Disinfection of Treated Sewage by Chlorine Jets

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Outline

1. Harbour Area Treatment Scheme (HATS) – disinfection for protection of public health
2. Field scale model for study of mixing and rapid chlorine demand in disinfection of primary treated (CEPT) effluent
3. Theoretical modelling of chemically reacting dense chlorine jet – optimal chlorine dosing strategies
4. Conclusions
**Cross-harbour Swimming Race revived after introduction of disinfection for CEPT treated sewage**

New World Harbour Race – **16 October, 2016**

(1.5 km; 2,400 participants)

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**Harbour Area Treatment Scheme (HATS) 香港浄化海港計劃**

Screening Plants/pumping stations

Stonecutters Island Sewage Treatment Work (SCISTW)

Submarine outfall

23.6 km deep tunnels (>100m below ground level)

**Chemically Enhanced Primary Treatment (CEPT) since 2001;**

23.6 km of deep tunnels;

**disinfection since March 2010**

**Stage 1:** \[ Q = 1.4 \times 10^6 \text{ m}^3/\text{d} \]

**Stage 2A:** \[ Q = 2.0 \times 10^6 \text{ m}^3/\text{d} \]
Hong Kong’s beach grading system
香港海灘水質評級系統

<table>
<thead>
<tr>
<th>Grading</th>
<th>Beach water quality /泳灘水質</th>
<th>E. coli * (counts /100 mL) 大腸桿菌</th>
<th>Minor illnesses rate ** (cases per 1000 swimmers) 發病率</th>
<th>Water Quality Objective / Compliance/Exceedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Good</td>
<td>≤ 24</td>
<td>Undetectable</td>
<td>Compliance</td>
</tr>
<tr>
<td>2</td>
<td>Fair</td>
<td>25 - 180</td>
<td>≤ 10</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Poor</td>
<td>181 - 610</td>
<td>11 - 15</td>
<td>Exceedance</td>
</tr>
<tr>
<td>4</td>
<td>Very poor</td>
<td>&gt; 610</td>
<td>&gt; 15</td>
<td></td>
</tr>
</tbody>
</table>

*Weekly Beach Grading: Geometric Mean E. coli level of the 5 most recent samplings ($C_{\text{MEG}}$)
Annual Beach Ranking: Geometric Mean E. coli level of all samplings in bathing season (March - October)

** Skin and Gastrointestinal illnesses (Cheung et al. 1990)

Water Quality Objective: $E$.coli < 180 counts/100 mL

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Stonecutters Island Sewage Treatment Works (SCISTW)
- Disinfection Facilities

- Flow distribution Chamber Chlorine Dosing
- Main Pumping Station
- Sedimentation Tanks
- Chamber 15 Dechlorination Dosing
- Effluent Box Culverts $2 \times 2.5 \text{ m} \times 2.5 \text{ m}$

First time high concentration chlorine used for sewage disinfection

300 tonnes/day of 10% sodium hypochlorite solution
Mysterious high chlorine consumption!
Engineering turbulent mixing

- **Chlorine disinfection** is essential to protect beach water quality in Hong Kong
- **Turbulent mixing** is the key to the large scale chlorine disinfection
- Chlorine disappears due to fast chemical reactions (~0.1 seconds) in complex turbulent shear flow
- Effective dosing (how much, where, how) can be engineered to ensure sustainable operation of HATS

Motivation for Chlorine Dosage Optimization

1. Chlorine has to be imported from mainland China - subjected to uncertainties in supply, export regulations, safety during transport.
2. Large storage tanks are required to store the concentrated chlorine (NaOCl).
3. Chlorine dosage optimization is necessary to ensure sustainability: reduce energy/chemical consumption and cost
4. Excessive Total Residual Chlorine (TRC) and Disinfection by-products (chlorinated organics) are harmful to environment
Flow Distribution Chamber (Chlorine dosing unit)

- An inclined weir of 1.8m height in the middle of FDC
- 10% chlorine solution is injected into the sewage flow through an array of dense jets (sp.gr.=1.2) in two rows

\[ Q = 25 \text{ m}^3/\text{s} \]

- An inclined weir of 1.8m height in the middle of FDC
- 10% chlorine solution is injected into the sewage flow through an array of dense jets (sp.gr.=1.2) in two rows

Mysterious Chlorine Consumption

*Measured TRC levels very low despite high dosage level*

![Graph showing TRC level variations](image)

**Summer**
Typical daily TRC level variations in FDC / Chamber 15A

**Winter**
Beaker Test vs Field Dosing

- Mixing in a beaker is very different from chlorine dosing in HATS field operations.
  
  *Beaker test results do not represent the field condition*

**Beaker test**
- Near-instantaneous mixing
- Limited reactants

**Field Dosing**
- Jet mixing, distance and time are required.
- Continuous supply of reactants

1:2 Physical Scale Model (with prototype sewage and chlorine)

The objectives are to study:
- the mixing achieved by the dosing unit in the FDC;
- chlorine demand at different key locations in the FDC;
- disinfection efficiency in the FDC; and
- degree of settling of organic solids in the FDC.

