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Dispersion of *Legionella*-containing aerosols from a biological treatment plant, Norway

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TABLE OF CONTENTS

1. ABSTRACT

Legionella was detected in aeration ponds (biological treatment plant) at Borregaard Ind. Ltd., Norway, and in air samples harvested directly above these ponds. Since 2005, three outbreaks of legionellosis occurred within a 10 km radius from this plant. This work addresses the dispersion patterns of *Legionella*-containing particles by characterizing the aerosol plume emitted from these ponds (outbreak source) < 500 meters using wind-tunnel measurements, CFD simulations, and real-life measurements. The most abundant particles directly over the ponds were < 6 and >15 µm. The results showed that the aerosol plume remained narrow; 180 meters wide at 350 meters downwind of the ponds, and that 2 and 18 µm aerosols were mainly deposited in the vicinity of the ponds (150 - 200 meters). Furthermore, the maximum aerosol concentration level appeared 5-10 meters above ground level and the maximum concentration 500 meters downwind was approximately 2% of the concentration level directly above the ponds. Our study demonstrates the strength of combining modeling with real-life aerosol analyses increasing the understanding of dispersion of airborne (pathogenic) microorganisms.

2. INTRODUCTION

The majority of infections causing Legionnaires' disease, which is the pneumonic form of legionellosis is generally acquired by inhalation or aspiration of *L. pneumophila* from contaminated environmental sources, including man-made wet and humid environments such as air conditioning systems, humidifiers, cooling towers, whirlpools, spas, fountains, dental devices, and public showers (1). Recently, the wet scrubber at a wood pulp treatment facility (Borregaard Ind. Ltd.) was identified as the outbreak source of legionellosis (inhalation) in Sarpsborg/Fredrikstad, Norway, in 2005 causing 56 patient cases and 10 deaths (2). All wastewater from Borregaard's wood refinement processing is biologically treated where the biological treatment facility consists of two large aeration ponds containing 30 000 m^3 of liquid. As about 30 000 m^3 of air is circulated through each pond per hour, large amount of surface evaporation and aerosolization takes place. *Legionella* spp. has been identified in aeration ponds at concentration levels up to 10^{10} CFU/L at Borregaard Ind. Ltd as well as at Swedish biological treatment facilities (3). Variable concentration levels of airborne *Legionella* spp. (including *L. pneumophila*) were detected directly above these ponds (the highest level of

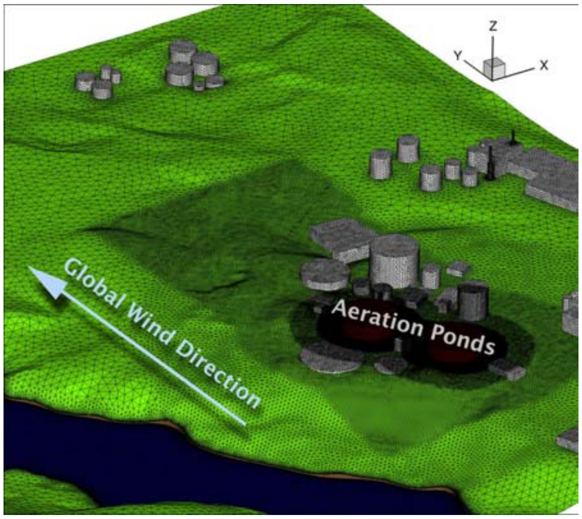

Figure 1. Schematic of the terrain and the surface grid used in the computations. The two aeration ponds are marked with dark color, and the blue area corresponds to the river Glomma.

3300 CFU/m^3) suggesting that the dispersion of *Legionella*-containing aerosols originating from these ponds may be a putative source for outbreak (4, 5). Subsequently, the aeration ponds at Borregaard Ind. Ltd. have been non-operational since September 2008. In Pas-de-Calais, France, 2006, a large community-wide outbreak of Legionnaires' disease was reported where a cooling tower located at a petrochemical plant was identified as the source whereas a wastewater basin (approximately 12000 m^3) was located about 300 meters from the cooling towers at the plant (6). In comparison, the aeration ponds at Borregaard Ind. Ltd. were located approximately 200 meters from the wet scrubber outbreak source at this industrial site.

Direct measurements of airborne *Legionella* demonstrate that *Legionella*-containing aerosols may be transported up to 300 meters downwind of the wastewater basins and 200 meters downwind of the aeration ponds of the plant in Pas-de-Calais and at Borregaard Ind. Ltd., respectively (4, 6), while epidemiological investigations from these outbreaks suggest that infectious *Legionella* bacteria may be dispersed up to ten kilometres from the source (2, 6). The mechanism by which the aerosols are generated leads usually to a continuous distribution of particle sizes, with only fractions within the inhalational size range. Complex physical processes are involved as larger aerosols may break up to become smaller, and smaller aerosols may agglomerate to form larger particles. The evaporation of aerosols may also be significant, especially at dry weather conditions. No detailed simulations of the dispersion of *Legionella*-containing aerosols taking into account the particle size distribution have been reported, neither for short nor long distances. This work attempts to analyze the dispersion of such aerosols over distances up to 500 meters from the aeration ponds that may be considered as a potential source for dispersion.

