Experimental Study on Diesel Exhaust Particles Agglomeration Using Acoustic Waves

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Abstract

Diesel exhaust particles are a complex mixture of thousands of gases and fine substances that contain more than 40 different environmental contaminants. Being exposed to these exhaust particles (called soot) can cause lung damage and respiratory problems. Diesel particulate filters are used in many countries for mobile sources as a legal obligation to decrease harmful effect of these fine particles. The size range of these particles is varied from 0.01 to 1 µm. Moreover, it takes a long time to be settled when they are outspread in atmosphere. In this paper, homogeneous plane standing waves are used to coagulate nano particles in order to achieve larger size which has a better gravitational settling. It means that fine particles are converted into a large one. Theoretical mechanisms are studied which led to experimental results in 155(db) and 160 (db). The results show that acoustic precipitators have a good performance in removing fine particles in diesel exhaust. Additionally, they indicate that at high pressure levels, the system has high efficiency for removing fine particles

Keywords: *fine particle, acoustic precipitator, acoustic agglomeration, diesel combustion.*

1. INTRODUCTION

In recent years, concerning about diesel exhaust emissions from mobile sources has been increased. In the motor industry, the diesel cars have been promoted more than petrol cars because of their lower fuel consumption. Moreover diesel is considered as a cleaner fuel than petrol. However, diesel cars have very different emission characteristics [1]. Therefore, an increase in diesel cars may cause important positive effects on urban air quality, smog formation, global warming and other environmental issues [2]. as diesel fuel burns in an engine, particles and gases which are formed by the combustion process travel out the exhaust system of the vehicle. The diameter of these particles is varied from 50 nm to1 µm [3, 4]. Furthermore, they easily disperse in atmosphere along hot gases. Because of this characteristic (aerodynamic diameter), it takes a long time for these particles to be settled. Therefore, they are spread out in the larger area; consequently, it increases the time of concentration process. There is increasing evidence that several health effects are associated with the ultra-fine particles with diameters below 100 nm [5, 6]. In this way, it is desirable to remove the particles from the gases (in diesel exhaust) before their emission in the atmosphere. The existing filtration procedures are not sufficiently efficient for removing small particle. Acoustic aerosol agglomeration and precipitation can provide an appropriate method for removing these fine particles [7,8]. Acoustic agglomeration is a process in which small aerosol particles agglomerate with larger ones and with each other to eliminate small particles from the gas stream [9]. Many experimental investigations have proven that this mechanism increases the size of the particles and therefore can lead to improvement in the collection efficiency of some conventional air filters [10].The propose of this paper is to present and discus results of an experimental study into the effect of acoustic wave in agglomerating soot particle in low frequency and sound pressure level more than 130 Db.

2. Theory and Methodology

Here are some theories that describe acoustic wave effects on agglomeration of fine particle. In order to show the effects of each mechanism, the

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acoustic agglomeration frequency function β (agglomeration kernel) is needed. Agglomeration kernel is an index that represents coagulation rate and dependency of each parameter. Thus the agglomeration kernel characterizes the agglomeration process. It means that different agglomeration process and mechanism have a different agglomeration kernel. There are several main mechanisms that describe acoustic agglomeration in the fields including orthokinetic, hydrodynamic and turbulence.

2-1. Orthogenetic Agglomeration

Mednikov introduced the orthokinetic agglomeration process in 1965 [11]. In this mechanism, aerosol particles with different sizes have different entrainment factors in the oscillating gas, which leads to relative motion between suspended particles. Since the large particles are stationary but small particles are moving, small particles near the large particles come into contact and adhere to them in order to cause agglomeration [12]. The large particles have a certain volume, so that if any small particle exists, it agglomerates with the large particle. This volume is called the agglomeration volume. During the first cycle, any small particle present in this volume is collected by larger ones, but the process of acoustic agglomeration will continue by refilling. Scattering interactions, hydrodynamic interactions, and Brownian motion are the main refill mechanisms for being filled up with the acoustic agglomeration volume [13]. Following Song (1990) [14], the orthogenetic kernel is expressed as Eq (1):

$$\beta^{Or} = 2(r_1 + r_2)^2 U_0 \eta_{s12} \tag{1}$$

Whereη_{12}, the relative entrainment factor between particles 1 and 2, and U_0 is the velocity amplitude of a sound wave, m/s. r_1 and $r_2$areparticle diameter, m

