MODELING AND MEASUREMENT OF PARTICULATE MATTER (PM) COLLECTION FROM BOILER EXHAUST GAS IN ELECTROSTATIC WATER SPRAYING SCRUBBER

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SUMMARY

Boiler exhaust gas consists of many components that cause air pollution, such as: particulate matter (PM), SOx, NOx, COx, etc. These pollutants normally are mixed. To eliminate them, an electrostatic water spraying scrubber is used, depending on a coal fuel used for combustion source in the furnace. For PM, new guidelines will be changed from the existing 10 to 2.5 microns 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. This study presents computed and experimented results of PM collection efficiency in an electrostatic water spraying scrubber. In this scrubber electric attraction between charged PM and charged water droplet improves PM collection considerably over conventional scrubber. Computed model takes into account initial liquid momentum, hydrodynamic and electric forces. The effects of operating parameters, such as gas velocity, applied voltage, charge to-mass ratio on PM collection efficiency within the scrubber, were also investigated. Computed results are in good agreement with the experimental data obtained in the laboratory. Compared to inertial scrubbers, the electrostatic water spraying scrubbers can operate at lower flow rate, but total collection efficiency is over 98% of all PM sizes.

NOMENCLATURE

C_c	Cunningham slip correction factor
M_c	mass collected
N_i	PM mass concentration enter scrubber section (height dh), (g/m^3)
N_0	initial PM mass concentration (g/m^3)
N	PM mass concentration after scrubber (g/m^3)
d_{ps}	Stock diameter (m)
d_p	diameter of PM (m)
d_d	diameter of water drop (m)
G	water flow rate (kg/s)
h	scrubber tower height (m)
I	spray current (mA)
J	hydrodynamic factor
K	hydrodynamic factor
K_{EM}	coefficient, charged PM-neutral droplet
K_{EI}	coefficient, neutral PM-charged droplet
K_{EC}	coefficient, charged PM-charged droplet
k	dielectric constant of PM
Q_w	water flow rate (m^3/s)
Q_g	exhaust gas flow rate (m^3/s)
q_d	droplet charge (C/kg)
q_p	PM charge (C/kg)
E_c	average electric field strength at the collecting plate surface (V/m)
E	local electric field strength of charge (V/m)
S_{tk}	Stock number
T	absolute exhaust gas temperature (K)
W	the width of wire to plate (m)
v_g	gas velocity (m/s)
v_d	water droplet velocity (m/s)
v_p	PM velocity (m/s)
V	applied voltage to charge PM (V)

Greek Symbols

ε_0	permittivity constant of vacuum (F/m)
ρ_p	density of PM (kg/ m^3)
ρ_m^q	charge-to-mass ratio per drop (mC/kg)
μ	viscosity of gas (kg/m.s)
δ	experimental coefficient
σ	viscosity ratio of liquid to gas
α	packing density
λ	the ionic mean free path, m
η_{SD}	single droplet collection efficiency (%)
η_{DI}	direct interception collection efficiency (%)
η_{II}	inertial impaction collection efficiency (%)
η_{BD}	Brownian diffusion collection efficiency (%)
η_E	electrostatic collection efficiency (%)
$\eta_{overall}$	overall collection efficiency (%)

1. INTRODUCTION

Removal of PMs smaller than a few micrometers from exhaust gas presents a serious problem. PMs of this size, such as smoke, fine powders, or oil mist, which are usually hazardous to human health, are not easy to remove by conventional methods. Existing filters, cyclones, or inertial wet scrubbers, which employ inertial forces to remove PM contaminants, are ineffective in cleaning the gases from fine PMs [1]. 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. Dry electrostatic precipitators use electrostatic forces, but charging of PMs smaller than 1 μm inefficient, and the collection efficiency sharply drops with decreasing PM size. Irrigated electrostatic precipitators can only partially solve the problem of particle re-entrainment. In such precipitators, the PMs are charged similarly to conventional electrostatic

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precipitators, but the collection electrodes are washed instead of wrapped. Washing removes problems with back-corona discharge, but the issue of fine PM charging still remains unsolved. Therefore, an effective control of PM in the size range from 0.01 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 marine exhaust gas and to improve PM collection efficiency.