Traditionally, classical Gaussian models are used to simulate the atmospheric dispersion and transport of aerosols released from potential sources taking into account meteorological information. The primary disadvantage using Gaussian models are their inability to account for terrain modulations and building structures. Rapidly varying terrain affects the released aerosols by channelling the cloud causing a relatively narrow plume with potentially high aerosol concentrations. The potential source at Borregaard Ind. Ltd. considered here, i.e. the aeration ponds, are located among complex industrial building structures which will have an impact on the near-field dispersion properties of aerosols (Figure 1). Gaussian models are therefore not well suited. The present study therefore utilizes the Computational Fluid Dynamics (CFD) approach focusing on the dispersion, transport, as well as ground deposition of aerosols emitted from the two aeration ponds at Borregaard Ind. Ltd. up to 500 metres from this potential source. Although the variability of meteorological conditions and the size of the area of interest causes full scale dispersion and transport measurements on site very challenging, a 1:300 scaled model of the area in vicinity of the aeration ponds at Borregaard Ind. Ltd. was tested under isothermal conditions in an environmental flow wind-tunnel (7, 8 and references therein for details).

The primary objective of this study was to investigate the short range (500 m) transport of aerosols generated from the surface of the aeration ponds (considered as an outbreak source) at Borregaard Ind. Ltd. The combination of methods were used to verify the simulation results and thus to decrease estimation uncertainties. The verified CFD methodology may provide useful information about the transport process of aerosols and thereby representing a method that can be used to study various aspects of transport of *Legionella*-containing aerosols in complex environments. Propane (C_3H_8) was used as a tracer gas to simulate a release of *Legionella*-containing aerosols from the aeration ponds to create a scaled emission in the wind tunnel environment. It should be noted that the use of a tracer gas to simulate aerosol dispersion is justified if the particle inertia can be neglected by estimating the particle Stokes number (St) (9). Here, we are considering aerosols < 20 μm in diameter under such atmospheric conditions that St << 1 which justifies the present approach. Furthermore, the aerosol plume emitted from the aeration ponds was characterized at distances up to 500 meters downwind as well as ground level deposition of aerosols. The analyses are based on realistic aerosol concentration levels and characteristics measured directly above the ponds on site at Borregaard Ind. Ltd. To our knowledge, this is the first report describing the combination of modeling with actual data *on – site* from optical particle counting ("real-life measurements") real-life aerosol analyses in order to provide detailed particle transport mechanisms of aerosols that may contain (human pathogenic) airborne microorganisms.

3. MATERIALS AND METHODS

3.1.Monitoring site and weather conditions

The measurement site was located directly above the aeration ponds at Borregaard Ind. Ltd., Sarpsborg (N 59° 16.176', E 11° 6.734', WGS 84 coordinates) as high

Table 1. Conversion factor for transforming raw FLAPS light scatter data to particle concentration

FLAPS bins	Raw FLAPS counts	Interpolated APS Diameter (µm)	Factor to convert raw FLAPS counts	New FLAPS counts
2	5382	1.50	0.0037	19.7
3	3833	2.14	0.0031	11.9
4	3364	2.78	0.0034	11.3
5	3305	3.41	0.0037	12.1
6	2888	4.05	0.0034	9.9
7	2379	4.69	0.0028	6.7
8	2026	5.33	0.0022	4.5
9	1719	5.97	0.0017	2.9
10	1592	6.60	0.0013	2.1
11	1452	7.24	0.0011	1.6
12	1193	7.88	0.0010	1.1
13	1095	8.52	0.0009	1.0
14	968	9.16	0.0009	0.9
15	845	9.79	0.0009	0.8
16	745	10.43	0.0009	0.7
17	649	11.07	0.0011	0.7
18	512	11.71	0.0013	0.7
19	424	12.34	0.0019	0.8
20	333	12.98	0.0030	1.0
21	243	13.62	0.0047	1.1
22	239	14.26	0.0087	2.1
23	188	14.90	0.0127	2.4
24	155	15.53	0.0251	3.9
25	125	16.17	0.0396	4.9
26	128	16.81	0.0450	5.8
27	94	17.45	0.1027	9.7
28	73	18.09	0.0988	7.2
29	77	18.72	0.2318	17.8
30	65	19.36	0.1683	10.9
31	370	20.00	0.0308	11.4

concentration levels of airborne *Legionella* have been detected at these sites (4). Monitoring was performed continuously during day and night time for three consecutive days; June 4-6, 2007.The weather conditions during the day was generally warm (sunny, 17-22˚C, average wind speed 2.4-5.5 m/s, wind direction from North/North-East during the morning and from South-West during the evening, relative humidity 40-50%) and somewhat cooler at night.

