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Review of electrostatic precipitator device for reduce of diesel engine particulate matter

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Abstract

In the last few decades, electrostatic precipitators (ESP) have been modernized and many new methods have been implemented to increase in term of cleaning efficiency for particles in the sub micrometer size range. An electrical force has been implemented to increase the collection efficiency for removing particulate matter (PM) in the diesel engine. Based on results of particle properties and health effects studies, measurement systems are being discussed. This paper reviews the works that have been done in term of fundamental of ESP and electrical properties of ESP. The concept of ESP is ESPs only give electrostatic force to the particle. Thus, the gasses are not directly to the ESP and will results comparatively lower pressure drop. Therefore, the cost can be lowered down than the other filtration systems such as cyclonic and mechanical filtration. ESP In order to accumulate the charge by the particles, several factors will be taken into account such as particle size, dielectric constant and residence time in ESP. Also there are two type charging mechanism which are diffusion and field charging. The result of study is ESP can archive 99 percent of removal efficiency for a certain type of particulate.

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Keywords: diesel engine; particulate matters; electrostatic precipitator

1. Introduction

In the last few years, diesel particles have been a great concern due to their adverse effects in the urban area [1]. The adverse health effects by particulate matter (PM10, PM2.5), have been establish by many toxicological and

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epidemiological studies [2]. Besides, there is many evidence in health effect associated with the ultra fine particle with diameter below 100 nm [3]. From the research shows that it can penetrate the cell membranes, enter the blood and even reach the brain [4].

Thus, stricter regulation and more efforts are taken to reduce emissions. Table 1 shows European limits for on-road vehicles [2]. All limits are defined in mass per distance (g/km, light-duty vehicles) or mass per energy (g/kWh, heavy-duty engines).

Table 1. European limits for on-road vehicles.

	Year	Light Duty (g/km)	Heavy duty (g/kWh)
Euro 1	1992	0.14	0.61
Euro 3	2000	0.05	0.1
Euro 4	2005	0.025	0.02
Euro 5	2009	0.005	0.02
Euro 6	2014	0.005	0.01

As a consequence, various methods have been developing to reduce the PM. The most widely used to reduce the PM emissions is particulate filter which is consist of a simple ceramic or silicon carbide filter with sequential regeneration [5] but this efficient technology is not without limitation. Thus, electrostatic precipitator (ESP) technology has become an important role to capture particulate emission in the diesel engine. Generally, ESP have a very low pressure drop and low electrical consumption [6]. Soot particulate matters are smaller than 10 µm in the atmosphere for a long time and low resistivity [7].

Many researchers have worked out on the ESP of aerosol emitted by diesel engine, targeting for automotive application. For example, Thimsen et al. [8] present about diesel particle in term of conversion efficiency of agglomerator. Kittelson [9] using a simple wire-cylinder electrostatic filter without corona discharge. Thonglek [6] presents the design of the electrostatic precipitator soot from the exhaust pipe using corona plasma technique from high voltage pulse.

Research in particulate technology is basically to find new, improved and less costly method in order to collect small particles that save energy and structural materials. Over the past few decades, a lot of developments have been made in term of new electrical technique for exhaust cleaning to increase cleaning efficiency in the small particle size range. As mentioned before, these particle are potentially danger to human health and are very difficult to remove by conventional device [2].

2. Size, density and composition of diesel particle

Diesel particles consist of a complex mixture of elemental carbon (EC), hydrocarbons (HC), sulfur compounds and others compound. They are differs in term of size, composition, solubility and toxic properties [2]. The compositions of particle from heavy-duty diesel engines are shows in Figure 1. Some of them are in volatile and the volatile fraction is depending on the temperature and other conditions. Some may remain in the gas phase or condense on existing solid particles or nucleate and form new particle.

From the combustion process, the particle will be formed and it may also created secondary particles due to cooling in exhaust and sampling area. Common diesel particles consists of mainly spherical primary particle in size range of about 15-40 nm in diameter. The primary particles produce from modern engine fuelled with Euro IV are smaller than from the old engines [10]. In term of particle microstructure, conventional engines were dominant with amorphous and graphitic structure.