2. THEORETICAL MODEL

2.1 BASIC ASSUMPTION

The following major assumptions are made in model to study the prediction for performance of an electrostatic water spraying scrubber:

- There is no evaporation of undergoing in tower of water droplets.
- The system is in a steady state operating condition.
- Water droplets are uniform in size.
- The spray droplet diameter and concentration are assumed to be stable and constant in the scrubber, and there is no interaction between spray droplets.
- Spray droplets fully cover the spray chamber as soon as injected.
- Droplets are assumed spherical
- The fluctuation of electric force effect is neglected.

2.2 PM COLLECTION EFFICIENCY A SINGLE DROPLET

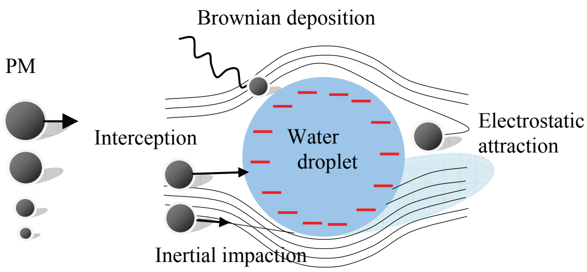

Figure 1: Mechanisms of PM collection by charged water droplet

As shown in figure 1, there are four major mechanisms of PM collection by water droplet [2]: (1) Interception; (2) Inertial impaction; (3) Brownian deposition; (4) Electrostatic attraction. The overall collection efficiency by a single droplet (η_{SD}) is sum of the above collection efficiencies [3]:

$$\eta_{SD} = 1-(1-\eta_{DI})(1-\eta_{II})(1-\eta_{BD})(1-\eta_{E}) \tag{1}$$

PMs collect by direct interception mechanism [4]:

$$\eta_{DI} = \left[\frac{(1-\alpha)}{(J+\sigma K)}\frac{1}{d_d^2}\right]d_p + \left[\frac{(1-\alpha)}{(J+\sigma K)}\frac{(3\sigma+4)}{2d_d^2}\right]d_p^2 \tag{2}$$

$$J = 1-\frac{6}{5}\alpha^{1/3}+\frac{1}{5}\alpha^2;\ K = 1-\frac{9}{5}\alpha^{1/3}+\alpha+\frac{1}{5}\alpha^2$$

PMs collect by initial impaction mechanism [4]:

$$\eta_{II} = \frac{S_{tk}^2}{(S_{tk}+0.25)^2} \tag{3}$$

PMs collect by Brownian diffusion mechanism [4]:

$$\eta_{DI} = \frac{2.8}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{1/2}\left[\frac{3\pi\mu d_d(v_d-v_g)}{2.609kT\sqrt{2\lambda}}\right]^{-1/2} d_p^{-3/4} + 1.4\left(\frac{\sqrt{3}\pi}{4}\right)^{2/3}\left[\frac{(1-\alpha)(3\sigma+4)}{(J+\sigma K)}\right]\left[\frac{3\pi\mu d_d(v_d-v_g)}{2.609kT\sqrt{2\lambda}}\right]^{-2/3} d_p^{-1} \tag{4}$$

PMs collect by electrostatic mechanism [3]:

- Neutral PM and charged droplet

$$\eta_E = \left[\frac{15\pi}{8}\left(\frac{k-1}{k+2}\right)\frac{2C_c d_p^2 q_d^2}{3\pi\mu d_p v_g \varepsilon_0}\right]^{0.4} \tag{5}$$

- Charged PM and neutral droplet

$$\eta_E = 2.89\left(\frac{C_c q_p^2}{3\pi^2 \mu d_p v_g \varepsilon_0 d_d^2}\right)^{0.353} \tag{6}$$

- Charged PM and charged droplet in opposite polarity

$$\eta_E = -4\frac{C_c q_q q_d}{3\pi d_p \mu v_g \varepsilon_0} \tag{7}$$

PM charging can be calculated as Cochet equation [3]:

$$q_p = \pi\varepsilon_0 E d_p^2\left[\left(1+\frac{2\lambda}{d_p}\right)^2 + \frac{2}{1+\frac{2\lambda}{d_p}}\frac{k-1}{k+2}\right] \tag{8}$$

