Aerosol and Air Quality Research, 13: 1807–1814, 2013

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2012.09.0245

Dispersion and Risk Assessment of Bacterial Aerosols Emitted from Rotating-Brush Aerator during Summer in a Wastewater Treatment Plant of Xi'an, China

Yanpeng Li[1,2*], Haifeng Zhang[1], Xionghui Qiu[3], Yanru Zhang[1], Huanran Wang[4†]

[1] *School of Environmental Science and Engineering, Chang'an University, Xi'an 710054, China*
[2] *Key Laboratory of Subsurface Hydrology and Ecology in Arid Areas, Ministry of Education, Xi'an 710054, China*
[3] *Technology and Standard of Environmental Protection Research Professional Committee of All-China Environment Federation, Beijing 100032, China*
[4] *School of Energy and Power Engineering, Xi'An Jiaotong University, Xi'an 710049, China*

ABSTRACT

A microbial risk assessment was carried out for the rotating-brush aerator used during summer in a wastewater treatment plant (WWTP) of Xi'an, China. Bacterial aerosols were first collected by an Andersen cascade impactor at selected sampling sites near the rotating-brush aerator. The concentrations of airborne bacteria were used to obtain microbial emission rate by back calculation. The downwind concentrations of airborne bacteria were then calculated by a modified Gaussian dispersion model accounting for environmental impact and microorganism decay. Subsequently, the exposure parameters suitable for Chinese people were incorporated into a risk assessment model to evaluate non-carcinogenic risks of airborne mesophilic bacteria to sewage workers and surrounding residents. The results indicate that both mean bacterial concentrations at ground level and the exposure hazard quotient decrease rapidly with downwind distance. The exposure hazard quotient by inhalation route is over 10^5 times more than by dermal contact route for both children and adults, suggesting that inhalation route is the major exposure pathway of microbial aerosol intake for surrounding people. Although the present model gives acceptable low risk values at various downwind distances, it is worth noting that health risks of microbial aerosols associated with rotating-brush aeration for children are generally much more than those for adults.

Keywords: Wastewater treatment plant; Microbial aerosols; Dispersion; Risk assessment; Rotating-brush aerator.

INTRODUCTION

Aeration is an essential operation in the activated sludge wastewater treatment process widely used at wastewater treatment plants (WWTP) in China. Generally, aeration systems serve two functions: mixing adequately and supplying oxygen necessary to the microorganism metabolism, either by shearing the liquid surface with rotating brushes or turbines (surface aerators), or by releasing air through spargers or porous materials at the bottom of the tank (coarse- or fine-bubble aerators) (Rosso and Stenstrom, 2006; Wang *et al.*, 2009). However, it has been revealed that splashing and bubble bursting resulting from these aeration modes can produce large amount of microbial aerosols (Fracchia *et al.*, 2006; Sánchez-Monedero *et al.*, 2008; Li *et al.*, 2012). Microbial aerosols usually contain a variety of microorganisms, including pathogens potentially capable of infecting man through inhalation, dermal contact and ingestion (Stellacci *et al.*, 2010). Because they may be transported and dispersed over considerable distances, depending on environmental and physical factors (Marthi *et al.*, 1990), these microbial aerosols might pose a health risk to sewage workers and surrounding residents (Thorn and Kerekes, 2001; Medema *et al.*, 2004; Grisoli *et al.* 2009; Haas *et al.*, 2010). Thus, it is significantly important to characterize microbial dispersion and to assess potential risk of microbial aerosols associated with aeration systems.

Over the past decade, a large number of studies have been conducted to quantify concentrations and size distributions of microbial aerosols generated from WWTP. Aerosolized microorganisms have been found at various stages of wastewater treatment, particularly in those operations containing forced aeration and mechanical agitation (Brandi *et al.*, 2000; Sánchez-Monedero *et al.*, 2008; Li *et al.*, 2012). The mean concentrations of microbial aerosols emitted from aeration tanks have been reported to vary depending upon many factors such as type and amount of wastewater, aeration modes and local weather conditions (Oppliger *et al.*, 2005; Fracchia *et al.*, 2006; Karra and Katsivela, 2007;

* Corresponding author.
E-mail address: liyanp01@chd.edu.cn
† Corresponding author.
E-mail address: huanran@mail.xjtu.edu.cn

Sánchez-Monedero *et al.*, 2008; Heinonen-Tanski *et al.*, 2009), among which the impact of aeration modes on bioaerosol release is remarkably significant. However, most previous studies have focused on bioaerosol emission from coarse- or fine-bubble aerators while few studies on emission from surface aerators, especially from rotating-brush aerators. Sánchez-Monedero *et al.* (2008) found that microbial concentrations were higher in aerosols generated by horizontal rotors than by bubble diffuser aerators. Due to good treatment efficiency and inexpensive running costs, oxidation ditch process with rotating-brush aeration is most widely used in Chinese WWTP. Furthermore, there will be continued construction of new WWTP with rotating-brush aeration systems due to rapid economic growth in China. Therefore, there is also a need for the assessment of potential risk of microbial aerosols from rotating-brush aerators used in WWTP in China.