2-2. Hydrodynamic Mechanism

Hydrodynamic Mechanism coagulate nano particle by two ways:

2-2-1. Acoustic Radiation Pressure

Acoustic radiation pressure is generated whenever an acoustic wave is either absorbed or scattered by an obstructing object. This phenomenon is induced by momentum and leads to the attracted particles. When a single particle is in a medium, due to scattered waves from the other nearby particles, secondary radiation pressure influences it. This is a so-called mutual radiation pressure (MRP) [15]. Recently, studies show that if the centrelines of two adjacent particles are aligned on the acoustic wave axis, the force between them becomes repulsion. With an increase in the angle, attraction will govern and have a maximum of 90°. Also, such studies confirm that the MRP mechanism has a short-range influence [16].

2-2-2. Acoustic Wake Effect

In acoustic wake mechanisms, particles interact through the surrounding fluid due to hydrodynamic forces and asymmetry of the flow field around each particle [17]. These mechanisms, which are not dependent on the relative differences in the acoustic particle entrainments, can act from distances larger than the acoustic displacements, and have to be considered the main mechanism in the agglomeration of mono-disperse aerosols, where particles are equally entrained [18]. In an ideal fluid the hydrodynamic agglomeration kernel can be described by the classic expression of konig as Eq (2)

$$\beta^{Hy} = \frac{\sqrt{3}\rho_0 U_0^2}{9\mu} \frac{r_1^2 r_2^2}{r_1 + r_2} \tag{2}$$

Where the μ viscosity of air, kg/m s

2-3. Turbulent Mechanism

Acoustically induced turbulence is a main mechanism in agglomeration of particles. When sound pressure level exceeds a certain threshold value (160 dB) the flow be turbulence and small eddies created .if two particle trap in eddy have different inertia they carried along eddy by different velocity and this relative velocity among particle cause them to impact and agglomerate.(turbulence inertia)

Diffusion turbulent interactions are produced between particles of the same size carried by two Adjacent eddies (turbulence diffusion) [19]. these two kernel, turbulence inertia Eq (3) and turbulence diffusion Eq (4) are written as:

$$K_{TI} = \pi E_{TI} (a_1 + a_2)^2 (1 - \frac{\rho_g}{\rho_p}) \left(\frac{\varepsilon^3}{\upsilon_g} \right)^{\frac{1}{4}} \times (\tau_1 - \tau_2) \tag{3}$$

$$K_{TD} = \pi (a_1 + a_2)^3 E_{TD} \left(\frac{\varepsilon}{V_g} \right)^{\frac{1}{2}} \tag{4}$$

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2-4. Browning Diffusion

In submicron particle browning diffusion found as a main mechanism in coagulation of particles [20, 25]. In diesel exhaust more than 90 percent of particle mass are less than 1micrometer and gas temperature is high [9]. Therefore Brownian kernels must be impressive in agglomeration**.** The kernel for Brownian coagulation, with Cunningham slip correction applied, is Eq (5)

$$\beta^B = \frac{2kT}{3\mu}(r_1 + r_2)\left(\frac{C_1}{r_1} + \frac{C_2}{r_2}\right) \quad (5)$$

3. Test Set Up and Measurement Procedure

The experimental facilities basically consist of a mono disperse and a poly disperse aerosol generator, an acoustic filter chamber, sound source and sampling and measurement station (see Fig.1.). The glass chamber is excited at one end by an exponential horn acting as a sound source. It is terminated at the other end with a reflecting plate. The sound wave within the chamber is resonated so as to obtain a nearly infinite standing wave ratio (a high intensity for an anti-node and low intensity for a node). The cylindrical chamber which has a circular cross-section is mated to a horn and an exponential flare. In this study, the test chamber is made of a glass cylinder and it has 56 mm inner diameter with a length of 1.6 m; additionally, the wall of the chamber is 2mm thick. The other end of the chamber is terminated by a stainless steel plate which has 12 mm thick. The plate is milled so that it can be extended about 8mm into the chamber. Acoustic source consists of audio generator (model ARMA AGA-101), power amplifier (model ECOCHANG XPA6010), frequency counter, speakers, current-meter and voltmeter. This collection supplies acoustic wave as well as defines frequency and power. The power is measured with current-meter and voltmeter. Aerosol flow is supplied with aerosol generator.

