± 0.1	7.2 ± 0.1
Turbidity (NTU)	22.3 ± 2.3	7.5 ± 4.3	17.7 ± 2.5

available of systematic study of the effect of SRT on the particle size distribution in different types of activated sludge process.

The objective of this study is to investigate the effect of SRT on particle size distribution, sludge settleability, effluent turbidity, and removals of chemical oxygen demand (COD), NH_4^+-N, in a lab-scale MLE reactor, a lab-scale integrated fixed film activated sludge (IFAS) reactor. In addition, particle size distribution profiles were surveyed in full-scale water resource recovery facilities (WRRFs) including step-feed nitrification/denitrification (step-Feed NDN) process, MLE nitrification/denitrification (MLE NDN) process, and high purity oxygen (HPO) process. Microscopic examination is applied to evaluate the effect of different SRTs on sludge morphology. This study provides direct evidence of the effects of SRT on particle size distribution and sludge settleability in lab-scale reactors and full-scale WRRFs.

Materials and Methods

Lab-Scale Modified Ludzak–Ettinger Reactor Setup. A lab-scale MLE reactor was established. The working volume of the reactor is 16.0 L with 12.0 L of aeration zone and 4.0 L of anoxic zone, as illustrated in Figure S2 and Figure S3. (Supplementary [S] material is available online only.) Operational condition of the reactor is summarized in Table 1. Receipt of the synthetic wastewater was adopted and modified from a previous study with modifications (Babcock et al., 1993). The influent COD and NH_4-N were 250 and 40 mg/L, respectively. Synthetic influent was prepared using the following receipt: 350 mg/L glucose, 150 mg/L NH_4Cl, 55 mg/L K_2HPO_4, 20 mg/L $CaCl_2{\cdot}2H_2O$, 20 mg/L $MgSO_4{\cdot}7H_2O$, 10 mg/L $FeSO_4{\cdot}7H_2O$, 20 mg/L $MnSO_4{\cdot}H2O$, and 20 mg/L KCl. Information about trace elements is available elsewhere modifications (Chae et al., 2008). The dissolved oxygen (DO) was maintained at 6.3 ± 0.7 mg/L by supplying filtered air (0.45-μm filter) through two fine bubble air diffusers. Feed was delivered to the anoxic zone, and solids were continuously recycled from the aerobic zone to the anoxic zone at a recycle rate of 100%. Solids retention time was controlled by wasting appropriate amount of activated sludge from the aerobic zone. Solids retention times of different reactor operation phases were reported in Table 1. Temperature, pH, and DO were recorded using oxygen and pH meters. Concentrations of COD, ammonium, nitrite, and nitrate were measured using HACH kits and electrodes in compliance with the U.S. Environmental Protection Administration (U.S. EPA) Standard Methods. pH of the mixed liquor was maintained at approximately 7.6 by adding $NaHCO_3$ buffer. The reactor was aerated using filtered ambient air. The DO concentration in mixed liquor was maintained 3.5 ± 0.5 mg/L. Seeding activated sludge sample was collected from the Joint Water Pollutant Control Plant. Fifty milliliters of activated sludge from the Donald C. Tillman Water Reclamation Plant was seeded on Day 10 as source of nitrification microorganisms.

Lab-Scale Integrated Fixed Film Activated Sludge Reactor Setup. The experiment was conducted in a lab-scale IFAS reactor for 200 days in a temperature control room. The rectangular reactor was 50 cm high, 25 cm long, and 20 cm wide with a working volume of 20 L. The reactor was inoculated with activated sludge from a conventional municipal WRRF. Polyethylene carriers with a density of 0.95 to 0.98 kg/m^3 and a specific surface area of 500 m^2/m^3 were added into the reactor. The carrier was a cylindrical shape with height of 8 mm diameter of 12 mm. The carriers were collected from an aerated batch reactor that was fed the same synthetic wastewater as for the IFAS reactor. The carriers were maintained in the aerated batch reactor for about 50 days. The batch reactor was drained twice a day and refilled with the same synthetic wastewater as feed to the IFAS reactor. By the start of the IFAS reactor study, noticeable biofilm was formed on the carriers. The reactor was filled with 4-L carriers to achieve a filling fraction of 20%. Influent was automatically pumped into the reactor at the flow rate of 2 L/h with a theoretical hydraulic retention time of 10 hours. A settler was placed after the reactor for sludge separation (Figure S4 and Figure S5). A peristaltic pump provided 0.6 L/h of returned activated sludge (RAS) to the inlet of the rectangular reactor tank. The SRT was controlled by wasting appropriate amount of activated sludge from the settler. The SRTs of different reactor operation phases were reported in Table 2. Synthetic influent was prepared in the same ways as for the MLE reactor reported in the previous paragraph. Seeding activated sludge sample was collected from the Joint Water Pollutant Control Plant. Fifty milliliters of activated sludge from the Donald C. Tillman Water Reclamation Plant was seeded on Day 31 as additional source of nitrification microorganisms. Temperature, pH, and DO were recorded using oxygen and pH meters. Concentrations of COD, ammonium, nitrite, and nitrate were measured using HACH kits and electrodes in compliance with the U.S. EPA Standard Methods.

