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ABATEMENT OF PARTICULATE MATTER AND SO_2 EMISSION BY SHIPS

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Abstract

Ship engines emit noxious gases (SO_2, NOx, and VOC) and particulate matter (PM), mostly black carbon. Since 1990, the International Maritime Organization (IMO) regulations gradually restricted the level of emission of NOx, which since 2016 have to be lower than 2-3.4 g/kWh, depending on engine power. SO_2 emission reduction has begun since 2010 and now the content of sulphur in marine fuels is limited to 3.5%. At the same time, the Sulphur Emission Control Areas (SECA) has been established, at which the sulphur content in fuel cannot be higher than 0.1%. Since 2020, only a fuel of 0.5% sulphur can be used at all cruising areas outside SECA. It should be noted that due to lack of efficient technology, IMO still has not issued regulations regarding the PM emission by ships. The paper discusses various electrostatic techniques used for the reduction of PM emission in Diesel engine exhausts. Electrostatic scrubber systems, using seawater, allow removal of PM from exhausts with high efficiency and simultaneously SO_2 gas. Electrostatic agglomerators allow increasing submicron and nanoparticles by coagulation of those particles to the larger ones, which could be removed by conventional techniques.

Keywords: *marine transport, Diesel exhausts, air pollution control, environment protection, PM removal*

1. Introduction

Ship transport services more than 90% tonnage of international trade, including raw materials, industrial products, foodstuffs, fuels etc. [9]. Exhaust gases emitted by a typical ship engine of power of 5 MW by 20% load, fed with fuel of 3.5% sulphur, are composed of 5-8% CO_2, 10-13% O_2, 75% N_2, 5% H_2O and some noxious gases: SO_2 (600-750 ppm), NO_x (1500 ppm), VOC (180 ppm). There is usually over 100 mg/m^3 particulate matter (PM) in those gases. It is estimated that ship transport contributes to global contamination of atmosphere at a level of about 15% of NO_x,

3-9% of SO_2, and 2.5-4% of greenhouse gases (comprising of CO_2 and hydrocarbons) [6-9, 28, 30]. Total emission of PM by ships has been estimated at 3-8% of world's PM production [8] that provides over 1.8 million tons of PM annually [28]. The main component of PM is black carbon; to which ship contribute at about 2% of total world's production [26].

Diesel engine particles consist of solid carbon (41%), unburned lubricant (25%), unburned fuel (7%) and ash (13%), and contain polycyclic aromatic hydrocarbons, which are very dangerous to human health. The composition of particles may vary depending on the kind of fuel and engine operating conditions. The rest is condensed water and sulphur compounds. The sulphur in fuel is oxidized during combustion mainly to SO_2, with a small amount SO_3, resulting in the production of sulphuric acid and sulphates particles. Most of the primary particles emitted by Diesel engine are smaller than 50 nm. Those particles coagulate with decreasing temperature of the exhaust, forming secondary particles of size from 100 nm to 1000 nm, which can further aggregate to millimetre-size particles before leaving the funnel [20]. Those particles can also be carriers of sulphuric acid because of water condensation on them and absorption of SO_2 [18, 31].

The emission by marine transport has been unregulated for many years because the emission was noticeable only at near harbour areas, far from large human agglomerations, that abated its harmful impact. Other reasons for postponing the regulation were potentially high investment and running costs for ship holders, and lack of sufficiently cheap and efficient technology of gas cleaning. The first restrictions in the emission by ships, issued by International Maritime Organization (IMO), known as MARPOL 93/97 Annex VI *Regulations for the Prevention of Air Pollution from Ships*, Regulation 13, entered into force on 19 May 2005. That regulation has limited the emission of nitric oxides (NO_x) depending on rotational speed of each Diesel engine on board and engine construction date. The maximum emission level depending on the engine speed for three intervals of engine construction dates is shown in Fig. 1. The maximum emission by engine constructed after 1 January 2016 is between 3.4 and 2 g/kWh. Selective catalytic reduction systems of efficiency higher than 95% are usually used for the NO_x emission abatement.

