Breathable membrane enclosures for faecal sludge stabilization

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Problems with basic pit latrines

- Spread of pathogens and pollution through soil or during high water conditions
- Unsanitary conditions for clearing filled pits

Proposed Improvement

Non-piped toilet equipped with membrane distillation system

- Breathable membrane lining (hydrophobic, nonwetting – differs from geomembranes, RO and filtration membranes)
- Simple, appropriate technology
- Retains particulate and dissolved contaminants including pathogens
1. The process uses a hydrophobic membrane, only permeable to water vapor.

2. On one side of the membrane, hot seawater or brine flows through the compartment.

3. On the other side, cold distillate flows in a countercurrent direction.

4. The temperature difference leads to different vapor pressures, causing water vapor transport across the membrane.

5. The vapor re-condenses to form distilled water on the distillate side.

• MD is an emerging technology for desalination

• Uses a temperature gradient as the driving force for pure water production
Apply this to sanitation needs

Hot brine → Membrane → Cold distillate
Apply this to sanitation needs.
Temperature difference could be from biodegradation or passive solar

Features

- Small temperature gradient
- Gradual escape of water vapour
- Enclosure prevents release of pathogens and dissolved constituents
- Drying is facilitated
- Resists fouling and scaling – reusable (tests confirm)
Hydrophobic membrane after 2,000 hours in desalination process

SEM images of PVDF membrane surface (A) and (B) and cross section (C) and (D) after 1200 hours DCMD of instant ocean salt.
But:

• Faecal sludge is different from salt water.

• Drying is different from desalination.

• Privies are different from industrial processes.

• Much to do!
Understanding the Process

- Initial feasibility
- Characterization
- Material and condition optimization
- Practicality
- Scale-up
Initial Feasibility:
- Thumb cut-out from a breathable membrane glove
- Filled with sludge, placed on warm hot plate ($\Delta T=15^\circ C$)
- Lost 50% of moisture in 24 hr
- Conductivity of water on filter pad same as distilled water
Understanding the Process

- Initial feasibility
- **Characterization**
- Material and condition optimization
- Practicality
- Scale-up
Experimental Setup-1: Membrane Enclosures

- Membrane Enclosures
  - PE impermeable plastic
  - Layered membrane
  - Hot plate heating
  - Water bath heating

- Temperature Gradients
- Control Experiments
- Scale
- Measurement

- Initial thickness: 1 cm
- PTFE membrane
- PE plastic

Water bath heating

Hot plate heating
Experimental Setup-2: Two-Column Configuration

- **Scale**
- **Applied Temperature**
- **Measurement**
Results

Drying with/without membrane

- ΔT = 2°C
- V = 2 mL

Graph showing sludge weight (g) and percent solids over time (day) for no membrane and membrane treatments.
Easily attained complete dryness
Effect of temperature difference ($\Delta T$)

Greater $\Delta T$ speeds up drying, but 2C difference seems sufficient.
In contact with water instead of air

Slower water removal, but 2/3 of water is still removed
Bacterial die-off

99.4% removal of fecal coliform. ND across membrane.
Understanding the Process

• Initial feasibility

• Characterization

• Material and condition optimization

• Practicality

• Scale-up
Studies of rate-limiting factors

Moisture loss has three limiting steps

I. Moisture transfer in sludge
II. Vapor transfer across membrane
III. Vapor transport from membrane surface to surrounding area
Experimental Results

Typical Drying Curves

Original initial solid content, layered membrane

High initial solid content, layered membrane

High initial solid content, no membrane

ΔT=2°C, V=100 ml

Constant rate

Falling rate

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# Sludge Drying Kinetics

## I. Two Period Model

\[
\frac{w}{w_0} = (1 - N_0 \frac{t}{w_0}) + \frac{N_0 \sigma \sqrt{\pi}}{2w_0} \left(1 - \text{erf} \left(\frac{t_f - t}{\sigma}\right)\right)
\]

*\text{(Efremov, 1998)}*

**constant rate period**

**falling rate period**

\[
\sigma = 2 \left( t_f - \frac{w_0 - w_{eq}}{N_0} \right)
\]

Characteristic time (day)

- *w* solid based moisture content (g/g)
- *w_0* initial moisture content (g/g)
- *w_{eq}* equilibrium moisture content (g/g)
- *N_0* constant drying intensity (1/d)
- *t* drying time (d)
- *x* location (m)
- *D* diffusivity of water in sludge (m²/d)
- *D_{eff}* effective diffusion constant (m²/d)
- *k* mass transfer coefficient (m/d)

**MR:** moisture reduction (g/g)

## II. Fick’s Second Law

\[
\frac{\partial w}{\partial t} = \text{div}(D \text{grad} w)
\]

One-dimensional isotropic diffusion

\[
\frac{\partial w}{\partial t} = D_{eff} \frac{\partial^2 w}{\partial x^2}
\]

**BC1:** \(x = 0\) (surface)

\[
N = -D_{eff} \frac{\partial w}{\partial x} = k (w^* - w)
\]