So far, several studies have been conducted on the health risk of exposure to airborne microbial infection for sewage workers and surrounding residents. Medema *et al.* (2005) showed that during normal operation the annual probability of infection for the average sewage workers was high. Westrell *et al.* (2004) reported that the highest individual health risk for workers via aerosols was at the belt press for sludge dewatering (virus infection risk = 1). More recently, Stellacci *et al.* (2010) carried out a quantitative microbial risk assessment (QMRA) to the population surrounding Gennarini WWTP in Tarato and indicated that the infection risk decreased sharply downwind to the plant and became lower than the USEPA guideline for drinking water (10^{-4}) at the 100 m distance dictated by Italian regulation. This means that the adverse health effects related to aerosol exposure is insignificant on the surrounding residents. It seems that the assessment of biological risks is currently seriously hampered due to insufficient knowledge of the complex behaviour of microbial activity and particle release, and due to unavailable approved criteria for dose-response relationships and for occupational exposure limits (Teixeira *et al.*, 2012).

The aim of the present study is to characterize microbial aerosol dispersion from rotating-brush aerators in a WWTP of Xi'an, China, and then to perform a quantitative microbial risk assessment during summer in order to estimate the potential adverse health effects of microbial aerosol exposure on sewage workers and surrounding residents.

MATERIALS AND METHODS

Plant Description

The study was performed in a WWTP with oxidation ditch process located in the eastern part of Xi'an city, China. As described previously (Li *et al*., 2012), this plant has been operated continuously throughout the year since 2006, with a treatment capacity of 2×10^5 m^3/d, corresponding to about 290,000 inhabitants served. Similarly to many other WWTPs in China, this plant has become surrounded by new residential and commercial districts due to rapid urbanization and industrialization in recent years. In this plant, influent wastewater is pre-treated by screens and aerated grit chamber. The biological treatment is then conducted in an Orbal oxidation ditch with horizontal rotor aeration, followed by primary and secondary settling tank. Purified wastewater after chlorine disinfection is finally discharged through an effluent outlet to a drainage ditch flowing to the Ba River. The sludge is thickened by centrifugation in a sludge dewatering house.

Sampling

According to the seasonal feature in Xi'an city (33°39'N, 107°49'E and 424 m above sea level), summer and winter are dominant season while period of spring and autumn is very short. Moreover, climatic conditions in summer are favorable for the survival and proliferation of airborne microorganisms so that it is much easier to detect the number of airborne bacteria in summer than in winter. Therefore, actual sampling for airborne bacteria was conducted only in summer season in this study.

An Andersen six-stage cascade impactor (Westech, UK) with six glass petri dishes of 93 mm in diameter was employed to collect bioaerosol samples with different size ranges. Sampling was conducted in June 2011, July 2011 and July 2012 at the eight sampling sites as shown in Fig. 1. According to the prevailing wind direction, the sites were at a distance of 2, 5, 10, 30, 50, 100 m directly downwind from a rotating brush aerator, and 5 m (G_1 and G_2) laterally. The height of the rotating brush aerator was 2 m above ground level. Note that data obtained from sites A, B and C were used to determine the emission rate of the microorganisms released from rotating brushes by back calculations. Data from other sites were mainly employed to examine the validity of the dispersion model modified in this study.

Each sampling took place in a single sunny day with similar climatic conditions to reduce the measurement uncertainty resulted from weather variations. At the same time as aerosol sampling, the wind speed, ambient temperature and relative humidity were monitored. During sampling, the outdoor temperature and relative humidity ranged from 26.9 to 30.2°C, and 47–62%, respectively. The prevailing wind direction was north with average wind speed of 0.4 m/s. At each of the sampling sites, the sampler was mounted at 1 m above ground surface. The samples were collected for about 10 min by sucking the air at the rate of 28.3 L/min with three repetitions each time.

Microbiological Analysis

The airborne mesophilic bacteria were captured on petri dishes with nutrient agar described previously by Li et al (2012). After sampling, the agar plates were immediately transported to the laboratory and were incubated at 37°C for 48 h. The sampler was disinfected with 75% ethanol to prevent contamination before and after each sampling. After incubation, the colonies were counted followed by the positive-hole correction method to revise colony overlapping (Lawless, 2000). Each concentration of airborne microorganisms, which is generally expressed as total colony-forming units (CFU/m^3) for respective particle size, was then calculated by dividing the number of colonies cultured separately for each stage by the sampling air volume.

