Pursuing a Viable Plasma-Based Water Treatment Process: Identifying Transport Limitations and Investigating the Effect of Reactor Design on the Degradation of Bisphenol A

C. Bellona¹, F. Dai¹, J. Franclemont², T. Holsen¹, G. Stratton², S. M. Thagard²

¹Department of Environmental Engineering
²Plasma Research Laboratory, Department of Chemical Engineering
Clarkson University, Potsdam, New York

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Project motivation and objectives

Project motivation:
• Current work on plasma-based systems focuses primarily on chemical degradation mechanisms\(^1,2\)
• Very few investigations examine reactor design and process parameter optimization
• EPA grant for developing a pilot-scale plasma-based drinking water treatment system

Project objectives:
• Choose appropriate model contaminants
• Optimize the process design
  - Reactor design
  - Electrical parameter optimization

Electrical discharge plasmas in water

- Oxidative potential of OH: 2.80 V
- Plasma pressure: ~10⁹ Pa
- Plasma temperature: >2000 K

Features of plasma important in treatment process:

• Source voltage: 16-18 kV
• Discharge frequency: 43 Hz (unless stated otherwise)
• Capacitance: 2 nF (unless stated otherwise)
• Solution volume: 600 mL
• Initial solution conductivity: 300-330 μS/cm
• Initial solution pH: ~5
• Headspace gas: Argon
1. Choose contaminants

Are Some Molecules More Suitable For Plasma Treatment Than Others?

2. Optimize the process design
   2.1. Reactor diameter
   2.2. Discharge phase
   2.3. Load capacitance
   2.4. Ground plate diameter
Emission spectra of plasma in aqueous solutions containing different concentrations of acetone

OH peak in higher resolution
Rhodamine B (RhB) dye

Bisphenol A (BPA)
1. Choose contaminants

2. Optimize the process design
   2.1. Reactor diameter
   2.2. Discharge phase
   2.3. Load capacitance
   2.4. Ground plate diameter
Reactor diameter

The effect of reactor diameter was assessed using the calculated $G_{50}$ value:

$$G_{50} = \frac{0.5 \cdot C_0 \cdot V}{t_{50} \cdot f \cdot E_{\text{pulse}}} \left[ \frac{g}{kWh} \right]$$

- $C_0$: initial contaminant concentration (g/L)
- $V$: solution volume (L)
- $t_{50}$: time to reduce concentration by 50% (s)
- $f$: discharge frequency ($s^{-1}$)
- $E_{\text{pulse}}$: discharge energy per pulse (kWh)
Treatment efficiency vs. reactor diameter

$G_{50}$ (g/kWh)

Reactor diameter (cm)
1. Choose contaminants

2. Optimize the process design
   2.1. Reactor diameter
   2.2. Discharge phase
   2.3. Load capacitance
   2.4. Ground plate diameter
• High voltage electrode: nickel chromium (NiCr) (0.8 mm in diameter)
• Ground electrode: stainless steel (SS)
RhB removal for “point-plane with liquid discharge”

Normalized RhB concentration vs Treatment time (min)
Point-plane with gas and liquid discharge

- High voltage electrode: NiCr
- Ground electrode: reticulated vitreous carbon (RVC)
RhB removal for different reactor configurations

- Point-plane with liquid discharge
- Point-plane with gas and liquid discharge

Normalized RhB concentration vs. Treatment time (min)
Point-plane with gas discharge

- High voltage electrode: NiCr
- Ground electrode: SS
RhB removal for different reactor configurations

- Two sets of parameters were investigated using this configuration.
1. Choose contaminants

2. Optimize the process design
   2.1. Reactor diameter
   2.2. Discharge phase
   2.3. Load capacitance
   2.4. Ground plate diameter
Load capacitor

For a limited HVDC power supply output increasing the capacitance will result in a lower achievable discharge frequency for the specified source voltage

\[ C = \frac{P_c}{V_c^2 \cdot \ln\left(\frac{V_c}{V_c - V_s}\right)} \cdot \frac{1}{f} \]

- \( C \): capacitance of load capacitor (F)
- \( f \): discharge frequency (Hz)
- \( V_s \): voltage at capacitor (source voltage) (V)
- \( P_c \): HVDC supply output power (W)
- \( V_c \): charge voltage (PS output voltage) (V)

