Next Generation of Marine Scrubbers for Advanced Gas Cleaning

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The maritime sector is responsible for substantial emissions of air pollutants and contributes to the emission of climate-forcing agents, including CO_2 and particulate matter, which affect the climate both through their greenhouse gas (GHG) potential and their role as cloud condensation nuclei. A vessel's emission profile depends on factors such as fuel quality, engine type, and maintenance, and varies widely due to the diversity in ship design and the long operational lifetimes of modern fleets. Several classes of biofuels and e-fuels have been proposed to reduce the GHG footprint of shipping. These fuels have negligible sulfur and ashes, leading to a partial, but not satisfactory, reduction in air pollutant emissions. In a mid-term scenario, exhaust gas cleaning systems remain a key solution for controlling emissions when used with both conventional and alternative fuels. Among these, marine scrubbers are the most established and widely deployed technologies for removing PM and sulfur compounds.

Our research group is developing a next-generation marine scrubber that integrates wet electrostatic scrubbing (WES), structured packings, and artificial intelligence (AI) to achieve enhanced pollutant removal with a reduced system footprint. WES operates as a two-stage process involving gas ionization and scrubbing with electrified sprays. It provides exceptionally high removal efficiency for particles in the size range typical of marine engine exhausts, while also accelerating gas absorption into seawater or alkaline scrubbing solution. This approach enables the simultaneous removal of gaseous and particulate pollutants in a single and compact unit. Tests within the CN4 MOST spoke 3 confirmed its reliability also as a tool for treating exhausts from marine engines using methanol or ammonia. Newly designed structured packings act both as high-efficiency gas-liquid contactors and integrated demisters, improving separation performance while reducing system volume. In parallel, hybrid AI methodologies support advanced plant design and enable the development of digital twins for real-time monitoring, control, and optimization. These methodologies maintain high removal efficiency while minimizing energy and reagent consumption, and support predictive maintenance and fault detection, improving reliability and operational uptime. Experimental and computational studies demonstrate SO_2 removal efficiencies exceeding 98% and PM/PN abatement above 95%, with a 30-40% reduction in volume and/or water consumption compared to conventional open-loop scrubbers. This integrated, multi-technology approach surpasses IMO 2020 requirements and offers a sustainable, future-ready solution for marine emission control.

Keywords: *Maritime shipping; Emission reduction; Wet Electrostatic Scrubbing; Structured packings; Artificial Intelligence*