**BC2:** \(x = L\) (bottom)

\[
\frac{\partial w}{\partial x} = 0
\]

\[
\frac{w - w_{eq}}{w_0 - w_{eq}} = \text{erf} \left(\frac{x}{2\sqrt{D_{eff}t}}\right) + e^{\left(\frac{k}{D_{eff}}\right)x + \left(\frac{k}{D}\right)t} \text{erfc} \left(\sqrt{\frac{t}{D_{eff}}} + \frac{x}{2\sqrt{D_{eff}t}}\right)
\]

\[
MR = \frac{w - w^*}{w_0 - w^*} = \exp \left[\frac{1}{\pi} \left(\frac{t}{\sigma}\right)^n\right] \text{erfc} \left(\sqrt{\frac{1}{\pi}} \left(\frac{t}{\sigma}\right)^n\right)
\]

\[
\sigma = \frac{D_{eff}}{\pi k^2}
\]

Characteristic time (day)
Characteristic Time (\(\sigma\)) Estimation

\[
MR = \frac{w - w^*}{w_0 - w^*} = \exp \left[ \frac{1}{\pi} \left( \frac{t}{\sigma} \right)^n \right] \operatorname{erfc} \left( \sqrt{\frac{1}{\pi}} \left( \frac{t}{\sigma} \right)^n \right)
\]

\[
\sigma = \frac{D_{\text{eff}}}{\pi k^2} = \text{Characteristic time (min)}
\]

<table>
<thead>
<tr>
<th>(\Delta T) (°C)</th>
<th>Membrane</th>
<th>No Membrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11,630</td>
<td>9,440</td>
</tr>
<tr>
<td>2</td>
<td>7,2130</td>
<td>4,990</td>
</tr>
<tr>
<td>5</td>
<td>5,620</td>
<td>5090</td>
</tr>
<tr>
<td>10</td>
<td>5,300</td>
<td>3450</td>
</tr>
</tbody>
</table>

\(n = 2.5\)

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i. Vapor transfer across the membrane: Stagnant Film Model

\[ N_A = k^* \ln \left( \frac{P - p_{A1}}{P - p_{A2}} \right) \]

\[ k^* = \frac{D_{\text{eff}} P}{RT_{\text{avg}} \delta} \]

Stagnant film mass transfer coefficient

\[ D_{\text{eff}} = D_{AB} \frac{\varepsilon}{\tau} \]

- \( N_A \) = flux of water across membrane (mol \cdot m^{-2} \cdot s^{-1})
- \( P \) = total pressure of water vapor and air (Pa)
- \( p_{A1} \) = partial pressure of water vapor on feed side (Pa)
- \( p_{A2} \) = partial pressure of water vapor on exit side (Pa)
- \( D_{AB} \) = diffusivity of water vapor in air (m^2 \cdot s)
- \( D_{\text{eff}} \) = effective diffusion constant (m^2 \cdot s)
- \( R \) = gas constant (J \cdot K^{-1} \cdot mol^{-1})
- \( T_{\text{avg}} \) = avg. membrane temperature (K)
- \( \varepsilon \) = membrane porosity (-)
- \( \tau \) = membrane tortuosity (-)
- \( \delta \) = membrane thickness (m)
Stagnant Film Model Validation

\[ N_A = k^* = 12,187 \frac{D_{AB@T_{avg}}}{T_{avg}} \left( \frac{\varepsilon}{\delta\tau} \right) \ln \left( \frac{P - p_{A1}}{P - p_{A2}} \right) \]

\[ N_A = 12,187 \frac{D_{AB@T_{avg}}}{T_{avg}} \left( \frac{1}{\lambda} \right) \ln \left( \frac{P - p_{A1}}{P - p_{A2}} \right) \]

\[ \lambda = \delta\tau / \varepsilon = \text{membrane diffusion resistance (m)} \]
Understanding the Process

- Initial feasibility
- Characterization
- Material and condition optimization
- Practicality
- Scale-up
Process quantification using stagnant film model

Three different membranes have similar resistances, ~ 1/3 of total
Understanding the Process

• Initial feasibility
• Characterization
• Material and condition optimization
• Practicality
• Scale-up: initial estimates
Predicting the Drying Rate

Is this process feasible?

Drying rates now known for sludge/membrane/air: assume this applies unsaturated soil

Water Table
Predicting the Drying Rate

Portions of pit in saturated or flooded depths only lose moisture at rate measured in sludge/membrane/water tests.

Water Table
Predicting the Drying Rate

Water Table

Lowest moisture loss if soil is fully saturated or flooded

Predict water removal vs. water elevation and vs. $\Delta T$
Predicting the Drying Rate

Lowest moisture loss if soil is fully saturated or flooded

Water table elevation relative to pit base

Water Table

2 m

0 m
Performance Prediction

Water table elevation relative to pit base

Drying rate (L/day)

ΔT (°C)
82 L/d
\sim 186 \text{ person capacity}

Even worst case assumptions give 18 person capacity
Summary

- Process is effective in lab tests with \( \Delta T \) as little as 2°C, in contact with air or water
- Water is lost from sludge while protecting the environment
- Membrane can be re-used

Future Plans

- Faecal sludge to be used in place of digested sludge
- Scale up/practicality tests
- Compare other important membrane properties (strength, heat conductivity, etc.)
- Work with membrane companies to assure affordable membrane
Applications not limited to basic pit toilets

- With or without urine diversion
- Pumped latrine wastes
- Combined with other evolving toilet technologies
- Commercial applications at larger scale
- Et cetera

Discussions/collaborators welcome
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