



Number Size Distribution and Concentration of Droplets Generated by Sailing Ships

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Abstract

Ship diesel engines are a significant source of aerosol nanoparticles on water bodies. The nanoparticles, significantly enriched with various environmental pollutants, are transported ashore by air currents or deposited on the water surface. The predominance of transport over deposition depends on the sedimentation rate of the nanoparticles. In general, the sedimentation rate of nanoparticles is very low, but can be significantly accelerated by scavenging nanoparticles on microdroplets. The mist of microdroplets, a kind of sea-spray aerosol, is generated by sailing ships through hull motion and/or propeller rotation. Therefore, the number and size of microdroplets are critical parameters for the environmental fate of the nanoparticles. The number size distribution and number concentration of microdroplets generated by sailing ships were measured using commercially available disdrometer mounted on the prow of an inflatable boat, which chased the ship. A Meteorological Particle Spectrometer (MPS) was deployed in the Baltic Sea, where a ship with a length of 140 m and a maximum diesel engine power of 7.9 MW was tracked. The distance between the ship and the MPS ranged from 40 to 800 m. The microdroplet number concentration was in the range of $8.2 \cdot 10^{-4}$ - 3.1 cm^{-3} and microdroplet size distribution exhibited mode at 0.05 – 0.10 mm. A Laser Precipitation Monitor (LPM) was used on the Vltava River in Prague, where four ships ranging in length from 30 to 50 m with maximum diesel engine power from 125 to 229 kW and a ferry 8.5 m long with engine power of 22 kW were measured. The distance from the ship stern to the LPM varied between 18 and 120 meters. Out of a total of 54 measurements made, 28 were evaluated. An average speed of the ships was $4.5 \text{ m}\cdot\text{s}^{-1}$. The microdroplet number concentration ranged between $4.6 \cdot 10^{-5}$ - $2.6 \cdot 10^{-2} \text{ cm}^{-3}$, microdroplets number size distributions always showed mode at 0.16 – 0.25 mm. Besides the difference of detection capabilities of the LPM and MPS, the differences between the sea and river experiments for droplet number concentrations and size distribution can be attributed to the difference in size and power of the ships being tracked.

Keywords: Ship, Diesel, Nanoparticles, Water Microdroplets, Sea Spray Aerosol, Wake

1. Introduction

Sea spray aerosol (SSA) is omnipresent above the sea surface. SSA is primarily formed when water disintegrates into droplets. It is naturally generated by strong winds ($>5 \text{ m/s}$), which cause the surface water to move faster than the water below. This leads to the formation of breaking waves under the influence of gravity [1]. During wave breaking, the air is entrained into the water and dispersed into a cloud of bubbles [2], which subsequently rise, forming a whitecap, and burst at the surface [1]. Bubble bursting produces film and jet droplets. Film droplets originate from the ruptured film of a bursting bubble; one bubble can produce up to several hundred film droplets from $0.01 \mu\text{m}$ to several hundred micrometres in radius [3]. Jet droplets are formed from a liquid jet produced after the rupture of the bubble cap, as the cavity left by the bubble fills with liquid [3]. The bubble with a radius of 0.35 mm produces about six droplets, 1.5 mm radius means no or one droplet, each measuring 5–15% of the parent bubble's radius [3]. Additionally, droplets can be generated by the tearing of wave crests - spume drops [4], particularly at higher wind speeds [3]. Spume drops typically range from tens of micrometres up to several millimetres in radius, with atmospheric residence time ranging from a few seconds to minutes [5].

Sailing ships generate SSA through two mechanisms. First, splashing occurs when the hull of the ship interacts with the crest of a wave while the ship is moving [6]. This creates a sheet of water that rises along the bow and hull. The sheet then breaks into ligaments that the wind disperses into spume droplets [6,7]. Second, bubble bursting occurs. Unlike natural processes, these bubbles are formed through cavitation caused by the rotation of the ship's propeller [8]. Consequently, the ship leaves behind a wake filled with bubbles that resembles intense shear rather than regular surface waves.