The mono-disperse and poly-disperse aerosols of D.O.P (C_6H_4 ($COOCH_2CH$ (C_2H_5) C4H9)) which are used in this experiment are produced by two aerosol generator devices. (T.S.I. model 3475 and GRIMM model 78225)

In order to analyze the aerosols during the tests, cascade impact or aerosol counter (model Grimm) are used.

The test's temperature are T = 298 (K) and the mean temperature and pressure respectively. During the experiment, the test chamber is not isolated from outside condition; therefore the measured pressure is equal to acoustic pressure.

When a sound wave is propagated in a tube, there is several frequencies that have maximum sound pressure (SPL) called resonance frequency. The maximum agglomeration usually happens in maximum sound pressure level. The sound is emitted based on the geometric shape of the tube and it can be measured by testing [23]. The resonance frequencies which are used in this study are as follows (table 1):

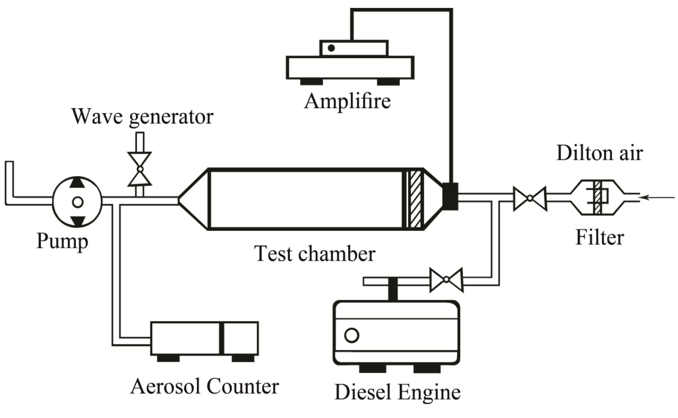

Fig1. Experimental Set up

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Table.1. Resonance Frequency

Resonance frequency (Hz)	870	550	650	749
Sound pressure level (db)	148	150	155	162

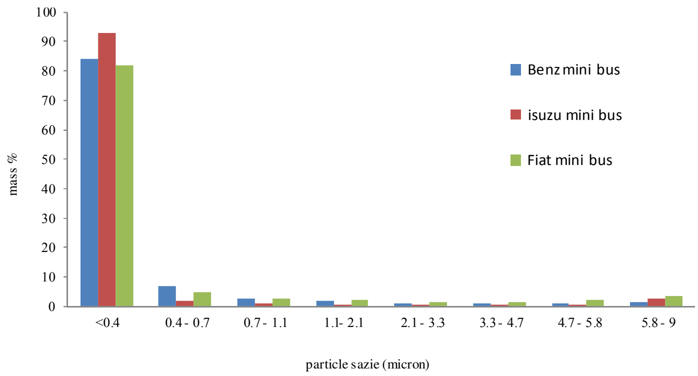

Fig .2. Particle size range in Sampling Test

In this paper, at first the size of diesel exhaust particles is measured. Then the same size is generated by aerosol generator. Moreover, many tests are performed in the condition similar to diesel exhaust in order to reach the best case with a maximum efficiency. The parameters including sound pressure level, resonance frequency, temperature, flow and time relating to acoustic wave swing in stand tube are changed in each test. Four resonance frequencies which have a best efficiency are selected. Finally, test is carried out by real diesel exhaust particles to verify the tests result.

4. Results and Discussion

The 98 percent of soot particles is composed of carbon and is typically spherical in shape. While most of these particles are only less than 1 micron in size, they often clump together to form a larger particles. In order to measure the size of diesel engine particles, a convertor is used. In this way, particles' impact is decreased, otherwise they will clump together and the test will be incorrect. This way of measuring is carried out on 3 kinds of diesel engine. Results which are shown in fig 2 and suggest that the sizes of 90% of particles are less than 0.4 micrometer.

In order to have a similar result in diesel exhaust concentrated aerosols, generate 7×108 particles per liter.