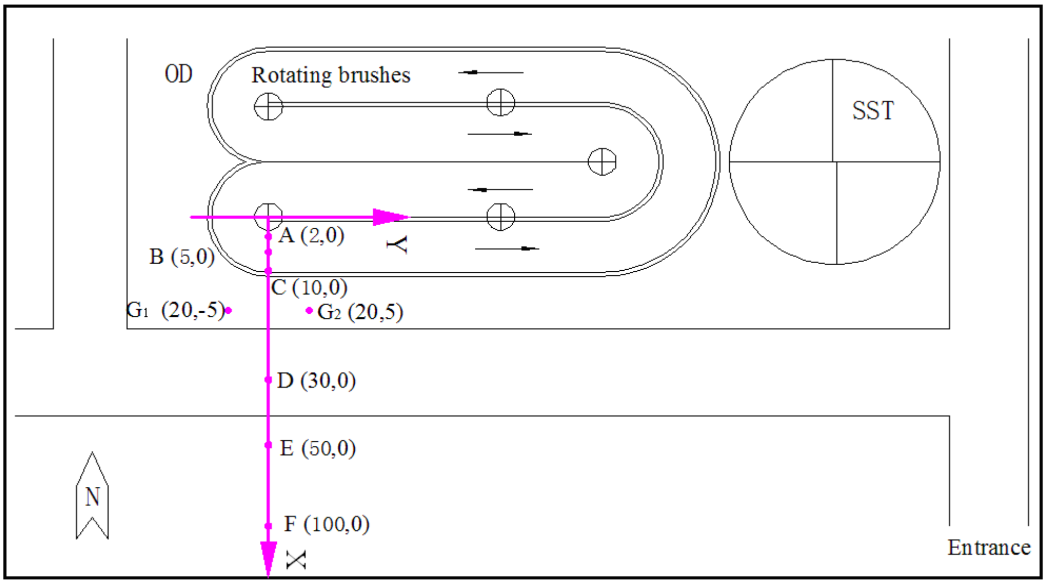

Fig. 1. Schematic diagram of sampling site locations. OD: oxidation ditch; SST: secondary settling tank.

Dispersion Model

According to Dowd *et al.* (2000), a modified Gaussian plume model can be used to estimate microbial concentrations at different downwind distances by taking into account microbial inactivation. As reported by Stellacci *et al.* (2010), however, low temperature, high humidity and low solar radiation tend to favor microorganism survival while opposite weather conditions promote their rapid die-off. Therefore, we modified Dowd's model to account for the various environmental conditions in the present study as following:

$$c(x,y,z,H) = \frac{QI}{2\pi u\sigma_y\sigma_z}\exp(-\frac{y^2}{2\sigma_y^2})\times[\exp(-\frac{(z-H)^2}{2\sigma_z^2})+\exp(-\frac{(z+H)^2}{2\sigma_z^2})]\times\exp(-\lambda\frac{x}{u}) \quad (1)$$

where c is the microbial concentration in air; x, y and z are the distance along the wind direction, lateral and vertical to wind direction, respectively; σ_y and σ_z are horizontal and vertical dispersion coefficients; Q represents the emission rate from the source; H is the source height; u is the mean wind velocity; and I and λ presents environmental impact factor and die-off factor, respectively.

Note that it is not easy to accurately measure the emission rate (Q) of microorganisms from a large point (Dowd *et al.*, 2000). Accordingly, actual sampling data were employed in Eq. (1) to estimate this variable by back calculations in this study.

Exposure and Risk Assessment Model

After the microbial concentration was obtained, the exposure and risk assessment can be evaluated based on models developed by USEPA (US Environmental Protection Agency, 1999). Since only a handful of bacteria emitted from WWTP are of cancer risks, the mesophilic bacteria detected here were assumed as non-carcinogenic pollutants in the present study. Moreover, two main exposure pathways were taken into account: inhalation of bioaerosols and dermal contact with bioaerosols, because ingestion route was reported to have negligible contributions to risk evaluation in WWTP (Cangialosi *et al.*, 2008).

According to USEPA (1999), exposure was expressed in terms of a daily dose and was calculated separately for each exposure pathway. Dose contacted through inhalation of microbial aerosols (ADD_{inh}) can be given as:

$$ADD_{\mathrm{inh}}[CFU/(kg\cdot d)] = \frac{c\times IR\times EF\times ET}{BW\times AT} \quad (2)$$

Dose absorbed through dermal contact with microbial aerosols (ADD_{dermal}) can be written as:

$$ADD_{\mathrm{dermal}}[CFU/(kg\cdot d)] = \frac{c\times SA\times SL\times ABS\times EF\times ET}{BW\times AT} \quad (3)$$

where c is the concentration at exposure point, IR the inhalation rate, EF the exposure frequency, ET the exposure time, SA the exposure skin surface area, SL the skin adherence factor, ABS the dermal absorption factor, BW the average body weight, and AT is the averaging time to define non-carcinogenic exposure.