Sample Collection from Lab-Scale Reactors. Influent samples were collected at the combined inlet tube with a 50-mL sample volume. Ammonia concentration and pH of influent samples were analyzed immediately after sample collection.

Table 2—The operating condition and performance of the IFAS reactor.

Reactor operation and performance	Phase (Duration in days) Phase 1 (1–28)	Phase 2 (29–120)	Phase 3 (121–200)
Influent			
DO (mg/L)	3.36 ± 0.15	3.39 ± 0.20	3.43 ± 0.24
COD (mg/L)	250 mg/L in synthetic wastewater using glucose as carbon source		
NH_4^+-N (mg/L)	41.4 ± 1.7	40.5 ± 1.7	41.8 ± 1.4
pH	7.2 ± 0.4	7.2 ± 0.15	7.2 ± 0.1
Mixed Liquor			
MLSS (mg/L)	2380 ± 308	2970 ± 361	2050 ± 134
SVI (mL/g)	117.1 ± 19.1	92.6 ± 11.6	111.8 ± 4.6
SRT (days)	4	13.3	4
Effluent			
COD (mg/L)	30.1 ± 8.8	26.9 ± 6.3	22.6 ± 6.3
NH_4^+-N (mg/L)	24.1 ± 6.2	6.6 ± 4.8	18.5 ± 1.6
DO (mg/L)	3.36 ± 0.15	3.39 ± 0.20	3.43 ± 0.24
pH	7.1 ± 0.3	7.2 ± 0.1	7.2 ± 0.1
Turbidity (NTU)	20.2 ± 3.8	7.5 ± 3.9	17.7 ± 2.5

Influent DO was not measure using the 50-mL sample. Rather, DO concentrations in the storage tanks of inorganic and organic solutions were measured directly using a DO probe. The influent DO concentration were calculated based on the pump rate of inorganic and organic solutions and their representative DO concentrations. Influent samples of the IFAS reactor were collected in a similar manner.

Effluent samples were collected at the top layer of the supernatant in the sedimentation tank. Care was taken to prevent disturbing the sludge blanket at the bottom of the sedimentation tank. Occasionally, a thin layer of floating activated sludge was observed at the top of the supernatant in the sedimentation tank. In this case, a pipette was used to collect the supernatant and minimize the inclusion of the floating activated sludge. Concentrations of ammonia, pH, turbidity, and DO in effluent samples were measured immediately after sample collection. Samples reserved for COD analysis were acidified to pH of 2 and preserved at 4 °C in amber glass bottles. Effluent samples of the IFAS reactor were collected in a similar manner.

Mixed liquor samples of the reactors were collected using a customized wide-bore pipette (Leu et al., 2012). Collected mixed liquor samples were analyzed for particle size distribution immediately after sample collection in the lab.

Selection of Full-Scale Water Resource Recovery Facilities. The major WRRFs in Los Angeles County include Modified MLE process, step-feed nitrification and denitrification (NDN) process, MLE NDN process, and HPO process, as listed in Table S1. The total current flow of major WRRFs in Los Angeles County was 2866 megaliters per day (MLD) based on most recently available data. Five full-scale WRRFs were selected for the survey of particle size distribution, namely Donald C. Tillman Water Reclamation Plant (Plant 1), San Jose Creek Water Reclamation Plant East (Plant 2), San Jose Creek Water Reclamation Plant West (Plant 3), Whittier Narrows Water Reclamation Plant (Plant 4), and Joint Water Pollution Control Plant (Plant 5), as indicated in Table S1. The SRTs of the selected plants were reported in Table 3. The treatment plants were selected based on their service area coverage, treatment process, and thoroughness of plant operation and operation. Selected treatment plants were well operated with historically stable treatment performances and stable sources of wastewater to minimize variation of unintentional changes of operations.

Table 3—Comparison of MPS of samples collected from primary sedimentation tank effluent of surveyed WRRFs.

WRRFs	SRT (days)	Integrated to 50 μm MPS (μm)	SD	Integrated to 100 μm MPS (μm)	SD	Integrated to 500 μm MPS (μm)	SD
Plant 1 8/27/2015	8.4	11.0	0.4	15.3	0.5	17.5	0.5
Plant 2 9/17/2014	12.0	10.9	0.4	12.0	0.4	12.2	0.4
Plant 2 3/3/2015	12.0	11.3	0.4	12.4	0.5	12.7	0.5
Plant 3 9/17/2014	12.0	8.6	0.5	12.4	0.3	11.9	0.2
Plant 3 3/26/2015	12.0	11.3	0.4	12.4	0.5	12.7	0.5
Plant 4 3/26/2015	10.0	10.3	0.7	10.6	0.7	10.7	0.6
Plant 5 9/12/2014	3.3	9.2	0.4	9.8	0.5	10.1	1.6
Plant 5 2/9/2015	3.3	6.4	1.3	8.1	1.0	8.0	1.0

SD = standard deviation.

