Review and Perspectives About the Applications of Geometrically Constrained Hyperbolic Vortices in Water and Wastewater Treatment

Klymenko, R.*, Cerutti, L.M.A.**, Colombo M.B.A.**, Agostinho, L.L.F.**

* Department of Electrical Engineering, Electrical Energy Systems group, Eindhoven University of Technology, 5612 AP Eindhoven, The Netherlands

** Water Technology Research Group, NHL Stenden University of Applied Sciences, Rengerslaan 8-10, 8917 DD Leeuwarden, The Netherlands

Highlights:

- **Geometrically constrained hyperbolic vortices are an efficient aeration technology;**
- **The hyperbolic vortex plasma discharge reactor is highly efficient for the degradation of micropollutants, particularly PFAS.**

Keywords: aeration; vortex; hyperbolic funnel; PFAS; degradation; micropollutants.

INTRODUCTION

Aeration is one of the largest operational costs in water and wastewater treatment plants [1]. Traditional methods, like mechanical aerators and diffused air systems, face challenges such as high capital costs, energy consumption, and clogging [2]. A promising alternative is the hyperbolic Schauberger funnel, which creates a vortex purely through water flow, eliminating the need for mechanical stirring devices [3,4]. This method has proven highly effective in oxidizing iron in groundwater and offers a cost-efficient, energy-saving solution. Its unique design and lack of moving parts reduce clogging risks and limit energy use to water pumping, making it ideal for efficient water treatment.

Additionally, integrating water vortex dynamics with plasma discharge technology shows great potential for degrading persistent micropollutants (MPs) [5], including pharmaceuticals, pesticides, PFAS, and microplastics. While some MPs are biodegradable, others are highly persistent, posing risks to ecosystems. The complex nature of MPs complicates detection and removal, often leading to further environmental contamination. Conventional wastewater treatment is often ineffective, contributing to the spread of MPs in water bodies.

Plasma discharge technology integrates multiple advanced mechanisms, such as ultraviolet irradiation, electrolysis, advanced oxidation, surface bombardment by energetic electrons and ions, and shockwave-induced purification. This combination enables the efficient and cost-effective degradation of micropollutants, including PFAS. Studies have demonstrated the hyperbolic funnel's effectiveness in enhancing aeration and its ability to achieve energy-efficient micropollutant degradation through plasma discharge, representing a significant advancement in sustainable water treatment technologies [5].

METHODOLOGY

Figure 1 presents a schematic of the setup used for aeration experiments with a hyperbolic funnel. Groundwater is pumped into the funnel (7) through a control valve (2), which regulates the water flow rate, monitored by a flow meter (3). The water enters the reactor tangentially, generating a vortex due to the combined effects of the reactor's hyperbolic and cylindrical shapes, along with the helical flow of the water. Dissolved oxygen (DO) was measured both before the reactor inlet and after the water reservoir (4). The DO saturation concentration depends on the water temperature, which was recorded at all points where DO measurements were taken to ensure accurate results. Data collection was carried out using a data logger and processed with SoftProSens software.

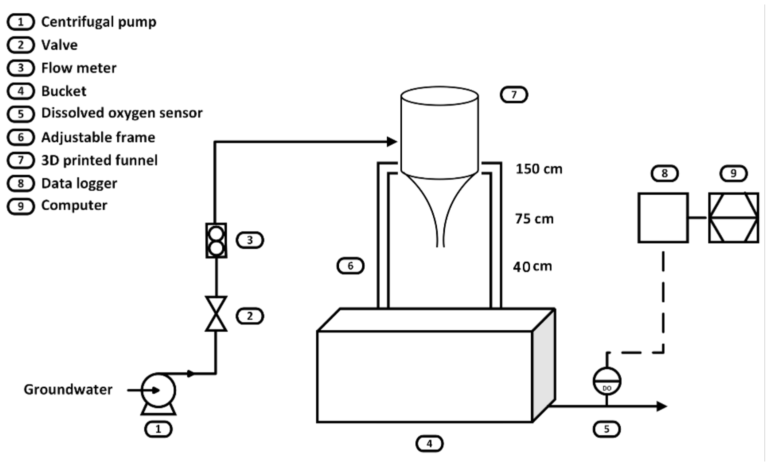

Figure 1 – Sketch of the setup for aeration experiments with a hyperbolic funnel.