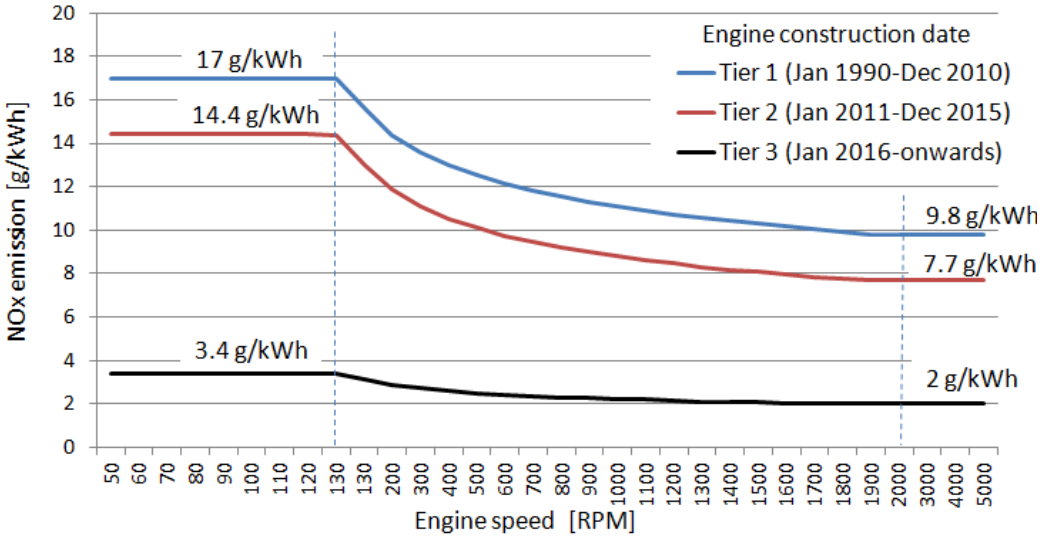

Fig. 1. The maximum NO_x emission level by ship Diesel engine depending on the engine speed for three intervals of engine construction date (IMO Annex VI, Regulation 13)

In the same IMO document, Regulation 14 limits the sulphur content in fuel and the emission of SO_x. The history of the limits of SO_2 content in fuel used by category 3 ships, i.e., ships with an engine of cylinder displacements above 30 dm^3, is given in Table 1. The same Annexe VI has defined the special Sulphur Emission Control Areas (SECA), at which the content of sulphur in fuel used has been further limited to 0.5% and 0.1% S since 1 January 2015. The SECAs comprise Baltic Sea (since 19 May 2006), North Sea with English Channel (21 November 2007), and North

America costal zones (1 August 2011) with Puerto Rico and US Virgin Islands (1 January 2014), extending 200 nautical miles offshore. Since 2025, SECAs will also comprise of Mediterranean Sea, and the costal zones of Korea, Japan, Singapore and Australia. At other cruising areas, only 0.5%S fuel will be used since 2020. However, following IMO regulations any gas cleaning system is allowed on-board to comply with those restrictions, but in this case, the emission is measured as the ratio of ppm SO_2/%CO_2 at the funnel outlet. In that case, the emission of SO_2 is determined via recalculation of actual ship emission to the sulphur content in fuel. The sulphur emission ratio equivalent to sulphur content in fuel is shown in Fig. 2. For example, in SECA, the level of emission should not exceed 4.3 ppm SO_2/%CO_2 to comply with the 0.1% S limit in fuel.

