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Particulate matter in marine diesel engines exhausts: Emissions and control strategies

Francesco Di Natale [a,*], Claudia Carotenuto [b]

[a] Dipartimento di Ingegneria Chimica, dei Materiali e della Produzione Industriale, Università di Napoli "Federico II", P.le Tecchio 80, 80125 Napoli, Italy
[b] Dipartimento di Ingegneria Industriale e dell'Informazione, Seconda Università di Napoli, Via Roma 29, 81031 Aversa (Caserta), Italy

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ABSTRACT

Marine diesel engines emit particles that have a complex nature, being composed by carbonaceous particles, with size spanning from few nanometres to less than one micron, and inorganic particles of micron size mainly made by ashes and sulphates.

On a global scale, international shipping is responsible for few percentages of the particulate matter emissions, which also affect climate, but the regional distribution of naval traffic suggests the insurgence of significant exposure risk for population living along the coastal areas, due to chronic exposure effects. Specific strategies should be implemented to reduce the emissions of all the components of particulate matter. This paper aims to present a survey on the current and innovative strategies to remove particles from marine diesel engine exhausts, along with a critical review of the most recent findings on ships emitted particles. Evidences on physical–chemical properties, toxicology and emission factors of the particles were reported. This survey indicates that several strategies can provide a significant reduction of particulate matter emissions from ships and integration between innovative after-treatment systems, ships design and operation procedures can potentially lead to overall reduction of more than 99% even with parallel fuel savings.

Introduction

Shipping is the most energy efficient and environmental friendly conventional (fossil fuel-fired) transport modality, being the emission rate per ton-mile far lower than that required for aviation, rail and car transport (European Environment Agency, 2014; Natural Resources Defence Council, 2014). For this reason, around 85% of world trading shipments follow maritime routes. Almost 70% of these routes are concentrated within 400 km from the coastline (Corbett et al., 1999; Endresen et al., 2003; Eyring et al., 2010; Eyring et al., 2005b). Shipping emissions influence air quality at long distances from the emitting source (Attica Project, 2009; Eyring et al., 2010; Eyring et al., 2007) and some pollutants have a worldwide dispersion (Bond et al., 2013; Seinfeld and Pandis, 1998) also affecting climate.

The most widely adopted ship propulsion systems are the slow-speed two strokes (60–300 rpm) and medium-speed four strokes (300–1000 rpm) diesel engines fuelled with the relatively inexpensive intermediate (or "heavy") fuel oil (IFO) that, unfortunately, leads to massive emissions of pollutants. Statistical results on the emissions from existing ships based on data of the Lloyd's Register and of the US Coast Guard (EPA, 2000) reported a typical range of concentrations as follows: O_2 10–12% $v/v_{dry\ basis}$; CO_2 3–10% $v/v_{dry\ basis}$; NO 600–1500 ppm $v_{dry\ basis}$; SO_2 80–1000 ppm $v_{dry\ basis}$; CO 50–500 ppm

* Corresponding author. Tel.: +39 0817682246; fax: +39 0815936936.
E-mail address: Francesco.dinatale@unina.it (F. Di Natale).

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$v_{dry\ basis}$; VOC 50–400 $ppm_{wet\ basis}$ (volatile organic compound). The 6th European Framework Programme project QUANTIFY (2010) provided further details on the VOC compounds, which are mainly formed by benzene, toluene, butyl-acetate and xylene (Moldanová et al., 2009). Cooper et al. (1996) reported tentative emission factors for selected hydrocarbons, Polycyclic aromatic hydrocarbon (PAH) and Polychlorobiphenils (PCB), emitted by two passenger ferries under normal operating conditions (four-stroke medium-speed main engines). Ethene, propene, isobutene, benzene and C9–C12 alkanes dominated the hydrocarbon compositions, although their relative proportions differed considerably between the two ferries. The PCB emissions were negligible while the PAH accounted for around 1% of the total VOC.