Figure 2 depicts the experimental setup for MP degradation using hyperbolic vortex plasma discharge. Stainless steel electrodes (9) were connected to a high-voltage power supply (12) and positioned above the water vortex surface within the funnel (6). A plasma discharge was ignited between the electrodes and the water surface, facilitating direct interaction between the water and the plasma. Further information on the analysis of pulsed electric signals, the experimental setup, and the electrical circuit is available in [5]. MP samples were collected at specific time intervals and analyzed for concentrations using liquid chromatography-mass spectrometry. Defluorination was assessed by measuring the concentration of free fluoride ions (F^-) in the water samples using a fluoride sensor. During the PFAS experiments, surfactant was continuously dosed into the pipeline before entering the reactor to ensure continuous interaction with PFAS. Water was recirculated in the reactor, and its pH, ORP, and EC were monitored throughout the treatment process (3, 4, 5, 8).

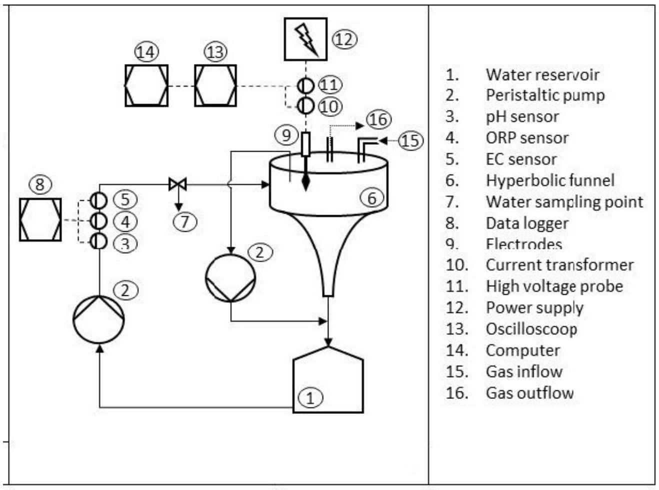

Figure 2 – Sketch of the setup for experiments for MPs degradation by hyperbolic vortex plasma discharge [5].

RESULTS AND CONCLUSIONS

Some of the results are presented in Figures 3 and 4. Figure 3 shows a comparison of the standard aeration efficiency (SAE) between commercially used mechanical aeration systems and the tested hyperbolic funnel, after evaluating other aeration parameters such as the standard oxygen transfer rate (SOTR) and the volumetric mass transfer coefficient (K_{La}). The results indicate that the SAE of the tested hyperbolic funnel reached 2.9 $kgO_2\ kWh^{-1}$, a notably high value compared to other mechanical aeration systems.

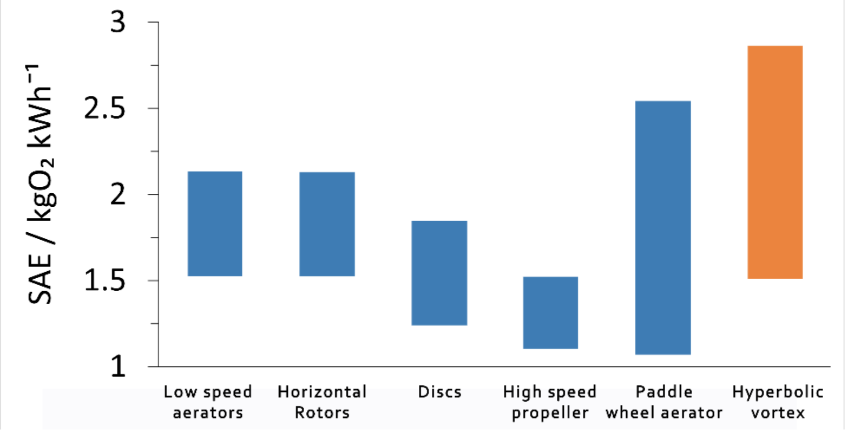

Figure 3 – SAE comparison between commercially used mechanical aeration systems and the hyperbolic funnel [6].