For non-carcinogenic risk evaluation, the daily dose was compared with the reference dose for chronic exposure (RfD) in order to estimate if the contaminant presents a human health risk. Risk for non-carcinogenic pollutants was expressed by the hazard quotient (HQ) as follows:

$$HQ = \frac{ADD}{RfD} \quad (4)$$

$$HI = \sum HQ_i \quad (5)$$

where hazard index (*HI*) represents the sum of hazard quotient for each pathway and for each target pollutant. When $HQ \leq 1$ or $HI \leq 1$, non-carcinogenic effects are not of concern whereas $HQ > 1$ or $HI > 1$, carcinogenic effects are of concern.

RESULTS AND DISCUSSION

Distribution of Airborne Viable Bacteria and Emission Rate from Rotating Brushes

Table 1 shows the mean concentration of airborne viable bacteria detected at selected sampling sites (A, B and C). The concentration results here are the mean and standard deviation of the plate counts obtained at each sampling site. At the site 2 m downwind from the rotating brush, the highest concentration of airborne viable bacteria is detected, with an average value of 4168 ± 263 CFU/m^3. At the site 10 m downwind, the mean concentration of airborne viable bacteria decreases to 1929 ± 98 CFU/m^3. As indicated by Li *et al.* (2013), compared to the threshold value (1000 CFU/m^3) of airborne bacteria (1000 CFU/m^3) recommended by American Conference of Governmental Industrial Hygienist (ACGIH), the mean bacterial concentration here is much higher, suggesting to some extent that substantially strong air pollution occurs in the present WWTP in Xi'an.

It is necessary to provide input parameters for the dispersion model. Table 2 lists these parameter values used in the present dispersion model. Note that the values of environmental impact factor (I) and die-off factor (λ) employed here were chosen based on actual meteorological conditions (shown in Table 1) during the present sampling period.

After both actual sampling data and input parameters for the dispersion model are determined, the emission rate of the microorganisms from the rotating brush is calculated. The resulting value is 3.2722×10^4 CFU/s. Thereafter, the predicted concentrations of airborne bacteria at any selected downwind distances can be obtained using Eq. (1). Fig. 2 shows the ground concentrations of airborne bacteria directly under the plume centerline vs. downwind distance from the rotating brush. As expected, mean bacterial concentrations decrease rapidly with the increase of downwind distance. It can be seen that mean bacterial concentrations at 30, 50 and 100 m away from the aerator are 153, 70 and 17 CFU/m^3, respectively. It is clear that a finite bacterial concentration may still be expected away from the source.

Table 1. Mean concentration of culturable airborne bacteria and average weather parameters at each sampling site.

Site	Mesophilic bacteria (CFU/m^3)	Wind Speed (m/s)	Wind direction	Temperature (°C)	Humidity (%)
A (2 m)	4168 ± 263	0.4	N	23	54
B (5 m)	2422 ± 132	0.4	N	28	42
C (10 m)	1929 ± 98	0.4	N	21	43

Table 2. Parameter values used in the present dispersion model.

Parameters	I	λ (1/s)	σ_y (m)	σ_z (m)	H (m)	u (m/s)	Stability
Value	0.21	0.004	$0.281846 \cdot x^{0.91437}$	$0.12719 \cdot x^{0.964435}$	2	0.4	B

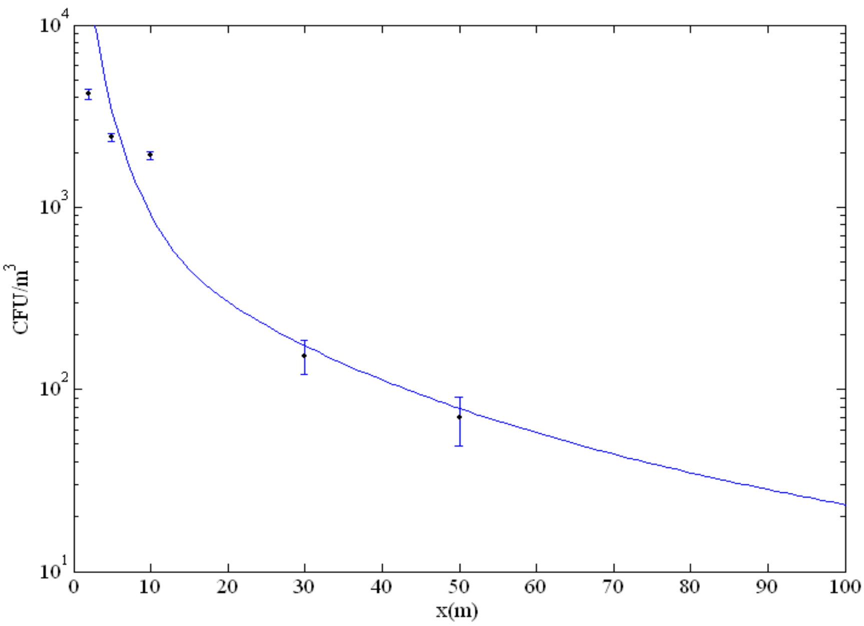

Fig. 2. Ground concentrations of airborne bacteria directly under the plume centerline vs. downwind distance from the rotating brush. Solid line and scattered points present the predicted and measured results, respectively.