3.2.Monitoring particle distribution in air

The Fluorescence Aerosol Particle Sizer, FLAPS, version 3 (Model 3317, TSI), was used to monitor the total particle distribution and concentration in air directly above the aeration ponds at Borregaard Ind. Ltd. The FLAPS uses a light scattering principle for optical particle counting providing the data output in sorted bin sizes instead of size numbers as, and measures the particle concentration every 3 sec. The instrument is designed for use with a virtual impactor concentrator to enhance signal to noise characteristics (10, 11). In order to correctly interpret the bin sizes provided by the FLAPS, a calibration curve was elaborated by subjecting the FLAPS and two APS instruments (APS 1, APS2) to a biological aerosol dispersion using *Bacillus atrophaeus* (BG) in an enclosed large aerosol chamber (50 m^3). The biological aerosol was produced by a Sonotek disseminator (Nozzle Model 8700-48, Sono-Tek Corporation, Milton, NY) using a BG slurry as source. The APS particle data were presented as size versus particle numbers while that for the FLAPS were in bin number versus raw particle counts per sampling interval (3 sec). The flow rates for the FLAPS and APS were about 500 L/min and 5 L/min, respectively. Thus, the FLAPS instrument monitors more particles over the same time period compared to APS. The FLAPS bin numbers were synchronized with the APS size distribution intervals by modelling the APS data set with the Savitzky-Golay spline method to permit interpolation of exactly 30 equally sized intervals in the range 1.5 to 20 µm using the software TableCurve 2D (Version 5, Systat Software, California) (12, Table 1). Bins 2 to 31 corresponded well to the particles size between 1.5 to 20 µm (Table 1). The shape of the raw FLAPS particle counts was similar to that of the APS counts and a conversion factor was constructed to derive a new FLAPS particle concentration component for each size bin.

3.3. Sampling and growth of *Legionella*

A wetted-wall cyclone SASS 2000^{PLUS} (Research International, USA), an impingement method, was used for collecting air in 5 mL PAGE buffer (120 mg NaCl, 4 mg $MgSO_4$, 4 mg $CaCl_2$, 142 mg Na_2HPO_4, 136 mg KH_2PO_4 per litre distilled water, pH 6.8 ± 0.2 at 25 ºC). The collection efficiency of SASS 2000^{PLUS} is above 50% for 1-2 µm particles (www.resrchintl.com). The sampling time was one hour, corresponding to 19.5 m^3 air (flow rate; 325 L/min) and performed directly over the aeration ponds. Cultivation and detection of *Legionella* spp. was performed according to the European standard ISO 11731: 1998 (E).

The liquid air samples were acid- (0.2 M HCl, 0.2 M KCl, pH 2.2± 0.2) (5 min) and heat-treated (50 °C, 30 min) in order to reduce the growth of non-*Legionella* organisms prior to microbial growth analysis on selective growth medium for *Legionella* spp. (GVPC).

3.4. Computational fluid dynamics

The CFD approach used in this study is based on the numerical solutions of the fundamental equations governing conservation of mass, momentum, and energy of an incompressible fluid. The method is based on three-dimensional and time-dependent Large Eddy Simulations (LES) which simulates the largest and most energetic scales of the wind field; these features are the most significant contributors to turbulence mixing of aerosols. Smaller, unresolved, scales are modeled using a sub-grid scale model. The LES method is particularly well suited for dispersion modeling in complex topographies, such as the industrial site of interest here, involving regions of strong free shear flows (13). The LES solution provides detailed information about the wind field that is used to simulate aerosol transport and deposition. LES is, in practice, limited to near-field dispersion and transport (1 – 2 km downwind the source) due to very high computational demands.

Two different methodologies to model aerosol transport and ground deposition are used. The ground deposition of (assumed spherical) water particles is modeled using a Lagrangian approach accounting for particle inertia and diameter. It has been assumed throughout the study that the particle concentration can be considered dilute whereby effects asserted by the aerosols on the wind field can be neglected. This assumption fits well with the conditions at the release site due to the relative low emission velocity and since we are considering a case with $St \ll 1$.

In the second approach, the transport of aerosols downwind of the aeration ponds is modeled using a passive scalar field approach; an additional advection-diffusion equation for the concentration of aerosols is solved in addition to the LES equations. Time averaged scalar field data are compared with time-averaged concentration measurements obtained in the wind tunnel under the same global conditions. It should be noted that the reason for using two different computational approaches is that the scalar field approach (computed in an Eulerian frame of reference) cannot be used to determine ground deposition. To obtain the latter, a Lagrangian frame of reference where each aerosol is followed individually is used. The change of reference from an Eulerian to a Lagrangian frame does not change the underlying estimations in this study as $St \ll 1$. The two approaches will differ when inertia effects are important to be considered.

The LES Smagorinsky-Lilly sub-grid scale model was used which is somewhat better, but computationally more intensive than that used in our previous study (4). The computational grid consisted of approximately 42×10^6 cells and the size of the computational domain corresponded to the 1:300 wind tunnel model: 2.3x2.6 x 1.4 m^3 (approximately 780 x 700 x 400 m^3 in full scale). The terrain features and surface grid of the computational model are displayed in Figure 1. The LES equations were solved numerically using a second-order implicit temporal scheme with the time step $\Delta t = 0.0146$ s and a second-order bounded central differencing scheme to approximate spatial derivatives. The numerical solution was iterated twenty times at each time step in order to achieve sufficient convergence before the solution was subsequently advanced to the next time step. The inflow boundary conditions were approximated from the experimental results at a position that corresponds to the inflow boundary of the computational box. The average stream wise velocity profile was obtained from the experiments whereas velocity fluctuations in all three directions were superposed with an intensity that was estimated from the measured root-mean-square velocity fluctuations (14).

