Removal of Fine Particulate Matter (PM) from Boiler Exhaust Gas in Electrostatic Water Spraying Scrubber*

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Boiler exhaust gas consists of many components that cause air pollution, such as: particulate matter (PM), SO_x, NO_x, CO_x, etc. These pollutants normally are mixed. To eliminate them, a scrubber is currently used, depending on a coal fuel used for combustion source in the boiler. For PM, new guidelines will be changed from the existing PM₁₀ to PM_{2.5} within the next few years; The scrubber is widely used for the collection of PM from industrial exhausts because of its low equipment and maintenance costs combined with operational safety and high collection efficiency. The electrostatic water spraying scrubber, studied in this paper, is one of such types of devices, which combines advantages of electrostatic precipitators and inertial wet scrubbers, and removes many shortcomings inherent to both of these systems operating independently. Unlike wet electrostatic precipitators in which PMs are precipitated only on the collection electrode, in electrostatic water spraying scrubber, the collection of PMs takes place in the entire the scrubber. Compared to inertial scrubbers, the electrostatic water spraying scrubbers can operate at lower droplet velocities, but total collection efficiency is over 93% of all PM sizes

1. Introduction

Particulate matter is one of the most significant kinds of emission for marine gases. The inhalation and further deposition of particulates, particularly those several micrometers in size, is prone to cause respiratory organ diseases or even lung cancer. Removal of PMs smaller than a few micrometers from gases presents a serious problem. Existing filters, cyclones, or inertial wet scrubbers, which employ inertial forces to remove PM contaminants, are ineffective in cleaning the gases from fine PMs. This is because the motion of such PMs is mainly governed by drag and molecular forces, and inertial force plays a diminishing role with decreasing PM size. Tighter fibrous filters can help in finer PMs removal, but they operate at a high-pressure drop. Nozzle or Venturi scrubbers require liquid droplets of high velocity, but the pressure drop is also large in such devices [1]. Therefore, an effective control of PM in the size range from 0.01 μm to 2 μm is still a great challenge for engineers. To solve these problems, electrostatic water spraying scrubber which combines advantages of dry and irrigated electrostatic precipitators, and conventional inertial scrubbers. In electrostatic water spraying scrubber, PMs and

scrubbing droplets are electrically charged to opposite polarities. The charged droplets capture the oppositely charged PMs due to Coulomb attraction forces. Hereinafter in this paper, the scrubber using electrostatic forces will be referred to as “electrostatic water spraying scrubber” and the precipitation process as “electro scrubbing”. The major objective of this study was to evaluate the potential of electrostatic water spray in controlling pollutant in boiler exhaust gas and to improve PM removal efficiency. Specific objective was to: Compare no water spray, neutral water spray, charged water spray, charged water spray and charged PM in terms of PM collection efficiency.

2. Mechanisms of PM collection

Fig.1 Mechanisms of PM collection

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As shown in Figure 1, there are four major mechanisms of PM collection by water droplets [2]: (1) Interception; (2) Inertial impaction; (3) Brownian deposition; (4) Electrostatic attraction. Electrostatic attraction occurs because the droplet sufficient electrical charge to overcome the inertial forces; the charge on the droplet will be larger than the random ions on it, then for some droplet sizes the electrostatic attraction is the dominant mechanism for PM removal.

3. Experimental apparatus and method

3.1 Experimental set up

A furnace of the marine boiler a horizontal cylinder 2.75 m long and of 0.4 m i.d., was used to test emission and combustion performance. The furnace is formed by four annular segments, a roof and a convergent exit section. All these elements are cooled by separate water jackets, with independent measurements of the flow rate and the exit water temperature. Coal fuel oil with specifications in table 1 was used in this experiment. The electrostatic water spraying scrubber shown schematically in Figure 2 it consists of two chambers. In the 1st chamber, the water from tank No1 was pumped through two nozzles (orifice diameter 1mm) with flow rate 3.4 l/min. A mount of larger course PM are