Local electric field strength of charge E was calculated as following equation [5]:

$$E = E_c = \frac{V}{W} \tag{9}$$

Water droplet charging can be calculated as equation:

$$q_d = \rho_m^q \rho_d \frac{\pi d_d^3}{6} \tag{10}$$

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2.3 OVERALL PM COLLECTION EFFICIENCY

The overall PM collection efficiency is calculated from the following equation:

$$\eta_{overall} = \frac{N_0 - N}{N_0} = 1 - \frac{N}{N_0} \qquad (11)$$

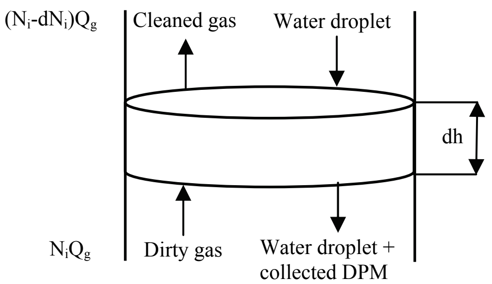

Figure 2: Schematic of the control volume of mass balance

The continuity equation was used to get the overall efficiency of the scrubber. Applying the continuity equation to a cylindrical element of height dh taken inside the spray column as shown in figure 2, we get applying mass balance [1]:

Mass in – Mass out = Mass collected

$$N_iQ_g - (N_i - dN_i)Q_g - M_c = 0 \qquad (12)$$

Separate the variables and integrate

$$-\int_{N_0}^{N} \frac{dN_i}{N_i} = \frac{3}{2}\eta_{SD}\int_{o}^{h}\left(\frac{v_d - v_p}{v_d - v_g}\right)\left(\frac{Q_l}{Q_g}\right)\frac{dh}{d_d} \qquad (13)$$

$$\frac{N}{N_0} = \exp\left\{\frac{3}{2}\eta_{SD}\left(\frac{v_d - v_p}{v_d - v_g}\right)\left(\frac{Q_l}{Q_g}\right)\frac{h}{d_d}\right\} \qquad (14)$$

Application of the equation usually involves the following assumptions:

$$\eta_{overall} = 1 - \frac{N}{N_0} = 1 - \exp[-0.3\frac{Q_l}{Q_g}\frac{h}{d_d}\frac{v_d}{(v_d - v_g)}\eta_{SD}] \qquad (15)$$