Regulations for operational CO_2 emissions were adopted in July 2011 as Amendment of MARPOL Annex VI. In January 2013, IMO introduced the Ship Energy Efficiency Management Plan (SEEMP) in order to monitor the energy efficiency and CO_2 emission by ships. In 2013, European Commission announced the introduction of Monitoring, Reporting and Verification scheme for CO_2 emissions by ships, which will be obligatory to ships of 5000 GT and above. The monitoring of emission of CO_2, NO_x, SO_x, refrigerants, oil from bilge water, and wastes will be obligatory for all vessels, independently of their size and type, starting from January 2018.

Tab. 1. The limits of SO_2 content in fuel used by category 3 ships (IMO Annex VI, Regulations 14.1 and 14.4)

Year onward	SECA	EU ports	Other areas	California coastal
2010	1.0 wt.%	0.1 wt.%	4.5 wt.%	0.5 wt.%
2012	1.0 wt. %	0.1 wt.%	3.5 wt.%	0.1 wt.%
2015	0.1 wt.%	0.1 wt.%	3.5 wt.%	0.1 wt.%
2020 (2025)	0.1 wt.%	0.1 wt.%	0.5 wt.%	0.1 wt.%

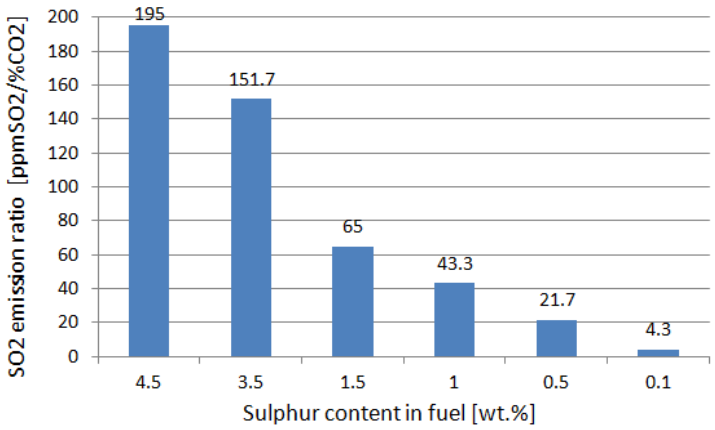

Fig. 2. Sulphur emission ratio equivalent to sulphur content in fuel (IMO Regulations 14.1 and 14.4)

Regarding the PM emission by ships, IMO has not issued any detailed regulations, although US Environmental Protection Agency (EPA) is working on a program for evaluating the efficiency of reduction of PM10 and PM2.5 emitted by Diesel engines fed with low sulphur fuels, and similar regulations regarding PM emission reduction will be expected in the future [32]. It should be noticed that still lack an efficient technology for PM removal, and in particular selective emission control technology for black carbon [26].

2. Technical means to reduce PM and SO_2emission

Ship owners and ship holders have three main solutions to comply with IMO requirements regarding SO_2 emission [15, 32]: (1) switching between cheap (>0.5%S) fuel outside the SECA and expensive low-sulphur (0.1% S) fuel at control areas; (2) installing feed system for permanent

using alternative fuels for ship propulsion (LNG, propane, methanol etc.); (3) still feeding the engine with high-sulphur fuel and using an Exhaust Gas Cleaning System (EGCS) for the removal of SO_2. By the third solution cheap, high-sulphur fuel can be permanently used at all cruising areas. The first two solutions (1) and (2) allow decreasing sulphur emission but are ineffective in the reduction of PM. Scrubber systems, using sea water, allow removal of SO_2 and partially also PM from exhausts.

Fuel switching requires only upgrading of fuel supply installation by installing secondary fuel storage tanks, pipeline systems and additional combustion equipment compatible with both fuels. The switching process requires 1-2 hours for HFO warming before injection, when the ship crosses the border of ECA. For these reasons, the requirement for 0.1% S for ships at berth is applied only for the berthing longer than 2 h [15, 32]. Regarding alternative fuels, in case of LNG, 3-4 times larger space on-board might be necessary for LNG tank than for an equivalent liquid fuel that reduces cargo space even by 3.5% at container ships and car carriers, when LNG tanks are placed on deck [28]. The conventional, available on market, scrubber systems, using sea water, allow removal of SO_2 with high efficiency but PM can be removed with low efficiency, usually lower than 60% [27]. Various electrostatic techniques have therefore been developed and tested in order to further increase the collection efficiency of PM from Diesel exhausts.