Since only a portion of the area surrounding Borregaard Ind. Ltd. was modeled, special care was taken to specify proper inflow boundary conditions. The time averaged inflow velocity profile and turbulence intensity were chosen to match measurements upstream the aeration ponds. The turbulence anisotropy was furthermore specified partly based on experimental data and partly by assuming an axisymmetric state in the plane perpendicular to the global wind direction. The latter assumption is viable *in situ*ations with large building structures such as in this case. For further details on computational approach see Fossum *et al.* (14).

3.5. Wind tunnel experiments

A 1:300 scale wind tunnel model, covering approximately 1 km^2 (full scale) of the terrain and buildings was manufactured using high density polyurethane foam. The model was assembled in the large atmospheric wind tunnel at the Environmental Flow Research Centre located at the University of Surrey, Guildford, UK (15). The tunnel has a 20 m long test section with a cross-section area of 3.5 x 1.5 m^2 operates at wind velocities between 0.8 and 2.5 m/s. The first 10 meters of the wind tunnel is used for flow conditioning purposes to create realistic incoming atmospheric turbulent boundary layer. This is achieved by mounting a large number of planar roughness elements on the wind tunnel floor upstream the model. An advanced heating/cooling system is integrated into the tunnel which enables different atmospheric flow conditions, such as neutral, stable and unstable boundary layers, to be created. The circular model (diameter of 3.4 m) was mounted on a rotatable disk on the floor of the tunnel whereby different wind directions can be tested by rotation. Here we focus on one wind direction and one wind speed (2.5 m/s) (Figure 1).

Even though the model of the site involves many details in terms of terrain and building structures at Borregaard Ind. Ltd., the model does not include vegetation present on site or in its immediate vicinity. The wind tunnel measurements presented herein is limited to isothermal atmospheric conditions and the passive release from the two aeration ponds.

The concentration measurements were conducted using a fast flame ionization detector (FFID) at a sampling frequency of 200 Hz. The released contaminant consisted of a mixture of air with a trace of propane (C_3H_8). The tracer was released from the aeration ponds of the model to create a scaled emission in the wind tunnel environment.

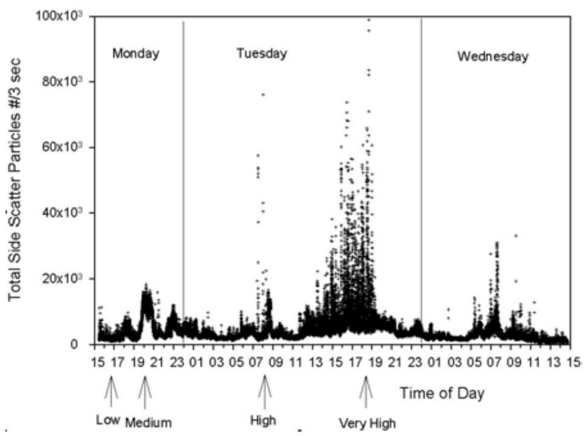

Figure 2. Monitoring total particle concentration above the aeration ponds using FLAPS during June 4-6, 2007 at Borregaard Ind. Ltd. The arrows indicate the raw total particle counts showing periods of low, medium, high and very high particle concentrations measured. Y-axis: raw particle concentrations per 3 second determined by light scatter.

Ground level concentrations, 10 mm above the model surface (corresponding to approximately 3 m above the ground in full scale), were measured as well as vertical variations of the concentration. The data were collected in blocks, in total 200 at each measurement position in order to ensure statistical convergence of the data. The use of tracer gas in place of particles is justified in cases where the particle inertia can be neglected. This is valid for our study as the Stokes number (St), defined as the ratio between the particle relaxation time ($\tau = \rho_p d^2 /(18 \mu)$) and the characteristic time scale (t) for the wind field, is $<< 1$. The particle relaxation time scale is computed using the aerosol (H_2O) density (ρ_p = 998 kg m^{-3} at 20°C), the molecular viscosity of the surrounding air ($\mu_{air} = 1.67x10^{-5}$ N s m^{-2} at 20°C), and the particle diameter (d): $\tau \approx 9.3x10^6 d^2$. The characteristic time scale for the wind field can be estimated to be in the order of $t \sim 10^{-1}$ (16) which in combination with aerosol diameters d < 20 µm gives $St_{max} \approx 3.7 \times 10^{-2} << 1$. The maximum Stokes number is thus sufficiently small to justify our use of a tracer gas in place of particles in the experiments. It should be noted that the characteristic time scale for the wind field varies both in time and space. A shorter time scale (due to e.g. increased wind speed caused by accelerations around sharp corners), with fixed aerosol diameter, thus corresponds to a larger Stokes number. Furthermore, the primary mixing in the building wakes downwind the ponds occur on a time scale in the range of 1-10 s (shedding frequency). In our estimate, we have used 0.1 s to be on the conservative side, i.e. towards the upper limit of possible Stokes numbers.