Sailing ships, besides SSA, also generate nanoparticles from their diesel engines. The nanoparticles can be scavenged by concurrently generated SSA. Number concentration N_{nano} coagulates with number of SSA particles N_{SSA} according to general equation [8] where K_{nano} and $K_{\text{nano-SSA}}$ are coefficient of nanoparticle self coagulation or nanoparticle-SSA coagulation, respectively, with the j -th sizes of the SSA particles occurring at time t . The $K_{\text{nano-SSA}}$ increases significantly with SSA particle diameter [9].

$$\frac{dN_{nano}(t)}{dt} = \frac{1}{2}K_{nano} \sum N_{nano}(t)N_{nano}(t) - K_{nano-SSA}N_{nano}(t) \sum_{j=1}^{\infty} N_{SSA}(t) \quad (1)$$

We can presume, that an SSA droplet of size larger than 50 mikrons can significantly scavenge ship diesel nanoparticles, thus significantly increasing their settling velocity and shortening their residence time. To quantify this effect, we conducted measurements of SSA particles large than 50 micrometres. We adapted commercially available disdrometers to determine the number size distribution of such large droplets behind the sailing ship.

2. Experimental

To measure the number and size distribution of droplets generated by ship movement, two types of disdrometers were used. Laser Precipitation Monitor – LPM (Thies Clima) and Meteorological Particle Spectrometer – MPS (Droplet Measurement Technologies). These disdrometers differ in size spectrum and integration time (Tab.1.).

Tab. 1. Technical parameters of disdrometers.

Parameter	Laser precipitation monitor LPM	Meteorological Particle Spectrometer - MPS
Droplets size	0.16 - 8 mm	0.05 – 3 mm
Integration time	60 s	0.1 – 1 Hz

Both disdrometers were mounted on the prow of an inflatable boat. The LPM's detector was positioned at a height of approximately 0.5 m above the water surface, and the MPS's detector at 1.2 m. The LPM was employed for measurements on the Vltava River in Prague, while the MPS was used for measurements in the Baltic Sea. On the Vltava, the boat was powered by an electric motor; on the Baltic Sea, it was powered by a combustion engine. The distance between the boat and the observed vessel was measured using a Nikon Forestry Pro II laser rangefinder. The boat travelled directly behind the observed vessel at a distance of 15-120 on the Vltava River and up to 800 m on the Baltic Sea.

3. Results and discussion

Measurement on the Vltava River was carried out between the Vyšehrad Railway and the Jirásek Bridges from June 9 to September 6, 2024. A 28 measurements were evaluated performed, of total of 54 conducted. Four sightseeing vessels, each 30–50 m in length, were monitored, as well as one small ferry (Tab.2). The average vessel speed was approximately 2.8 m s^{-1} , with a maximum of 4.5 m s^{-1} . The total droplet count ranged from 4.6×10^{-5} to $2.6 \times 10^{-2} \text{ cm}^{-3}$. The droplet size distribution was dominated by smallest detected droplets of 0.125 - 0.25 mm in diameter (Fig. 1).

Tab. 2. Name, dimensions, diesel power and displacement of the ships on the Vltava river.

Ship name	Ship length m	Ship width m	Power kW	Displacement t
Břehouš	8.5	2.5	22.0	11.0
Albatros	28.47	5.4	125.0	175.0
Andante	31.98	5.4	142.0	159.0
Hamburg	36.95	5.4	138.0	215.0
Moravia	38.2	6.7	229.0	304.0

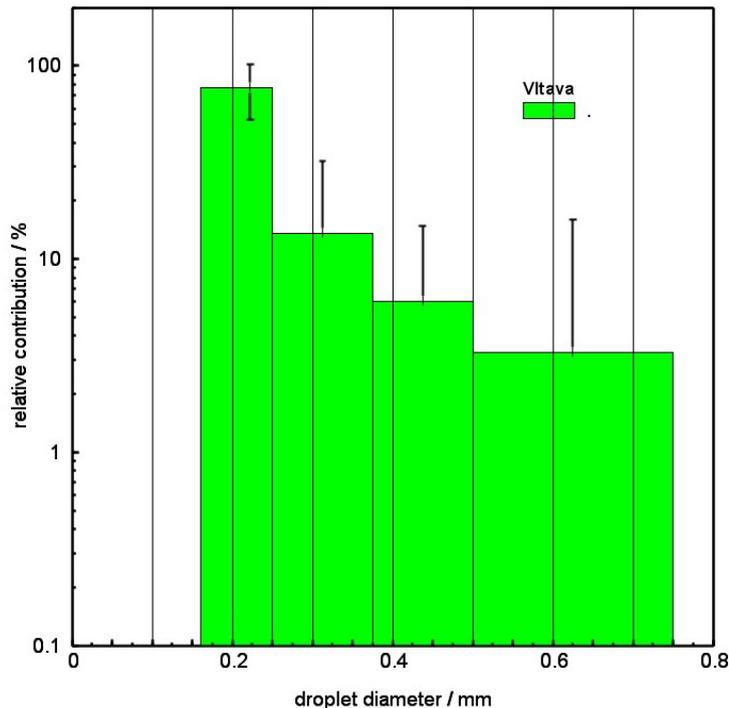


Fig. 1: Relative size distribution of droplets behind a ship on the Vltava River. Average values with standard deviations (n=24).