removed in this chamber. The fine PMs which could not be collected by neutral water in this chamber were pushed in the PM charger, then they were charged positively by a PM charger. The PM charger was made of stainless steel saws (4 pcs) as positive electrodes that connect to high voltage supplier adjusted to various voltages range from 1.0 kV to 10 kV. These saws were mounted between 5 steel plates which connected to earth. In the second chamber, the water was pumped from tank No2 by centrifugal pump and discharged through two nozzles (orifice diameter 0.5 mm) with flow rate 0.8 l/min. They generated droplets with 186-196 μm in diameter. A stainless electrode (induction electrode) of inner diameter 15 mm is placed around upper edge of spraying head of nozzles. The induction electrode was connected electrically to a high DC voltage power supply adjusted to various voltages range from 1.0 kV to 5.0 kV to charged water droplets. This arrangement can provide a strong charging field with a relatively low voltage. Thus under stable operating conditions, a negative charged water droplet cloud is formed to collect positive charged PM and fall down to the tank, then relatively clean water from the top of the tank is re-circulated by pump to the charging electro, where it is recharged, completing the cycle.

Fig.2 Schematic diagram of experimental set up

Table 1 Properties of coal oil

No	Parameter	Value	Unit
1	Specific gravity	1.1937	g/cm^3 ; @15°C
2	Kinetic viscosity	100	cSt; @50°C
3	Flash Point	116	°C
4	Pour Point	-7.5	°C
5	Ash	0.05	wt%
6	Sulfur	0.5	wt%
7	Water	0.1	vol%
8	Residual Carbon	250	wt%
9	Low heating value	8,880	kcal/kg

Table 2 Properties of the scrubber

No	Parameter	Value	Unit
1	Capacity of No1 pump	3.4	l/min
2	Capacity of No2 pump	0.7	l/min
3	Gas flow rate enter the scrubber	2280	l/h
4	Gas temperature Inlet scrubber Outlet scrubber	250 25	°C °C
5	PM charge by corona Voltage Current	12.5 0.5	kV mA
6	Water charge Voltage	5	kV

3.2 Measurement of water droplets

Fig.3 Schematic diagram of water spray measurement

The charged water spray was produced using stainless nozzles (orifice diameter of 0.5 mm), while the nozzle body is electrically grounded as shown in figure 3. The working fluid, fresh water, was pumped through two nozzles at a constant volumetric flow rate of 0.8 l/min. A DC high

voltage supply connected with a stainless electrode generated electric field. All cases presented in this paper were conducted using an applied voltage of 5 kV. In the induction charging spraying process, two currents were measured: the nozzle current from the water tube (I_1), the leakage current through the induction electrode to the power source (I_2) by ampere meter. The measurement tool for this experiment was a laser-based, Phase Doppler Particle Analyzer Aerometric (PDPA).

Fig.4 Distribution of SMD of uncharged water spray **Fig.5** Distribution of SMD of charged water spray

Figures 4,5 present the Sauter Mean Diameter distribution of water droplet at applied voltage of 5 kV for fresh water. The charged and uncharged droplets diameters were measured in the system as shown in figure 3. The droplet sizes were measured extend axially to 70 mm and radially to 20 mm from the nozzle tip. The droplet size measurements presented in this figure exhibit a decrease in

the droplet size with increased radial position for all axial locations, and an increase in size with axial position. At this voltage, there is good atomization of the water, charged droplets have a more uniform size distribution [3], and they also have a more widely dispersed distribution due to electrostatic repulsion.

3.3 Measurement of PM mass size and concentration

Fig.6 Impactor (AS-500)

Fig.7 PM mass collected on the filters

An impactor (AS-500) shown in figure 6 was used to quantify PM mass-size distributions in the raw and treated gas. The mass concentration of the raw and after-treated PM were directly sampled by the filter papers as in figure 7,

and the PM mass on each filter was determined gravimetrically by the difference in mass before and after each test PM mass concentrations in treated or untreated exhaust gas were determined by isokinetic sampling using EPA Method 5 "Sampling Method for Stationary Sources". At least five tests were conducted at each water scrubbing performance such as: no spray water (NS); neutral water-neutral PM (NW-NP); charged water-neutral PM (CW-NP); neutral water-charged PM (NW-CP); charged water-charged PM (CP-CW). In this method, the PM was collected on a 60-mm glass microfiber filters. The total PM mass was determined by the gravimetric method.