4. RESULTS

4.1. Particle concentration

The total particle distribution and concentration in air directly over the aeration ponds at Borregaard Ind. Ltd. was monitored for three consecutive days in June 2007. Periods of low, medium, and high levels of airborne particles were observed (Figure 2). In order to examine the particle data in more detail a selected data sets was extracted and used for further analysis (Figure 2). Medium and high levels of airborne particles were observed between 1930-2100h (June 4) and 0700-0900h (June 5), respectively. Also, high levels of airborne particles were observed the following day (June 6) at the same time period (0700-0900h) as well as during the afternoon on June 5 (1500-1900) (Figure 2).

4.2. Particle size distribution

In order to investigate the particle size distribution of the particle concentration monitored at a given time point, selected time points during the monitoring campaign were extracted for further analysis. Differences in the size distribution of the airborne particles present at different concentration levels were observed (Figure 3). During medium and high concentration levels, an enhanced level in the small (< 6 µm) and large (>15 µm) particle size ranges were observed compared to background (i.e. low) total particle concentration levels. The majority of the total particle levels are within the size range < 6 µm and >15 µm (Figures 3).

4.3. *Legionella* in air samples

Legionella was sampled for one hour into liquid using the wetted-wall cyclone SASS 2000 ^{PLUS} directly above the aeration ponds at Borregaard's biological treatment plant resulting in a concentration level of 166 CFU/ml (43 CFU/m^3) (calculations: (166 CFU/ml x 5 ml liquid)/ 19.5 m^3 air = 43 CFU/m^3). This is similar to that found previously during an extensive sampling campaign at the Borregaard's industrial area in 2006 and confirmed the presence of airborne *Legionella* bacteria still present at the industrial plant (4).

4.4. Near-field transport

The transport of aerosols generated from the aeration ponds at Borregaard Ind. Ltd. were analyzed utilizing both CFD and wind tunnel experiments to obtain as detailed information as possible about the transport process. Wind tunnel measurements taken at several positions downwind of the aeration ponds (Figure 4) were compared with the corresponding time averaged results from the passive scalar approach in order to verify the CFD approach. The width of the plume increases slowly with the distance from the ponds; from approximately 150 meters to 180 meters at 150 meters and 350 meters, respectively, downwind of the ponds showing that the plume remains narrow close to the ground. This is consistent with the CFD approach, which was able to predict the vertical variation of the plume at150 meters downwind of the ponds, and where the plume height reaches approximately 70 meters from the ground (Figures 5 and 6). Statistical analyses were performed according to Fossum *et al* (14) in order to provide means to judge the overall quality of the numerical simulations (16, 17). Experimental data was taken from approximately 20 lines (horizontally and vertically) located at different positions in the domain where each line comprised of 10-15 data points. The computational results showed overall good agreement with experiments. For instance the mean relative bias and mean relative square error was -0.284 and 0.385, respectively.

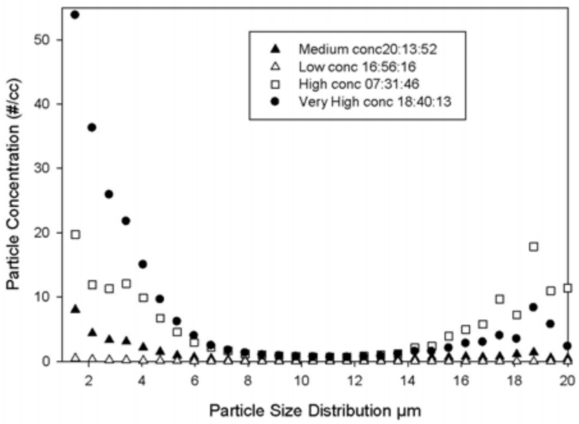

Figure 3. Size distribution of airborne particles at selected time points where the measured total particles were low (16:56:16), medium (20:13:52), high (07:31:46, 08:02:13) and very high (18:40:13) in abundance above the aeration ponds at Borregaard Ind. Ltd., June 4-6, 2007 (see Figure 2).

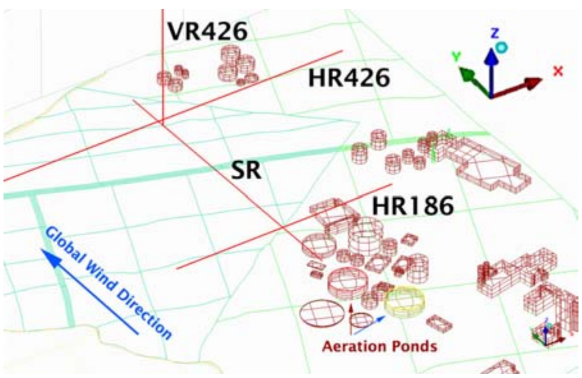

Figure 4. A schematic of the terrain and building structures in the vicinity of the two aeration ponds and the location of the measurements. The global wind direction is along the y-axis. The spanwise (x-direction) variation of the time averaged concentration field are measured along the lines HR186, HR426, VR426, and SR**.** HR186 and HR426, denoting horizontal rakes at the distance (m) from the first aeration pond given by the number included in the name. The vertical variation of the time averaged concentration field is measured along the vertical rake VR426, whereas streamwise concentration measurements are taken along the streamwise rake SR.