3. EXPERIMENT APPRATUS AND METHODS

3.1 EXPERIMENTAL SETUP

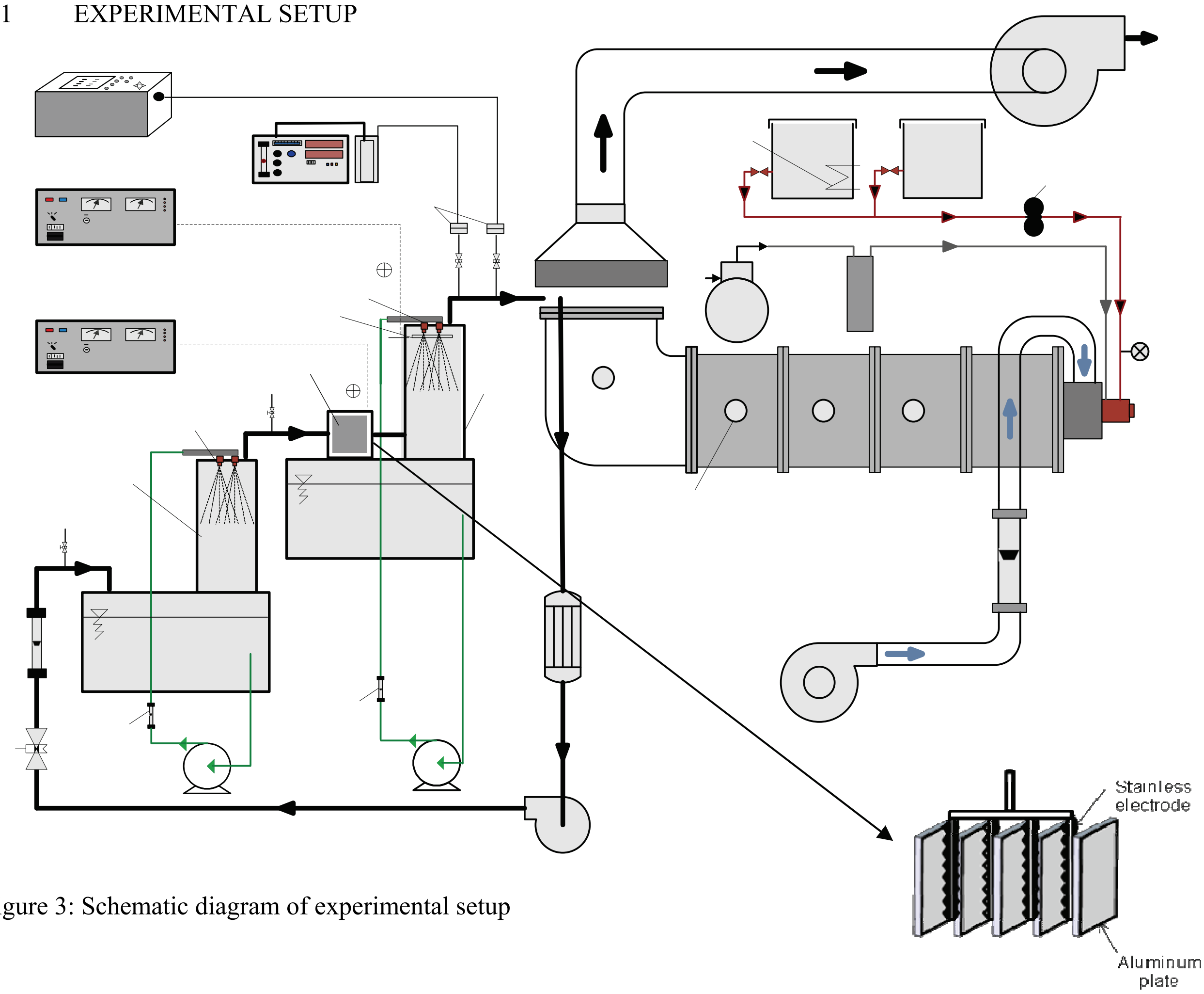

Figure 3: Schematic diagram of experimental setup

A combustion chamber of the boiler was used as PM and other pollutant emission source. Coal fuel oil in table 1 was used throughout these experiments. The experiments with exhaust gas cleaning by means of charged droplets were carried out in the scrubber shown schematically in Fig. 3 the scrubber consists of two chambers. In the first 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. Fine and condensable PM which could not be collected by water are grown to a few tenths of a micron in preparation for removal, and then remain PM were charged by a PM charger. The 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 to charge PM positive. 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 created droplets with 190 μm in Sauter mean diameter measured by Phase Doppler Particle Analyzer Aerometric. A stainless electrode (induction electrode) of inner diameter 15 mm is placed around upper edge of spraying head of nozzle. The induction electrode was connected electrically to a high DC voltage power supply adjusted to various voltages range from 1.0kV to 5.0kV to charged water droplets. This arrangement can provide a

Table 1. Properties of coal fuel oil

Property	Composition
Density [g/cm^3] @15^{0}C	1.1937
Flash Point [^{0}C]	116
Kinetic viscosity [cSt] @50^{0}C	100
Pour Point [^{0}C]	-7.5
Ash [mass%]	0.05
Sulfur [mass%]	0.5
Water [vol%]	0.1
Residual Carbon [mass%]	0.55
Low heating value[MJ/kJ]	38.26

Table 2. Operation parameters of combustion chamber

Coal oil consumption for burning [l/min]	3.2
Air supply into combustion chamber [l/min]	4700
Coal oil supply pressure [MPa]	0.05
Atomized air pressure [MPa]	1
Coal oil temperature inlet [^{0}C]	120
Gas flow rate enter scrubber [l/hr]	1800
Gas temperature inlet scrubber [^{0}C]	300
Gas temperature outlet scrubber [^{0}C]	25

strong charging field with a relatively low voltage. Thus under stable operating conditions, a positive charged water droplet cloud is formed to collect 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 electrode, where it is recharged, completing the cycle.

