Biofiltration Technology
For
Effective Control of Air Emissions

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VOCs?

Volatile organic compounds (VOCs)

- They are found in the waste stream emitted from most processes employing organic or petroleum based solvents.
1. The passage of the 1990 Amendments to the Clean Air Act: significantly heightened the interest in the development of innovative technologies for VOCs removal.

2. VOCs are precursors to the formation of ozone, and they have their own toxicity.

1. Source of VOCs to ambient atmosphere affected by the Clean Air Act Amendments.

2. Depends on domestic, commercial, and industrial sources

3. VOCs are transferred into the air mainly in case of aerated bioreactor (activated sludge process)
1. Thermal oxidation, Catalytic oxidation, Condensation, Carbon adsorption, Membrane separation…

2. Biological treatment: economical and ecological technology

3. Biofiltration
Air Treatment Processes

- Catalytic Oxidation: 28.0%
- Thermal Oxidation: 8.0%
- Adsorption: 36.0%
- Absorption: 19.0%
- Biological Treatment: 6.0%
- Condensation: 3.0%
Biofiltration

Basic Design Principles

- Support Media
- Nutrients
- Moisture
- pH Control
- Adequate Oxygen Level
- Temperature
TYPES OF BIOFILTERS

Classical Biofilters

- Natural Organic Media
  - Peat
  - Compost
  - Leaves
  - Wood bark
  - Soil

Biotrickling Filters or Trickle Bed Biofilters

- Synthetic Media
  - Inorganic
  - Plastic
1. Owner and location: Novartis; Basle, Switzerland
2. Air flow rate: 60,000 – 75,000 m$^3$/h (Exhaust air from plant)
3. Pollutants: toluene, xylene, methanol, isopropanol, chloroform...
   Total conc.: 180 – 500 mg/m$^3$
4. Biofilter Design
   Investment costs ($2,000,000)
   Treatment costs
     ($1.44 per 1000 m³ off gas)

5. Biofilter Performance
   Removal: 80 %
     (depends on inlet loading)
CLASSICAL BIOFILTERS

NATURAL ORGANIC MEDIA

Demonstrated Characteristics:

- Loading limited (degradation rate of the medium is much higher than the VOC degradation rate. The VOC input has minor effect on microbial activity)

- Sensitive to moisture content

- Very sensitive to temperature
Biofilter Applications History

**Pre 1990:** Principally for Nuisance Odor Control
- Sewage Treatment Odors
- Livestock Raising, Processing, and Rendering
- Flavors and Fragrances: Extraction / Processing
- Commercial Composting

**Post 1990:** Developed for VOC / Volatile Toxics Control
- Groundwater Remediation: Vacuum Extraction Venting
- Fibers Processing: Rayon Fiber
- Industrial Finishing: Painting, Lacquering, Printing
- Commercial Fermentation: Bakeries, Breweries
Conceptually identical process to the biofilter

- Microbial attachment: Synthetic inorganic or polymeric media
- Intermittent delivery of Nutrient & Buffer to the media

- ✓ Consistent Nutrient & pH control
- ✓ Optimizing the waste utilizing kinetics

Trickle-Bed Air Biofilter (TBAB)

- Consistent
- Long-term
- High

Removal Performance
Biotrickling Filters

for more successful application in industry

Challenges

Source Characteristics

- Transient loading
- VOCs composition
- Emission mode: non-use periods

Biofilter Maintenance

- Biomass accumulation
- Microbial activity
Performance of Pelletized Biofilter at 1 and 2 Minutes EBRT without Backwashing
Solution

In situ up-flow washing with water, i.e., backwashing at a rate sufficient to fluidize the media and permit rapid removal of excess biomass growth
The relative performance of two biofilters was evaluated by varying the form of nutrient nitrogen.