Sample Collection at Full-Scale Water Resource Recovery Facilities. Grab samples were collected for each plant visit event. Briefly, 50- to 75-mL samples were collected in 250-mL polyethylene bottles. Raw wastewater samples were collected at the designated auto-sampler under manual mode. Before collecting raw wastewater, the sampling tube was flushed with raw wastewater for 30 seconds to remove residue wastewater. Samples from the primary sedimentation tank were collected from the sampling window of the cover of the primary sedimentation tank. Care was taken to avoid collecting sum/foams. Mixed liquor samples in the biological treatment tank for the HPO process were collected from designated sampling hoses in underground pipeline galleries of the aeration tank. Mixed liquor samples in the biological treatment tank for other processes were grabbed directly from the open surface of the mixed liquor in the reaction tanks. Detailed sampling locations for selected WRRFs were provided in Table S2 to Table S6. Two sampling events, one for wet weather condition and one for dry weather condition, were conducted for Plant 2, Plant 3, and Plant 5, respectively. One sampling event was conducted each for Plant 1 and Plant 4, respectively.

Analysis of Particle Size Distribution. The particle size analysis was performed using an AccuSizer 780 optical particle

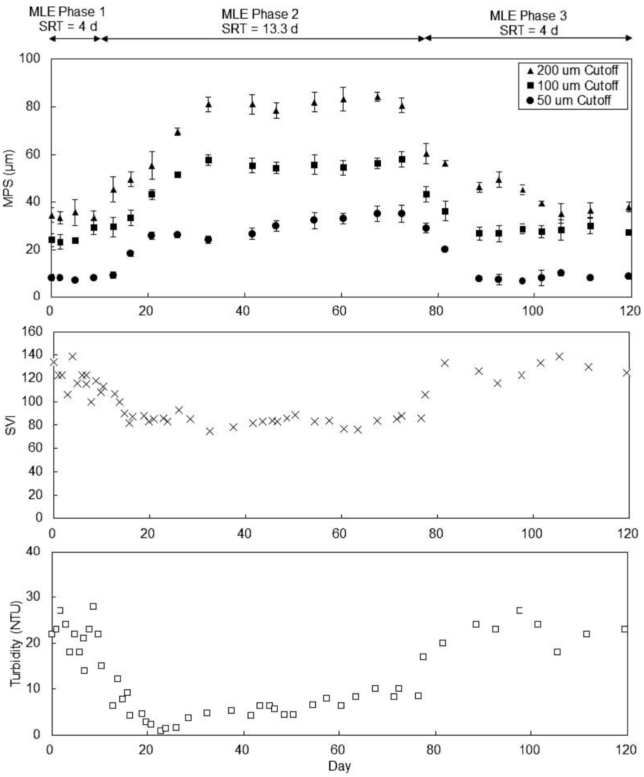

Figure 1—MPS, sludge SVI, and effluent turbidity of the MLE reactor under different SRTs.

sizer module (model LE400-0.5SE; Nicomp Particle Sizing Systems, Santa Barbara, California). To prevent interference between particles, samples were auto-diluted by the AccuSizer 780. For each experiment, 0.5 mL of liquid sample was delivered to the system by a customized wide-bore pipette (Leu et al., 2012). Between each particle size test, three auto-flush cycles were performed to ensure clean dilution chamber, system tubing, and sensor. Blank sample (reverse osmosis water) was used to check system baseline after every 15 sample injections. A detailed description of the particle detection by AccuSizer 780 is available online in the Supplementary Material (Chan et al., 2008, Leu et al., 2012; Li et al., 2006).

Morphological Analysis. Activated sludge floc was visually examined by Leitz Dialux 20 microscope. Images were captured by a digital camera system with image processing software. Morphological flocs were analyzed using wet mount, phase contrast microscopy, with digital photographs taken at 100× and 250× magnification. Five representative fields were analyzed per sample. Filament content was characterized by the filament index (FI) scale (0: none, 1: few, 2: some, 3: common, 4: very common, 5: abundant, and 6: excessive) as described by Jenkins (Jenkins et al., 2003).