Table 3 quantitatively compares the predicted and measured values of microbial concentration at sampling sites. It can be observed that relative errors between the predicted and measured values at all sampling sites investigated here are less than 20%, indicating that the agreement between the predicted and measured concentration values is good. Obviously, the present dispersion model may provide satisfactory predictions for downwind microbial concentrations.

Risk Characterization

Selection of exposure parameters is critical for the risk assessment. In most of previous studies of human risk assessment, exposure parameters were obtained from the framework of the USEPA exposure factors handbook (2011). However, a recent investigation by Wang *et al.* (2009) showed that there was obvious difference in physique between Chinese and the foreigners. For instance, the average dermal areas of Chinese adult male and female are generally lower than those of the American counterparts by 13% and 10%. Therefore, the appropriate exposure parameters of Chinese people proposed by Wang *et al.* (2009) were employed in this study (listed in Table 4). In order to consider different exposure parameters as a function of target age, receptors were grouped into children (< 6 yr old) and adult population (> 6 yr old).

Because the official reference dose (*RfD*) of bacteria has been not yet determined until now, it is not easy to conduct the risk assessment of microbial bacteria. Nevertheless, some researchers (Sigsgaard *et al.*, 1990) carried out the relevant epidemiological study and proposed that the amount of total bacteria that site workers may be exposed to should not be over 5000 CFU/m^3 for an eight-hour working day. In addition, although there was no official standard to regulate the permissible level of bacteria in China, the threshold value (5000 CFU/m^3) of airborne bacteria recommended by Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, has been applied to assessment of potential risk recently (Li *et al.*, 2012). Therefore, the value of 5000 CFU/m^3 was employed in this study. The results of the non-carcinogenic risk assessment are shown in Table 5. It is clear that the exposure hazard quotient (*HQ*) by inhalation route is over 10^5 times more than by dermal contact route for both children and adults, suggesting that inhalation route is the major pathway of microbial aerosol intake for human. Similar results were also reported by Tschopp *et al.* (2011). However, the present results are inconsistent with those reported by Carlander *et al.* (2009). They indicated that the ingestion played a predominant role compared to other exposure pathways associated with irrigation of municipal wastewater. Such difference of major exposure pathway seems to be attributed to different emission sources.

Table 3. Comparison between the predicted and measured values of microbial concentration at sampling sites.

Site	Measured value (CFU/m^3)	Predicted value (CFU/m^3)	Relative error
G_1 (20, –5)	172	156	10.2%
G_2 (20, 5)	164	156	5.1%
D (30,0)	134	153	12.4%
E (50, 0)	79	70	11.4%
F (100, 0)	21	17	19.0%

Table 4. Parameter values used in the present exposure assessment.

Parameters	Values
Inhalation rate (*IR*) (m^3/d)	7.6 (Children), 19.02 (Adult male), 14.17 (Adult female)
Exposure time (*ET*) (yr)	6 (Children), 24 (Adult)
Exposure frequency (*EF*) (d/yr)	180
Average body weight (*BW*) (kg)	15 (Children), 62.7 (Adult male), 54.4 (Adult female)
Averaging time (*AT*) (d)	69.6 × 365 (Male), 73.3 × 365 (Female)
Exposure skin area (*SA*) (m^2)	0.115(Children), 0.215 (Adult)
Skin adherence factor (*SL*) (kg/(m^3·d))	0.2 (Children), 0.07 (Adult)
Dermal absorption factor (*ABS*)	0.001

Table 5. Individual non-carcinogenic risks corresponding to different exposure pathways.

Exposure site	HQ_{inh}			HQ_{dermal}			*HI*		
	Children	Adult male	Adult female	Children	Adult male	Adult female	Children	Adult male	Adult female
2 m	1.75E-2	1.08E-2	8.76E-3	1.23E-7	1.22E-7	1.33E-7	1.75E-2	1.08E-2	8.76E-3
5 m	1.02E-2	6.25E-3	5.09E-3	4.54E-7	7.06E-8	7.73E-8	1.02E-2	6.25E-3	5.09E-3
10 m	8.10E-3	4.98E-3	4.06E-3	2.65E-7	5.62E-8	6.16E-8	8.10E-3	4.98E-3	4.06E-3
30 m	4.79E-4	2.94E-4	2.40E-4	7.24E-9	3.32E-9	3.64E-9	4.79E-4	2.94E-4	2.40E-4
50 m	1.37E-4	6.43E-5	6.21E-5	3.21E-9	1.73E-9	1.94E-9	1.37E-4	6.43E-5	6.21E-5
100 m	6.30E-5	3.87E-5	3.15E-5	9.53E-10	4.37E-10	4.79E-10	6.30E-5	3.87E-5	3.15E-5
300 m	1.27E-6	6.37E-7	6.12E-7	2.34E-11	1.21E-11	1.34E-11	1.27E-6	6.37E-7	6.12E-7

Table 6. Parameter variations for the sensitivity analysis.