3.2 MEASUREMENT OF PM MASS SIZE AND CONCENTRATION

An impactor (AS-500) was used to quantify PM mass size distributions 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 at the scrubber in the various PM scrubbing modes. To analyze PM mass concentration at the inlet and out let of the scrubber, a PM sample collector was used (Fig.3) to collect PM on the micro fiber filter at flow rate 10 l/min, collected PM was set to 20 liters volume of exhaust gas.

The raw and after-treated PM were directly sampled by the filters, 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 six tests were conducted in the scrubber such as no spray water (NS); after first chamber (1st); neutral droplet-neutral PM (ND-NP); charged droplet-neutral PM (CD-NP); charged PM-neutral droplet (CP-ND); charged PM-charged droplet (CP-CD). In this method, the PM was collected on a 60-mm glass microfiber. The total PM mass was determined by the gravimetric method.

3.3 CHARGED WATER DROPLET MEASUREMENT

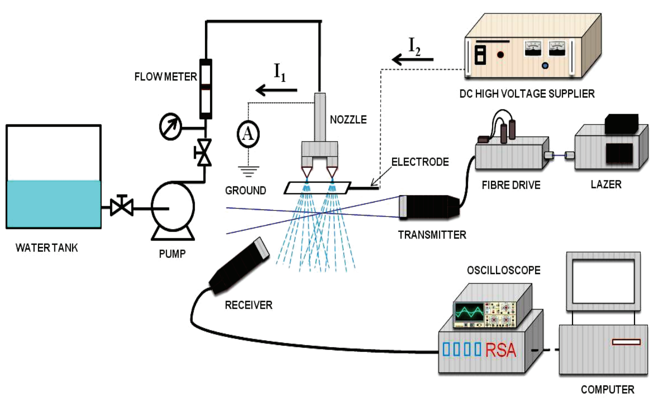

Figure 4: Schematic of water spray measurement

A system used to measure charge to mass and droplet size by Phase Doppler Particle Analyzer Aerometric is shown in figure 4. The fresh water was pumped from a tank by a pump and discharged through two nozzles with orifice diameter of 0.5mm. A stainless electrode was placed at a distance as shown in the figure. The water

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flow rate was changed ranging from 0.5–0.8 l/min and various applied voltages range from 1 to 5 kV by a high DC voltage supplier. 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. Considering the charge and mass loss in the spraying process due to leakage current, the spray current (I) was calculated as follow:

$$I = I_1 - I_2 \quad (16)$$

By dividing the spray current to the mass flow rate, the effective charge to-mass ratio is determined [6]:

$$\rho_m^q = \frac{I}{G} \quad (17)$$

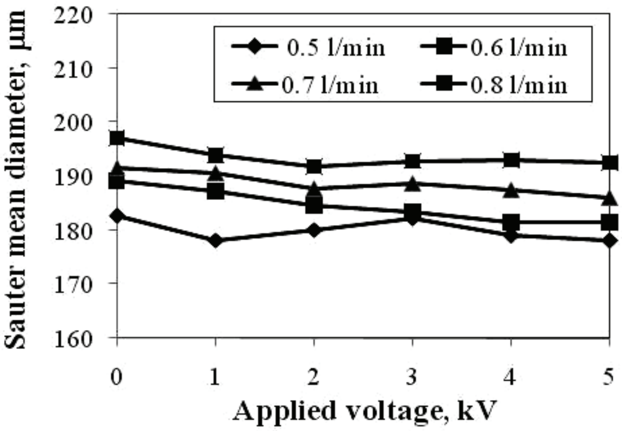

Figure 5: Charged water droplet size

Figure 5 shows effect of applied voltage on SMD size For water flow rate of 0.8 l/min the increase of applied voltage from 1kV to 5kV water droplet size decrease from 197 µm to 192 µm. The electric field to induce water that is atomizing from nozzles reduces the size of the droplet some micro meter. At smaller water flow rate of 0.5, 0.6 and 0.7 l/min the water droplet also decrease some micro meter with the increasing applied voltages. As the rerult charged droplets have a more uniform particle size distribution, and they also have a more widely dispersed distribution due to electrostatic repulsion.