**Nitrate-N vs Ammonia-N:**

Nitrate-N fed biofilter demonstrated the following advantages:

- Better steady state performance (overall)
- Better recovery after backwash with time
- Better removal with depth
- Lower microbial yield (about 40% less)
Effect of step-change in influent concentration (Phase I)

Effect of non-use periods (Phase I)

Effect of interchanging the feed VOCs (Phase II)

Effect of Varying VOCs composition (Phase III)
Materials and Methods

- Reactor: Independent lab-scale TBAB
- Media: pelletized biological support media
Materials and Methods

1. Electronic Air Cleaner
2. Mass Flow Controller
3. Syringe Pump
4. Nutrient Feed Control System
5. Nutrient Feed Tank
6. Spray Nozzle
7. Trickle Bed Biofilter
8. Pelletized Media

Sampling Location

Effluent Water
Effluent Air
Characterizing TBAB Performance

- Determination of critical loading
- Impact of non-use periods on performance
### Feed VOCs

<table>
<thead>
<tr>
<th></th>
<th>Hydrophobic compounds</th>
<th>Hydrophilic compounds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Toluene</td>
<td>Styrene</td>
</tr>
<tr>
<td><img src="image" alt="Structure" /></td>
<td><img src="image" alt="Structure" /></td>
<td><img src="image" alt="Structure" /></td>
</tr>
<tr>
<td>$K'_H$</td>
<td>0.280</td>
<td>0.109</td>
</tr>
<tr>
<td>$\text{Log } K_{ow}$</td>
<td>2.58</td>
<td>3.16</td>
</tr>
</tbody>
</table>

$K'_H = \text{dimensionless Henry’s law constant, } K_{ow} = \text{Octanol-water partition coefficient}$
### Experimental Conditions

<table>
<thead>
<tr>
<th></th>
<th>Toluene</th>
<th>Styrene</th>
<th>MEK</th>
<th>MIBK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inlet Conc., ppmv</strong></td>
<td>50 ~ 500</td>
<td>50 ~ 330</td>
<td>50 ~ 500</td>
<td>50 ~ 250</td>
</tr>
<tr>
<td><strong>Loading rate</strong>, kg COD/m³·day</td>
<td>0.7 ~ 7.03</td>
<td>0.64 ~ 3.17</td>
<td>0.7 ~ 7.03</td>
<td>1.09 ~ 5.43</td>
</tr>
<tr>
<td><strong>EBRT, min</strong></td>
<td>1.23</td>
<td>1.51 ~ 2.02</td>
<td>0.76</td>
<td>0.76</td>
</tr>
</tbody>
</table>
Phase I: Biofilter Study

Results – VOC removal capacity (Backwashing)

Aromatic compounds

Toluene

• Critical loading
  3.5 kg COD/m³·day
  (46.6 g/m³·hr)
• Maximum removal capacity
  6.0 kg COD/m³·day
  (79.9 g/m³·hr)
Phase I: Biofilter Study

Results – VOC removal capacity (Backwashing)

Aromatic compounds

Styrene
  • Critical loading
    1.9 kg COD/m³·day
    (25.8 g/m³·hr)
  • Maximum removal capacity
    2.7 kg COD/m³·day
    (36.6 g/m³·hr)
Phase I: Biofilter Study

- **Results – VOC removal capacity (Backwashing)**

**Oxygenated compounds**

**MEK**
- Critical loading
  5.6 kg COD/m³·day
  (95.6 g/m³·hr)
- Maximum removal capacity
  5.9 kg COD/m³·day
  (100.7 g/m³·hr)
Phase I: Biofilter Study

Results – VOC removal capacity (Backwashing)

Oxygenated compounds

MIBK

- Critical loading
  4.3 kg COD/m³·day
  (65.9 g/m³·hr)
- Maximum removal capacity
  4.9 kg COD/m³·day
  (75.1 g/m³·hr)
Phase I: Biofilter Study

- **Results – Comparison of VOC removal capacity**

![Bar chart showing VOC removal capacities]

<table>
<thead>
<tr>
<th>Compound</th>
<th>VOC Loading/Removal Rate, kgCOD/m³day</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIBK</td>
<td>5.43</td>
</tr>
<tr>
<td>MEK</td>
<td>7.03</td>
</tr>
<tr>
<td>Styrene</td>
<td>3.17</td>
</tr>
<tr>
<td>Toluene</td>
<td>7.03</td>
</tr>
</tbody>
</table>