Figure 2 shows the typical size distribution. The size is depending on the operating condition of the engine. Thus, an extreme condition will have a significantly different size distribution.

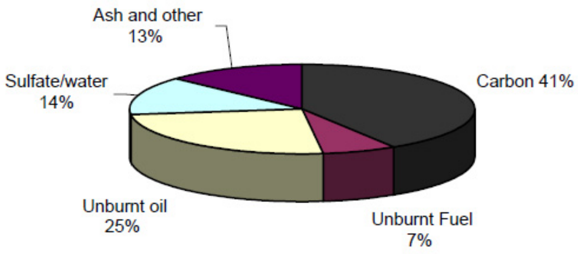

Fig. 1. Particle composition of a heavy duty diesel engine tested in a transient cycle [9]. The composition may vary depending on the engine design and operating condition.

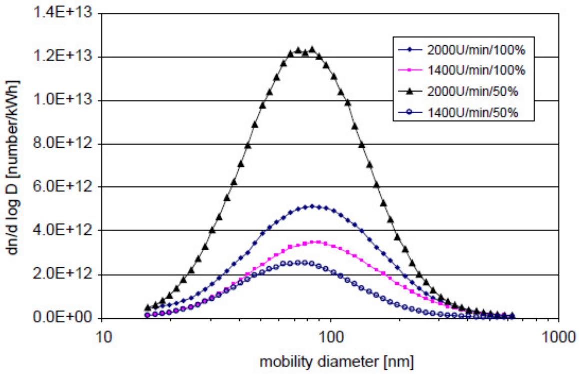

Fig. 2. Size distributions in term of lognormal distribution of diesel agglomerates. The geometric standard deviation stays fairy constant [11, 12].

As shown in Figure 2, a large number of measurements with different engines at different operating conditions, the geometric standard deviation stays fairy constant. The concept of fractals can be implemented in the structure of agglomerates. From the relation between diameter and mass, the value of fractal dimension is about 2.3 [13]. The mobility diameter of the effective density of the particle is 100 nm for a density of 0.8 g/cm^3 and increasing with decreasing density about 300 nm at 0.3 g/cm^3 [14]. In conclusion, at 300nm in mobility diameter, the aerodynamic diameter is 100 nm.

Using the lognormal distribution, it can represent the size distributions of diesel particle. An expected results of a self-preserving distribution with a smaller geometric standard deviation and slight asymmetry appears if the size distribution was due exclusively to coagulate [15]. When aging soot from laboratory are found in such distribution [16]. Assuming the fragmentation occurs in addition to coagulation, the lognormal found in diesel particle can be explained [12]. Details on oxidative fragmentation model is given by [17]. The fragmentation of combustion particles in early research occur by oxidation under lean fuel conditions in a laboratory flame [18].

3. Method for measurement

Several techniques will be discussed for measuring engine exhaust particle emission. There were many parameters to measure such as:

- Total particulate matter (PM) in gram (g),
- Size distribution in number/cm^3,
- Number of concentration in g/cm^3.

Recently, a comparison study has been performed by many researchers [2, 19] in term of high and low emissions and also comparison under stationary and transient conditions.

3.1. Total PM

All the measurement needs to be done after dilution by referring to current legislation in Europe and US, which is enough to drop the temperature below 52 ºC (125 ºF). Besides, all legal emission limits are defined in term of total mass and determined by gravimetric analysis. By dropping the temperature, volatile material is condensed and stationary test can be done in partial or full flow dilution tunnel whereby for transient test, only full flow is being done. There is a problem with this method in term of the detection limits for modern low-emissions engines. Thus, Environmental Protection Agency (EPA) 2007 [20] stated that new filter media, high resolution of the balance and tighter tolerance for temperature is allow for lowering the detection limit.