(C and \( f \) are inversely related)
RhB removal for different load capacitors

- Point-plane with gas discharge (0.75 nF, 68 Hz)
- Point-plane with gas discharge (2 nF, 43 Hz)
1. Choose contaminants

2. Optimize the process design
   2.1. Reactor diameter
   2.2. Discharge phase
   2.3. Load capacitance
   2.4. Ground plate diameter
RhB removal for different ground diameters

- Point-plane with gas discharge (1.75 cm)
- Point-plane with gas discharge (7.8 cm)
- Point-plane with gas discharge (12 cm)
Ground plate size

Up to 7.8 cm, increasing the ground plate size resulted in better removal

Possible reasons:

• Larger plate enables higher electrical discharge current
• Larger plate causes the plasma to spread wider over the surface, facilitating better contact with the dye
1. Choose contaminants

2. Optimize the process design
   2.1. Reactor diameter
   2.2. Discharge phase
   2.3. Load capacitance
   2.4. Ground plate diameter
      2.4.1 Electrical current hypothesis
      2.4.2 Contact hypothesis
Electrical discharge current hypothesis

Point-point with dual gas discharge

High voltage and ground electrodes: RVC
RhB removal for different reactor configurations

- Point-plane with gas discharge (12 cm)
- Point-point with dual gas discharge
1. Choose contaminants

2. Optimize the process design
   2.1. Reactor diameter
   2.2. Discharge phase
   2.3. Load capacitance
   2.4. Ground plate diameter
      2.4.1 Electrical current hypothesis
      2.4.2 Contact hypothesis
Contact hypothesis

Incorporating liquid feed: 5 configurations in which liquid was pumped through or around the discharge electrodes to improve the contact rate

- Discharge in liquid fed through RVC HV
- Dual discharge in liquid fed through RVC HV and ground
- Discharge in turbulent liquid jet
- Dual discharge in laminar liquid jets
- Discharge in multiple liquid jets
Dual discharge in laminar liquid jets

Discharge in liquid fed through RVC HV
RhB removal for different reactor configurations

- Point-plane with gas discharge (12 cm)
- Discharge in liquid fed over RVC HV and ground
- Discharge in turbulent liquid jet
- Discharge in multiple liquid jets
- Dual discharge in laminar liquid jets
RhB removal for all reactor configurations

![Graph showing RhB removal over treatment time for various reactor configurations.](image-url)

- **Point-plane with liquid discharge**
- **Point-plane with gas discharge (1.75 cm)**
- **Point-plane with gas discharge (7.8 cm)**
- **Point-plane with gas discharge (12 cm)**
- **Discharge in liquid fed over RVC HV**
- **Discharge in multiple liquid jets**
- **Discharge in liquid fed over RVC HV and ground**
- **Discharge in turbulent liquid jet**
- **Point-point with dual gas discharge**
- **Dual discharge in laminar liquid jets**
$G_{50}$ for RhB experiments for all reactors

$G_{50}$

[g/kWh]

Point-plane with liquid discharge

Point-plane with gas and liquid discharge

Point-plane with gas discharge (1.75 cm)

Point-plane with gas discharge (7.8 cm)

Point-point with dual gas discharge

Discharge in liquid fed through RVC HV

Discharge in turbulent liquid jet

Discharge in laminar liquid jets

Discharge in multiple liquid jets
$G_{50}$ with different reactors for RhB and BPA

$G_{50}$ [g/kWh]

- BPA
- RhB

- Point-plane with liquid discharge
- Point-point with dual gas discharge
- Discharge in turbulent liquid jet
Conclusions

Effect of transport properties
• For plasma discharges in liquid, a compound’s hydrophobicity determines its ability to diffuse into the plasma channel
• Considering the hydrophobicity of known contaminants may help to determine the applicability of this treatment strategy

Effect of process design
• Increasing the diameter of the reactor and ground plate strongly enhances removal efficiency, until some maximum is reached
• Gas phase discharge is more effective than liquid phase discharge
• Increasing capacitance at expense of frequency yields faster removal
• Discharges directly in feed achieve more rapid removal
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