4-1-1. the Effect of Sound Pressure Level

Amplitude of sound wave velocity (U0) is usually one of the main parameter that increases agglomeration rate. Orthokinetic kernel and hydrodynamic kernel are proportional to U0 and the square of U0 respectively. According to Eq (6), by increasing in sound pressure level, U0 will be increased as well as orthokinetic and hydrodynamic kernel [14]. It means that the maximum sound pressure level leads to the maximum agglomeration.

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$$U_0 = \frac{1}{c_0 \rho_0} 10^{(SPL-94)/20} \qquad (6)$$

The theories are confirmed by Experimental test. Fig 3 indicates the effect of sound pressure on particles coagulation clearly. The ratio of Ni to Ni0 varies through different sound pressure. In the size range less than 0.4 micron, the nano particles collide into one another, make them coagulate. Hence the concentration of particles with the size of 0.26-0.4 is decreased. By contrast, new particle (coagulating particle) increases concentration of the particles with the size of 0.4-1.0 micron. The acoustic agglomeration is directly proportional to the sound pressure; it means that mounting sound pressure can bring an increase in the acoustic agglomeration. It is expected that the ratio is added because of precipitation; therefore, coagulating particle is removed from the system. It's the reason why the ratio is decreased. Bigger particles sweep the smaller one; moreover, fine particles are eliminated by precipitation.

As it is discussed before, from pressure level higher than159-160 dB, the media in the experimental chamber is totally turbulent [21, 24]. In the sound pressure higher than 159 (dB), turbulence is the main mechanism in acoustic agglomeration. As it is shown in fig 4, it differs considerably from other mechanism.

4-1-2. the Effect of Time

In fig 5, the variation of each particle size at different times is investigated at the frequency of 749 Hz with 162 (db). It's clear that when a particle lasts in acoustic field longer, more particles are swept by acoustic wave. Consequently, particles' impact and acoustic agglomeration rate are increased. Time relating to each kernel is already explained in this paper except KTD which increases agglomeration rate in other mechanism. The theories are confirmed by experimental results. In fig, the variation of each particle size at the different time is investigated. After a minute, number of particles with the size less than 0.45 is decreased, especially for a range between 0.3-0.35. But in bigger sizes, no variety has been seen. It means that after a minute, coagulation just has been happened for the particles with the size of 0.26-0.45. After 5 or 10 minute, the number of particles of each size is decreased equally

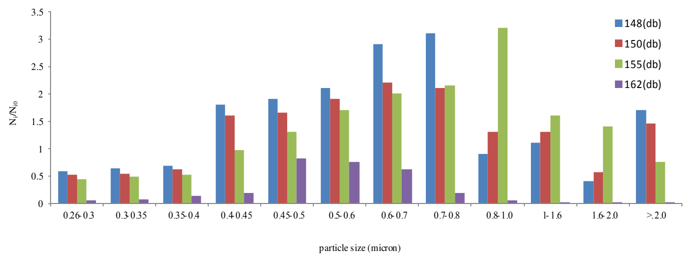

Fig.3. Relaion Particle Size to (N_i /N_{i0}) in different sound pressure After Acoustic Agglomeration

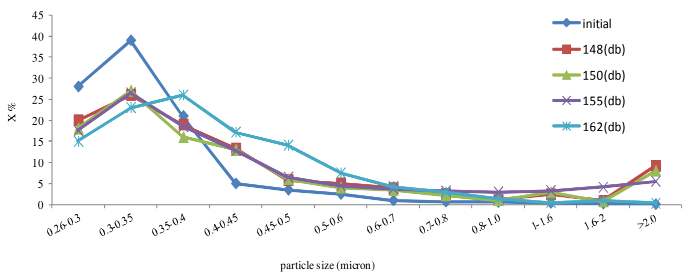

Fig.4. Relation Particle Size to X= 100× (N_i /N_{tot}) in different sound pressure After Acoustic Agglomeration