Parameter	Base case	Case1	Case 2	Case 3	Case 4
I	0.21	0.036	0.11	0.35	1.2
λ (1/s)	0.004	0.12	0.02	0.006	0
RfD (CFU/m^3)	5000	2500	10000		

As found in Table 5, individual risk presents low values at various downwind distances investigated, always below maximum acceptable levels issued by USEPA (1 for non-carcinogenic pollutants). Moreover, the exposure hazard index (*HI*) is also found to rapidly decrease with the increase of downwind distance. At 300 m downwind distance, in particular, risk values reach 1.27×10^{-6}, 6.37×10^{-6} and 6.12×10^{-6} for children, adult male and adult female, respectively, several orders of magnitude lower than those inside WWTP (< 100 m distance from sources). Obviously, the safety protection distance (300 m) dictated by Chinese regulation seems quite appropriate for health safety purposes.

It can be also found that the order of exposure hazard quotient (*HQ*) by inhalation route is: children > adult male > adult female while the order by skin penetration is: children > adult female > adult male. The difference of hazard index (*HI*) between adult female and male is small. However, it is worth noting that both exposure hazard quotient and hazard index for children are generally much more than those for adults at each site, in spite of their lower intake. This is mainly due to children's lower body weight. Therefore, it is necessary to pay more attention to prevent health risk of children living near WWTP.

It must be pointed out, however, that the present assessment may underestimate the individual risk. One reason is that only risk of mesophilic bacteria were taken into account in the present evaluation because there are no available hygienic standards to regulate the reference dose of fungi and viruses in China. In fact, other airborne microorganisms such as fungi and viruses emitted from aeration might produce serious health risk. Another important reason might be that the reference dose value (5000 CFU/m^3) of bacteria used in the present study is somewhat low. Finally, according to Cangialosi *et al.* (2008), the uncertainties related to parameter values used in dispersion model and exposure estimation is also an non-ignorable cause.

In order to evaluate the uncertainty of risk assessment, a sensitivity analysis was performed. Three parameters were increased or decreased from the base case of the previous assessment, as shown in Table 6. The degree of parameter perturbation was designated in order to cover the likely range of uncertainty.

For the sake of simplicity, effects of parameter variations on the exposure hazard index (*HI*) of children were only shown in Fig. 3. It can be seen that the value of exposure hazard index rapidly decreases with the increase of downwind distance near the emission source and then tends to remain a nearly constant beyond 100 m downwind distance, for three parameters tested here. This indicates that three parameters all strongly affect the exposure hazard index (*HI*) and the risk assessment is sensitive to three parameters uncertainties only within a certain range (near the source location).