Results

Particle Size Analysis for the Modified Ludzak–Ettinger Reactor. The MLE reactor was operated for 120 days in four phases. Prior to Phase 1, the MLE reactor performance was stable. The operational parameters were summarized in Table 1. Figure 1 shows the change of mean particle size (MPS), sludge SVI, and effluent turbidity. Chemical oxygen demand and NH_4^+-N removals, pH, DO, and mixed liquor suspended solids (MLSS) of the MLE reactor are reported in Figure S6. As SRT of the MLE reactor increased from 4 days to 13.3 days, MPS at 50, 100, and 500 μm cut-off values increased from 7.9 ± 0.5 μm, 25.1 ± 2.8 μm, and 34.3 ± 1.2 μm to 26.9 ± 7.8 μm, 50.0 ± 10.0 μm, and 71.8 ± 14.7 μm, respectively. With the increased SRT, NH_4^+-N removal increased from less than 5.0 to 79.6%. Meanwhile, the COD removal of the reactor was maintained higher than an average of 89%. Activated sludge showed a moderate and consistent decrease of SVI from an average of 106 ± 13 mL/g to 89 ± 9 mL/g.

To further verify the effect of SRT on reactor performance, the SRT of the MLE reactor was reduced from 13.3 to 4 days in Phase 3. The MPS of the reactor at 50, 100, and 500 μm cut-off values gradually decreased from 26.9 ± 7.8 μm, 50.0 ± 10.0 μm, and 71.8 ±1 4.7 μm to 11.8 ± 0.6 μm, 30.5 ± 5.6 μm, and 45.2 ± 8.8 μm (Figure 1). An immediate effluent turbidity jump on Day 81 was observed after SRT was decreased from 13.3 to 4.0 days by waste appropriate amount of biomass from the aeration tank. A higher SVI of 111 ± 5 mL/g was observed in Phase 3 compared with that in Phase 1 when the reactor was operated at the same SRT of 4 days. As expected, the NH_4^+-N removal decreased sharply from an average of 79.6 to 8.6% (Figure S6).

To evaluate the effect of SRT on the particle size distribution in the reactor effluent, supernatant samples of mixed liquor after 90 minutes of sedimentation were analyzed when the reactor was operated at the most stable condition based on reactor performances. This sedimentation time is equal to the retention time of the sedimentation tank for the MLE reactor. Use of the supernatant instead of reactor effluent minimized the effect of potential confounders such flow pattern in sedimentation tank. Each phase contained at least three sampling events. The average value of particle counts for samples collected from each phase were shown in Figure S10.

Further analysis of the accumulative particle mass percentage shows distinct patterns for Phase 1 to Phase 3 (Figure S11). Ninety-nine percent of the accumulated particle mass in supernatant were reached at 138, 422, and 224 μm, in Phase 1, Phase 2, and Phase 3, respectively. Accumulated particle mass calculation was sensitive to the number of particles with larger diameters, making the calculation a sensitive tool to evaluate the presence of larger activated sludge flocs at longer SRT. In regard to particle number in mixed liquor, at least 99.5% of flocs in all phases were smaller than 100 μm and at least 91.7% of flocs in all phases were smaller than 10 μm (Figure S12).

Particle Size Analysis for the Integrated Fixed Film Activated Sludge Reactor. The IFAS reactor was originally operated as a conventional activated sludge process before converting to an IFAS reactor by adding packing media on Day 10. The IFAS reactor performance was stabilized prior Phase 1. The operational parameters are summarized in Table 2. Influent DO, COD, NH4+-N, and pH were maintained relatively stable through Phase 1 to Phase 3. The effects of SRT on IFAS reactor performance and sludge characteristics were evaluated. The

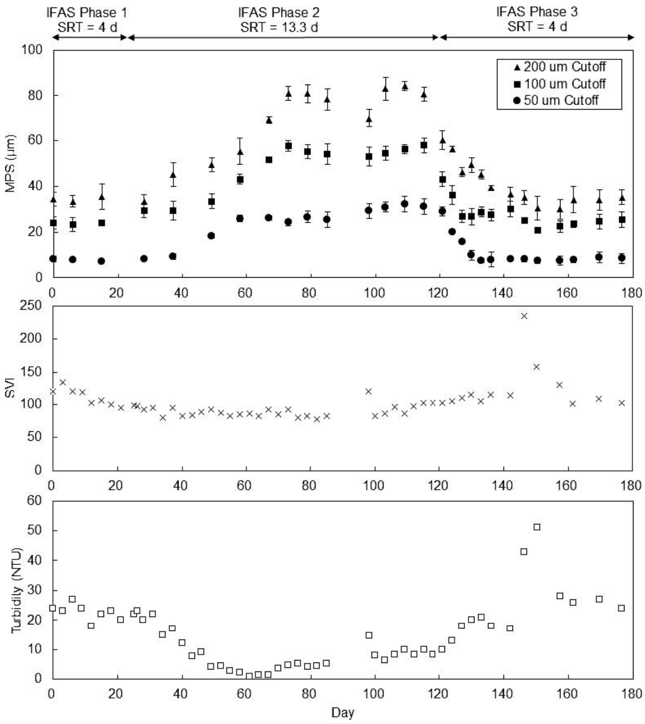

Figure 2—MPS, sludge SVI, and effluent turbidity of the IFAS reactor under different SRTs.