Cyclone or pre-classifier is being used to capture the coarse material before entering the filter. There is a collection of organic vapor by the filter reported [21]. A similar approach is being tested and compared to the existing method for future European regulations [22]. Another technique for gravimetric analysis is thermal mass analysis in term of organic carbon (OC) and sulfates [23]. Therefore, carbon and sulfur will oxidize and measured as CO^2 and SO^2. Thus MEXA 1370 PM was produced by Horiba for super low mass particulate matter analyzer. In contrast, ash cannot be detected. More techniques for mass determination will be discussed. Tapered element oscillating microbalance (TEOM) [24] and quartz crystal microbalance (QCM) are based on a change of resonance frequency device to collect the mass. Both offers good time resolution and good sensitivity. QCM seems promising by Booker System [25] but has its own disadvantages. It is found that, the performance is depending on total mass loading [26].

Opacimeters is also one of technique as the indirect mass measurement which is widely used in the past. For more cases, especially for modern engine, such instrument is facing problems with the detection limit. Thus, a long optical path to reduce the detection limit for multiple path system [27]. It uses three wavelengths and a multiple path system with an optical length up to 15 m in order to obtain a good sensitivity. Thaller et al. [28] discussed the transient measurement of low concentrations by light extinction technique. At low particle concentration, NO_2 causes light extinction [19].

3.2. Number of concentration

The number of concentration was measured with condensation particle counter (CPC) [29]. The main problems measuring the number of concentration are coagulation. Thus, shorter time and high enough dilution are required to obtain good results. Moreover, to avoid undesired nucleation particle dominate the number of concentration, a careful treatment of volatile is required. The other potential problems are the lower size limit of CPC around 3 nm to 15 nm. If the size is around the detection limit, the measurement becomes unreliable.

3.3. Size distribution

Size of the distribution is mainly measured in term of mobility analysis or impaction. Scanning mobility particle sizer (SMPS) is commonly used [30]. Besides, Electrical low pressure impactor is (ELPI) is being used [31]. Using mobility analysis, it allows a very good size resolution which is can cover from small nm until up to 700 nm depending on the instrument and flow rate. For lower limit, indicates due to diffusion and for upper limit it shows multiple charging of larger particles.

4. Fundamental of ESP

Since 1984, the corona discharge and electrostatics in separating gasses and airborne particle has been studied. Corona discharge to clear smoke in the bottle was being used by Hohlfeld [32]. Lately, ESPs are the most common particulate emissions control device which is widely used in coal-fired power plants and industrial. In mechanical filtration concept, the flow of the gasses will go through a porous media, fiber or porous foam and the bending of the gas streamlines based on the separation concept. Pressure drop will be started when the gas flow hit the filter surface.

Moreover, ESPs only give electrostatic force to the particle. Thus, the gasses are not directly to the ESP and will results comparatively lower pressure drop. Therefore, the cost can be lowered down than the other filtration systems such as cyclonic and mechanical filtration. As a result, ESP can archive 99 percent of removal efficiency for a certain type of particulate with a lower pressure drop.

Usually, discharging electrode used a wire while the collecting electrode can be a plate or a tube. ESP works when the air flows into the ESP, it will create high voltage electric field generated by a wire and electrode. The negative and positive component form when the gas is ionized. Thus, negative ions will move in the electric field, creating an electric current between the electrodes. Some of the ion will diffuse to the surface of particle and charge them. Charged particle will migrate to collecting plate due to electrostatic force. Therefore, the particle will deposit on the collecting electrodes. Lastly, in the ESP operation is to remove the suspended particulate from collecting electrode [33].

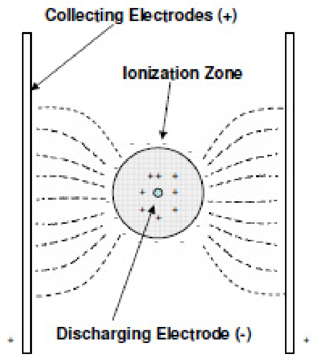

Fig. 3. Schematic diagram of ESP [34].