Figure 4 illustrates the degradation and defluorination of PFAS by a hyperbolic vortex plasma reactor. The results demonstrate that, with the constant dosing of Hyamine 1622 surfactant, the reactor can effectively degrade both long-chain PFAS, such as PFDA, PFNA, PFOS, PFOA, and PFHpA, and short-chain PFAS, such as PFBS and PFBA, which are generally more difficult to remove through degradation and absorption processes. The reactor achieved a significant defluorination level of 80%, while consuming only 1.2 kWh m^{-3} of plasma energy.

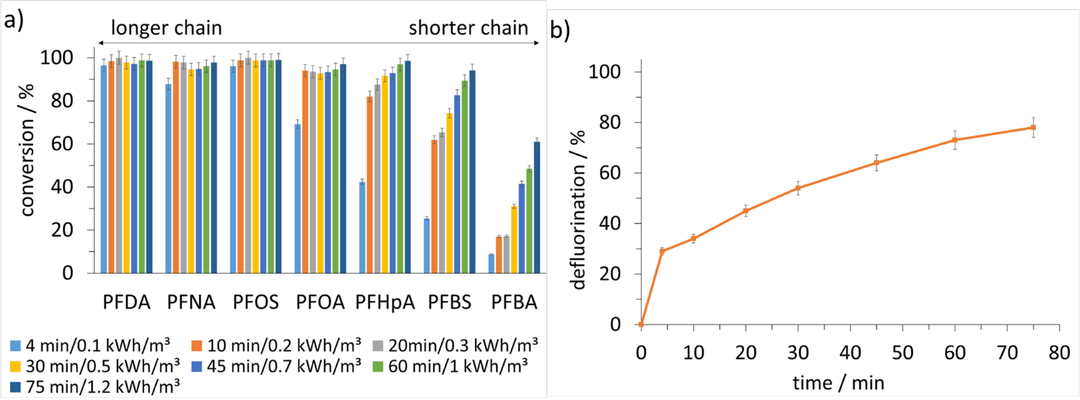

Figure 4 – PFAS matrix conversion and degradation (a) and defluorination over time (b) under plasma discharge with constant Hyamine 1622 surfactant dosing.

ACKNOWLEDGMENTS

We would like to thank Elmar C. Fuchs, Jakob Woisetschläger, Wilfred F L M Hoeben and Maarten V. van de Griend for their valuable contributions to this work. This work was performed in the cooperation framework of Wetsus European Center of Excellence for Sustainable Water Technology (www.wetsus.eu) within the Applied Water Physics theme. Wetsus is cofounded by the Dutch Ministry of Economic Affairs and Ministry of Infrastructure and Environment, The Province of Friesland and the Northern Netherlands Provinces. This research has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie Grant Agreement No. 665874 and the Gilbert—Armstrong lab.

REFERENCES

1. Brandt, M., et al. (2011). Energy efficiency in the water industry: A global research project. Water Practice & Technology, 6(2). https://doi.org/10.2166/wpt.2011.028
2. Von Sperling, M. (n.d.). Basic principles of wastewater treatment. IWA Publishing.
3. Agostinho, L., et al. (2022). Enhanced oxygen volumetric mass transfer in a geometrically constrained vortex. Water, 14, 771. https://doi.org/10.3390/w14050771
4. Klymenko, R., et al. (2023). Preparation of free-surface hyperbolic water vortices. Journal of Visualized Experiments, 197, e64516. https://doi.org/10.3791/64516
5. Klymenko, R., et al. (2024). Characterization of a hyperbolic vortex plasma reactor for the removal of aqueous phase micropollutants. Journal of Physics D: Applied Physics, 57, 215204. https://doi.org/10.1088/1361-6463/ad2b22
6. Samstag, R. W., & Engineers, P. C. (2011). Overview of wastewater aeration. Retrieved from https://rsamstag.wordpress.com/wp-content/uploads/2015/02/aeration.pdf