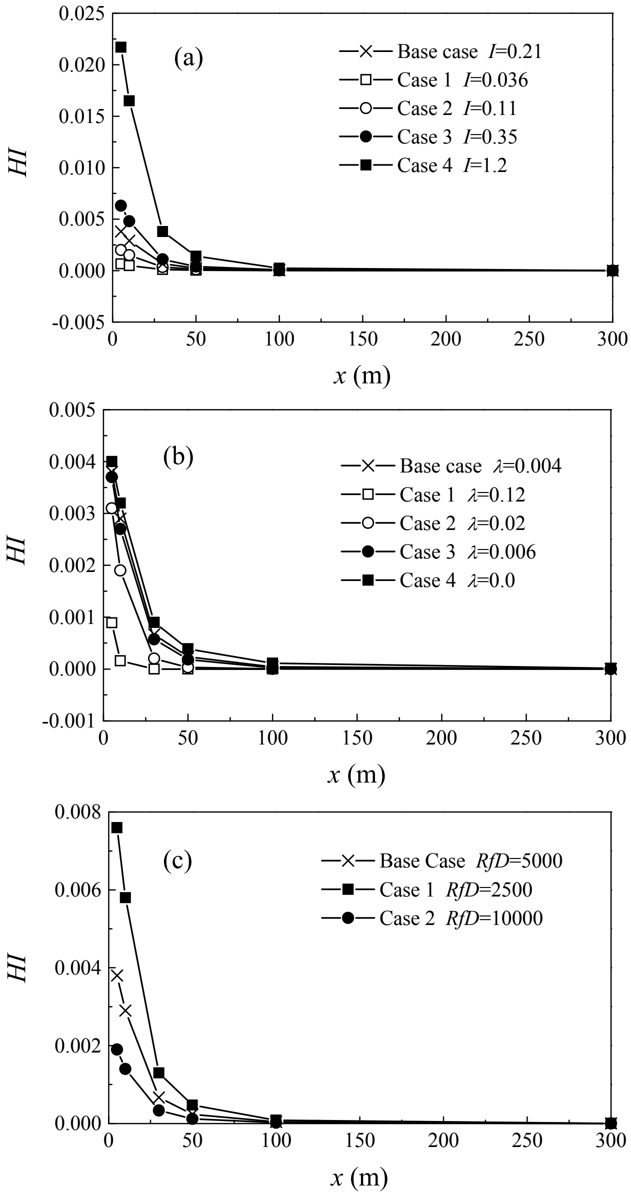

Fig. 3. Effects of parameter variations on the exposure hazard index (*HI*) of children (a) environmental impact factor (*I*), (b) die-off factor (λ), and (c) the reference dose (*RfD*).

CONCLUSIONS

The classical Gaussian point-source model was modified to quantify concentrations of microbial aerosols downwind from the rotating-brush aerator in a WWTP by accounting for environmental impact and die-off factors in the present study. It was shown by comparison with actual data detected at sampling sites that the present dispersion model may provide satisfactory predictions for downwind microbial concentrations. On the basis of those predicted data, a risk assessment model coupled with the appropriate exposure parameters of Chinese people was then used to evaluate the non-carcinogenic risks of airborne bacteria emitted from the rotating-brush aerator to surrounding residents.

Model estimation indicates that mean bacterial concentrations at ground level decrease rapidly with downwind distance. Inhalation route is found to the major exposure pathway of microbial aerosol intake for surrounding people. Although the present model gives acceptable low risk values at various downwind distances investigated, it is worth noting that both exposure hazard quotient and hazard index for children are generally much more than those for adults, implying that it is necessary to pay more attention to prevent health risk of children living near WWTP.

The risk assessment provides a valuable view for understanding potential risk of bioaerosols from rotating-brush aerators used in WWTP although the present results may underestimate the individual risk.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the State Key Lab of Urban Water Resource and Environment (QA200806), the State Key Lab of Fluid Power and Mechatronic Systems (GZKF-201026) and the Special Fund for basic Scientific Research of Central Colleges, Chang'an University (2013G2291013).

REFERENCES

Brandi, G., Sisti, M. and Amagliani, G. (2000). Evaluation of the Environmental Impact of Microbial Aerosols Generated by Wastewater Treatment Plants Utilizing Different Aeration Systems. *J. Appl. Microbiol.* 88: 845–852.

Cangialosi, F., Intini, G., Liberti, L., Notarnicola, M. and Stellacci, P. (2008). Health Risk Assessment of Air Emissions from a Municipal Solid Waste Incineration Plant – A Case Study. *Water Manage.* 28: 885–895.

Dowd, S.E., Gerba, C.P., Pepper, I.L. and Pillai, S.D. (2000). Bioaerosol Transport Modeling and Assessment in Relation To Biosolid Placement. *J. Environ. Qual.* 29: 343–348.

Fracchia, L., Pietronave, S., Rinaldi, M. and Martinotti, M.G. (2006). Site-related Airborne Biological Hazard and Seasonal Variations in Two Wastewater Treatment Plants. *Water Res.* 40:1985–1994.

Grisoli, P., Rodolfi, M., Villani, S., Grignan, E., Cottica, D., Berri, A., Picco, A.M. and Dacarro, C. (2009). Assessment of Airborne Microorganism Contamination in an Industrial Area Characterized by an Open Composting Facility and a Wastewater Treatment Plant. *Environ. Res.* 109: 135–142.

Haas, D., Unteregger, M., Habib, J., Galler, H., Marth, E. and Reinthaler, F.F. (2010). Exposure to Bioaerosol from Sewage Systems. *Water Air Soil Pollut.* 207: 49–56.

Heinonen-Tanski, H., Reponen, T. and Koivunen, J. (2009). Airborne Enteric Coliphages and Bacteria in Sewage Treatment Plants. *Water Res.* 43: 2558–2566.

Karra, S. and Katsivela, E. (2007). Microorganisms in Bioaerosols Emissions from Wastewater Treatment Plants during Summer at a Mediterranean Site. *Water Res.* 41: 1355–1365.

Korzeniewska, E. and Harnisz, M. (2012). Culture-dependent and Culture-independent Methods in Evaluation of Emission of *Enterobacteriaceae* from Sewage to the Air and Surface Water. *Water Air Soil Pollut.* 223: 4039–4046.