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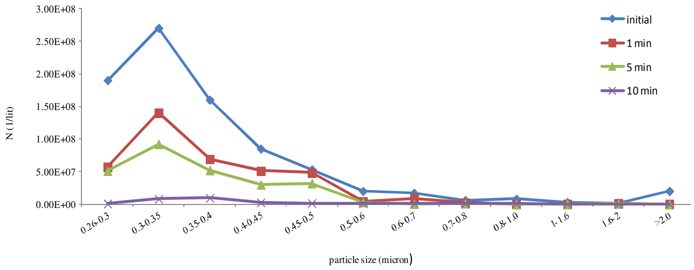

Fig.5. particles countered after acoustic wave in frequency 749 Hz (162db)

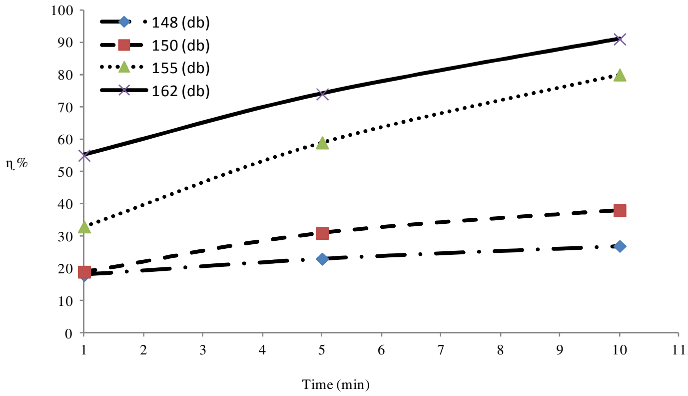

Fig.6. *Influence of time on acoustic removal efficiency* (η) in f= 749 Hz

Furthermore, the acoustic wave has an enough time to coagulate all particles with different sizes. From 5 to 10 minute, efficiency of the system is raised from 55 % to 91%. The value for other sound pressures is shown in fig. It indicates that in order to achieve same efficiency in lower sound pressure, less time is needed in high sound pressure.

4-1-3. the Effect of Frequency

Fig 8 and 9 indicate particle size variation before and after acoustic wave in comparison to Ni /Ni0 (Ni, Ni0 are number of particle before and after acoustic wave). The peak of Particles' distribution size is shifted to the right, additionally; the concentration of particles with the size of 0.35-0.8 is increased. In higher frequency, the size peak is shifted further to the right and the concentration of particles with the size of 0.6-2 micron is decreased. This chart suggests that bigger particles are considered as a kernel for the clusters. Acoustic precipitations are shown in fig. Due to difference dependency for each kernel, there is no difference between these two graphs. Accordingly, a conclusive opinion cannot be provided.

4-1-4. Effect of Temperature

The exhaust temperature to vary between 100 and 350 ◦C, but in experiment, temperature considered 25 ◦C [20]. The temperature of the gas medium affects the agglomeration rate or acoustic precipitator efficiency though the change of the acoustic impedance and the viscosity. For an ideal gas, the acoustic impedance, defined by the product if the gas density and sound speed, is expressed as Eq (7) and Eq (8)

$$\rho_0 c_0 = P_0 \sqrt{\frac{\gamma R}{T_0}} \qquad (7)$$

the amplitude of acoustic velocity becomes

$$U_0 = \frac{1}{P_0} \sqrt{\frac{T_0}{\gamma R}} 10^{(SPL-94)/20} \qquad (8)$$

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For the fixed SPL, U_0 is proportional to the square root of T_0. Thus the higher the temperature, the lower the acoustic impedance and higher the acoustic velocity. Consequently, the total agglomeration rate or acoustic precipitator efficiency becomes larger. The variation of the agglomeration rate with the temperature for two particles of 10 µm and 1µm in diameter are shown in Fig.9 Where SPL is 154 and is 1 atm. The reason that β^{Hy} is nearly constant over the temperature change becomes clear when the effect of the temperature on viscosity is included. The viscosity of air also increases with the temperature. This tends to counterbalance the effect of the reduction of the acoustic impedance on the agglomeration rate since it is inversely proportional to the viscosity [14]. Therefore the experiment condition is agreeable to use in actual condition (exhaust diesel). Because from this matter, with increasing temperature the efficiency of acoustic precipitator is increased, in diesel exhaust condition have upper efficiency to remove fine particles