SRT of the IFAS reactor was increased from 4 days in Phase 1 to 13.3 days in Phase 2 and subsequently decreased to 4 days in Phase 3. Chemical oxygen demand removal was above 90% consistently. NH_4^+-N removal increased from about 40.0 to 84.4% as mixed liquor SRT increased to 13.3 days and decreased to about 53.8% after SRT reduced to 4 days (Figure S7). It took about 42 days for the MPS of mixed liquor to stabilize, increasing from 11.2 ± 1.5 μm, 22.9 ± 1.8 μm, and 28.1.6 ± 1.1 μm to 24.4 ± 2.9 μm, 53.8 ± 4.5 μm, and 77.0 ± 9.2 μm for 50, 100, and 500 μm MPS cut-off values, respectively (Figure 2).

To further test the effect of SRT on reactor performance, the SRT of the IFAS reactor was changed from 13.3 days to 4 days from Phase 2 to Phase 3. NH_4^+-N removal decreased from about 84.4 to 53.8%. The MPS of mixed liquor decreased from 24.4 ± 2.9 μm, 53.8 ± 4.5 μm, and 77.0 ± 9.2 to 11.4 ± 4.8 μm, 19.2 ± 3.3 μm, and 36.3 ± 3.3 μm to for 50, 100, and 500 μm MPS cut-off values, respectively. Effluent turbidity increased from 7.5 ± 3.9 NTU to 17.7 ± 2.5 NTU. A moderate increase of SVI from 92.6 ± 11.6 mL/g to 111.8 ± 4.6 mL/g was observed.

Survey of Particle Size Distribution in Full-Scale Water Resource Recovery Facilities. Particle size distributions from raw wastewater to secondary sedimentation effluent were surveyed in five full-scale WRRFs. Mean particle size values of surveyed WRRFs were reported at cut-off values of 50, 100, and 500 μm, as shown in Figure 3, Figure 4, Figure 5, Figure S8, and Figure S9. The MPS of raw wastewater in all surveyed samples were in the range of 10.0 ± 0.3 μm to 22.0 ± 0.2 μm. Across rectangular primary sedimentation tanks in all survey WRRFs, the MPS values of the primary effluent ranged from 8.0 ± 1.0

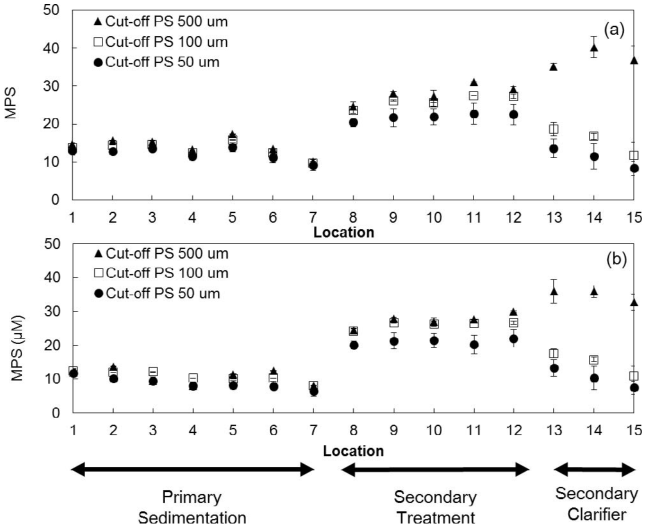

Figure 3—Mean particle size of activated sludge flocs at different cut-off values of a HPO plant (Plant 5) on (a) 09/12/2014 and (b) 02/08/2015.

μm to 17.5 ± 0.5 μm at cut-off of 500 μm. No consistent trends of change in particle size distribution of primary effluent particles were observed between dry weather condition and wet weather condition (Table 3) The MPS of activated sludge flocs collected from the end of aeration basins and secondary sedimentation tanks from full-scale WRRFs were reported in Table 4 and Table 5, respectively. Survey at five WRRFs supported the observation in lab-scale MLE and IFAS that longer SRT lead to larger MPS in mixed liquor of three common activated sludge processes, namely HPO, Step-Feed NDN, and MLE NDN.

Discussion

Impact of Solids Retention Time on Particle Size Distribution and Sludge Settleability in the Modified Ludzak–Ettinger Reactor. Results in this study showed immediate effect of SRT on the particle size distribution in the mixed liquor of the MLE reactor (Figure 1 and Table 6). The mean particle size data indicated that increased SRT had more significant effect on the generation of larger flocs. Similar findings are observed in previous field studies. Bisogni and Lawrence observed the decrease of small activated sludge flocs with increase SRT (Bisogni and Lawrence, 1971). Knocke and Zentkovich observed a significant increase of activated sludge floc size when SRT was increased from 4 to 8 days, but with no further increase when SRT was increased from 8 to 15 days (Knocke and Zentkovich, 1986). Settling test with activated sludge with sludge ages ranging from 0.25 to 12 days shows that percent dispersion (nonflocculent or pinpoint floc) decreased exponentially with increased SRTs. Recent survey of particle size distribution at the end of the treatment chain in conventional activated sludge process, HPO, MLE process, step-anoxic process, and oxidation ditch process shows that the mean particle size of activated sludge flocs increased with increasing