4. Results and discussion

The effect of installing an electrostatic water spraying scrubber in the exhaust line of a marine boiler on the emission characteristics under varying water scrubbing performance was investigated.

Fig.8 PM concentration at various scrubbing performance of water droplet

Fig.9 PM collection efficiency at various scrubbing

performance of water droplet

Figure 8 shows the PM mass concentrations under various scrubbing performances. A constant flow rate of the exhaust gas 2280 l/h was fed into the scrubber. PM mass concentration was measured in untreated gas 0.24 g/m^3 . Comparison of the results of water scrubbing performances in the second chamber such as no spray water, neutral water-neutral PM, charged water-neutral PM, neutral water-charged PM, both charge PM and water droplets. In the case of neutral water-neutral PM, the water droplets mainly collected PM from gas by conventional mechanisms such as interception, impaction and Brownian diffusion. But fine PMs were difficult to catch by those mechanisms, because of their very lightweight, therefore fine PMs are pushed out of the part of the neutral water droplets and are forced to follow the streamlines; therefore PM mass concentration was removed in this case about 0.17 g/m^3 and the PM collection efficiency only reaches to 71% as show in figure 9. It can be note that the same amount of spraying water, charged droplets have more effective in collection of PM from the exhaust gas than neutral droplets. The effect of charged water droplet in the scrubber that led to increase removal of PM mass up to 0.18 g/m^3 , PM collection efficiency of 74%. The main mechanism causing an increase in the efficiency of PM collection by a charged droplet is image forces [4]. These forces lead to the PM-droplet attracted each other that stronger than impaction and interception mechanism. The results show the good collection of PM when PMs were charged positively by corona. Charged PM induced neutral water droplets by image forces many time stronger than charged droplets, therefore, PM collection efficiency gained relatively high 78%. The better results were obtained when both PM and water droplets were oppositely charged as high as 93% corresponding to positive PM and negative water droplets. Collection efficiency was more stronger than neutral droplets and neutral PM 25%. It was demonstrated experimentally that the electrical charging of droplets and particulate matter allows an increase of the collection efficiency of PM from exhaust gas, as high as 93% at very low water consumption about 0.8 l/min.

Figures 10 and 11 shown PM collection efficiency of various mass-size distribution in the raw and treated exhaust gas. The gas flow rate pass the impactor was about 25 l/min. Samples were measured by the impactor before and after second chamber of the scrubber in the various PM scrubbing modes. For neutral droplet-neutral PM, the collection efficiency is low from 17-19% at all PM size in range

0.5-0.9 μm , respectively. In those size of PMs the neutral water droplets were difficulty collected. It can be seen that the effect of electric force on fine PM collection. In case CW-CP, a significant increase of PM collection efficiency from 78% to 90 % for PM smaller than 0.9 μm . Compared with NW-NP case, it is evident that superior collection efficiency for fine PM was achieved under same water flow rate of 0.8 l/min in the second chamber. For PM size upper than 2 μm , the easier to be collected by charged droplets, and hence the higher collection efficiency for PM can be attained.

Fig.10 PM mass-size concentration before and after scrubber

Fig.11 PM mass-size collection efficiency after the scrubber

4. Conclusion

From the results presented above, the actual exhaust gas emissions from combustion furnace was measured before and after treatment of an electrostatic water spraying scrubber. The measurement exhibits a good performance of

the scrubber: at the operating conditions, it captures PM smaller than 1 μm with high efficiency from 75-87%. The total collection efficiency of PM in range of all size as high as 93%.

Although this paper provides a description of an electrostatic water spraying scrubber effects on collection of PM in actual boiler exhaust gas emission, there are a number of aspects that should be investigated, such as using energy to charge water and PM, the influence of contaminant in the water for rechargeable. In the future research, we will give more attentions to these aspects.

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