4. RESULTS AND DISCUSSION

The experimentation on PM scrubbing in a electrostatic water spraying scrubber was conducted with variations in scrubbing performances. The values of the variables are used in the theoretical estimation of single droplet efficiency in the prediction of overall efficiency. The developed mathematical model equations were computed by matlab programme for the PM collection efficiency. The program was compute for variable like gas flow rate and applied voltage. The results are plotted and the values estimated for the parameters of model are presented.

4.1 EFFECT OF WATER SCRUBBING PERFORMANCE ON PM COLLECTION EFFICIENCY

Figure 6 indicates the predicted overall PM collection efficiency that was computed to compare the various scrubbing performances in second chamber. The spray system operated with water flow rate of 0.8 l/min, the PM mass concentration was 0.07 g/m^3 (measured after fist chamber) at constant gas flow rate 1800 l/hr. For ND-NP, the collection efficiency is low from 13% - 66% at all PM size in range 0.1-10 µm, respectively. For CD-NP or CD-NP the collection efficiency further increase. The charge on the PM or droplet induces an image charge opposite in sign, on the PM or droplet which results in a force of attraction between PM and droplet. For both CP-CD, the main mechanism causing an increase in the efficiency of PM collection by a charged droplet is Coulomb attraction. This mechanism was many times stronger than interception and impaction mechanism. It can be seen that the collection efficiency for PM smaller than 1µm PM improved from 13 % (uncharged) to 78 %, whereas for PM upper 1.5 µm, the collection efficiency improved from 19 % to 100 %. This force leads to greatly PM-droplet coalescence and to removal of the PM from exhaust gas.

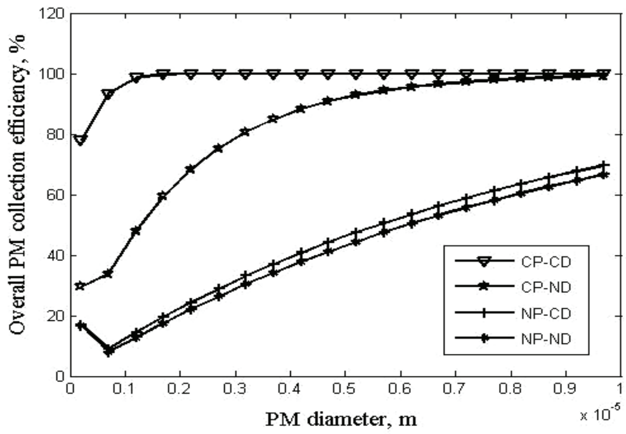

Figure 6: Effect of water scrubbing performance on PM collection efficiency

4.2 EFFECT OF APPLIED VOLTAGE ON PM COLLECTION EFFICIENCY

Figure 7 shows the predicted PM overall collection efficiency as a function of PM diameters for various values of the charging voltages at constant gas flow rate 1800 l/hr. The variable with the single most significant effect on charged PM was applied voltage. At low voltage 1 kV, in a region of weak electric field, there is not enough charge to give the intensity of the field and strength of electric forces required for optimal charging because positive corona is initiated by an exogenous ionisation event in a region of high potential gradient. PM collection efficiency attained 50-75 % for PM size less than 1 µm. At higher voltage, where the strong corona charges occur thus enhances the PM charging and collection processes inside the scrubber. At increasing voltage from 1 kV to 7.5 kV, the corona current increased, which led to an increasing ion density. The improvement with increasing voltage occurred, as expected, there is a strong effect of the applied voltages on collection efficiency. The PM reached the optimal charge concentration in the 7.5 kV range. At this voltage, there was enough charge for good. The PM collection efficiency as high as 97-100 % for PM size in range 0.2-1 μm.