After recognizing the severity of health effects related to PM, NO_x and SO_2 exposure and the relevance of shipping on the worldwide and regional atmospheric pollution, specific guidelines were introduced in the Regulations 13 and 14 of the Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) of the International Maritime Organization (IMO) that entered in force on the 19th of May 2005. According to the MARPOL VI Article 14, SO_2 and sulphates particles emissions should be reduced either by using proper scrubbers as after-treatment system or by lowering the sulphur content in the fuels. In specific Environmental Control Areas (ECA), the admitted sulphur weight content in the fuel had to be lower than 1% from the 1st of January 2010 to the 31st of December 2014. Nowadays the maximum admitted sulphur content is 0.1% that will be extended to all ships in the world by 2020. The former limit allowed the use of low sulphur fuels as Marine Diesel (Gas) Oil, known by the acronyms MDO or MGO. Ultra low sulphur fuels (ULSF) are required to comply with current limits. Unfortunately, the unit costs of these fuels is far higher than that of conventional IFO and cost benefit analyses are now driving part of the Maritime Sector towards the adoption of after-treatment systems to comply with regulations. Cullinane and Bergqvist (2014) recently highlighted that the introduction of ECA regions did not produce a modal shift towards other transport means. The same authors also envisaged that the large socio-economic benefits and the global challenges of containing pollution in densely populated areas, such as the Mediterranean and Asia, emphasize the importance of designating more regions as ECAs.

Diesel particulate matter (PM) emitted by ship engines is a mixture of different kinds of particles with size spanning from few nanometres to several microns. Among them, the soot particles are related to severe pathologies and classified as carcinogenic of Class I by the World Health Organization (International Agency for Research on Cancer, 2012). Marine diesel engines also contribute to the emission of black carbon, which is recognized as an important climate-forcing agent.

Ships are responsible for a small fraction of the worldwide particles emissions, but the regional distribution must be carefully considered (Eyring et al., 2007). For example, biomass combustion is dominant and diffused in the South hemisphere, while around 70% of the emissions in Europe, North America and Asia derives from industry and transportation (Bond et al., 2013). The impact of shipping on environmental pollution levels is the highest along the west and east coasts of the United States, North Europe, North Pacific and Mediterranean Sea and close to Indian coasts (Eyring et al., 2005a,b; Eyring et al., 2007). The impact on population is still largely unrecognized but widely diffused. In fact, census data show that in the USA and in the European Union about 53% (Crosset, 2004) and 40% (Collet and Engelbert, 2013) of the resident population lives in coastal areas. In South America and Asia (with the exception of India) from 60% to 75% of the population lives within 400 km from the sea (Hinrichsen, 1998). On a global scale, 23% of the world population density live within 100 km from the shoreline (Nicholls and Small, 2002), and 23 up to 28 of the largest megalopolis, with more than 10 million inhabitants are in coastal areas.

In spite of these findings, to date there are no specific regulations pertaining to the emission of particulate matter, apart from the side effect related to the use of low sulphur fuel in the Marpol VI. Nevertheless, in the last years, the IMO started a panel to investigate the black carbon emission, measurements and possible mitigation strategies with reference to its climatic effects.

The evaluation of exposure risk associated with ships' engine emitted particles and the assessment of strategies to control particulate emissions are important research topics echoing a concrete societal need. The mitigation strategies must take into account the different constituents of particulate matter. The coarse particles in the ship's engine exhausts are related to the presence of sulphur and ashes in the fuel and can be effectively removed by using distillate fuels or by adopting scrubbers, as indicated by the MARPOL Annex VI. Finer particles with submicron size are related to both fuel properties and combustion processes. Strategies to reduce their emissions include optimization of ship and engine designs, use of cleaner fuels and adoption of proper exhaust gas cleaning systems. The implementation of ship operation practices to reduce energy consumption is also of interest.

Unfortunately, the absence of specific regulations does not allow to collect significant amount of quantitative data on the effective removal of particulate matter associated with these different strategies. However, reliable indications on the reduction of particles emissions can be derived from experimental studies at laboratory and pilot scale, from the experience on the removal of PM associated pollutants (e.g., CO_2, SO_2) or from data on composition and usage of fuels.

This paper presents a survey on the state of the art of the current knowledge on the physical–chemical properties, the toxicology and the emissions of particles from ships, together with an analysis of the mitigation strategies commercially available, as well as of those concepts and emerging technologies under development and proved either at pilot or laboratory-scales.

For the sake of simplicity, this paper is divided into two main parts. The first one provides an overview of the current knowledge on particulate matter emissions and characteristics. To simplify this description, this part is divided into paragraphs discussing characteristics, toxicology, climatic effects, emissions and regulations. The second part reports a critical review on the consolidated and innovative mitigation strategies to reduce particulate emissions from the exhaust gases.