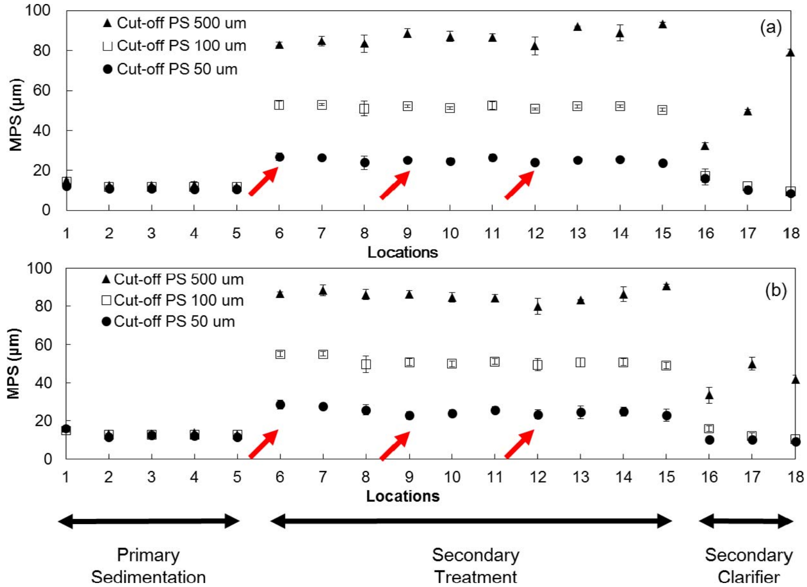

Figure 4—Mean particle size of activated sludge flocs at different cut-off values of a Step-Feed NDN plant (Plant 2) on (a) 09/17/2014 and (b) 03/26/2015. Arrows indicates the locations of step feed.

SRT, and the number of particles in the sedimentation supernatant decreased with longer SRT (Leu et al., 2012). The current study under well-controlled lab-scale reactor showed that SRT was an important parameter affecting particle size distribution in the activated sludge process. Both increase and decrease of SRT seems to have an immediate effect on the particle size distribution in the mixed liquor. Consequently, the particle size distribution of a certain activated sludge system may be used as an indicator of proper SRT control via proper sludge wasting.

Effect of Solids Retention Time on Particle Size Distribution and Sludge Settleability in the Integrated Fixed Film Activated Sludge Reactor. The effect of mixed liquor SRT of the IFAS reactor on the particle size distribution was evaluated (Figure 2 and Table 6). Previous studies have generated mixed results on the settleability of activated sludge from IFAS systems (McQuarrie et al., 2004; Sriwiriyarat et al., 2008). Full-scale test of an IFAS reactor showed improved sludge settleability with improved nitrogen removal (McQuarrieet al., 2004). Another full-scale study indicated that IFAS reactor provided more stable ammonia removal at low temperature, sludge settleability was slight increased (Stricker et al., 2007). Studies on sludge production and sludge settling characteristics indicated that IFAS produced less activated sludge with better sludge settling performance than conventional activated sludge (Li et al., 2015; Ross et al., 2004). No obvious difference of sludge settleability was observed between a MLE reactor and an IFAS reactor under different carbon/nitrogen (C/N) ratio and

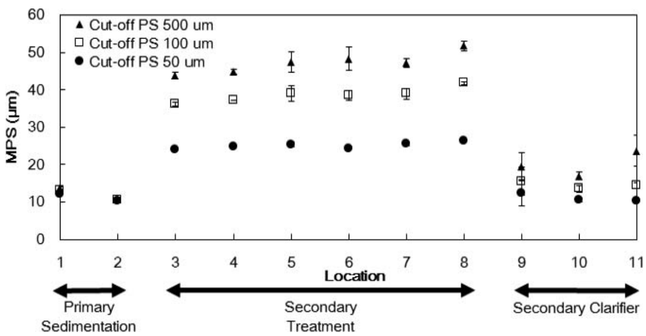

Figure 5—Mean particle size of activated sludge flocs at different cut-off values of a MLE NDN (Plant 4) on 03/26/2015.

Table 4—Comparison of MPS of samples collected from the end stage of aeration basins of surveyed WRRFs.

WRRF	SRT (days)	Integrated to 50 μm MPS (μm)	SD	Integrated to 100 μm MPS (μm)	SD	Integrated to 500 μm MPS (μm)	SD
Plant 1 8/27/2015	8.4	28.6	3.3	40.1	1.7	53.2	0.7
Plant 2 9/17/2014	12	23.7	0.8	50.5	1.8	93.5	3.9
Plant 2 3/3/2015	12	23.0	3.3	49.0	1.7	90.7	0.7
Plant 3 9/17/2014	12	25.9	1.7	54.4	3.1	77.4	3.3
Plant 3 3/26/2015	12	23.0	1.8	53.2	1.7	76.3	0.7
Plant 4 3/26/2015	10	26.4	0.1	41.7	0.5	51.7	1.4
Plant 5 9/12/2014	3.3	22.5	0.6	27.3	0.5	29.2	0.6
Plant 5 2/9/2015	3.3	22.0	0.5	26.6	0.4	29.5	0.4

SD = standard deviation.