2.1. Electrostatic scrubbers for PM removal

Inertial scrubber is a device in which water droplets are sprayed in order to capture the dust particles carried by the gas. In inertial scrubbers, particles are deposited onto droplets due only to their inertia, and for this reason scrubbers are constructed as counter-flow to obtain high relative velocities. In electrostatic scrubbers, water droplets are charged electrically to employ electrostatic forces acting on oppositely charged particles. In such devices, droplets are atomized in a scrubber chamber and the collection efficiency increases in case of low relative velocities between particles and droplets. For this reason, electrostatic scrubbers are constructed as co-flow devices. Electrostatic scrubbers are particularly suitable for the removal of submicron particles (PM1) because electrostatic forces are higher than inertial force for particles smaller than 5 μm [2, 4]. It was demonstrated that electrostatic scrubbers require 4-7 times less water from inertial scrubbers for achieving the same removal efficiency [10].

Three main processes: particle charging charged spray generation, electrohydrodynamic mixing of both these charged aerosols are involved in the wet electrostatic scrubbers. The operation of those processes is schematically shown in Fig. 3 [13]. The collection efficiency of wet electrostatic scrubbers for particles < 1 μm is higher than for other methods, and water-soluble gaseous contaminants (SO_2) can simultaneously be removed. The pressure drop in scrubber is low and similar to electrostatic precipitators or inertial scrubbers.

A novel construction of electrostatic scrubber has been developed within the EU FP7 DEECON project as a part of an on-board, after-treatment system, which was designed to abate of PM, SO_x, NO_x, and VOC emission [1, 13]. The system combined electrostatic sea-water scrubber, non-thermal plasma reactor and selective catalytic reactor. A photograph of a head of electrostatic scrubber for charging particles and generating charged droplets mounted on scrubber column is shown in Fig. 4. The scrubber was installed and tested at the Ship Engine Laboratory of the Gdynia Maritime University. The 90% of PM removal efficiency and 95% of SO_2 from Diesel engine exhausts in this system were reported [6, 13].

Similar to on-board inertial scrubbers, electrostatic scrubbers can also be constructed as hybrid systems, which can operate as open loop or closed loop, depending on regulations specific to cruising areas. The gas cleaning efficiency of hybrid system is independent of the sea-water alkalinity because alkaline can be added if pH of sea water is too low. Although the investments costs of hybrid system are higher than for closed or open loop systems operating alone, the operational costs can be lower because each kind of marine fuel can be used.