4.1. Corona formation

Formation of the corona is to ionizable gas near the electrode and also creates a strong electric field in order to energize the molecules. Usually, the compounds in the air are easily ionized by a strong electric field either in polluted or clean air. The corona is the location of many chemical reactions, which produce a current in positive and negative ions for a normal air in electrostatic corona [35]. The chemical reactions are formed in the negative and positive corona is differing and negative corona typically produce twice current compared to positive corona. The type of the corona and the charge that will be imparted to the particle depends on the polarity of the discharging electrode. The corona will produce negative ionic current when the discharge electrode is negative and travel from discharge electrode to the collecting electrode through air gap. In contrast, the corona will produce positive ionic current when the discharge electrode is positive and travel from discharge electrode to the collecting electrode. For ESPs researcher, they agreed that negative corona showed a good or superb in term of particle collection efficiency [36].

5. Electrical properties of ESP

The quantity of charged given to the particle is effect on the ability of an ESP to remove suspended particles. Particle charging is a function of ionic current produced by the electrodes in which depend on the voltage of ESP is operated. Two type of voltage endpoint to determine ESP operating range. The first one is onset voltage which is the lowest voltage different across the electrode to start the ionization of air molecules and produce ionic current. The second one is the sparkover voltage which is the highest voltage that produces steady current output in ESP. Thus, ESP can be only operated in the range of two endpoints. A gradual increase in current with increasing voltage is a trend known as voltage-current relationship. Therefore, onset voltage, sparkover voltage and voltage-current relationship are the fundamental of ESP and a very important in designing the ESP component.

5.1. Onset voltage

Study on electrostatic coronas was pioneered by F.W. Peek [37]. General Electric funded this research and the result is published with the title of "The Law of Corona". It describes the details in formation and physically modeled it for the first time. The strengths of electric field required to start corona were investigate extensively and the onset equation of Peek's onset electric field strength equation is shows Equation 1.

$$E_o = \delta A + B\sqrt{\frac{\delta}{a}} \tag{1}$$

where E_o is onset electric field, δ is relative density of the gas. The value of $3*10^6$ V/m and $9*10^4$ V/m$^{1/2}$ for the coefficients A and B was suggested by Peek. Even though the value of coefficient for the onset equation is different among researchers, but the value were closed to the Peek's value and the general form of the equation is remains unchanged [38, 39]. Equation 2 can be used in order to convert onset electric field to onset voltage for the geometry of plate and ESP's wire.

$$V_0 = aE_0 Ln\left(\frac{\pi b}{2a}\right) \tag{2}$$

where V_0 is onset voltage, a is wire diameter, E_0 is onset electric field and b is plate-to-plate distance in ESP.

5.2. Sparkover voltage

Sparkover voltage is the voltage that ESP cannot works or operates due to sparkling or in some citation called flashover voltage. Thus, Peek's equation is only valid for room temperature and there is no consideration or effects of the temperature and pressure take into account. Therefore, Turner has done some modification in Peek's sparkover relationship in a function of temperature and pressure.

$$V_s = 30a\left(1 + 0.01\frac{b}{a\sqrt{a}}\right)Ln\left(\frac{b}{a}\right) \tag{3}$$

$$E_s = 6.3*10^5\left(\frac{273}{T}P\right)^{1.65} \tag{4}$$

where V_s is sparkover voltage, T is temperature and P is a pressure.

5.3. Voltage-current relationship

Voltage-current relationship was performed by J.S. Townsend [40]. In Townsend's equation, the relationship between applied voltage and current are depends on the distance between the electrode and the diameter of the wire.

$$V = V_0 + aE_0\left[\left(\sqrt{1+\frac{2ib^2}{KE_0{}^2a^2}} - 1 - \ln\left(\frac{1+\sqrt{1+\frac{2ib^2}{KE_0{}^2a^2}}}{2}\right)\right)\right] \quad (5)$$

where V is applied voltage, i is the current per length of wire and K is mobility of the ions in m^2/v.sec.