Lawless, PA. (2000). Improvements in the Positive-hole Correction for Multijet Aerosol Impactos Collecting Viable Microorganisms. *J. Aerosol Sci.* 31: 743–744.

Li, L., Han, Y. and Liu, J. (2013). Assessing Genetic Structure, Diversity of bacterial Aerosol from Aeration System in an Oxidation Ditch Wastewater Treatment Plant by Culture Methods and Bio-molecular Tools. *Environ. Monit. Assess.* 185: 603–113.

Li, Y.P., Qiu, X., Li, M., Ma, Z., Niu, T. and Feng, Y. (2012). Concentration and Size Distribution of Airborne Actinomycetes in a Municipal Wastewater Treatment Plant. *Pol. J. Envion. Stud.* 21: 175–181.

Li, Y.P., Yang, L., Meng, Q., Qiu, X. and Feng, Y. (2013). Emission Characteristics of Microbial Aerosols in a Municipal Sewage Treatment Plant in Xi'an, China. *Aerosol Air Qual. Res.* 13: 343–349.

Marthi, B., Fieland, V.P., Walter, M. and Seidler, R.J. (1990). Survival of Bacteria during Aerosolization. *Appl. Environ. Microbiol.* 56: 3463–3467.

Medema, G., Wullings, B., Roeleceld, P. and van del Kool, D. (2004). Risk Assessment of *Legionella* and Enteric Pathogens in Sewage Treatment Works. *Water Sci. Technol. Water Supply* 4: 125–132.

Oppliger, A., Hilfiker, S. and Duc, T.V. (2005). Influence of Seasons and Sampling Strategy on Assessment of Bioaerosols in Sewage Treatment Plants in Switzerland. *Ann. Occup. Hyg.* 49: 393–400.

Pascual, L., Pérez-Luz, S., Yáñez, M.A., Santamaría, A., Gibert, K., Salgot, M., Apraiz, D. and Catalán, V. (2003). Bioaerosol Emission from Wastewater Treatment Plants. *Aerobiologia* 19: 261–270.

Rosso, D. and Stenstrom, M.K. (2006). Surfactant Effects on α–Factors in Aeration Systems. *Water Res.* 40: 1397–1404.

Sánchez-Monedero, M.A., Aguilar, M.I. and Fenoll, R. (2008). Effect of the Aeration System on the Levels of Airborne Microorganism Generated at Wastewater Treatment Plants. *Water Res.* 42: 3739–3744.

Sigsgaard, T., Bach, B. and Malmro, P. (1990). Respiratory Impairment among Workers in a Garbage-handling Plant. *Am. J. Ind. Med.* 17: 92–93.

Stellacci, P., Liberti, L., Notarnicola, M. and Haas, C.N. (2010). Hygienic Sustainability of Site Location of Wastewater Treatment Plants: A Case Study. II. Estimating Airborne Biological Hazard. *Desalination* 253: 106–111.

Teixeira, J.V., Mirand, S., Monteiro, R.A.R., Lopes, F.V.S., Madureira, J., Silva, G.V., Pestana, N., Pinto, E., Vilar, V.J.P. and Boaventura, R.A.R. (2012). Assessment of Indoor Airborne Contamination in a Wastewater Treatment Plant. *Environ. Monit. Assess.* 185: 59–72.

Thorn, J. and Kerekes, E. (2001). Health Effects among Employees in Sewage Treatment Plants: A Literature Survey. *Am. J. Ind. Med.* 40: 170–179.

Tschopp, A., Bernard, A. and Thommen, A.M. (2011). Exposure to Bioaerosols, Respiratory Health and Lung-specific Proteins: A Prospective Study in Garbage and Wastewater Workers. *Occup. Environ. Med.* 68: 856–859.

USEPA (1999). Human Health and Ecological Risk Assessment Support to the Development of Technical Standards for Emissions from Combustion Units Burning Hazardous Wastes, Background Document, Washington, DC.

USEPA (2011). Exposure Factors Handbook, Office of Research and Development, Washington, DC.

Wang, H., Li, Y.P. and Zhao, Z. (2009). Computational Study on Microscale Behavior of Bubble Generated by Aeration in a Plug-flow Aeration Tank. *Water Sci. Technol.* 59: 2065–2072.

Wang, Z., Duan, X., Liu, P., Nie, J., Huang, N. and Zhang, J. (2009). Human Exposure Factors of Chinese People in Environmental Health Risk Assessment. *Res. Environ. Sci.* 22: 1164–117. (In Chinese).

Westrell, T., Schönning, C., Stenström, T.A. and Ashbolt, N.J. (2004). QMRA (Quantitative Microbial Risk Assessment) and HACCP (Hazard Analysis and Critical Control Points) for Management of Pathogens in Wastewater and Sewage Sludge Treatment and Reuse. *Water Sci. Technol.* 50: 23–30.

Received for review, September 15, 2012
Accepted, February 27, 2013