VOC Loading/Removal Rate, kgCOD/m³day
Phase I: Biofilter Study

- **Results – VOC removal capacity**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Loading Rate (kgCOD/m³day)</th>
<th>Backwashing Rate (kgCOD/m³day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIBK</td>
<td>5.43</td>
<td></td>
</tr>
<tr>
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<tr>
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<tr>
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Phase I: Biofilter Study

Results – VOC removal capacity

<table>
<thead>
<tr>
<th>Compound</th>
<th>Loading</th>
<th>Backwashing</th>
<th>Non-use Period</th>
</tr>
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<tbody>
<tr>
<td>MIBK</td>
<td>2.17</td>
<td>4.34</td>
<td>5.43</td>
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<td>4.30</td>
<td>5.64</td>
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<td>3.52</td>
<td></td>
<td>7.03</td>
</tr>
</tbody>
</table>

VOC Loading/Removal Rate, kgCOD/m³/day
Phase I: Biofilter Study

Results – Critical loading vs. Kow

![Graph showing critical loading vs. Kow for different compounds]

- MEK
- MIBK
- Toluene
- Styrene

Critical loading, kg COD/m³/day

K_{OW} (octanol-water partition coefficient)
1. Up to the critical VOC loading rate, the backwashing was effective biomass control to attain consistently high removal performance.

2. Non-use periods can be considered as another means of biomass control at lower VOC loading rate.

3. Reacclimation was a critical factor in biofilter performance. After non-use periods, the active biomass affects biofilter response.

Experimental findings supported the handling limitation of performance of the current biofiltration system.
Impact of Interchanging VOCs on the Performance of Trickle-Bed Air Biofilter

Phase II
Interchanging VOCs

- Operating Condition
  - Sequence of Feed VOCs
    - Styrene → MEK → Toluene → MIBK → Styrene
  - Inlet concentration of feed VOCs
    - 50 ppmv ~ the maximum allowable inlet concentration
  - Flow rate
    - Nutrient solution: 1.5 L/day
    - Air: 1.35 L/min (EBRT = 2.02 min)
  - Biomass control: Periodic in-situ backwashing
    - Frequency: 1 hour of duration / a week
Results

- Biofilter Response after interchanging VOCs
Results

- Biofilter Response after interchanging VOCs

![Graph showing biofilter response for Styrene, MEK, and Toluene over acclimation period in minutes.]
Results

- Biofilter Response after interchanging VOCs

![Graph showing removal efficiency over acclimation period for Styrene, MEK, Toluene, and MIBK.](image)
Results

- Biofilter Response after interchanging VOCs

![Graph showing removal efficiency over acclimation period for different VOCs]
Results

Nitrogen Utilization and CO₂ Production

- High N utilization
- High CO₂/COD

Why?
Discussion

1. Need more proteins to make up the enzymes for utilizing new substrate
   - More utilization of nitrogen

2. Facultative organisms: Denitrifying microorganisms
   - Nitrogen utilization and CO₂ Production

Study of Microbial community structure & diversity

High N utilization
High CO₂/COD

Possible Reason
High removal performances were observed in the interchanging VOC-fed TBAB.

TBAB easily acclimated to hydrophilic compounds (MEK & MIBK), while TBAB acclimations to hydrophobic compound (Toluene & Styrene) were delayed for more than 45 hrs.

Right after interchanging feeding VOCs, TBAB has shown unusual performances (high nitrogen utilization & high CO$_2$/COD).
Effect of Varying VOC Concentration

Phase III
Use of Integrated Systems

Load fluctuation

Solution = Buffer unit

Adsorption unit can be a buffer unit for a biofilter

Current application: Single bed of carbon filter

Consideration of current adsorption unit
High loading & Large fluctuation → Losing buffer capacity
Initial period of operation → No contaminant in effluent
Conceptually simple process to PSA

PSA (Pressure Swing Adsorption) :
→ A technology for separation and purification for gas mixtures
→ 4 Steps for operational function

2-Bed Adsorption Unit

- Feeding (Adsorption)
- Depressurization
- Purging (desorption)
- Repressurization
- Regeneration
2-Bed Adsorption Unit