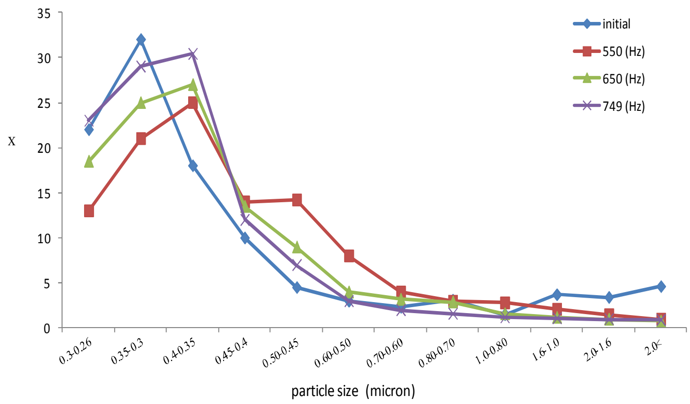

Fig.7. Relation Particle Size to (N_i /N_{i0}) in frequency 749 Hz, (162 db) and t=10 min

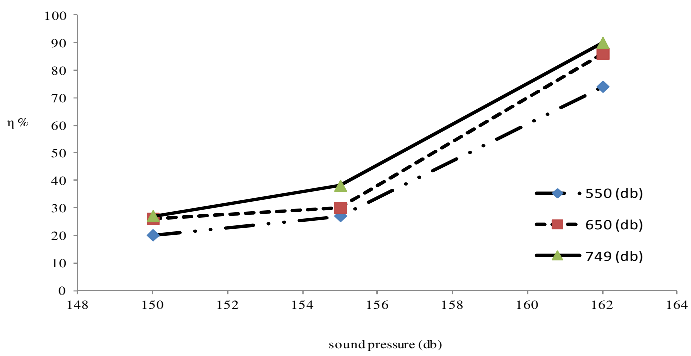

Fig.8. Influence of frequency in acoustic removal efficiency

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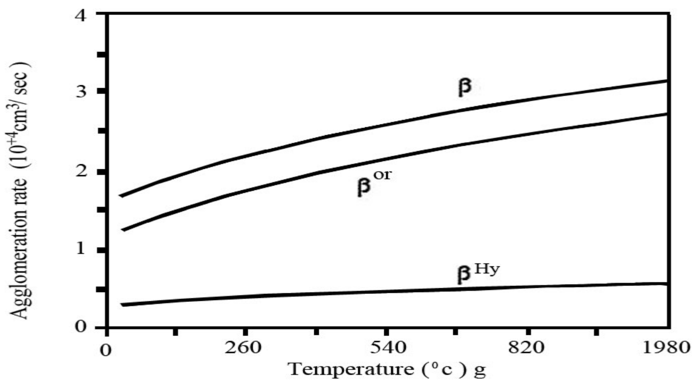

Fig.9. Influence of frequency in acoustic removal efficiency [14].

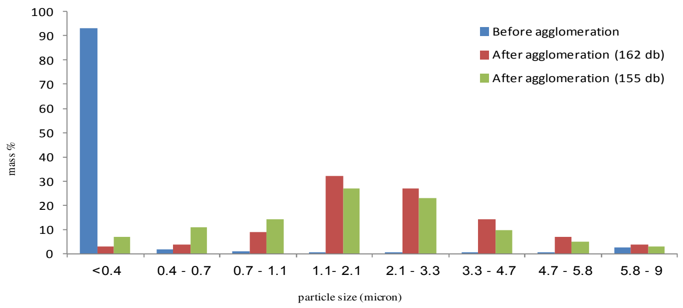

Fig.10. Agglomeration test on mini buss (Isuzu), f=749,650 Hz, t=10 min

4-2 The Test of Diesel Engine

The Result for diesel engine is presented in fig.10 the efficiency of system for particle less than 0.4 micrometre is more than 97 % at f=749 Hz and t=10 min. Therefore, the experiment condition is agreeable to use in actual condition (exhaust diesel).

5. Conclusion:

Acoustic agglomeration in lab gives an efficient result in real diesel engine and will be applicable in busses and trucks. It can be used in all temperature and have not any secondary pollution. But noise pollution is the main problem of acoustic precipitator in diesel engine; moreover, it uses sound pressure level higher than 140 (db) which has a negative effect on human health. REFRENCE

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