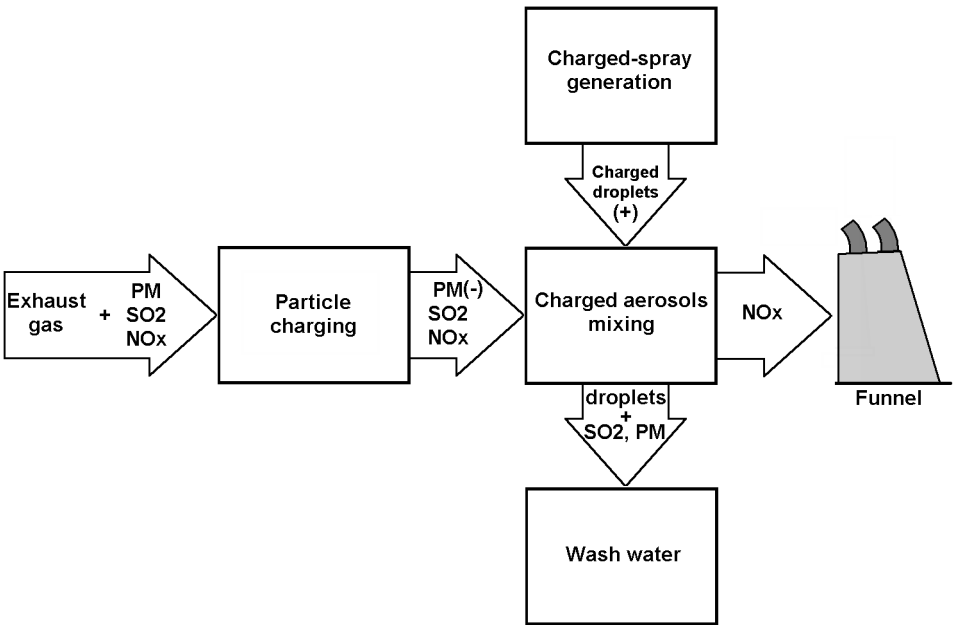

Fig. 3. Schematic of operation of wet electrostatic scrubber

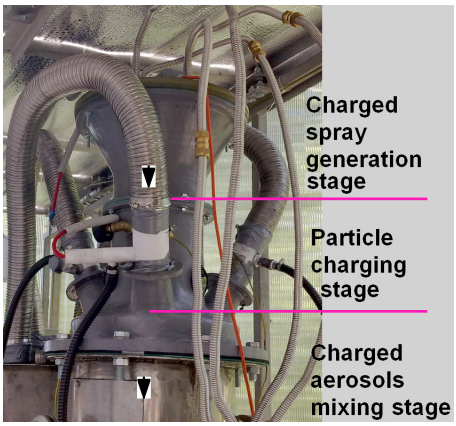

Fig. 4. A photograph of head of electrostatic scrubber charging the particles and generating charged droplets mounted on scrubber column

In open loop mode, the system uses seawater for the gas scrubbing process. During the scrubbing, particles are captured by droplets and SO_2 is simultaneously absorbed. The absorption process relies on the natural alkalinity of seawater, which depends on the sum of concentrations of alkaline species. An advantage of open loop system is that the scrubbing process requires no hazardous chemicals and seawater is the only scrubbing agent. A disadvantage of such system is that operation with brackish or fresh water with low alkalinity or in high water, temperatures can inhibit scrubbing of SO_x although the collection efficiency of PM is unaffected

In closed-loop mode, the system operates in the same manner as the open-loop one except that most of the scrubbing water re-circulates in the system with only small bleed-off and effluent discharge. In closed loop system, alkaline (usually NaOH) is added in order to control alkalinity of wash water. An advantage of the closed loop system is that the system can operate in all regions regardless of seawater alkalinity or temperature. A disadvantage of such system is that it requires a constant supply of alkaline for SO_x absorption, a hazardous substance requiring special handling and care that generates additional costs.

Regardless of technique used for exhaust gas cleaning, ship deadweight and stability has to be revised due to additional weight of the system (scrubber column, water and sludge storage tanks, pumps, particulates separators, etc.), which can exceed tens of tons. It is the rule that all heavy

auxiliary components have to be located in the engine room, but scrubber have to be located near the funnel, i.e., at the upper deck, due to operational reasons, that can change vessel stability. Ship equipped with EGCS system requires additional power for operation of the system: pumps for spraying water, water and gas cooling system, sludge removal, alkaline dosing, additional fan at the funnel outlet, and control and monitoring systems. The main power results from the energy required for raising the water against the gravity at a height from tanks located in the lower engine room to the scrubber located near the funnel, which is estimated to about 50 m, and the power required for increasing water pressure necessary for fine droplets spraying, which can be as high as 6 bar at the nozzles. When these loads exceed the electric capacity available in an existing vessel, an additional generator has to be considered.