Table 5—Comparison of MPS of samples collected from the secondary sedimentation tank effluent of surveyed WRRFs.

WRRF	SRT (days)	Integrated to 50 μm MPS (μm)	SD	Integrated to 100 μm MPS (μm)	SD	Integrated to 500 μm MPS (μm)	SD
Plant 1 8/27/2015	8.4	13.5	0.2	20.3	0.2	38.5	2.1
Plant 2 9/17/2014	12.0	8.6	0.2	9.8	0.2	79.1	1.5
Plant 2 3/3/2015	12.0	9.1	0.2	10.3	0.2	1.9	2.1
Plant 3 9/17/2014	12.0	12.6	1.3	15.8	3.2	45.2	4.4
Plant 3 3/26/2015	12.0	9.2	1.3	10.4	0.2	84.2	3.6
Plant 4 3/26/2015	10.0	10.5	0.2	14.4	0.7	23.7	4.1
Plant 5 9/12/2014	3.3	8.3	1.9	11.7	3.5	36.8	3.7
Plant 5 2/9/2015	3.3	7.4	1.6	11.0	2.7	32.8	2.4

SD = standard deviation.

Table 6—Comparison of mean particle size of samples collected from aeration tanks of the lab-scale MLE reactor and the lab-scale IFAS reactor.

WRRFs	SRT (days)	Integrated to 50 μm MPS (μm)	SD	Integrated to 100 μm MPS (μm)	SD	Integrated to 500 μm MPS (μm)	SD
MLE reactor Phase 1	4	7.9	0.5	25.1	2.8	34.3	1.2
MLE reactor Phase 2	13.3	26.9	7.8	50.0	10.0	71.8	14.7
MLE reactor Phase 3	4	11.8	0.6	30.5	5.6	45.2	8.8
IFAS reactor Phase 1	4	11.2	1.5	22.9	1.8	28.1	1.1
IFAS reactor Phase 2	13.3	24.4	2.9	53.8	4.5	77.0	9.2
IFAS reactor Phase 3	4	11.4	4.8	19.2	3.3	36.3	3.3

SD = standard deviation.

DO concentrations (Sriwiriyarat et al., 2008). However, another study suggested that a MLE reactor produced sludge with lower SVI values (Kim et al., 2010). This study supported the observation that the IFAS reactor generated sludge with good settleability but slight higher SVI values compared with sludge generated from the MLE reactor. Sludge with good settleability was defined as SVI less than 150 mL/g (Jenkins et al., 2003). Increased of SRT from 4 days in Phase 1 to 13.3 days in Phase 2 led to a decrease of SVI from 117.1 ± 19.1 mL/g to 92.6 ± 11.6 mL/g. Subsequent decrease of SRT back to 4 days increased the SVI to 111.8 ± 4.6 mL/g. It has been observed that the SVI is related to the median floc size for non-filamentous sludge (Andreadakis, 1993; Barber and Veenstra, 1986). It was also observed that higher SVI was associated with lower activated sludge density at longer SRT in the IFAS system, when biomass phosphorus content was low (Kim et al., 2010). Observations of this study's authors, however, suggested that increased SRT in the IFAS reactor improved sludge settleability. Increase of SRT was expected to produce higher ratio of nonvolatile materials, which has been linked with higher sludge density (Ekama and Wentzel, 2004; Schuler and Jang, 2007).

Particle Size Distribution in Surveyed Water Resource Recovery Facility. The MPS of raw wastewater in all surveyed samples were in the range of 10.0 ± 0.3 μm to 22.0 ± 0.2 μm. As shown in Figure 3, Figure 4, Figure 5, Figure S8, and Figure S9, the MPS of supernatant particles across primary sedimentation tanks were relatively stable. In this study, the MPS in primary effluent ranged from 8.0 ± 1.3 to 17.5 ± 0.5 μm (Table 3). Further removal of particles in primary effluent could be achieved by coagulation or filtration (Landa et al., 1997; Levine et al., 1991; Tiehm et al., 1999). Previous study showed that treatment kinetics could be influenced by particle size of particulate organic substances (Levine et al., 1991). Pretreatment of wastewater could have a major effect on process performance and reliability of high-rate biological treatment processes, such as HPO process.

