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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/110522

Vorgeschlagene Zitierweise/Suggested citation:
Lee, Joseph H. W.; Qiao, Q. S.; Choi, David K. W.; Chau, Henry K. M. (2022): Fluid mechanics for carbon reduction in wastewater treatment plants. In: Hydrolink 2022/3. Madrid: International Association for Hydro-Environment Engineering and Research (IAHR). S. 84-87. https://www.iahr.org/library/hydrolink?hid=472.

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Fluid mechanics for carbon reduction in wastewater treatment plants

By Joseph H W Lee, Q S Qiao, David K W Choi and Henry K M Chau

Fluid mechanics can play an important role in carbon reduction in waste-water treatment plants operations. Full scale in-plant experiments in the Hong Kong Harbour Area Treatment Scheme (serving population of 5.7 million) demonstrated that significant savings in chlorine dosage in CEPT sewage disinfection can be achieved by optimal jet diffuser design and placement. At nominal applied chlorine dosages of 12mg/L (20 mg/L) in winter (summer) respectively, the chlorine demand can be reduced by up to 30% as compared to the conventional dosing design. As large quantities of chlorine (300 tonnes of 10% sodium hypochlorite solution) are used every day, the reduction in chlorine dosage translates to a saving in 1.6 million kWh/year associated with chlorine production, and around 1200 tonnes per year in CO_2 emission reduction. The relatively simple dosing reconfiguration results in significant savings in chlorine and energy, reduces harmful impact to the environment, and improves plant operation reliability-thus enhancing the environmental sustainability of the city as a whole.

Introduction

Turbulent mixing is at the core of hydrodynamic transport calculations required to predict the impact of man-made processes on the environment. Two- and three-dimensional (2D and 3D) hydrodynamic and water quality models are routinely used in drainage and environmental impact assessment (EIA) studies for many urban and coastal developments. Over the past two decades, the water and environmental industry has benefitted greatly from the progress in turbulence modeling and the development of powerful numerical methods for solving the Navier-Stokes equations or their variants. Coupled with rapidly increasing computing power, affordable and user-friendly CFD models have played an important role in enhancing the sustainability of the environment.

While CFD models have been extensively used in EIA studies (e.g., setting of water quality standards), emergency response (accidental pollution spills), and detailed engineering design of infrastructure works, their use has mainly been limited to predictions in the receiving water. On the other hand, there is great potential in the use of fluid mechanics in reducing carbon emissions and improving operations in many of the energy- and resource-intensive urban water and wastewater treatment plants – beyond just showing beautiful colorful graphics of complex flow simulations from CFD models. The use of CFD to substantially enhance cost effectiveness for waste-water treatment plants (WWTP) has increasingly been recognized[1].

Mixing is an important aspect in any reactor process inside a WWTP. However, when modeling for design or operation, simplified plug flow or complete mix stirred reactors are often assumed with the chemical kinetics based on bench scale jar tests. The simplifications may lead to design flaws resulting in sub-optimal performance of WWTP. This article presents an overview of a case study of optimization of sewage disinfection in the Hong Kong Harbour Area Treatment Scheme (HATS) - the largest Chemically Enhanced Primary Treatment (CEPT) plant in the world. Through understanding the interaction between jet mixing and chlorination kinetics, significant savings of chemicals and energy (up to 30%) can be achieved by optimal design and placement of the chlorine dosing.

Optimisation of sewage disinfection using dense chlorine jets

The Hong Kong Harbour Area Treatment Scheme

Chlorine is commonly used in disinfection processes in wastewater treatment plants. The chlorine solution is typically dosed by turbulent mixing; the chlorine reacts with the inorganic and organic nitrogenous compounds at a fast rate (in the order of 0.1 second). A significant portion of the dosed chlorine can be rapidly consumed by these reactions instead of destroying the pathogens - a waste of chemicals and energy -. Despite decades of use of chlorine for sewage disinfection, the interaction of turbulent mixing with chlorine consumption in the complex sewage environment remains an elusive problem.

The Hong Kong Harbour Area Treatment Scheme (HATS) serves a population of 5.7 million on both sides of the Victoria Harbour (https://www.dsd.gov.hk/others/HATS2A/en/). Sewage is collected from a number of nodes through a deep tunneled system to the Stonecutters Island Sewage Treatment Works (SCISTW) for centralized chemically enhanced primary treatment (CEPT) (**Figure 1**). In order to protect nearby beaches, a concentrated 10% sodium hypochlorite solution (specific gravity of 1.2) is used to disinfect the CEPT effluent. The dense chlorine solution is injected into the sewage flow through multiport jet diffusers in a Flow Distribution Chamber (FDC) at the end of the sedimentation tanks (**Figure 2**). The chlorinated sewage flows over a weir in the FDC and exits into an underground tunnel to allow for sufficient contact time. The total residual chlorine (TRC) concentration is monitored both at the end of the FDC and at a downstream chamber (Chamber 15A) before discharge into the submarine outfall (**Figure 3**).