A trend in empirical experiments was predicted by Townsend in a parabolic relation between the voltage and current. Another alternative of parabolic equation was suggested by Seaver and Mizuno in Equation 6 [34, 41].

$$i = MV(V - V_0) \quad (6)$$

where i is the current per length of wire, M is the empirical constant to calculate current in ESP and V is applied voltage. In the equation, M is an empirical constant and the equation is much simpler than the Equation 5. Moreover, the empirical constant A representing a few parameters from the Townsend equation which varies in term of the function of plate-to-plate distance, dielectric constant and wire diameter.

In 1952, Cooperman has developed a quite similar for the Townsend equation mainly for the low current constant [42].

$$A = \frac{K}{b^2 Ln\left(4b/\pi a\right)} \quad (7)$$

where A is a parameter of Peek's model for onset voltage which has the unit of electric field (V/m). For instant, this equation is only valid if the plate-to-plate distance is less than the distance between the rows of wires. Another equation for large currents was performed White [43].

$$i = \frac{K}{2b^2}\left[V - aE_0 Ln\left(\frac{b}{12a}\right)\right]^2 \quad (8)$$

where i is the current per length of wire, K is mobility of the ions in m^2/v.sec and V is applied voltage. Numerous alternative methods done by many researchers to calculate the voltage-current relationship such as Fazel and Parsons [44], McDonald et. al [45], McLean et. al [46, 47], and Talaie et. al [47]. In Equation 5 performed by Townsend classical equation, it was used to compare with the experimental and the theoretical data. For fundamental of electrical properties of ESP, Equation 1 to 3 was used to calculate.

6. Particle charging

An ionic current flow between the discharge and collecting electrodes is established by strong electric fields. Thus, the ions may collide when the suspended particle between the electrodes is filled. In order to accumulate the charge by the particles, several factors will be taken into account such as particle size, dielectric constant and residence time in ESP. There are two type charging mechanism which are diffusion and field charging.

6.1. Diffusion charging

For particle with the diameter less than 200 nm, diffusion charging is the main mechanism [48]. Due to Brownian motion and random collisions with air ions, the small particles will be charged. In order to calculate the charge on particle after diffusion charging, White [43] has been developing the equation.

$$q(t) = \frac{d_p kT}{2e} Ln(1+\tau) \tag{9}$$

where *q(t)* is charge on the particle (Coulomb) at a time, *t*, d_p is particle diameter, *k* is Boltzmann constant, *e* is electron charge equals $1.6*10^{-19}$ C, *T* is absolute temperature and τ is dimensionless parameter representing time. From the equation, τ is a dimensionless parameter for time which is defined by the next equation:

$$\tau = \frac{\pi d_p \overline{c_i} N_i e^2 t}{2kT} \tag{10}$$

where $\overline{c_i}$ is average thermal velocity, N_i is number of concentration of the particle and *k* is Boltzmann constant. Another equation which is more complex of diffusion and required numerical analysis to solve was develop by Lawless [49]. Particle will receive a distribution of charges due to diffusion charging is a stochastic phenomena. Thus, there will be a probability either the particle will have more or less charge compared to the predicted Equation 9 and Equation 10. Commonly, the charging process using diffusion will become very slow after about three dimensionless time units [50].

6.2. Field charging

In contrast, field charging plays a role in charging particles bigger than 1μm. For this particle, it has sufficient size and surface to be impacted by moving ions that comprise the current in the air gap of the ESP. When the path intercepts line of force in the electrical field, the particle will obtain the charge. This is happens due to the ionic current follows the line of force from discharge are to the collecting electrode area.

Due to particle charging, the number of charge on the particle at a time, *t* can be calculated using the equation below:

$$n_t = \left(\frac{3\xi}{\xi+2}\right)\left(\frac{Ed^2}{4K_E e}\right)\left(\frac{\pi K_E eKN_i t}{1+\pi K_E eKN_i t}\right) \tag{11}$$

where n_t is the number of charge on the particle at a time, *t* and K_E is constant in Coulomb's equation of electrostatic force with equals $9*10^9$ Nm^2/C^2.