Immediately after the inlet of the biological treatment tank, the MPS was controlled by activated sludge flocs instead of primary effluent particles. The MPS of activated sludge flocs collected from aeration basins from full-scale WRRFs were compared in Table 4 and Figure 6. Based on MPS analysis, it was observed that long SRT particularly associated with the presence of particles larger than 100 μm. The MPS values integrated to 50 μm were relatively stable under various treatment processes and SRTs. A previous study surveyed double-step activated sludge system, medium-load activated sludge system, extended aeration system, and membrane bioreactor system indicated that particle size distribution could be fitted to power law model with variable β *coefficient* (slope of double logarithmic diagram). Moderate correlation between *A coefficient* (total concentration of particulate matter) and suspended solids concentration, turbidity, and COD were established (Garcia-Mesa et al., 2012).

The presence of large particles during secondary sedimentation was observed, evidenced by increased MPSs at 500-μm cutoff values along secondary sedimentation processes (Table 5). This observation was in contrast with theoretical calculation of particle removal by sedimentation, as shown in Figure S13. It was speculated that the movement of flight travel in the rectangular sedimentation tank may have carried over small amount of activated sludge from the sludge blanket and introduced large particles into the supernatant. Effluent particle might be a particular concern for secondary effluent disinfection. Disinfection of secondary effluent is mandated by many water agencies for the discharge of secondary effluent (Bourgeous et al., 2003). The presence of particle-associated coliform

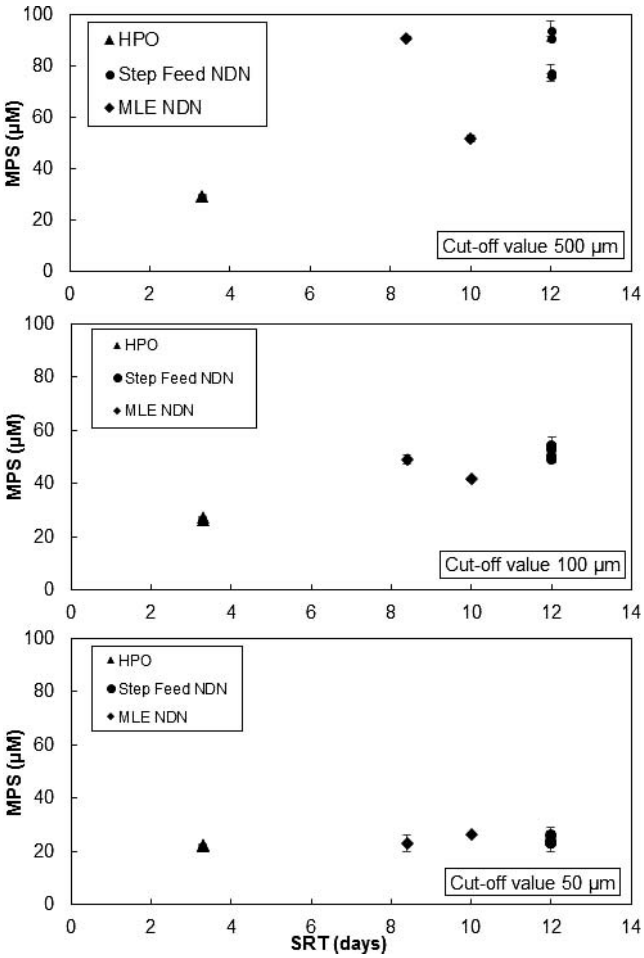

Figure 6—MPS of samples collected from the end stage of aeration basins of surveyed WRRFs with different SRTs.

reduces the efficacy of disinfection agent, increases operational cost, and imposes compliance risk (Loge et al., 2002). Scattering, adsorption, reflection, and diffusion of incident UV light are common mechanisms of interference by particles (Vaezi et al., 2007). Particles can also shield microorganisms from UV light by particle-microbe association that microbes are encapsulated in colloidal particles (Christensen and Linden 2003; Passantino, 2004). Recent study demonstrated that free-swimming bacteria that have full exposure to UV can be inactivated at UV doses lower than 9 mJ/cm^2. Free-swimming bacteria are much higher in number compared with particle-associated bacteria. After the majority of free-swimming bacteria are disinfected, the inactivation of particle-associated bacteria determines the efficacy of overall disinfection. Bioflocculation has a statistically significant role of reducing log reduction of bacteria for particles with a diameter larger than 25 μm (Kollu and Ormeci, 2012).

Conclusion

- The current study under well-controlled lab-scale reactors showed that SRT was an important parameter affecting particle size distribution in MLE and IFAS processes. Both increase and decrease of SRT had immediate effect on the particle size distribution in the mixed liquor. Survey of five WRRFs provided additional evidence on the co-relationship between SRT and MPS in mixed liquor. The WRRFs that were operated at longer SRT produced mixed liquor with larger MPS.
- Operating activated sludge process at longer SRT may bring multiple benefits including improved sludge settleability and reduced effluent turbidity.
- MPS may be utilized as a useful monitoring parameter for proper control of SRT, evaluation of sludge settleability, and optimization of secondary effluent disinfection.

Supplementary Material

Supplementary material (S) associated with this article can be found online.

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