2.2. PM agglomerators

One of the concepts considered for increasing the efficiency of removal of PM from exhaust gases is agglomeration of nano- and submicron particles to the larger ones, for a time sufficiently long for their precipitation. Agglomerated particles, when stable, can be removed by conventional techniques with higher collection efficiency than the smaller ones. Acoustic agglomerators [5, 35] or electrostatic agglomerators are the most frequently mentioned devices in the literature. However, acoustic agglomerators require too much energy for large-scale industrial applications.

Two types of electrostatic agglomerators can be distinguished: bipolar and unipolar. In bipolar agglomerator (Fig. 5) the gas stream conveying the particles is split to two equal sub-streams flowing through two separate chargers, which impart opposite electric charges to those particles [11, 14, 17, 19, 21, 22, 27, 33, 36, 37]. In the second stage, the two streams are mixed, and the particles collide forming larger ones. Those agglomerates remain stable when the cohesive forces are larger than aerodynamic and electrostatic forces, due to remnant charge on the agglomerate. Bipolar agglomerator with turbulent mixing of oppositely charged particles flowing between obstacles was also developed [16, 34].

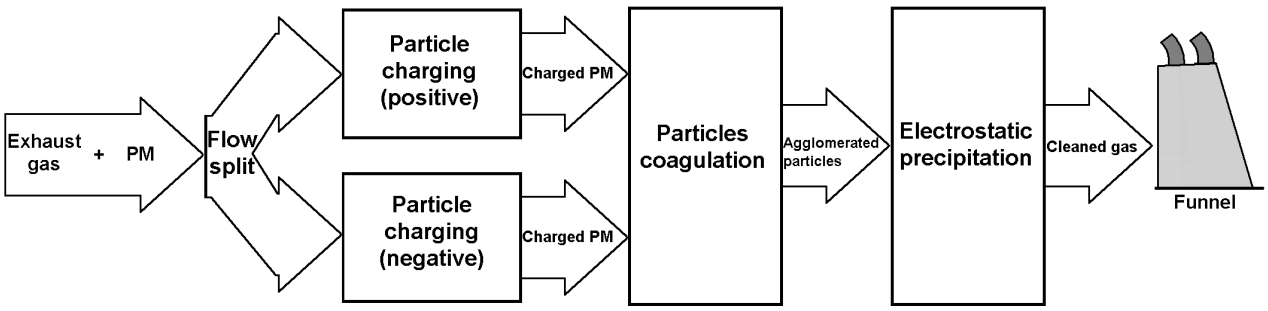

Fig. 5. Bipolar electrostatic agglomerator

The disadvantage of bipolar agglomerators is that the charges of two colliding particles neutralize each other after collision and those particles do not continue to agglomerate. It was reported that the number concentration of submicron particles could be reduced by about 30% (cf. [11]) after agglomeration, or even from 75% to 18% [17].

In unipolar agglomerators (Fig. 6), all particles are charged to the same polarity, and the agglomeration is mainly hydrodynamic [3, 11, 12, 17, 29]. Charged particles are subjected to oscillatory motion in AC electric field. They collide due to differences in their mobility. The agglomerated particles remain stable when the cohesive forces are higher than repulsive electrostatic forces. This process is difficult to accomplish because the electric charge on particles can cause disintegration of the agglomerates. However, at the same time the particles can be easier precipitated in DC electric field between parallel plate electrodes without the need of their re-charging. Particles <0.1 μm can be agglomerated easier than the larger ones (>1 μm) [27].