The maximum aerosol concentration within the plume is reduced with increasing distance from the ponds and appears to be about 5 – 10 meters above the ground (Figure 6). The maximum concentration at 500 meters downwind of the ponds is reduced significantly to only approximately 2% of the aerosol concentration measured immediately above the ponds.

Figure 8 displays an instantaneous picture of the aerosol cloud in a horizontal and vertical plane downwind the ponds. A notable feature of the cloud shape is that it remains relatively narrow, not only close to the ground (5 meters) where maximum concentration occurs, but also at larger distances from the ground.

4.5. Aerosol ground deposition

When considering the deposition of aerosols on surfaces such as the ground or building structures it is important to include effects of inertia for aerosols and atmospheric conditions leading to St > 1. As we are dealing with St << 1, and the effects of inertia are anticipated to be negligible, we still decided to include inertia effects in the simulations to improve the accuracy of the results. The wind tunnel methodology based on tracer gas is not appropriate to address ground deposition, and therefore CFD simulations based on the Lagrangian approach were used. Two discrete aerosol diameters were selected based on the real-life measured total aerosol size distribution (Figure 3): 2 µm and 18 µm particles. The CFD simulation approach taken is to instantaneously release a large number of particles from the pond liquid surfaces, and then individually track these as they move downwind and to determine whether they deposit on the ground or not. The deposition criterion was that if the particle trajectory hits the ground it was considered deposited. The ground was assumed to be sticky and the effects of re-aerosolization were thus neglected.

A notable feature of the deposition pattern is that it appears highly irregular, which indicates that unsteady mixing and turbulence effects are important (Figure 9). The computational results also indicate that the ground deposition is greatest in the close proximity of the ponds (within 150 – 200 meters). This is caused by increased mixing due to the presence of building structures. The ground deposition decreases further downwind (>150 m). Results also showed that approximately 15 – 25% of the released aerosols were deposited on the ground independently of aerosol size (computational studies). These results indicated that the aerosol transport process seem relatively insensitive to the aerosol sizes considered here.

5. DISCUSSION

Inhalation of aerosols of size 0.5 – 10 µm are of clinical interest since these may enter the human respiratory tract system. Exposure to biological aerosols (e.g. bacteria, fungi, viruses endotoxins, mycotoxins etc) are often associated with respiratory diseases exemplified by tuberculosis, pneumonia, legionellosis or whooping cough (2, 6, 19, 20). The deposition of the particles in the lung is dependent on a number of factors, e.g. particle size and age, susceptibility of the individual) (21, 22). In this study, the transport of airborne particles with a size of 2 and 18 µm were modeled as representatives from the major pool of aerosols from real-life measurements at Borregaard's biological treatment plant in Sarpsborg, Norway.

The total airborne particle concentration level and size was measured directly over the aeration ponds. Aerosol particle peaks occurred occasionally daily (Figure 2) and may be due to the differences in the agitation of air pumped through the aeration ponds. However, as the time points for these peaks coincide with the time points for the

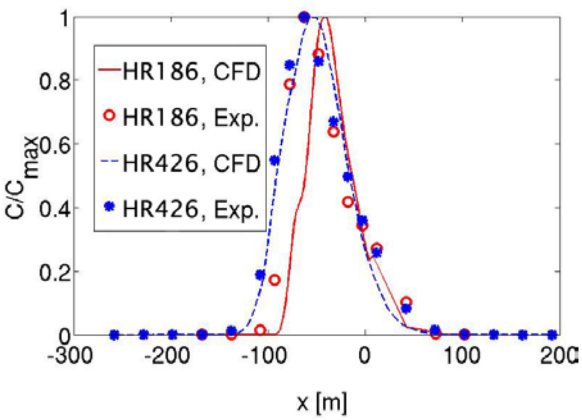

Figure 5. Spanwise variations of the time averaged concentration along HR186 and HR426 (see Figure 4), respectively. The symbols denote experimental results whereas the lines represent CFD results. HR186: open circles and dashed line; HR426: filled circles and solid line. C_max denotes the measured/computed maximum concentration at each position. For HR186 and HR426, C_max is approximately 0.08*C_source and 0.03*C_source, respectively, where C_source is the concentration at the ponds.

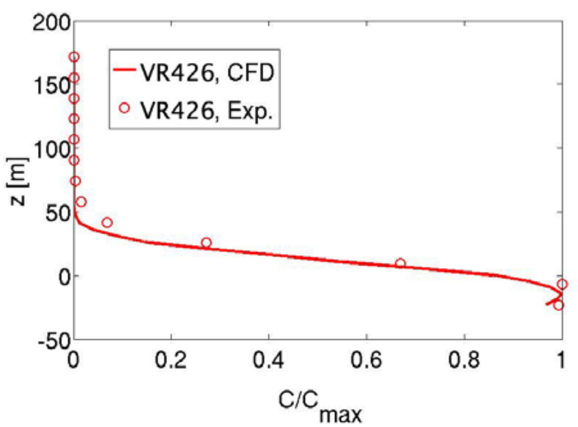

Figure 6. Vertical variations of the time averaged concentration field along VR426 (see Figure 4). The symbols denote experimental results whereas the lines represent CFD results. C_max denotes the measured/computed maximum concentration at each position. For VR426, C_max is approximately 0.02*C_source, where C_source is the concentration at the ponds.

morning hours of 7 to 8 AM the increase in the particle concentration level may be traffic related (Figures 1 and 3). Polidori *et al.* (23) noted that particle number, and 'black' carbon concentrations, were 4-8 times higher at 09:00-11:00 a.m. than between 17:00 and 18:00 p.m. A diurnal pattern of elemental carbon EC (PM2.5) has been observed in urban environments where the EC peak occurred during the morning rush hour traffic on weekdays but not on weekends (24). Morning traffic may cause an increase in the total particle number concentrations including ultra fine particles (25, 26).