Figure 1 | The Hong Kong Harbour Area Treatment Scheme (HATS) and the nearby bathing beaches in Tsuen Wan.

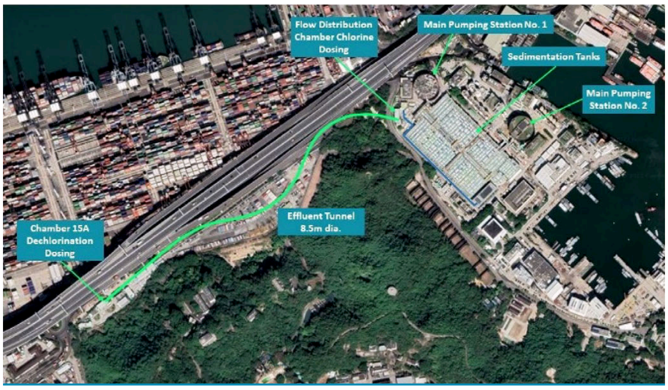

Figure 2 | Chlorine disinfection facilities in the Stonecutters Island Sewage Treatment Works (SCISTW) of HATS (top view).

Since commissioning of disinfection in HATS in 2010, it was found that the disinfection dosage based on bench scale tests failed to work in practice as designed. Operation experience revealed mysteriously large fluctuations of chlorine consumption and hence variable bacterial quality of the HATS effluent into coastal waters[2, 3, 4]. It should be noted that excess chlorine in the SCISTW effluent is also harmful to the environment.

Mixing chlorine with a river of sewage

As good mixing is a pre-requisite for acceptable disinfection performance, how to mix the concentrated chlorine dosing flow (6 L/s) with a large flow of sewage (1.8 million m^3/d, or 20.8 m^3/s) is a most challenging engineering problem. The mixing of sewage with chlorine (and hence the chlorine demand) in a small beaker in the laboratory is very different from the mixing of a chlorine jet in a sewage flow inside the WWTP (Figure 4). For example, if a full mixed TRC concentration of 10 mg/l is desired; in the laboratory we can mix 0.1ml of 10% sodium hypochlorite solution (100,000 mg/l) with 1l of water almost instantaneously. In the beaker we can then study the chlorine demand (or kinetics) for this sample of known concentration. On the other hand, in a real chlorination setting, different sewage parcels are 'sucked' into different parts of the chlorine jets by turbulent entrainment – the overall chlorine consumption is the composite of the chlorine demand of the different sewage parcels at different TRC concentrations. It turns out the optimal jet diffuser design and placement can make a big difference to the chlorine and energy consumption. On the other hand, the interaction of the turbulent mixing with the complex chlorination kinetics is a most challenging problem.

Mixing and chemical reaction of chlorine jets in treated sawage

The importance of mixing in chlorine disinfection has long been recognised[5, 6]; there has been a general recognition of dosing in points of high turbulence (e.g. hydraulic jumps). However, probably due to the small flows and relatively low chlorine concentrations no comprehensive field experiments involving the coupling of fluid mechanics and chlorination kinetics has been attempted.

The mixing and chlorine consumption of a chlorine jet discharging into primary treated effluent are studied for the first time at field scale in a 1:2 scale sectional physical model located inside the sewage treatment plant, using CEPT treated sewage and chlorine solution obtained on site (Lee et al 2017). The TRC concentration distribution is measured at different cross sections of the chlorine mixing chamber. It is confirmed that at a fully-mixed TRC concentration of 10 to 20 mg/l, approximately 70-80 percent of the chlorine mass flux is consumed within a very short distance (0.5-1 m, or a matter of several seconds) from the chlorine dosing unit (Figure 5a; first point dosing).

The field experiments in the unique physical model laid the foundation of several theoretical, CFD and laboratory studies that unveiled the role of organics and ammonia nitrogen in the chlorination kinetics[3, 7]. Building on the theory of buoyant jets in a turbulent crossflow[8], the effect of chlorination kinetics from the turbulent mixing can be isolated. Due to breakpoint chlorination and oxidation of organics the chlorine consumption depends on the source chlorine concentration in a highly non-

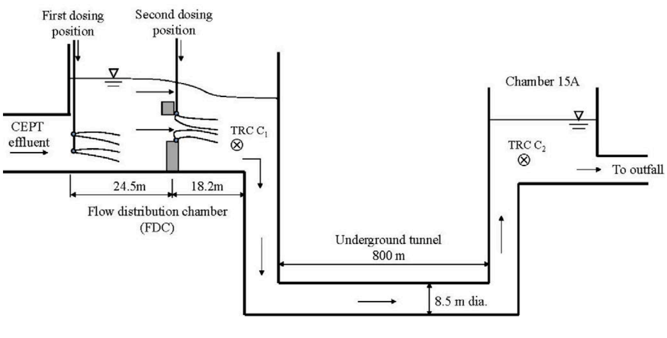

Figure 3 | Longitudinal view of chlorine disinfection facilities in HATS (not to scale).