- Conceptually simple process to PSA
- Hypothetically, adsorption rate is equal to its desorption rate
  → Operational function is simplified to a 2-step

Feeding (Adsorption) → Regeneration
Purging (desorption)
Theory of 2-Bed Adsorption

2-Bed Adsorption Unit

- Cyclic operation: Shift of air flow direction
  - Each bed will not be fully saturated with adsorbate

Clockwise

Waste Gas to biofilter

Counterclockwise

Waste Gas to biofilter
Phase II: Adsorption Study

2-Bed Adsorption

Concept

Will serve as

- Polishing unit during the initial acclimation period of the biofilter
- Buffer unit in load fluctuation
- Feeding source without any feeding phase during non-use periods
Objective

Main Objective
Evaluate Cyclic operation of 2-bed adsorption unit as load equalization
For air biofiltration system

Specific Objective
• Mathematically simulate 2-bed adsorption unit performance
to compare Cyclic operation vs. Non-cyclic operation

• Experimentally evaluate the performance of the integrated scheme of
2-bed adsorption unit with air biofilter under transient loading of
toluene (Integrated unit vs. control unit)
Phase II: Adsorption Study

2-Bed Adsorption

Experimental Methods

- 2 Beds
- Dimension: 2.5 cm (D) × 20 cm (L)
- Duration of one cycle: 8 hours
- EBRT: 5.6 sec (2.2 L/min)

- Adsorbate: Toluene
- Adsorbent: GAC (BPL 6 × 16)
1. Air cleaner
2. Mass flow controller
3. Syringe pump
4. Equalizing tank
5. Flow meter
6. 2-bed adsorber
7. 4-way solenoid valve
8. Supplemental air valve
9. Biofilter

Control Unit

Combined Unit
Results: Model Simulation
Model Simulation

- Model simulation of **cyclic operation** of 2-bed adsorption
- Model simulation of **non-cyclic operation** of 2-bed adsorption
Model Simulation

- Model simulation of cyclic operation of 2-bed adsorption

Mathematical model is formulated for a packed bed for simulation of the proposed cycle, which consists of overall and component material balances.
- Linear driving force model is incorporated into the model in order to include a mass transfer resistance with an adsorbent from a bulk gas phase.
- Freundlich isotherm equation is used for expression of isotherm capacity.

Assumption: (1) no pressure drop along a bed, (2) an isothermal operation, and (3) a plug flow through a bed with no dispersion.

- Model simulation of non-cyclic operation of 2-bed adsorption
Model Simulation

- Model simulation of cyclic operation of 2-bed adsorption

- Model simulation of non-cyclic operation of 2-bed adsorption

Plug flow homogeneous surface diffusion model (PFHSDM) which is embedded in an Adsorption Design Software (AdDesignS™) developed by Michigan Technological University is used.

The mechanisms incorporated in this model are:
- Homogeneous surface diffusion
- Film transfer resistance at the adsorbent surface
- Advection dominates axial transport in bed.
- Local equilibrium Freundlich isotherm exists at the adsorbent surface.
- Freundlich isotherm equation is used for expression of isotherm capacity.
Model Simulation

- Effluent Response in 2-bed Adsorption

**Transient Feeding Condition 1:** Square wave change of inlet concentration
- Base = 200 ppmv
- Peak = 400 ppmv (15 mins / hour)
Model Simulation

- Effluent Responds in 2-bed Adsorption

a) Cyclic operation

Critical inlet Conc. (250 ppmv) to biofilter
Model Simulation

- Effluent Responds in 2-bed Adsorption

a) Cyclic operation

b) Non-cyclic operation
Model Simulation

Effluent Responds in 2-bed Adsorption

a) Cyclic operation
b) Non-cyclic operation

- Exp. observation
Results I: Feeding Condition 1

- **Integrated unit vs. Control unit**

**a) Integrated unit (2-bed adsorption + biofilter)**

**b) Control unit (biofilter)**
Results: Further Application

Feeding Condition
- Type A: 46.9 g/m³·hr

- a) 8-hr average effluent
- b) Reaction rate constant

Effluent, mg/m³

Rate constant, sec⁻¹

Feeding Condition

Control unit
Integrated unit
Peak
Base
Results: Further Application

Feeding Condition

- Type B: 46.9 g/m³·hr (High Peak)

