Membrane Filtration for Sustainable Safe Drinking Water Supply

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Outline

- Water supply situation and water scarcity.
- Urban water cycle.
- Membrane filtration technology.
- Treatment of highly turbid surface water and particle rejection by membrane filtration.
- Gravity-driven ultra low pressure membrane filtration in off grid region and biofilm role on flux stabilization.
- Summary
Water supply coverage / Water scarcity

By 2015, 181 countries had achieved over 75% coverage with at least basic services³

Fig. Proportion of national population using at least basic drinking water services, 2015
(WHO/UNICEFF, 2017)

Sustainable Development Goals (SDGs):
Goal 6.
Ensure availability and sustainable management of water and sanitation for all
6.1
By 2030, achieve universal and equitable access to safe and affordable drinking water for all
Fig. Proportion of national population using at least basic drinking water services, 2015 (WHO/UNICEF, 2017)

Sustainable Development Goals (SDGs):

Goal 6.

Ensure availability and sustainable management of water and sanitation for all

6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water

Water supply coverage / Water scarcity

Fig. Global physical and economic water scarcity (UNESCO, WWDR4, 2012)
Urban water resource and water cycle

- Drinking water treatment plant
- Wastewater Treatment Plant
- Rain water
- Surface water
- Groundwater
- Sea water desalination plant
- Sea water
- Waste water
- Water reuse
- Drinking water treatment plant
Urban water resource and water cycle

- Drinking water treatment plant
- Sea water desalination plant
- Wastewater treatment plant
- Rain water
- Surface water
- Groundwater

Unstable water quantity

High turbidity

Infectious diseases (Cholera, typhoid, etc.)

Protozoa (Giardia, etc.)

Pathogenic microorganisms
Organic matter → Disinfection by-products

Water reuse

Crypotsporidium
Norovirus
Urban water resource and water cycle

- Drinking water treatment plant
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- Sea water desalination plant
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- Rain water
- Surface water
- Groundwater
- Waste water

As, F

Arsenic health effect

Dental and skeletal fluorosis due to Fluoride uptake

Groundwater

Water reuse

Wastewater Treatment Plant

Sea water

Salt → High energy requirement
Challenges for water purification by membrane filtration

**Highly turbid surface water (MF/UF)**

**Surface water (MF/UF)**

**GW (MF)**

**Sea water desalination (MF/UF+RO)**

**Water reuse (MF/UF+NF/RO)**

**Energy consumption**

**Cost**

**Process Complexity**

**Raw water quality**

**Treated water quality**

- **Microbial safety**
- **Taste / Odor**
- **Chemicals / Ions**

**Chemical contaminants**

- 

**Ions**

- Na⁺
- Cl⁻

**Particles / Protozoa**

- Cryptosporidium
- Norovirus
- E.coli

**Virus**

**Bacteria**

**Process Complexity**

- High

**Raw water quality**

- High

**Treated water quality**

- Low

**Energy consumption**

- High

**Cost**

- Low

**Process Complexity**

- Low
Membrane filtration application in Southeast Asia

- Inappropriate operation and maintenance.
- Less availability of repairing parts.
  → Not enough, or Unsustainable.
- Simple and sustainably operational system is required.
PARTICLE REJECTION IN MEMBRANE FILTRATION OF HIGHLY TURBID SURFACE WATER
Membrane filtration of highly turbid surface water (Fouling resistance / particle rejection)

Fig. Highly turbid surface water in Southeast Asia (Thailand)

Fig. Fouling resistance (Kanezawa et al., 2017)
Conventional Blocking filtration models

Water flow in membrane pore

Hagen-Poiseuille equation:

\[ J = N \times \frac{\rho \pi r^4}{8 \delta_m} \times \frac{\Delta P}{\mu} \]

- \( J \): Flux (m/s)
- \( N \): pore density
- \( r \): pore radius
- \( \Delta P \): TMP
- \( \mu \): viscosity
- \( \delta_m \): membrane thickness
- \( \rho \): water density

Complete Blocking
(m=2)

Intermediate Blocking
(m=1)

Standard Blocking
(m=1.5)

Cake Filtration
(m=0)

\[ \frac{d^2 t}{dV^2} = k \left( \frac{dt}{dV} \right)^m \]

- \( t \): time (s)
- \( V \): filtration volume (m³)
- \( J \): Flux (m/s)
- \( A \): filtration area (m²)
- \( k \): constant

Structure of polymeric membrane and models

Uniform pore size
Cylindrical channel

Nonuniform pore size
Complex channel

Applicable?