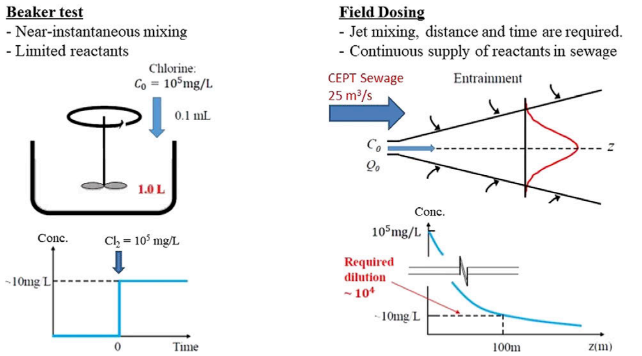

Figure 4 | Beaker test vs field dosing of chlorine in SCISTW.

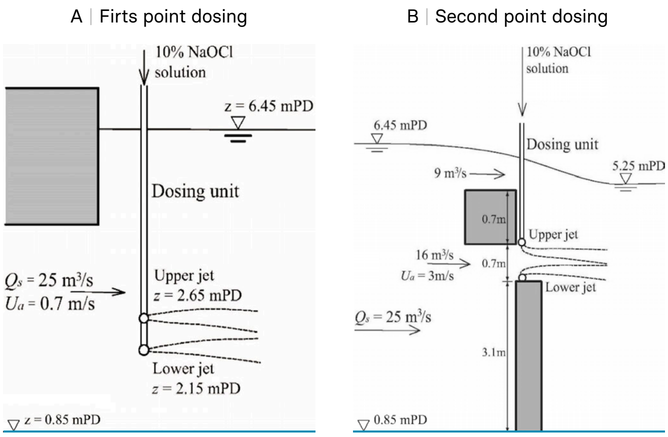

Figure 5 | Section view of hydraulic flow conditions at first and second dosing position.

Figure 6 | Testing of chlorine dosing unit for the second (optimal) dosing position in the SCISTW.

linear manner: the higher the chlorine concentration, the greater the consumption. Hence it is of utmost importance to minimize the time of exposure of sewage to high TRC concentrations. Various alternatives to optimize disinfection dosage have been investigated, including: (I) use of lower source chlorine concentration; or (II) reduce the TRC concentration as quickly as possible. The optimal solution is to discharge the chlorine jet at a position of maximum sewage flow velocity (minimize the reaction time) which can result in up to 30% savings in chlorine dosage.
In the optimal design, the chlorine jets are placed at a position of maximum velocity at the weir (**Figure 5b**). **Figure 6** shows the chlorine jet diffuser tested in open air before installation at the SCISTW plant. The simple and effective design has been proven in actual operation in both the winter and summer seasons. For example, in the summer season, the chlorine dosage required for disinfection can be reduced from 98% to 70%.

Concluding remarks

Fluid mechanics can play an important role in carbon reduction in WWTP operations. Full scale in-plant experiments demonstrated that significant savings (up to 30 percent) in chlorine dosage in CEPT sewage disinfection can be achieved by optimal jet diffuser design and placement[10]. The reduction of chlorine disinfection dosage has significant implications on carbon neutrality and sustainability. First, the daily usage of the 10 percent sodium hypochlorite solution is around 300 m^3.

On the other hand, the power consumption for production of sodium hypochlorite is around 500 kWh/m^3. For 30 percent chemical saving, the corresponding saving in power consumption can be estimated to be around 1.6 million kWh/year.

The annual savings in life-cycle power consumption is comparable to the total renewable energy produced by photovoltaic (PV) solar panels operated by the Drainage Services Department. In terms of reduction of carbon footprint (assuming 1 kWh = 0.71kg CO_2-emission), the saving in CO_2 emission can be estimated to be 1170 tonnes/year. Furthermore, as the supplier of the sodium hypochlorite solution is located 90 km away in Guangdong Province, the carbon footprint of the delivery trucks for such long haul would also be reduced significantly - not to mention the reliability of supply for WWTP operation during chronic or emergency crisis situations. The understanding of the causes of chlorine demand and dosing control greatly enhances the certainty and robustness of the sewage treatment plant operation - thus enhancing the environmental sustainability of the world city as a whole.

In general, the savings are particularly notable in primary effluents with organic solids. In recent years there has been a trend to employ CEPT to enhance carbon redirection for recovery and substantially reduce the organic load to secondary treatment processes[9].

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Acknowledgement

The research reported herein has been supported at various times by the Hong Kong Research Grants Council (RGC) and the Drainage Services Department (DSD) of the Hong Kong SAR Government.

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