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Optimizing Plasma Bubbles at Pilot Scale for Organic Pollutant Degradation in Water

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Abstract This study investigates the scalability of nanopulsed plasma bubble technology for water remediation, transitioning from lab to pilot scale. The pilot-scale plasma bubble reactor was optimized to degrade toxic organic pollutants, including dyes (methylene blue, MB), antibiotics (sulfamethoxazole, SMX), and pharmaceuticals (valsartan, VAL). High degradation efficiencies were achieved: >99% for MB after 10 min, >99% for SMX after 20 min, and >98% for VAL after 40 min. The reactor produced high concentrations of short-lived hydroxyl radicals (·OH, ~25 mg/L under O_2), with minimal long-lived species (O_3, H_2O_2, NO_3^-/NO_2^-), maintaining stable pH (~7). Energy efficiency was superior at the pilot scale, with electrical energy per order (EEO) values of 0.18 kWh/m^3 for MB, 0.42 kWh/m^3 for SMX, and 0.88 kWh/m^3 for VAL, 2-3 orders of magnitude lower than other advanced oxidation processes (AOPs). The system's performance was consistent across tap and ultrapure water, demonstrating its applicability in real-world conditions. These findings highlight the potential of nanopulsed plasma bubbles for rapid, effective, and energy-efficient water remediation at larger scales.

Keywords: non-thermal plasma, water remediation, plasma bubbles, pilot scale, organic pollutants

1. Introduction

Non-thermal plasma technology is a promising approach for water purification, effectively degrading persistent organic pollutants such as dyes, antibiotics, and pharmaceuticals, which conventional methods struggle to eliminate [1-3]. Plasma bubbles enhance the mass transfer of reactive species, particularly short-lived hydroxyl radicals (·OH), into the aqueous phase, improving degradation efficiency compared to traditional gas-liquid plasma systems [4]. This study scales up a lab-scale nanopulsed plasma bubble reactor to a pilot-scale system, evaluating its performance in degrading methylene blue (MB), sulfamethoxazole (SMX), and valsartan (VAL). Key parameters, including plasma gas, pulse voltage, and gas flow rate, were optimized to ensure high degradation efficiency and energy efficiency under real-world conditions.

2. Experimental section

A pilot-scale plasma bubble reactor (2.5 L) was designed with a coaxial dielectric barrier discharge (DBD) configuration, using air, oxygen, or argon as plasma gases. Pollutants (MB, SMX, VAL) at 10 mg/L were treated in tap water. Operating conditions included pulse voltages of 19.4–24.0 kV, pulse frequencies of 300–600 Hz, and gas flow rates of 5–15 L/min. Degradation was monitored via UV-Vis spectroscopy (MB) and HPLC (SMX, VAL). Reactive species (·OH, H_2O_2, O_3) were quantified, and energy efficiency was assessed using the electrical energy per order (EEO).

Figure 1. Photographs of the pilot-scale nanopulsed plasma bubble reactor during pollutant degradation experiments: with the stainless-steel grid serving as the grounded electrode, and without the grid, presented for illustrative purposes to highlight bubble formation.

3. Results and discussion

The pilot-scale reactor achieved high degradation efficiencies: MB (>99% in 10 min), SMX (>99% in 20 min), and VAL (>98% in 40 min) under optimal conditions (24.0 kV, 400 Hz, air, 10 L/min). The system generated high concentrations of ·OH (~25 mg/L under O_2, ~20 mg/L under air), with low levels of long-lived species, maintaining stable pH (~7) suitable for water reuse.

The comparison of energy efficiency (EEO) between the lab-scale (70 mL) and pilot-scale (2.5 L) reactors, as shown in Figure 2, highlights the superior performance of the pilot-scale system. For MB, the EEO decreased from 0.37 kWh/m^3 in the lab-scale to 0.18 kWh/m^3 in the pilot-scale, for SMX from 0.50 kWh/m^3 to 0.42 kWh/m^3, and for VAL from 1.54 kWh/m^3 to 0.88 kWh/m^3. This significant improvement is attributed to enhanced bubble dynamics, better fluid recirculation, and optimized mass transfer of reactive species in the larger reactor, enabling more efficient utilization of plasma-generated ·OH radicals. The pilot-scale system also outperformed other AOPs, as shown in Table 1, with EEO values 2-3 orders of magnitude lower than competing technologies.

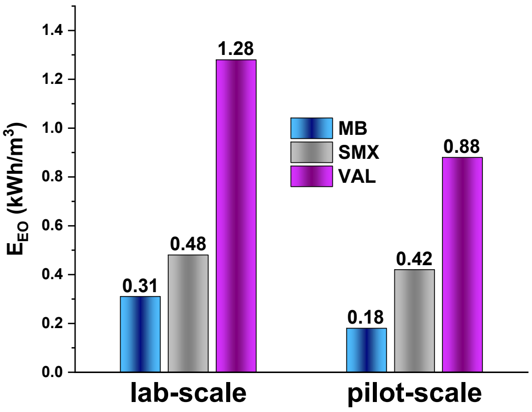

Figure 2. The EEO values for MB, SMX, and VAL in the lab-scale and the pilot-scale plasma bubbles.

Table 1. Comparison of EEO for Pilot-Scale AOPs

Method	Pollutant	Volume (L)	Time (min)	DE (%)	EEO (kWh/m3)	Ref.
Plasma Bubbles	MB, 10 mg/L	2.5	10	99.3	0.18	This study
Plasma Bubbles	SMX, 10 mg/L	2.5	20	99.2	0.42	This study
Plasma Bubbles	VAL, 10 mg/L	2.5	40	98.2	0.88	This study
Photocatalysis /ZnO	Acid Yellow 36	1	122	90	36.6	[5]
UV/Fenton	Industrial wastewater	1	60	>99	25.04	[6]

Conclusions

The pilot-scale nanopulsed plasma bubble reactor demonstrates exceptional potential for water remediation, achieving near-complete degradation of MB, SMX, and VAL with low energy requirements (EEO: 0.18–0.88 kWh/m^3). The system's high ·OH production and stable pH make it suitable for real-world applications, outperforming other AOPs by 2-3 orders of magnitude in energy efficiency. These results confirm the scalability and practicality of nanopulsed plasma bubbles for large-scale water treatment.

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