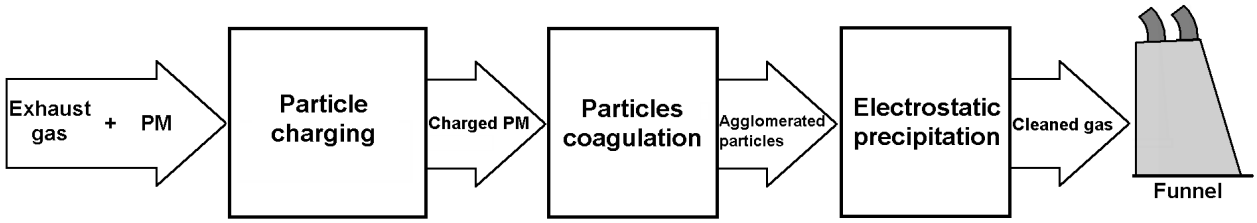

Fig. 6. Unipolar electrostatic agglomerator

A new type of unipolar electrostatic agglomerator has been proposed and tested in the laboratory scale [12]. In such agglomerator, the particles are permanently charged by ionic current generated by corona discharge, and simultaneously subjected to oscillatory motion in AC electric field generated by another pair of electrodes. The particles are agglomerated due to their collision in periodically changing electric field. The charged particles pass to precipitation stage, which can be a conventional electrostatic precipitator with corona discharge, or a system of parallel-plate electrodes with electric field driving the particles to the collection electrode. Laboratory tests have shown that in such a system, the mass collection efficiency for PM2.5 fly ash particles was higher than 99% [12, 23]. The number collection efficiency, was higher than 95% (for >1 μm), and about 90% for particles in the range from 300 nm to 1 μm.

A photograph of experimental stand comprising of electrostatic agglomerator and electrostatic precipitator for submicron particles removal is shown in Fig. 7. The agglomerator/precipitator system was installed and tested at the Ship Engine Laboratory of the Gdynia Maritime University. The PM removal efficiency in submicron range in this system was higher than 90%. This type of agglomerator is also considered for the removal of black carbon from marine Diesel engine.

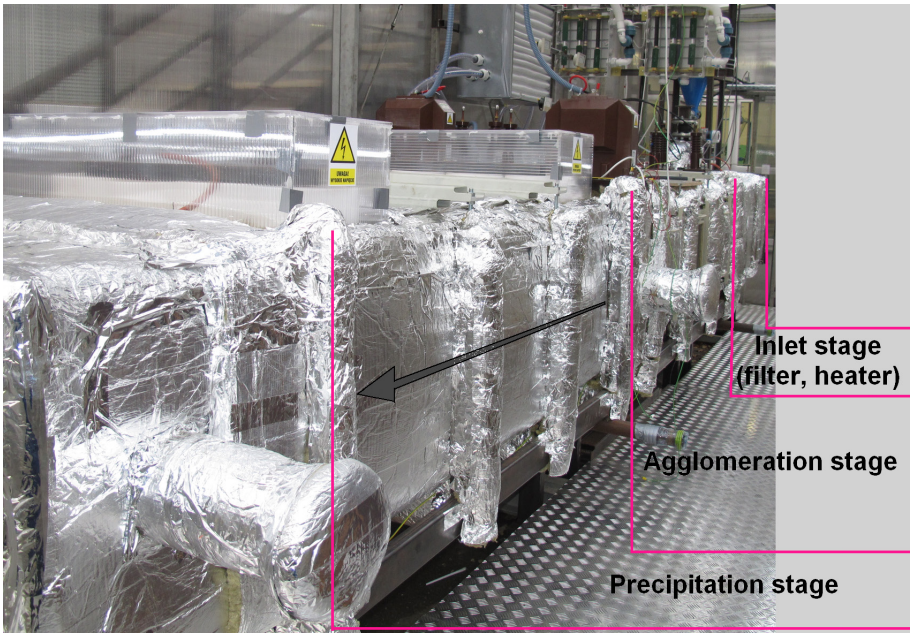

Fig. 7. A photograph of stand of electrostatic agglomerator with one-stage electrostatic precipitator for submicron particles removal

3. Conclusions

Electrostatic techniques were considered as an efficient tool for the removal of submicron and nanoparticles from exhaust or flue gases. Two such techniques have been presented: wet electrostatic scrubber and dry electrostatic agglomerator. Both types of those devices were tested experimentally and shown mass collection efficiency higher than 95% for PM1 particles that are higher than for conventional gas cleaning systems.

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