*The 1:2 physical model represents a “1/16 slice” of the FDC treated sewage flow*
CEPT Sewage inflow from sedimentation tank

Head tank

Dosing unit

Discharge of sodium hypochlorite solution

Test flume

Outlet tank

1:2 Physical Scale Model in SCISTW for study of chlorine mixing (1/16 slice of FDC sewage flow)

<table>
<thead>
<tr>
<th>Prototype/model</th>
<th>ratio</th>
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<tbody>
<tr>
<td>Length $L_p/L_m$</td>
<td>2</td>
</tr>
<tr>
<td>Velocity $V_p/V_m$</td>
<td>1.41</td>
</tr>
<tr>
<td>Time $t_p/t_m$</td>
<td>1.41</td>
</tr>
<tr>
<td>Flow rate $Q_p/Q_m$</td>
<td>5.657</td>
</tr>
<tr>
<td>Density difference $\Delta \rho_p/\Delta \rho_m$</td>
<td>1</td>
</tr>
</tbody>
</table>

Dosing sugar solution ($\rho = 1.168 \text{ g/mL}$) into cross flow in 1:2 model

Initial mixing of upper dosing jet with dyed sugar solution (tap water flow $Q_s = 60 \text{ L/s}; U_a = 0.2 \text{ m/s}$; total jet discharge $q_d = 20 \text{ mL/s}$)

Lee et al. *ASCE Journal of Environmental Engineering*, 2017
**Integral model of a reacting dense chlorine jet in sewage coflow**

Jet Trajectory:

\[
\frac{dx}{ds} = \cos \phi \quad \frac{dz}{ds} = \sin \phi
\]

Spreading hypothesis (top-hat):

\[
\frac{dB}{ds} = \beta_s \left( \frac{V - U_a \cos \phi}{V} \right) + \beta_n \left( \frac{U_a \sin \phi}{V} \right) + \beta_* \frac{\sigma}{U_a}
\]

Excess x-momentum flux:

\[
\frac{d}{ds} \left[ \pi B^2 (U - U_a) \right] = 0
\]

\[z\text{-momentum flux:} \quad (1 + k_n) \frac{d}{ds} \left[ \pi B^2 VW \right] = \frac{F_0}{U_a}
\]

TRC mass flux:

\[
\frac{d}{ds} \left( \pi B^2 V C \right) = \begin{cases} 
-C_m R_a \frac{dC}{ds} & \text{for } C_T/C_{m0} \geq R_a \\
0 & \text{for } C_T/C_{m0} < R_a
\end{cases}
\]

Ammonia mass flux:

\[
\frac{d}{ds} \left( \pi B^2 V_{m0} \right) = \begin{cases} 
0 & \text{for } C_T/C_{m0} \geq R_a \\
C_{m0} \frac{dC}{ds} & \text{for } C_T/C_{m0} < R_a
\end{cases}
\]

Assuming instantaneous break point reaction

**Break-point reaction of chlorine with ammonia in sewage**

- When Cl₂/NH₃ < 7.6 (below breakpoint), chlorine reacts with ammonia to form combined chlorine (chloramines, NH₂Cl, NHCl₂, NCl₃) with disinfection ability;

- When Cl₂/NH₃ > 7.6 (beyond breakpoint): chlorine reacts rapidly with ammonia to form nitrogen gas, only free chlorine remains.

\[2NH_3 + 3HOCI \longrightarrow N_2 + 3Cl^- + 3H^+ + 3H_2O\]

**NH₃ in sewage = 30 ppm**

**Breakpoint of Cl₂ = 230 ppm**

Chlorine/ammonia stoichiometric reaction coefficient (by mass) of a dense chlorine jet in ammonia solution

ref. White (1992)
**Chlorine reaction in sewage**

High concentration chlorine can oxidize organic debris and sewage constituents; the chlorine demand can be 2-3 times higher at high chlorine concentration.

Chlorine consumption (mg/L) vs. chlorine conc. at jet centerline

Higher chlorine concentration results in the reaction with organic debris

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**CFD modeling of the 1:2 scale FDC model**

900,000 grid cells
Free surface determined by volume of fluid (VOF) method

Dosing jet flow = 20mL/s
\[ C_0 = 100,000 \text{ mg/L} \]
\[ \Delta p/\rho = 0.2 \]

Dosing unit
\[ Q_j = 15.7\text{mL/s} \]
\[ Q_l = 4.3\text{mL/s} \]
Jet mixing of the chlorine with the sewage co-flow achieves a rapid dilution in the order of 1000-2000 in the FDC. This high dilution however falls short of the value required to achieve full mixing (i.e. a dilution of 5000-10,000). Only approximately 60-80 percent of the sewage flow over the FDC weir is chlorinated.

Integral model predicted chlorine jet characteristics for 2.5% chlorine jet in CEPT sewage: 15-20% reduction in chlorine demand.
Strategy: Chlorine jet in high velocity flow

Utilize initial jet mixing in high speed flow supplemented by rapid mixing in highly turbulent recirculation flow downstream to reduce chlorine consumption by the ammonia and organics in sewage.

Design the jet mixing to dilute the $10^5$ ppm chlorine to < 230 ppm (below breakpoint) as quickly as possible.

Field tests in optimizing chlorine dosage (2019)

Significant reduction in chlorine demand as seen in field tests.

New dosing device for HATS 2A (Dec 2018)
Conclusion

- The chlorine demand of CEPT effluent has been studied by theoretical modeling of a chemically reacting chlorine jet and field scale experiments using prototype sewage and chlorine dosing solution.
- Jet mixing is not able to achieve full mixing of the 10 percent chlorine solution with the sewage flow in the flow distribution chamber. Only 60-70 percent of the sewage is in contact with chlorine.
- Over 90% of the chlorine mass flux can be consumed within 5-10 seconds from the source. Most of the chlorine is used in oxidation of organic debris at the high concentrations, and not used in bacteria (pathogen) kill.
- Full scale tests have confirmed that chlorine disinfection dosage can be optimized by discharging 10% chlorine solution through an optimal diffuser design in high speed flow.

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