![Graph showing effluent and reaction rate constant](image-url)
### Results: Further Application

**Feeding Condition**
- **Type C**: 56.3 g/m³·hr (Frequent Peak)

#### a) 8-hr average effluent

- Control unit
- Integrated unit

#### b) Reaction rate constant
- Control unit
- Peak
- Base

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**Graphs**
- Inlet Conc. vs. Time (min)
- Effluent mg/m³ vs. Feeding condition
- Rate constant sec⁻¹ vs. Feeding condition
### Results: Further Application

#### Feeding Condition
- **Type D**: 65.9 g/m³·hr (High & Frequent Peak)

#### Graphs

- **Graph 1**: Time vs. Inlet Concentration (ppmv)
  - X-axis: Time, min
  - Y-axis: Inlet Conc., ppmv
  - Peaks at 65.9 g/m³·hr

- **Graph 2**: Feeding Condition
  - X-axis: Feeding condition
  - Y-axis: Effluent, mg/m³
  - Comparison between Control unit and Integrated unit
  - Results for A, B, C, D conditions

- **Graph 3**: Reaction rate constant
  - X-axis: Feeding condition
  - Y-axis: Rate constant, sec⁻¹
  - Comparison between Control unit and Integrated unit
  - Results for Peak and Base conditions

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### Summary

- **a) 8-hr average effluent**
- **b) Reaction rate constant**

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Transient feeding condition 2: 10 hrs square wave change + 14 hrs starvation without toluene loadings

600ppmv (15min) → 200ppmv (15min) → 400ppmv(15min) → 200ppmv(15min) / 1 Hr
Desorption profiles of 2-bed adsorption unit

Square wave change loading  Starvation without toluene loading (only air flow)

Effluent Concentration, ppmv

Sequential time, hrs
Overall Removal Performance (with backwashing as biomass control)

a) Integrated unit (2-bed adsorption+biofilter)
Overall Removal Performance (with backwashing as biomass control)

**a) Integrated unit (2-bed adsorption+biofilter)**

- Effluent Concentration (ppmv) vs Sequential Time (hr)
  - Day 1
  - Day 3
  - Day 5
  - Day 7

**b) Control unit (biofilter)**

- Effluent Concentration (ppmv) vs Sequential Time (hr)
  - Day 1
  - Day 3
  - Day 5
  - Day 7

Removal Efficiency (%) plotted against Sequential Time (hr) for both units.
## Results: Further Application

Reactor volume of a single biofilter to achieve the same treatment goal as in the integrated system

<table>
<thead>
<tr>
<th>Feeding Condition</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
<th>Type D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak concentration ($C_{i,p}$), ppmv</td>
<td>400</td>
<td>700</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>(g/m$^3$)</td>
<td>(1.53)</td>
<td>(2.68)</td>
<td>(1.53)</td>
<td>(2.30)</td>
</tr>
<tr>
<td>Biofilter bed volume required (V), m$^3$</td>
<td>0.00435</td>
<td>0.00761</td>
<td>0.00435</td>
<td>0.00653</td>
</tr>
<tr>
<td>$V / V_{integrated}$</td>
<td>1.5</td>
<td>2.6</td>
<td>1.5</td>
<td>2.2</td>
</tr>
</tbody>
</table>

* Volume of the integrated unit = 0.00293 m$^3$
Summary

The net effect of the 2-bed adsorption was VOC concentration stabilization that makes it amenable for effective stable biodegradation.

1. The 2-step cycle in the adsorption unit successfully performed particular functions as
   - A polishing unit to abate the initial acclimation for the biofilter;
   - A buffering unit to mitigate the biofilter performance;
   - A feeding source for the biofilter without any feeding phase.

2. Details of the reactor volume suggest that capital expense can be minimized by achieving a careful design and operation of the integrated treatment scheme.
Acknowledgements

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