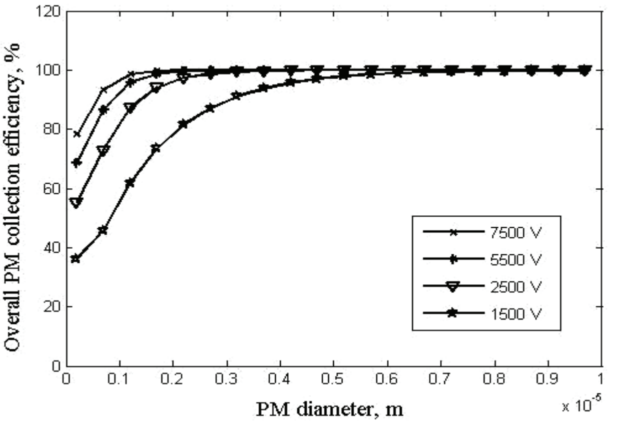

Figure 7: Effect of applied voltage on PM collection efficiency

4.3 EFFECT OF GAS FLOW RATE ON PM COLLECTION EFFICIENCY

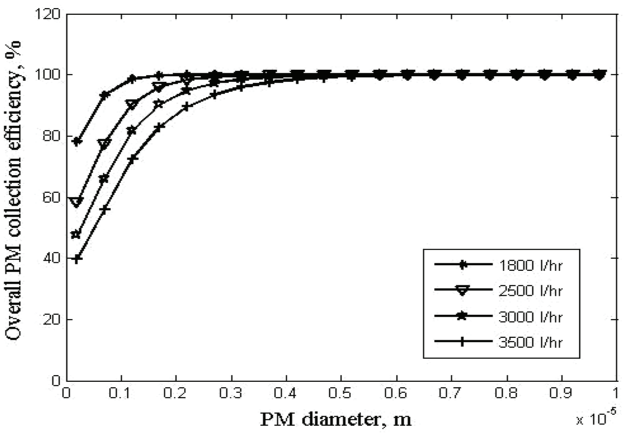

Figure 8: Effect of gas flow rate on PM collectio efficiency

Figure 8 represents results on the effect of gas flow rate on overall PM collection efficiency at constant water flow rate 0.8 l/min. The second chamber of the srcubber was operated at a constant applied voltage of 7.5 kV to charge PM corresponding to applied voltage of 5 kV to charge water spray. At gas flow rate of 1800 l/h, the PM size increases the overall collection efficiency also increases steadily and reaches the maximum, 100% for a PM of 1.5 μm. As the PM size increases above 1.5 μm the Stokes number in the impaction mechanism and the d_p value in the interception mechanism increase. On the other hand, the large PMs were charged by corona easier than fine PM led to charged PM concentration increase, therefore collection mechanism by electric increase. These contribute to maximize the overall collection efficiency. When the gas flow rate increases the collection efficiency drops for fine PM in range 1.5-4.5 μm. For higher gas flow rate of 3500 l/h, the maximum collection efficiency achieved for 4.5 μm PM size was 100%.

4.4 COMPARISON OF COMPUTED DATA WITH EXPERIMENTED DATA

Figure 9 shows the comparison of experimented results with computed results in case neutral PM-neutral droplets at constant gas flow rate of 1800 l/h. For PM size less than 1μm the agreement between computed and experimented data is fairly good in both chambers of the scrubber. The PM collection efficiency in this range of PM are very low because the fine PMs are collected mainly by Brownian diffusion, they have light weight and easily to be pushed out of the droplet and follow the gas flow. Therefore, they could not remove by neutral droplets. It can be seen that the predicted collection efficiency of PM size in range 1-10μm are relatively agreement with the experimental results whereas the difference is 5% (on average). Moreover, in first chamber PM scrubbing process in which droplets have high velocity and large size lead to short residence time of droplet, therefore experimented result in lower PM collection efficiency. In the second chamber, droplets have low velocity and small size, therefore they have longer residence time and collection area lead to experimented data tend to higher than computed data.