6.3. Maximum particle charge

When the particle collect charge in ESP, it will create local electric field whereby it will cause distortion in the external electric field, maintained by the electrode (Figure 4). The conductivity of the particle and the amount of charge depends on the magnitude of local electric field. In order to avoid the driving force for additional field particle charging, the localized electric field have a solution since the electric fields produced by ions to move on the particle surface will repel ions on the same polarity. Therefore, it reduces the rate of charging and no additional charging occurs on the particle at specific charge. Using Hinds [48] equation, this charge can be calculated. The charge is known as saturation charge.

$$n_s = \left(\frac{3\xi_p}{\xi_p+2}\right)\left(\frac{Ed^2}{4K_E e}\right) \tag{12}$$

where n_s is saturation charge, ξ_p is dielectric constant of the particle (infinite for conductive particles) and *d* is diameter of particle.

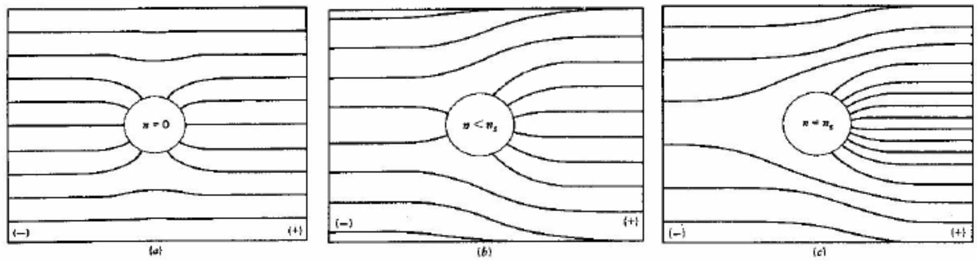

Fig. 4. Particle in a uniform field a) Uncharged particle b) Partially charge particle c) Particle at saturation charge [48].

6.4. Combined charging

For instance, diameter range between 0.2 μm and 1.0 μm are effective at putting the charges on particle. A simple way to predict the charge on particle is by diffusion mechanism in which by adding the charge using diffusion mechanism to the charge obtained by field charging mechanism. Turner [50] and Unger [51] has shown this method by experimental to provide a good approximation of the charge collected by the particle.

Cochet [52] also develop an analytical method which can be used to calculate the quantity charge collected by the particle. There is an assumption being made by Cochet which is if the time is infinite, particle will collect the same charge if the particle is same size.

$$q = \left\{ \left(1 + 2\frac{\lambda}{d_p}\right)^2 + \left(\frac{2}{1 + 2\frac{\lambda}{d_p}}\right)\left(\frac{\varepsilon_p - 1}{\varepsilon_p + 2}\right) \right\} \pi \varepsilon_0 d_p^2 E \qquad (13)$$

where q is charge on the particle, λ is mean free path of air molecules, and d_p is particle diameter. There is a numerical models introduced by Lawless to calculate the number of charge on the particle instead of these two analytical methods [49]. On the other hand, Sato have suggested that Equation 8 and 12 is the best for his experimental data [53].

7. Conclusions

In this paper, there are adverse effects in particulate matter in many toxicological and epidemiological studies. Besides, from the evidence shows that the ultra fine particle can cause health effect and can penetrate the cell membranes, enter the blood and even reach in the brain. Therefore, ESP is one of the methods to reduce the PM in the diesel engine. Several technique of measurement is being discussed in this paper such as total particulate matter (PM), size distribution and number of concentration for measuring the engine exhaust particle emissions. In this review, the fundamental of electrical properties of ESP, including the onset voltage, the voltage-current relationship and sparkover voltage is mentioned. This is important in order to calculate the most efficient current and voltage in ESP.

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