Particles in size range < 6 and > 15 µm seemed to be abundant in air at Borregaard Ind. Ltd. during the measurements (Figure 3) and aerosol particles containing *Legionella* are detected directly above the aeration pond (4 and this study). As bacteria are anticipated to travel as aggregates/agglomerates in ambient air, a 3.5 µm particle containing *Legionella* cells, which are generally 2 µm in length and 0.3 – 0.9 µm, may contain 147 cells (27). This is based on that the volume of such a particle and the *Legionella* bacteria (ellipsoid) is estimated to $V_\varphi = 2.3 \times 10^{-17}$ m^3 ($V_\varphi = 4/3\ \pi\ a^3$, a; radius) and to $V_s = 9.4 \times 10^{-20}$ m^3 ($V_s = 4/3\ \pi$ abc), respectively. The packing density of ellipsoid cells in a spherical particle may be estimated to 0.6 , suggesting that the number of individual *Legionella* cells in a 3.5 µm particle can be estimated to 147 cells (V_φ / V_s x 0,6) (27, 28, 29). This indicates that an inhalation time of 4.5 - 11 hours would be needed to accumulate an infective dose of 1000 *Legionella* cells at a breathing rate of 0.6 – 1.5 m^3/hour (100% deposition in lungs) (30). For comparisons, an anthrax aggregate may consist of >500 individuals that may not have a spherical shape depending on the spore density (31, 32). Still, further work would be needed to confirm that naturally occurring particles of such sizes contain *Legionella* cells.

Wind-tunnel measurements and CFD simulations showed that the width of the aerosol plume dispersed from the aeration ponds only increased from 150 meters to 180 meters over a downwind distance of 200 meters. The height of the plume reaches about 70 meters above ground level (Figures 5 and 6). The concentration level of *Legionella* was previously determined to be 3300 CFU/m^3 (at ponds) and 43 CFU/m^3 (180 meters downwind); e.g. 1.3 % of the concentration level of that detected directly above the ponds (4). These findings show that the aerosols generated and transported downwind of the ponds are significantly diluted. In this study, 2% of the maximum particle concentration level detected directly above the ponds was measured in the wind-tunnel (and simulated by CFD) to be present 500 meters downwind of the ponds (Figure 7). This number is considerably higher than the real-life measurements, but this is most likely due to differences in wind direction, wind speeds, and sampling locations. Most importantly, the aerosol plume originating from the ponds is found to be relatively narrow (Figure 8) and any offset between the center of the plume and the actual measurement position will significantly influence the result. Also, the wind-tunnel experiment was performed at isothermal conditions which are more stable than the meteorological conditions in real cases. Since the mixing processes are significantly reduced during stable atmospheric conditions, it can be anticipated that the detected concentration levels are lower in the real-life measurements. The maximum plume concentration appears 5 – 10 meters from the ground level whereas only a smaller fraction is transported closer to the ground. Our study showed that the aerosol plume generated from the ponds is narrow (Figure 8), and that ground deposition is relatively modest (15 – 25 % of the emitted aerosols from the ponds

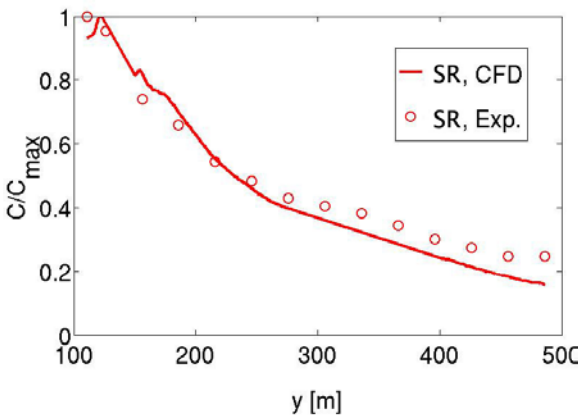

Figure 7. Variation of maximum concentration with distance from the ponds measured along the streamwise rake SR. The symbols denote experimental results whereas the lines represent CFD results. C_max denotes the measured/computed maximum concentration at each position. For HR186 and HR426, C_max is approximately 0.08*C_source, where C_source is the concentration at the ponds.