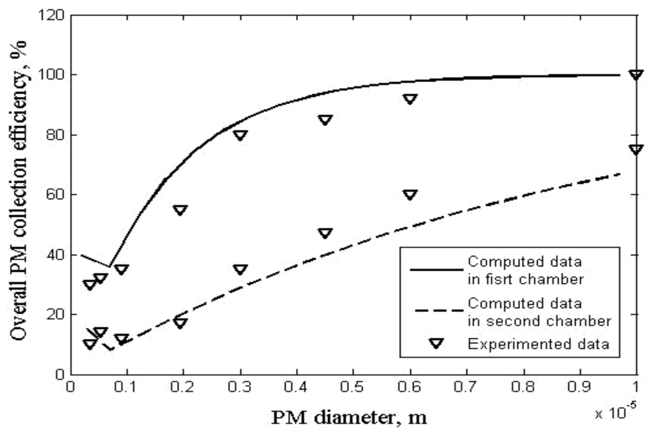

Figure 9: Comparison of experimented and computed data in case NP-ND

Figure 10 shows the comparison of experimented data with computed data in case of charged PM-charged droplet. The PM was charged at 7.5 kV. The water droplet was charged at 5 kV. The most dominating

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mechanism for PM collection efficiency in an electrostatic water spraying scrubber is electric attraction. As can be seen the experimented results are in good accordance with the predicted collection efficiency will all size of PM.

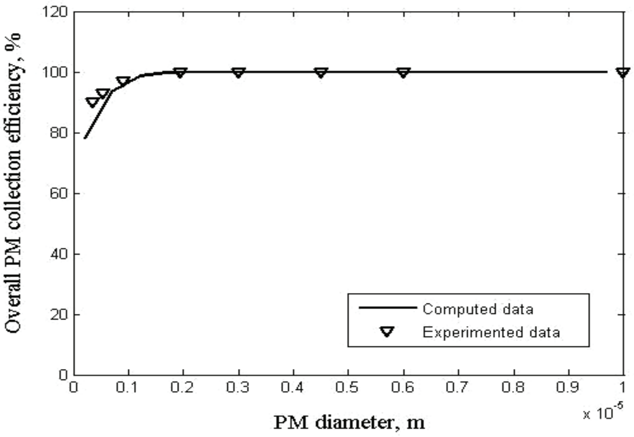

Figure 10: Comparison of experimented and computed data in case CP-CD

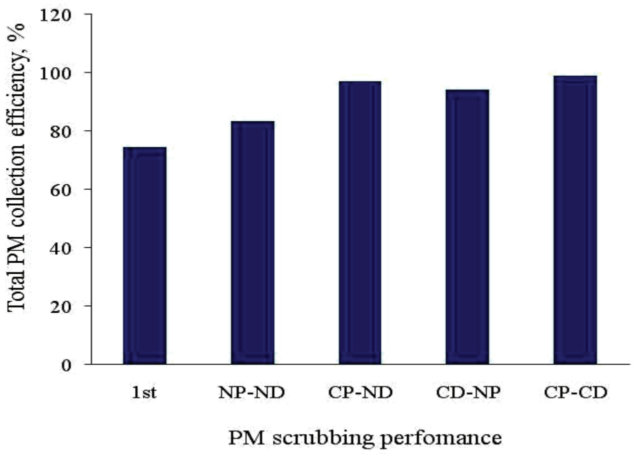

Figure 11: Total PM collection efficiency at various scrubbing performances of the scrubber

In figure 11 shows total PM collection efficiency of the scrubber. Comparison of the experimental results of water scrubbing performances such as in the first chamber and in the second chamber (no spray water, neutral water and neutral PM, charged water and neutral PM, spray neutral water and charged PM, both charge PM and water droplets). When the scrubber uses neutral water, it will only collects coarse PM by simple impaction mechanism, as per a conventionally system, the highest PM collection efficiency only reaches 85%. It can be note that using the same amount of spraying water, better results were obtained (high as 95-99%), when both PM and water droplets were oppositely charged, corresponding to positive PM and negative water droplets in the second chamber.

5. CONCLUSIONS

PM collection efficiency of an electrostatic water spraying scrubber has been theoretically investigated with a comprehensive analysis of model and experimentally. The outcomes of the results are summarized as follows:

(1) A mathematical model based on mass balance, momentum balance and continuity equation to a cylindrical element has been developed to predict overall PM collection efficiency.
(2) The experimented values of PM collection efficiencies are compared with the theoretically predicted values. Experimented results show that the theoretical equations based on mass transfer predict closely the performance of the scrubber for scrubbing of PM using water.
(3) The experimental results show that an optimum overall PM collection efficiency as high as 99%. The scrubber collected PM sizes in range 0.3-1μm with high efficiency.

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