The subject of the measurement in the Baltic Sea was a ship of 140 m in length and 22 m in width, with a displacement of 11 kt and a 7.9 MW diesel engine, was. This vessel was therefore significantly larger than the sightseeing boats on the Vltava River. It reached a speed of 4.2 m s^{-1} . The total droplet count ranged from 8.24×10^{-4} to 3.1 cm^{-3} , with microdroplets in the 0.50-0.10 mm range being the most abundant (Fig. 2).

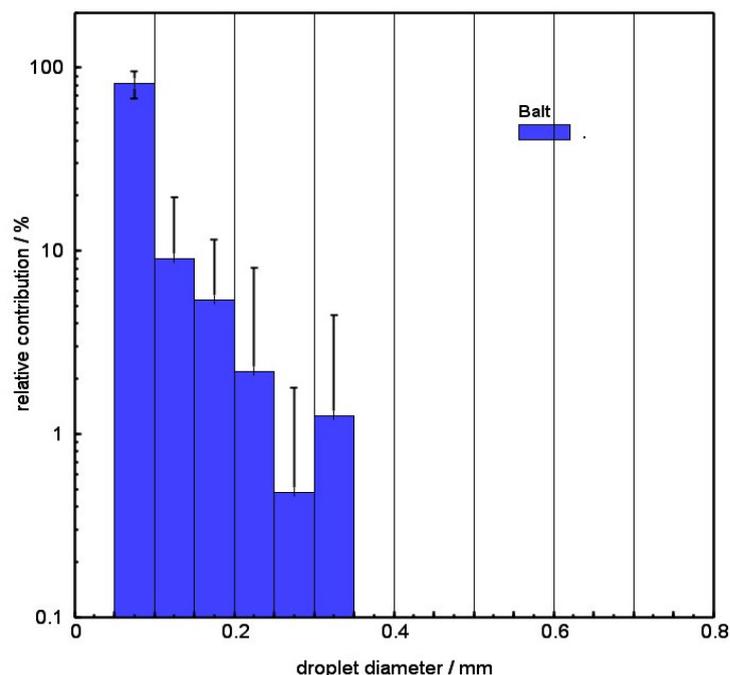


Fig. 2: Relative size distribution of microdroplets number concentrations behind a ship in the Baltic Sea. Average values with standard deviations ($n=8$). Total microdroplet number concentration varied in the range of 8.2×10^{-4} - 3.1 cm^{-3} .

The relative size distributions of droplets in both the Vltava River and the Baltic Sea were dominated by the smallest detectable droplet size. Therefore, it is difficult to explain the much higher number of droplets in the Baltic Sea than in the Vltava River simply as a consequence of different ship dimensions, displacement, or power. Nevertheless, an MPS measurement of a total SSA droplet concentration of 10 cm^{-3} suggests their significant impact on the residence time of diesel nanoparticles. The settling velocity of 500 μm droplets is about 2.7 ms^{-1} [10]. Therefore, diesel nanoparticles practically disappear immediately when scavenged by droplets of this size. Suppose that the diesel nanoparticles are dominated by particles with an aerodynamic diameter of 20 nm [11]. The coagulation coefficient between the 20-nm particles and a 500- μm SSA droplet can be calculated as $K_{20-500000} = \sim 5 \times 10^{-5} \text{ cm}^3$ [9]. According to equation (1) the residence time $\tau = 20 \text{ s}$ for 20 nm nanoparticles, at number concentrations of the 500 μm SSA droplets about 10^3 cm^{-3} , is very short and significantly influence environmental impact of the nanoparticles.

3. Conclusion

Our results from the first in-situ measurements suggest that SSA droplets generated by sailing ships can significantly affect the residence time of ship diesel nanoparticles. Therefore, this process should be considered when evaluating the environmental effects of ship diesel nanoparticles.

Acknowledgments

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