*CFD: Computational Fluid Dynamics

(Ando et al., 2010)

(Krupp et al., 2017)

(Sanaei and Cummings., 2017)
Overview of the particle rejection model for porous structured microfiltration membrane

New model: Estimate rejection ratio and depth of particles

Assumptions:
(1) **Multi-layered structure** with independent pore size distribution.

(2) **Particle rejection**: Pore size \( \leq \) Particle size
(Interaction between particle and membrane are not incorporated).

(3) **Particle rejection ratio**
   
   = Probability that particle reaches the pore with the size \( d \text{ (pore size)} \leq D \text{ (particle size)} \).
Model analysis of membrane filtration of mixture of two types of particles

Transition of clogged pore distribution during the filtration of mixture of PS-1.0 and PS-2.0 μm

Number of clogged pores after 50 mL filtration

Particles (<nominal pore size) were rejected near the membrane surface.
BIOFILM ROLE IN GRAVITY-DRIVEN MEMBRANE FILTRATION IN OFF GRID COMMUNITIES
(Gravity-driven) membrane filtration for drinking water production

Shallow well in rural area of Burkina Faso
(Gravity-driven) membrane filtration for drinking water production

Shallow well in rural area of Burkina Faso

Turbidity: ~ 40 [NTU]
E. coli: 95 [CFU/100ml]
Total coliform: 2750 [CFU/100ml]

Water Level Difference: ~3 m

Ceramic membrane (0.1 µm)

Turbidity: < 0.1 [NTU]
E. coli: 0 [CFU/100ml]
Total coliform: 0 [CFU/100ml]

Filtrate
(Gravity-driven) Ultra low pressure membrane filtration for POU

Fig. Biofilm growth on membrane surface through gravity-driven membrane filtration (Yamasaki et al., 2018)

Fig. Flux profile and stabilization (Yamasaki et al., 2018)

Lab-scaled gravity-driven membrane filtration system (Yamasaki, 2018)
Biofilm growth and structure on membrane

3D structure of biofilm

Day 2
Day 5
Day 8
Day 15

Cross section of biofilm

Live Cell
Dead Cell
Polysaccharide
Protein

(Yamasaki et al. J. JSCE 2018)
Roles of biofilm structure on membrane filtration

\[ R_a^* = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{L_{fi} - \bar{L}_f}{\bar{L}_f} \right| \]

- $R_a^*$: roughness coefficient,
- $L_{fi}$: $i$'th thickness,
- $\bar{L}_f$: average thickness,
- $N$: number of thickness measurements

**Roughness coefficient [-]**

![Graph showing roughness coefficient over time for live and dead cells.

**Surface to volume ratio [µm² µm⁻³]**

Live Cell Growth

- Dispersed
- Growth in plane (2 dimension)
- Growth in vertical direction (3 dimension)

![Graph showing surface to volume ratio over time for live and dead cells.](Hashimoto et al, J. JSCE 2018)
Gravity-driven ultra low pressure membrane filtration for POU

\[ \text{\sim 0.5 m} \quad = 5 \text{ kPa} \]

Gravity-driven membrane filtration system (Eawag, 2015)

Flux stabilization (Peter-Varbanets et al, 2010)

Channels and cavities in cake layer (Peter-Varbanets et al, 2011)

Microorganisms from cake layers (Wu et al, 2016)

Possible role of Metazoa (Klein et al, 2016)
Summary

◆ For **sustainable safe drinking water supply** in developing countries,
  – **Physical** and **economic** aspect of water scarcity should be considered.
  – Simple and sustainably operational system is required.

◆ **Membrane filtration of Highly turbid surface water**
  - Could be a **effective barrier** against small particles and colloids (include pathogens) with **lower energy** requirement.
  - New particle rejection model was developed for porous structure.

◆ **Roles of biofilm** on membrane in gravity driven drinking water production,
  – **Biofilm layer** contributes stabilization of water production in gravity-driven membrane filtration system.
Thank you for your kind attention.