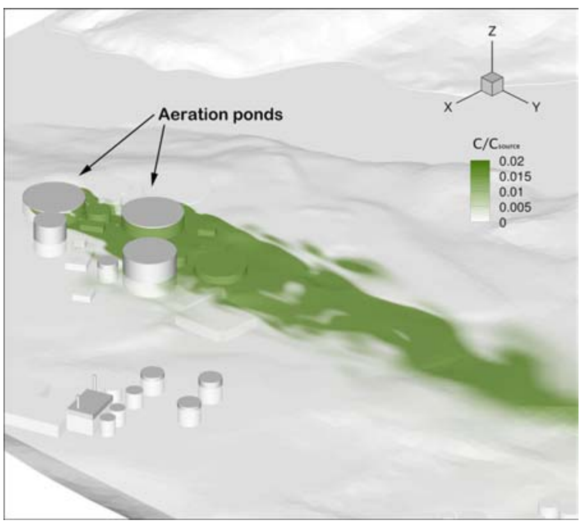

Figure 8. Instantaneous (non-dimensional) concentration field (scaled by the concentration at the ponds) obtained with CFD. The plume concentration is visualized in a horizontal plane (i.e. not following the terrain) located slightly below the liquid surface inside the ponds, and in a plane perpendicular to the wind direction in order to depict the cross-sectional shape of the plume.

are deposited on the ground). It was also found that particles of sizes 2 and 18 μm deposited within the same distance downwind of the ponds, suggesting that the effect of particle inertia, in this study, can be neglected as assumed. It can thus be anticipated that considerable larger aerosols (corresponding to St > 1) are the primary contributors to the near-field deposition. The ground deposition was found to be largest <150 – 200 meters from the ponds due to the increased mixing caused by the blockage from the building structures. The level of ground deposition was reduced further downwind where the influence from the buildings diminished. It should be noted that the level of deposition only depends on St; if the wind speed increases, the characteristic time scale of the wind field will decrease and St will thus increase. This implies that the deposition level can be expected to be higher at wind speeds > 2.5 m/s, and conversely lower for wind speeds < 2.5 m/s.

Our results suggest that individuals detained at ground are in general not subject to (inhaling) the highest concentration levels of aerosols dispersed from the aeration ponds. This is consistent with the observation that there were no fatalities at Borregaard Ind Ltd. and that only a small increase in IgG levels of the exposed population was observed, where these were mainly workers employed at Borregaard Ind. Ltd. in close distance to the aeration ponds (2, 33). Although there were an increased number of airway infections and chronic lung diseases among factory employees compared to non-exposed population there were no reports of diagnosed legionellosis cases among this group (33). Still, it is worth noting that the average age of the diagnosed patients within a 10 km distance from Borregaard Ind. Ltd was 69 years and where 50% of these had underlying diseases (2). As real-life measurements identified lower concentration levels of viable *Legionella* at 40-60 meters above ground level (0.9 – 4 CFU/m^3) compared to closer to ground levels (e.g. 440 CFU/m^3) at the same sampling day, our study demonstrates a consistency between real-life measurements and the modeling (4, and this study).

In this study, the maximum concentration levels within the aerosol plume were shown to decrease downwind to approximately 1/50 of the concentration directly above the ponds at 500 meters. Wind-tunnel measurements further downwind of the ponds have shown that only 1/200 of the initial aerosol concentration remained 3 km downwind the ponds (with maximum levels still at 5 – 10 meters height form the ground) (8). Thus, the dilution of the aerosol plume is greater in the near-field analysis, which is consistent with the observation of increased mixing caused by the building structures the first 150 meters from the ponds. The relatively modest terrain variations further downwind (> 3 km) makes an extrapolation of the concentration levels to larger distances feasible, and it can therefore be estimated that approximately 1/1500 of the initial aerosol concentration levels can be expected to persist 10 km downwind the aeration ponds.

The comparisons of the results obtained from the real-life measurements and the calculated models of the aerosol dispersion in this study showed both consistency and deviation. This clearly demonstrates the challenges involved combining these approaches and the need to jointly plan and carefully execute real-life measurements and in conjunction with simulations to assess health implications of aerosol plumes. However, modeling may be used to provide worse-case-scenarios. The chosen simulation methodology in this study has been verified by wind tunnel data such that it constitutes a viable approach

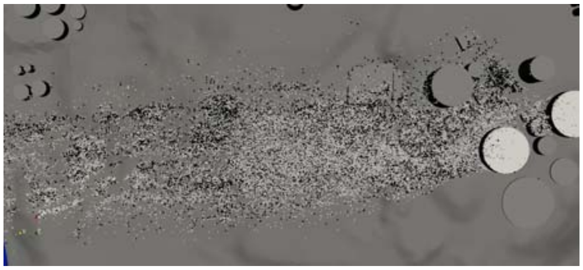

Figure 9. Computed accumulated ground deposition from an instant release of particles. Light color: 2 μm particles; dark color: 18 μm particles. The wind direction is from right to left, and the liquid surface inside the ponds is marked with light gray.

to describe the realistic transport of aerosols emitted from the aeration ponds at Borregaard Ind. Ltd. Our study demonstrates the scientific potential of combining the dispersion simulations and wind-tunnel measurements with real-life aerosol sampling and analyses to further increase our understanding of dispersion of airborne microorganisms that may be human pathogens, released from man-made environments important for occupational as well as public health.

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